Chilled Water Thermal Storage System and Demand Response at the University of California at Merced

DRAFT

Jessica Granderson
Postdoctoral Fellow

Junqiao Han Dudley
Research Associate

Sila Kiliccote
Sr. Scientific Eng. Associate

Mary Ann Piette
Staff Scientist

Lawrence Berkeley National Laboratory
Berkeley, CA United States of America

ABSTRACT

University of California at Merced is a unique campus that has benefited from intensive efforts to maximize energy efficiency, and has participated in a demand response program for the past two years. Campus demand response evaluations are often difficult because of the complexities introduced by central heating and cooling, non-coincident and diverse building loads, and existence of a single electrical meter for the entire campus. At the University of California at Merced, a two million gallon chilled water storage system is charged daily during off-peak price periods and used to flatten the load profile during peak demand periods, further complicating demand response scenarios. The goal of this research is to study demand response savings in the presence of storage systems in a campus setting. First, University of California at Merced is described and its participation in a demand response event during 2008 is detailed. Second, a set of demand response strategies were pre-programmed into the campus control system to enable semi-automated demand response during a 2009 event, which is also evaluated. Finally, demand savings results are applied to the utility's DR incentives structure to calculate the financial savings under various DR programs and tariffs.

INTRODUCTION

The goal of this study is to evaluate the demand response (DR) at the University of California at Merced (UCM), including the load reduction potential with thermal energy storage (TES) and to quantify demand savings by building and end use, under automated and semi-automated demand shedding strategies. Campus DR evaluations are often complicated by the presence of diverse building types and associated loads, and a variety of distributed and centralized heating and cooling systems. In addition although campuses typically feature one master meter under a utility tariff, the central plant and buildings themselves exhibit non-coincident peak loads. As a result, load reductions at the building level may be obscured at the campus master meter. Finally, many campuses are not metered to a degree that permits disaggregation of campus-wide load reductions to individual buildings, and end uses.

Opened in 2005, UCM is the newest University of California campus. Prior to opening, the campus made a strong commitment to energy efficient building design and energy plays a fundamental role in campus objectives (Brown 2002). UCM uses Automated Logic Corporation's WebCTRL energy management and control system (EMCS), through which energy and equipment data can be remotely accessed. One result of the campus' initial focus on energy is an especially comprehensive monitoring and metering system in which over 10,000 points are tracked across 800,000 ft^2 of built space (Brown et al. 2007). A variety of historic trends are stored ranging from whole-building meters, to electric panels, zone temperatures, thermostat overrides and fan power.

At UCM a two-million-gallon chilled water TES is charged daily during off-peak price period, and utilized during peak price period to flatten the load profile. This demand shifting complicates DR strategies by drastically reducing the mid-day peak that would otherwise exist. Chilled water from the central plant provides cooling to each of three academic buildings, as well as to the housing units, dining facilities, and auxiliary buildings. The central plant also supplies heating hot water to the primary academic buildings, and process steam to the Science and Engineering building. UCM utilizes variable air volume HVAC controls with variable frequency drive pumps and fans. Most of the campus lighting is scheduled, although some areas feature local occupancy or photosensor controls.

METHODOLOGY

Proceedings of the Ninth International Conference for Enhanced Building Operations, Austin, Texas, November 17 - 19, 2009

A suite of complementary analyses was conducted to gain a comprehensive understanding of demand reduction at the UCM campus. Three data sources were used: 15-minute interval data from the campus' utility account; 15-minute data from whole-building electric meters and submeters stored in Web-CTRL; and hourly temperature data from National Oceanic and Atmospheric Administration. (NOAA).

Campus loads were analyzed for load variability, weather sensitivity (Coughlin et al. 2009) and load shape statistical summary. DR potential was assessed through campus' historical DR participation and load shape statistical summary. Load variability (VAR) is essentially a measure of coefficient of variance; it is the ratio of standard deviation to average demand, for each hour during the time period of interest, as defined in Equation 1. The bigger the load variability, the more difficult it is to accurately predict the load. Load shape statistical summary (LSS) shows the average, minimum, maximum and standard error of 15-min demand across each day in the period of interest. LSS and VAR both reflect DR potential as they indicate when and where peak loads occur, or the extend to which loads vary or can be reliably predicted.

$$VAR = \frac{\sqrt{\frac{\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2}{N-1}}}{\bar{x}} \qquad (1)$$

where $\bar{x}$ *is the average hourly load in the period, and N is the number of days in the period*

Weather sensitivity reflects the degree to which loads are impacted by local weather, and is an important consideration in baseline selection. The baseline is critical to demand savings calculations, as it is used as the reference from which to measure the load shed during an event. Weather sensitivity was calculated by the rank order correlation (ROC) between paired load and outside air temperature, based on the Spearman rank order correlation coefficient, provided in Equation 2.

$$r_s = 1 - \frac{6\left(\sum D^2\right)}{N\left(N^2 - 1\right)} \qquad (2)$$

where D is the difference between each pair of ranks

Two baseline methods were used to calculate load reduction. The three-in-ten (3/10) baseline is common to California utility programs, and is based on the average of three days out of the prior ten weekdays, excluding holidays, in which energy consumption was highest during DR hours. The second baseline, the morning-adjusted outside air temperature regression (OAT_MA), was calculated based on a 20-day linear regression between interval meter data and outside air temperature (OAT). The baseline indicated by the regression is then calibrated with the actual demand on the DR event day, with an adjustment factor based on actual loads during the pre-event morning hours. The adjustment factor is the ratio of the actual load to the loads predicted in the regression (Han, et al. 2008).

TES impact and DR savings at the campus and building levels were determined by comparing interval meter data to the baseline. Submetered loads at the panel and component levels were used to disaggregate building load reductions into specific end uses, including lighting, plug loads, HVAC and mechanical equipment, and server or computer equipment.

The economic value of UCM's demand savings was calculated by first determining the utility programs for which the campus is eligible. UCM's observed demand savings were then used to compute the incentives that would have accrued under each DR program participation.

This set of analyses was applied to two DR events. A manual strategy was applied in August 2008, and a semi-automated strategy was implemented in July 2009. Under the manual strategy the campus energy manager increased zone temperature setpoints individually through the Web-CTRL system, and notices were sent to building occupants requesting that they turn off unused lights and equipment. Under the semi-automated strategy, temperature setpoints were globally programmed to rise 4ºF (2.2ºC) upon initiation by the energy manager. At the conclusion of the event, setpoints were programmed to return to normal in two steps, to avoid rebound (Motegi et al. 2007) and the creation of a new peak.

RESULTS

Load Shape and Variability

Table 1 and Figure 1 show the results of load variability calculations at UCM in the summer of 2008. In building applications, hourly load variability under 0.15 is considered low. Throughout the summer peak period (May through October), load variability between noon and 6 pm had a maximum value of 0.12, and average value 0.11. Hourly averages for the summer peak period are higher due to the month-to-month variations in the load.

Table 1. UCM load variability in the summer of 2008

Month	12:00	13:00	14:00	15:00	16:00	17:00	18:00	Average
May	0.07	0.07	0.07	0.08	0.08	0.08	0.08	0.08
Jun	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Jul	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Aug	0.10	0.10	0.11	0.10	0.10	0.11	0.10	0.10
Sep	0.02	0.03	0.03	0.02	0.02	0.03	0.03	0.03
Oct	0.04	0.04	0.03	0.04	0.04	0.04	0.04	0.04
May - Oct	0.10	0.11	0.11	0.11	0.11	0.11	0.12	0.11

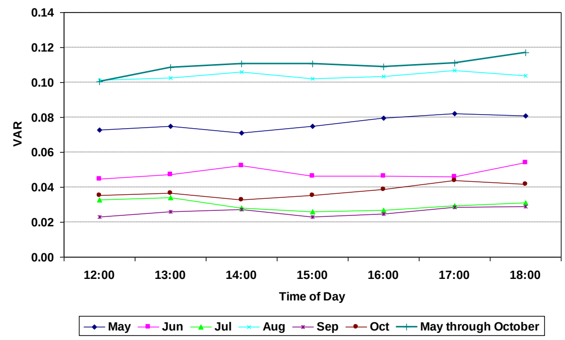


Figure 1. UCM load variability in the summer of 2008

The load shape statistical summary for UCM campus is shown in Figure 2. The load is flat during occupied hours with a small deviation from late morning to 7:00 PM. Early morning variability is likely due to daily differences in the amount of time required for the chillers to charge the TES tank.

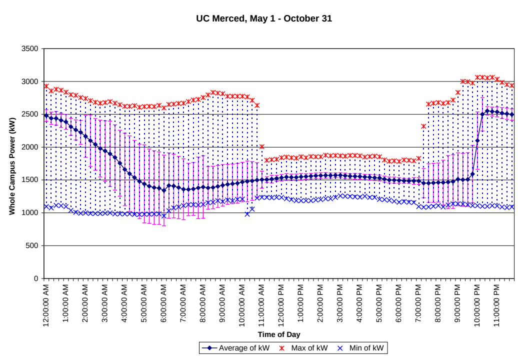


Figure 2. Load shape statistical summary for UCM (summer 2008)

Weather Sensitivity

Table 2 and Figure 3 summarize UCM's hourly ROC findings. For buildings, 0.7 is considered the sensitivity threshold, yet throughout the summer DR period, UCM ranges from 0.01 to 0.17. The weather sensitivity calculations may not be applicable to sites with on-site generation and storage. While overall the data do not indicate that UCM is a weather sensitive campus, there is a significant range in observed sensitivity in *individual buildings* from one month to another. The campus does however appear to be weather sensitive in months such as May, when temperatures can be high, yet the TES is not charged daily. Therefore, the weather-normalized baseline was used to evaluate the DR savings that are reported.

Table 2. UCM weather sensitivity in the summer of 2008

Month	12:00	13:00	14:00	15:00	16:00	17:00	18:00	Average
May	0.75	0.78	0.74	0.81	0.80	0.78	0.72	0.77
Jun	0.59	0.60	0.54	0.51	0.53	0.52	0.44	0.53
Jul	0.71	0.68	0.71	0.66	0.51	0.58	0.79	0.66
Aug	0.38	0.34	0.32	0.28	0.18	0.25	0.15	0.27
Sep	0.77	0.76	0.77	0.82	0.56	0.41	0.36	0.63
Oct	0.48	0.49	0.59	0.64	0.56	0.61	0.34	0.53
May - Oct	0.08	0.12	0.10	0.12	0.07	0.01	-0.17	0.05

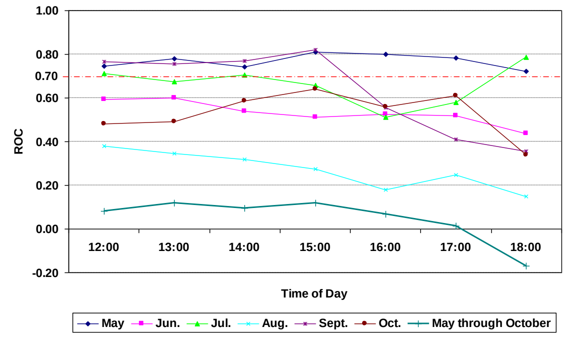
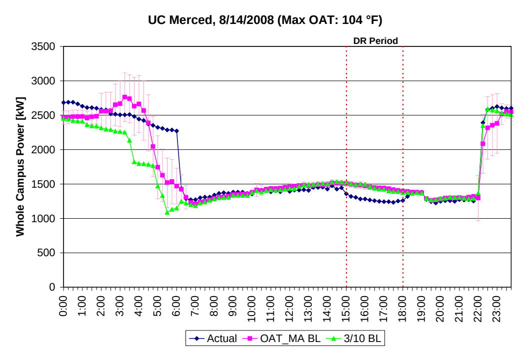


Figure 3. UCM's weather sensitivity in the summer of 2008

DR Savings

Figure 4 and Table 3 summarize the campus response during two DR events called in 2008 and in 2009. In the graphs, the OAT_MA baseline load is plotted with square markers and the error bars indicate standard error. The load on the event day is plotted with diamond markers and the DR period is indicated with the vertical dotted lines. In the table, average and maximum demand reduction are shown, as well as the average and maximum percent demand reductions relative to the OAT_MA baseline.



Proceedings of the Ninth International Conference for Enhanced Building Operations, Austin, Texas, November 17 - 19, 2009

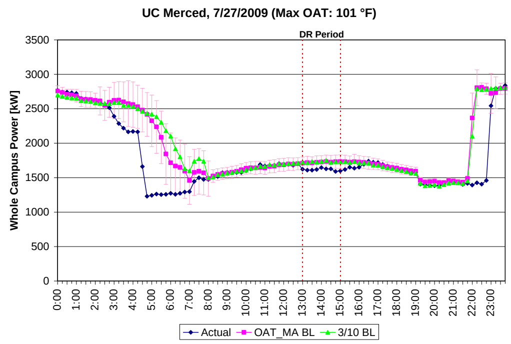


Figure 4. DR events at UCM, 2008 (top) and 2009 (bottom)

Table 3. Summary of whole campus DR savings from each DR event in 2008 and 2009.

Date	Time	Demand kW		Percentage	
		Max	Ave	Max	Ave
August 14, 2008	15:00-16:00	202	187	14%	13%
	16:00-17:00	199	193	14%	13%
	17:00-18:00	188	166	13%	12%
	15:00-18:00	202	182	14%	13%
July 27, 2009	13:00-14:00	110	100	6%	6%
	14:00-15:00	143	121	8%	7%
	13:00-15:00	143	110	8%	6%

In 2008 under the manual strategy the maximum and average demand reduction throughout the three-hour DR event period were 14% and 13%, respectively. In 2009 under the semi-automated strategy the maximum and average reductions throughout the two-hour DR event period were 8% and 6%.

The relative contribution of the individual buildings to the whole-campus reduction in 2008 is shown in Figure 5. The category labeled 'other' includes buildings such as the dining and common areas, gymnasium, and dorms. Taken together, the three main buildings make up half of the campus load reduction. The Library accounted for 30% of the campus load reduction, the Classroom and Office building (COB) 13%, and the Science and Engineering (S&E) building 6%.

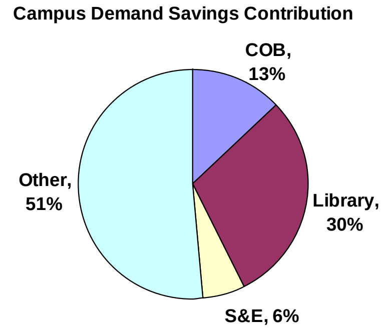


Figure 5. Relative building contributions to total demand savings

In addition to each building's relative contribution to the campus savings, the absolute savings at each building were evaluated. Table 4 summarizes the whole building load reductions measured against the individual OAT_MA baseline throughout the DR period.

Table 4. Demand savings at three larger buildings on campus, summer 2008

Building	kW		W/ft^2 (W/m^2)		Percent	
	Max	Ave.	Max	Ave.	Max	Ave.
COB	29	24	0.32 (0.03)	0.26 (0.02)	28%	23%
Library	77	54	0.39 (0.04)	0.27 (0.03)	28%	21%
S&E	39	11	0.20 (0.02)	0.06 (0.01)	6%	2%

Demand savings at the COB and Library buildings were disaggregated according to end uses. The S&E building was excluded, since due to the complexity of the electrical distribution, the majority of end uses are not submetered at the panel level. The data collected from the submeters show that the most significant savings were results of demand reductions in HVAC and mechanical equipment. Figure 6 shows that HVAC and mechanical shed ranged from 50-75%. As indicated in Figure 7, HVAC load reductions were largely due to decreases in power at air handler supply fans. Returning to Figure 6, lighting loads contributed from 15-40% to whole-building savings, while plug loads accounted for 7-10%.

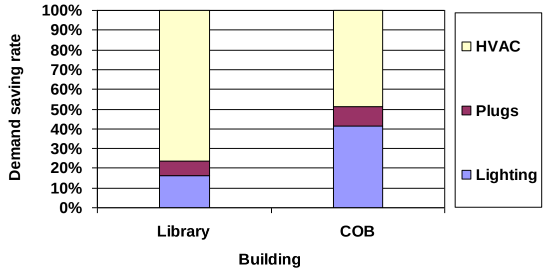


Figure 6. Library and COB end use demand savings on August 14, 2008

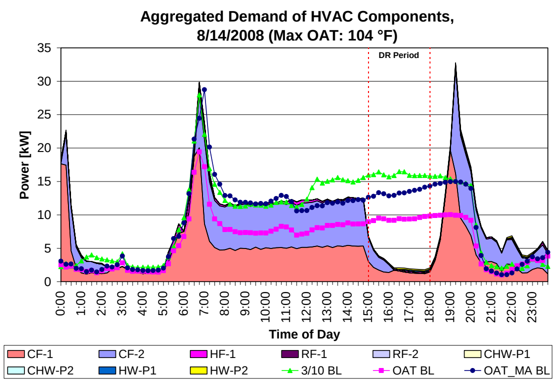


Figure 7. Aggregated demand of HVAC components in COB on August 14, 2008

UCM currently participates in DR through PG&E's aggregator managed portfolio (AMP) program in a semi-automated fashion. Should the facility choose to participate in fully automated DR programs offered by PG&E, it is eligible to participate in the demand bidding, critical peak pricing and peak choice programs. To calculate the rewards that could be earned under each program, UCM's achieved demand reduction in 2009 is applied to specific program incentives. The description of the programs and incentives are summarized below[1]:

- Demand Bidding Program (DBP): This is a voluntary price-based program where customers are encouraged to bid a demand reduction amount (kW) for at least two consecutive hours between noon and 8 pm and are offered 0.50/kWh for day-ahead or 0.60/kWh for day-of participation. The analysis assumed 12 DBP events and four-hour participation by UCM.
- Peak Choice: This DR program allows the participant to choose from a variety of options such as notification time, duration, total number of events, number of consecutive participation etc. It also has two subscription levels: Best Effort (no penalties) and Committed (penalty for not achieving the commitment amount). For both Peak Choice subscriptions UCM's participation is considered for 30 minute advance notice, 1pm to 7 pm participation, 2 to 3 hours of duration with up to 25 events including allowing for up to three consecutive events.
- Critical Peak Pricing (CPP): This is a tariff that is designed to be revenue neutral to the class average load shape. Between May 1st and October 31st, the participants receive credits from their peak and part-peak rates while being subject to three-times and five-times prices up to 12 times between noon and 3pm and 3pm to 6 pm, respectively.

The benefits of participating in each of the programs assuming an average 110 kW demand reduction is summarized in Table 5. Under DBP, with 110 kW reduction over four hours, the day-ahead benefits are $2,640 and the day-of benefits are $3,168. Under Peak Choice Best Effort, UCM has the potential to save $8,250. Peak Choice Committed participants receive the full payment amount if they participate in each event, and incur penalties for those events in which they either don't participate, or don't meet the committed load. CPP analysis shows the total credits minus charges that occur during the CPP period. Given the economic analysis, the most profitable DR program for UCM is the Peak Choice Committed option, although penalties may be applied if UCM is unable to maintain half of the 110 kW committed reduction. The least risky option is Peak Choice Best Effort where customers are not penalized for non-participation.

Table 5. Incentives from various DR programs for 110 kW demand reduction

DR Program	Incentive	Penalty
DBP (day-of)	$3,168	-
DBP (day-ahead)	$2,640	-
Peak Choice (Best Effort)	$8,250	-
Peak Choice (Committed)	$8,695.50	$4,328
CPP (assuming 5% reduction)	$1,435	-
CPP (assuming 12% reduction)	$4,504	-

[1] More information on PG&E's DR programs are available at http://www.pge.com/mybusiness/energysavingsrebates/demand response/

CONCLUSION AND DISCUSSIONS

As indicated by the load variability and load shape statistical summaries, the campus has 5-10% load reduction potential during DR events. During peak periods, load variability of the campus is low, around 0.1. Load shape statistical summary plots also indicate low variability, as the standard error of average load is small. The whole-campus weather sensitivity calculations are complicated by the operation of TES, pointing to the need for additional research in weather sensitivity calculations for buildings with on-site storage and generation.

The magnitude of potential demand reduction is smaller at UCM than it otherwise might be, because the TES shifts the maximum campus load to nighttime, resulting in a mostly flat load shape. However the study shows that even with TES and with non-coincident building loads, UCM can deliver campus-wide semi-automated demand reductions from fans and pumps of the HVAC system and manual demand reductions from lighting.

There is a significant difference in load reduction between 2008 and 2009. Although peak load is higher on the DR event day in 2009 (due to expansion of the campus), the achieved load reduction was 30% less. This may be due to some combination of the following:

- Time of day variation of the two DR event periods,
- the loads from lights and plugs were increased in 2009 reducing the gains from automating the HVAC reductions, or
- more people responded manually in 2008.

A detailed analysis of 2009 DR event is expected to yield a better understanding of this issue.

The contrasting load reductions observed at the buildings themselves are largely based on complexity of building type and end uses, and controls interoperability. The COB, and Library buildings contain relatively simple systems and end uses, whereas the S&E building contains complex laboratory spaces and equipment as well as two independent control systems. The percentage of floor space in which DR strategies can be implemented in the S&E building is much smaller than in the other buildings. Therefore, it is not surprising that the load reductions at the Library and COB buildings were on the order of 20%, while the science building was capable of only 2%.

In spite of similar ability to reduce load, the Library contributed nearly twice as much to the campus load reduction than did the COB building. This is likely due to the fact that the peak demand at the library is approximately double in magnitude, and is almost twice as large. In the same way, the S&E building has the highest peak and footprint on campus. Therefore while it was only able to reduce load by 2%, its relative contribution to the campus reduction was elevated to 6%.

At the end-use level, the most reliable sheds came from HVAC systems that were programmed; manual sheds on lights and plugs were sizeable, but not reliable.

When an average of 110 kW demand reduction is mapped to the incentives offered by the utility's DR programs, the analysis showed the most lucrative programs for UCM to be the peak choice programs. However, the assumptions behind the analysis should be carefully considered since some programs such as peak choice, were not dispatched in 2008 or in the fist half of 2009.

The analysis of the 2008 DR event at UCM revealed that improved recovery strategies, such as staging system return to normal operations slowly, should be considered to avoid the rebound peak. A slower recovery is pre-programmed and is visible in the campus load shape on July 27, 2008.

Overall, the existence of the pre-programmed global temperature adjustment strategy allows the campus to respond to DR events and may even be used for TES management by bringing the buildings to a lower power mode and extending the operations of TES for longer periods.

FUTURE WORK

As a next step to this research, we plan to analyze 2009 load reductions at the available end-use level and compare those with 2008 to better evaluate the differences between the two years in peak load and demand reduction. This analysis will also include occupant comfort parameters such as zone temperatures and CO_2 levels. We also plan to evaluate effectiveness of the recovery strategies that were implemented in 2009. Finally, as a separate project, we plan to investigate the effectiveness of weather sensitivity calculations for sites with on-site generation and storage.

ACKNOWLEDGMENT

The authors thank John Elliott at the University of California at Merced for his support of this research and Emma Stone for her assistance in organizing the data. Research funding was also provided through the Demand Response Research Center (drrc.lbl.gov) and funded by the California Energy Commission, Public Interest Energy Research Program, under Work for Others Contract No.150-99-003, Am #1 and by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

REFERENCES

Brown, K. 2002. Setting enhanced performance targets for a new university campus: benchmarks vs. energy standards as a reference? *ACEEE 2002*.

Brown, K., M. Anderson and J. Harris. How monitoring-based commissioning contributes to energy efficiency for commercial buildings. *ACEEE 2007*.

Coughlin, K., M.A. Piette, C. Goldman, and S. Kiliccote. Statistical Analysis of Baseline Load Models for Non-Residential Buildings. *Energy and Buildings* 41 (2009) 374–381

Han, J., M.A. Piette, S. Kiliccote. Field Test Results of Automated Demand Response in a Large Office Building. Proceedings of the Eighth International Conference on EcoBalance. *LBNL-1131E. December 2008*.

Motegi, N., M.A. Piette, D.S. Watson, S. Kiliccote, P. Xu. Introduction to Commercial Building Control Strategies and Techniques for Demand Response. California Energy Commission, PIER. *LBNL-59975. May 2007*.