Measurement and Evaluation Techniques
For Automated Demand Response Demonstration

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ABSTRACT

The recent electricity crisis in California and elsewhere has prompted new research to evaluate demand response strategies in large facilities. This paper describes an evaluation of fully automated demand response technologies (Auto-DR) in five large facilities. Auto-DR does not involve human intervention, but is initiated at a facility through receipt of an external communications signal.

This paper summarizes the measurement and evaluation of the performance of demand response technologies and strategies in five large facilities. All the sites have data trending systems such as energy management and control systems (EMCS) and/or energy information systems (EIS)[1]. Additional sub-metering was applied where necessary to evaluate the facility's demand response performance. This paper reviews the control responses during the test period, and analyzes demand savings achieved at each site. Occupant comfort issues are investigated where data are available. This paper discusses methods to estimate demand savings and results from demand response strategies at five large facilities.

Background

Project Summary

Lawrence Berkeley National Laboratory conducted a number of case studies and demonstrations for the California Energy Commission's Public Interest Energy Research Program to evaluate and assess demand-response technologies in large commercial and institutional buildings. The study focused on evaluating the performance of Demand Reponse (DR) technologies and strategies at five building sites. These facilities were selected to reflect a wide range of building types and state-of-the-art EMCS and EIS technologies. The shedding control, the process of controlling systems and equipment to reduce (or shed) electric demand, was fully automated. Levels of automation in DR can be defined as follows. **Manual demand response** involves a labor-intensive approach such as turning off lights or equipment. **Semi-automated response** involves the use of controls for load shedding, with a person initiating a pre-programmed load shedding strategy. **Fully automated demand response (Auto-DR)** does not involve human intervention, but is initiated at a home, building, or facility through receipt of an external communications signal.

This paper summarizes the results of the demand-shed measurements that are described in a larger project report (Piette et al, 2004). Two other ACEEE papers describe the technology approach, and the lessons from the participants' decision-making process (Watson et al, 2004,

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[1] Energy information systems refer to software, data acquisition hardware, and communication systems that can monitor and analyze building energy consumption and related data and can control the building systems throughout the Internet.

Shockman, 2004). The two weeks test period began on 11/10/2003. Two separate, three hour tests were conducted (11/12/2003 and 11/19/2003). LBNL initiated the sheds at each building by sending an extensive markup language (XML) -based price signal to each site via Internet. Control and communications systems at each site were programmed using web services to obtain the price signal. All of the sites had EIS and EMCS that were programmed to automatically begin shedding demand when the price rose above $0.10/kWh. During the tests, the price signal elevated the prices to two discrete levels, $0.30/kWh and $0.75/kWh. Each price level was in effect for at least an hour. The fictitious prices were elevated for three hours.

The participants were told that the objective of this phase of the project was to test the communication and control technologies, and that the level of savings that can be achieved during the test is of secondary importance as long as the savings are measurable. Communication and control problems were found at some sites during the first test. These problems were solved and the second test was more successful (Watson et al. 2004). The results discussed in this paper are based on the measurements of the second test (11/19/2003).

Objectives

The main objective of this paper is to present methodologies for measurement and evaluation of Auto-DR at the building and component level. Previously the only data available for evaluation of DR programs had been whole building electric interval data. State-of-the-art DR technologies shift the current methodologies into a new realm. A site where an EIS or advanced EMCS is installed to operate DR has advanced data trending capabilities such as real-time monitoring, data archiving, visualization and download. End-use data are available as well as whole building interval data. Those capabilities allow more detailed analysis of DR events. We selected several demand saving verification methods. Using the trend data, we estimated the demand savings achieved by the DR controls based on the saving verification methods. Since building owners are concerned about occupant comfort, we evaluated zone temperatures and CO_2 concentrations where data were available.

Methodology

Site Summary

Table 1 summarizes the characteristics of each site. The Auto-DR test sites include three office buildings, a supermarket, a university library, and a cafeteria. The buildings range from about 50,000 to 1,000,000 ft^2, and are located in Oakland, Concord, Palo Alto, and Santa Barbara. All sites are large facilities requiring more than 200 kW during the summer peak period (431 kW to 3795 kW per site). November 2003 monthly peak demand ranging from 401 to 2710 kW, or 2.8 to 8.0 W/ft^2. The types of end-uses included in the whole-building electric meter values vary from site to site. Three of the sites are part of a larger campus, thus two sites do not include cooling electricity use because a central plant on a different meter supplies cooling.

Table 1. Summary of Sites

	Site A	Site B	Site C	Site D	Site E
Location	Oakland	Concord	Oakland	Palo Alto	Santa Barbara
Use	Supermarket	Bank office	Government office	Pharmaceutical laboratory (office/cafeteria)	University library
Cooling system	Included	Not included	Included	Not included	Included
Area	50,000	211,000	978,000	192,000	289,000
2003 yearly WBP peak demand	431 kW	Not available	3795 kW	782 kW	1311 kW
WBP peak demand (Nov)	401 kW	999 kW	2710 kW	706 kW	866 kW
Peak W/ft^2 (Nov)	8.0	4.7	2.8	3.6	3.0

WBP: whole building power

Shed Strategies Implemented

Each facility manager developed unique demand shedding strategies (see Table 2). The component whose electric demand is directly controlled or affected by the strategies is defined as the "controllable component". End-use measurements for the controllable components are critical for evaluating the DR savings in detail.

Table 2. Summary of Shed Strategies

	$0.30/kWh	$0.75/kWh
Site A (Supermarket)	Overhead lighting 50% reduction	Anti-sweat door heaters are reset to night-mode setpoints
Site B (Office)	Duct static pressure reset 2.2" WC (normal) → 2.0"WC	
Site C (Office)	Global setpoint increase/decrease Cooling: 72 °F → 76 °F Heating: 70 °F → 68 °F	Global setpoint increase/decrease Cooling: 76 °F → 78 °F Heating: 68 °F → 66 °F
Site D (Pharmaceutical Laboratory)	Office-1: 3 of 6 supply fans turned off	Office-2: 1 of 4 air handler turned off Cafeteria: 2 of 4 supply fans and 1 of 2 return fan turned off
Site E (Library)	Supply fan VFD set to 70% limit Economizer dampers set to 100% OSA	Supply fan VFD set to 60% limit Static pressure set to 0.4"WC limit Cooling/heating valves closed

"WC: inch water column, VFD: variable frequency drive, OSA: outside air

Site Measurement Methods

The primary emphasis for the evaluation techniques was to measure each 15-minute increment of the 3-hour electric shed event. Where possible, we also developed non-energy measurements focusing on temperature or other indoor air environmental attributes. The shed events were followed by interviews with facility operators to inquire about any loss of service, occupant complaints or problems that may have resulted from the shed strategy. Numerous sources of data were used to measure and evaluate the load shedding. All five sites had some form of an EIS. Multiple sources of data including EIS, EMCS, and submeter were used in four of the five sites. At Site A, only one EIS was used for data collection and analysis. At the four sites with multiple sources of data, significant re-configuration of the EMCS and EIS trending points was required. Table 3 summarizes the measurements conducted at each site, including the

type of system, specific data points collected, number of points for each system, frequency of data sampling, and whether it has web-based data access. Because of lack of end-use monitoring, additional data trending equipment were installed or existing equipment were programmed for the Auto-DR test.

<div align="center">Table 3.   Measurement Summary</div>

Site	Type	Data type	# of points	Data freq.	Web-Based Assess
Site A	EIS	WBP, Overhead lighting Anti-sweat heaters, OAT	4	15 min.	Yes
Site B	EIS	WBP Fan status/temp/VFD/air flow/static pressure	35	5 min.	Yes
	EIS	WBP, OAT	2	15 min.	Yes
	EMCS	Chiller power, Chilled water energy Control status	21	15 min.	No*
	Submeter	Individual building power; Fan power	8	1 min.	No
Site C	EIS	WBP, OAT	6	15 min.	Yes
	EMCS	WBP, Chiller power/energy Fan status/temp/VFD/air flow/static pressure Cooling tower, Pump status/VFD, Zone temp	100	5-15 min.	No
	Submeter	Fan power, Pump power	6	1 min.	No
Site D	EIS/EMCS	Fan status, Zone temp, CO_2	19	5 min.	Yes
	EIS	Individual building power	3	15 min.	No
	Submeter	Fan power (spot)			No
Site E	EIS	WBP, Chilled water energy Fan power/VFD/static pressure Economizer position, Zone temp, OAT Cooling/heating valve position	150	5-15 min.	Yes
	EMCS	Trends through EIS			No

<div align="center">WBP: whole building power, OAT: outside air temperature, CO_2: carbon dioxide
* Web access was not available to LBNL because of the facility's firewall security.</div>

Saving Verification Techniques

In this study, demand savings were derived by subtracting the actual metered electric demand from the baseline demand. The baseline demand is an estimate how much electricity would have been used without demand shedding. We developed two primary methods for estimating baseline electricity demand: 1) a whole-building level method and 2) a component level method. The measurement and verification methods we developed for electric load shape analysis are consistent with the general principles established in the International Verification and Measurement Protocol (IPMVP, 2002).

Whole-building level method. The whole building, or premise-level, top-down analysis method consists of developing a whole-building power baseline load shape. Whole building power (WBP) is estimated using a weather regression model that assumes whole building power is linearly correlated with outside air temperature (OAT). The OAT data is from local weather stations[2]. Input data are 15-minute interval WBP and hourly OAT. This method was derived from previous work at LBNL (KEMA-Xenergy, 2003). In the previous work, this method was tested with Site C data, and statistically proven to be a better estimate than the conventional

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[2] The Santa Barbara weather station is at the airport, which is next to the UCSB campus.

method of simple averages[3] when the WBP has a linear correlation with OAT. The model is computed as:

$$L_{15min} = a_{15min} + b_{15min} \, T_h$$

where L_{15min} is the predicted 15-minute interval electric demand from the previous non-controlled working days. The number of previous days used in the model were selected to make the best use of available metered data. T_h is the hourly or 15-minute interval OAT, and a_{15min} and b_{15min} are estimated parameters calculated from the input data by linear regression. Separate regressions are developed for each 15-minute interval.

To develop the baseline electric loads for the demand sheds on November 19th (second test) we selected 18 "non-shed" days. These 18 baseline days were non-weekend, Monday through Thursday workdays. Fridays were eliminated in the development of the baseline because Site E has a different operating schedule on Fridays. The selection of the baseline days was based on availability of whole-building data at each site. The sub-metering for the Site B building was installed on October 15th, which was the first day of the 18-day baseline period.

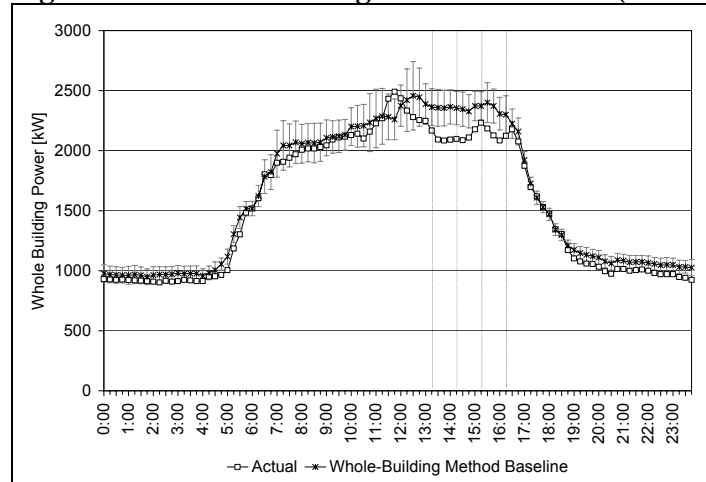**Figure 1. Whole-Building Method Baseline (Site C)**

Figure 1 shows an example of the whole-building method baseline, using test data from the second test at Site C. The vertical line at each "actual" data point shows the related standard error.

Component level method. The component level, or bottom-up evaluation method develops the WBP savings by combining the demand savings estimates for each component. The basic procedure is to 1) develop a baseline for each controllable component, 2) estimate the demand savings for the component by subtracting actual demand from the baseline, and 3) sum all the controllable load demand savings. The component level estimation method requires analysis of either direct power measurement or operational data for each controllable component. The component level method is more accurate than the whole-building method if the controllable

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[3] California Independent System Operator (Cal ISO)'s Demand Response Program used "previous 10 business days baseline", which is a simple average of previous days.

load and non-controllable load can be accurately measured. We developed several methods to develop the component level baseline load shape. These methods are described below.

Equipment Schedule Method – The controllable components' "normal-day" operational load shape can be used to define a baseline if the equipment schedule is well defined and consistent. This method can be applied to components with simple operational modes. If the operation is simple enough to extrapolate electricity demand, this method is very accurate. A weather-sensitive component load is not appropriate for evaluation with this method. Examples of components evaluated with the method include constant volume fans operating with a fixed schedule and non-dimmable lighting.

Outside Air Temperature Regression Model Method – If the component's electricity demand is weather sensitive, a simple average of the previous days' demand may provide a lower baseline demand if the controlled day's temperature is higher than the previous days. In this case, the estimate can be adjusted for OAT. This method forecasts the component demand by a regression model similar to the whole-building level method. The 15-minute component electric demand plus hourly OAT data are used. Examples of components evaluated with this method include chillers and fans with VFDs.

Prior Time Load Method – If none of above methods acceptably fits with respect to the actual demand, the forecast demand may be estimated from the data at 15-minute to a few hours immediately preceding the test. This is a rule-of-thumb method. This method may be applied only when the equipment operation is stable without the shed strategies, and the daily load shape is similar over the previous days. Depending on the demand profile, the calculation method can be selected from either using previous operation hours or previous 15-minute demand, or drawing a line from the pre-shed demand and the post-shed demand. This method should be used when the shed period is short, and there is no shed strategy applied in advance (such as pre-cooling).

   Table 4 summarizes the component-level savings estimation methods used for different components at each site. There are various reasons why different evaluation methods were used for the same type of equipment at different sites.

Table 4.   Component Level Methods for Each Component

| Site	Controllable Components	Equipment Schedule	OAT Regression	Prior Time Load
Site A	Overhead lights	✔		
	Anti-sweat heaters			✔
Site B	Fan system			✔
Site C	Fans		✔	
	Chillers		✔	
	Pumps		✔	
	Cooling towers		✔	
Site D	Fans	✔		
Site E	Fans		✔	✔
	Chillers		✔	

Results

During the tests, whole building and controllable component demand were measured at all five sites, and the demand savings were calculated by the savings verification methods defined earlier. Results are based on the second test (11/19/2003, and shown using the whole-building method and the component level method. The OAT of the second-test day was 46°F to 51°F at minimum, and 65°F to 69°F at maximum among the sites.

Saving Analysis by Site

This section describes the procedures used to develop a component-level baselines corresponding to the shed strategies for each site. Since each building has a unique shed strategy and a data trending method, the component level saving calculation methods are customized for each site and each component. The non-energy results are also discussed where comfort measurements such as zone temperature or carbon dioxide (CO_2) concentration were available.

Site A (supermarket). Site A controlled non-HVAC components for the shed strategies. Since these components are not weather-sensitive, the saving estimation was straightforward. The overhead lighting baseline was estimated using the equipment schedule method. The anti-sweat door heaters were not well modeled with an OAT regression model. Instead, the baseline was estimated from the previous 15-minute load (before the first higher price signal), because the previous days' loads were flat during the afternoon period and it could be considered that the previous 15-minute load might continue at the same demand level during the afternoon if the shed didn't occur. Fifteen-minute interval electric demand was collected by the EIS at the site. For this site, no measurement addition or reconfiguration was needed. The site achieved a 41 kW shed (11% of WBP, 0.83 W/ft^2) by the component method. Figure 2 shows WBP and the savings by the component method, and electric demands of the controllable components.

Figure 2.   Site A – WBP, Controllable Components, and Savings
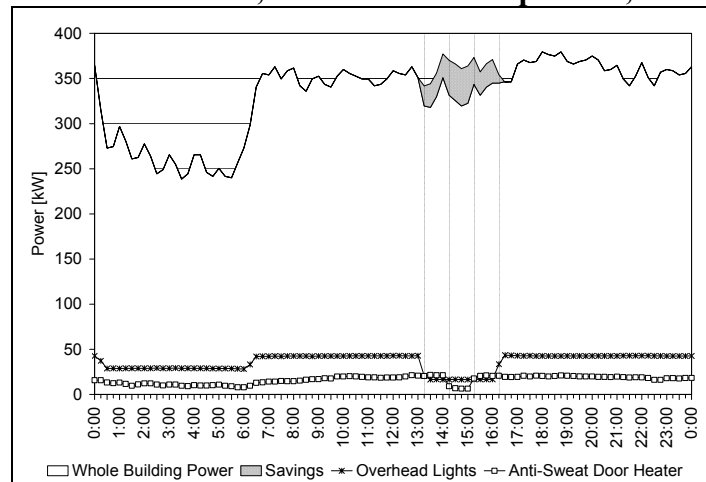

Site B (bank office). At Site B, the EIS implemented the shed at the entire facility that included two other large office buildings; the duct static pressure reset rotated through three buildings. Since the strategy was operated many times in previous days, the baseline might be affected. We examined the test at only one building. The supply fans and the return fans of the examined

building were considered as controllable components. Submeters were installed to collect fan electric demand data. The fan electricity usage was greater than the OAT regression model. The OAT regression model was not appropriate to determine the fan electricity usage baseline. Therefore, for this savings analysis, the previous 15-minute demand was used as the baseline during the test period.

The shed demand was small compared to the whole building demand. Figure 3 shows electric demand of the fan mechanical control center, which includes all supply and return fans and motors in the examined building. The component level method indicated maximum 12 kW of saving (1.6% of WBP, 0.06 W/ft^2). The demand drop occurred three times during the shed due to the strategy of rotating the shed between the different buildings in the complex in order to minimize the burden on each. The fan demand savings were approximately 10 kW for each time.

Figure 3. Site B – Fan Power and Savings
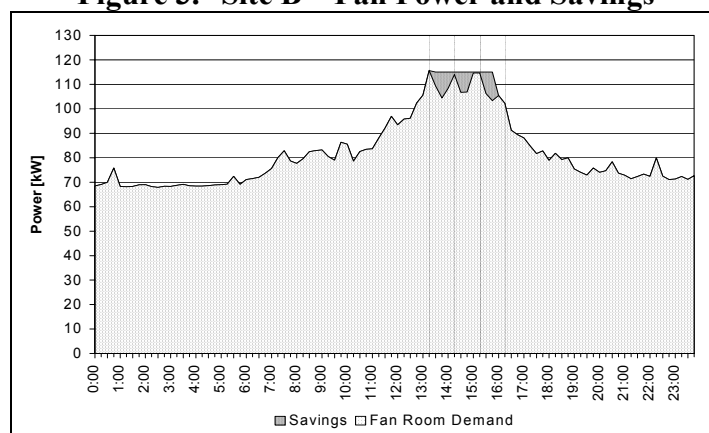
Site C (governmental office). Site C implemented a global set point increase for zones in cooling, and global setpoint decrease for zones in heating as its shed strategy. The average default setpoint was 72°F. The global setpoint increase strategy impacts the controls of most of HVAC end-use equipment. Correspondingly, the chillers, primary and secondary pumps, cooling towers, and fans were considered as the controllable components. The OAT regression model was used to develop a baseline for each controllable component. Although the EIS at Site C was necessary to receive the signal and execute the shed strategies, the data archive and download function of the EIS was not fully developed yet. Therefore, all the subsystem data was collected by the EMCS at the site and was downloaded manually after the test period.

Site C had a recently developed cooling strategy that maximizes free cooling by cooling towers.. Because of this strategy, the chiller and the other related HVAC equipment operations generate an irregular load shape.

Figure 4 shows the WBP and HVAC demand of Site C and savings by the component method. The global setpoint increase (76 °F) was executed at 1:00 pm responding to the 15-minute ahead $0.30/kWh price signal. The WBP dropped gradually over the next 30 minutes because the global setpoint increase strategy initiates a complete set of actions that include chillers, pumps, cooling towers, and fans.

The zone temperatures were also trended by the EMCS. During the shed, the average temperature from 39 zones rose by 1°F (72°F to 73°F), although the global setpoint increase strategy allowed rising up to 76°F or 78°F depend on the shed level. The temperature dropped to

pre-shed level after the shed ended. Although some zone temperatures responded closely to the strategy, most of them were not affected. Possible reasons for this are: 1) the damper positions were already at the minimum; and 2) the temperature difference might be within the deadband.

Figure 4. Site C – WBP, HVAC, and Savings
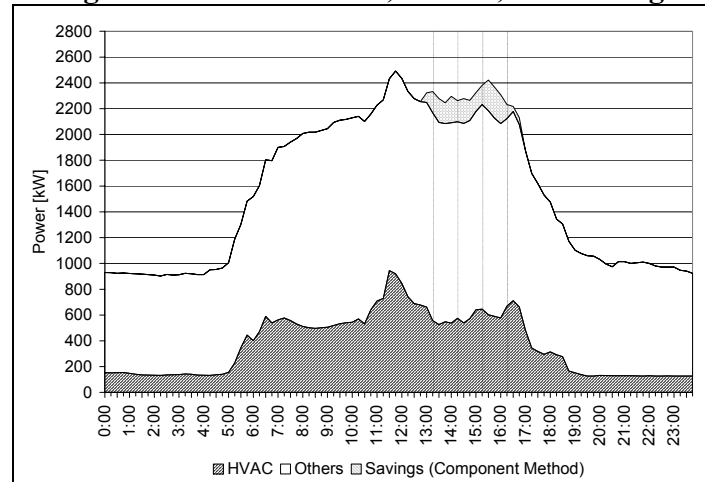
Site D (pharmaceutical laboratory). Three buildings including two office buildings and a cafeteria participated in the test at Site D. Each building switches off some of the building fans based on the price signal. Since all the fans are constant volume, the electric demand of the fans can be estimated from the spot measurement data and operating schedule (the equipment schedule method). The WBP was trended by the on-site standalone power measurement system that had already been installed. The component data was collected at 5-minute intervals. Figure 5 shows the WBP and controllable fan power of Site D and the savings by the component method. The site achieved 107 kW of savings (21% of WBP, 0.56 W/ft^2).

Figure 5. Site D – WBP, Controllable Fans, and Savings
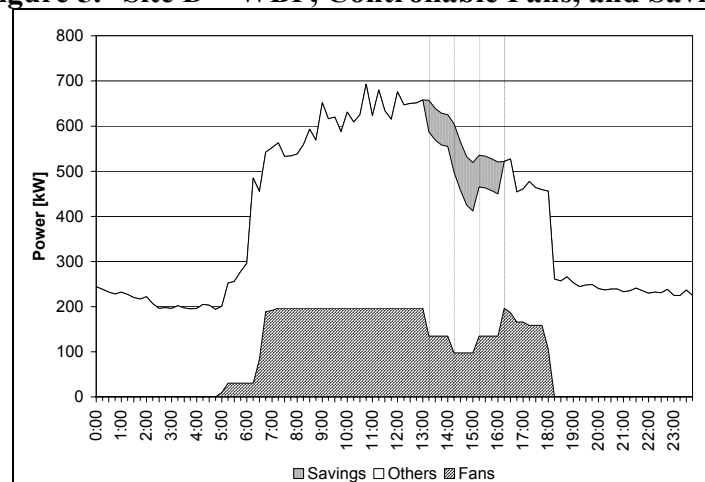
One building at Site D collected zone temperature and CO_2 concentration data. The zone temperature was around 74°F after 11:00 am, and persisted until the end of occupancy. There were no temperature or air flow complaints. During normal operation (a non-test day) CO_2 concentration was between 450 to 500 particle per million (ppm) in the morning, and reduced to

400 to 430 ppm after 12:00 pm.[4] The CO2 concentration is relatively low because of low occupancy of this space. On the test day, the CO_2 concentration stayed around 460 to 500 ppm from the morning through the afternoon, and reduced to 440 ppm after the test period, that is higher than the normal operation condition. This was caused by turning off the air handlers during the shed period. As the result, the CO_2 concentration could be kept at the morning levels or lower, and there was no complaint on the air quality.

Site E (university library). Site E implemented the test at the Main Library, which consists of three buildings next to each other. Since the energy manager at the site occasionally implemented some energy saving strategies, the days he manually operated the strategies (3 days in the previous 18 days) were eliminated from the baseline input data. All the data used in the saving analysis were collected by the EIS. Originally the building had only WBP and cooling energy data. For the component level evaluation, new data points were added to the EIS trend derived from the EMCS (see Table 3). The supply fans and cooling energy were considered as the controllable components.

Supply Fans – Measurements for the supply fans were from electric demand or current[5]. According to the average previous-day profile, afternoon loads of most of the supply fans were flat for the previous days. The actual fan load was higher than the maximum range of standard error of the fan OAT regression model. Therefore, assuming the afternoon fan load was flat, the baseline demands for the supply fans were estimated from 15-minute demand prior to the shed.

Cooling Energy – Though the Library has a central chiller plant, it is separated from WBP because the chiller supplies chilled water to a campus chilled water loop. The cooling energy [Btu] supplied to the Library is converted to electricity consumption [kWh][6]. Baseline cooling energy was estimated by an OAT regression model.

Figure 6 shows the WBP, cooling energy, and savings by the component method. The maximum savings by the component method was 129 kW (16% of WBP, 0.45 W/ft^2). The cooling energy was affected directly by the cooling valve shutdown strategy ($0.75/kWh) and indirectly by the fan VFD reduction ($0.30/kWh). At the end of $0.75/kWh-signal, the cooling energy demand increased by 120 kW, more than 40 kW over the baseline. This was caused by the release of the cooling valve. Because the cooling valve control responded immediately after reception of 15-minute ahead price signal, the chilled water demand increased 15 minutes before the $0.75/kWh-signal ended.

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[4] Comfort criteria, with respect to human bioeffluents (odor) are likely to be satisfied if the ventilation results in indoor CO2 concentrations less than 700 ppm above the outdoor air concentration (ASHRAE 62-2001).
[5] kW = Amps x 0.8 {power factor} x 1.73 x 480 [V] /1000
[6] Library cooling energy [kW] = central plant power [kW] x Library cooling energy use [Btu/h] / total cooling energy produced [Btu/h]

Figure 6. Site E – WBP, Cooling Energy, and Savings
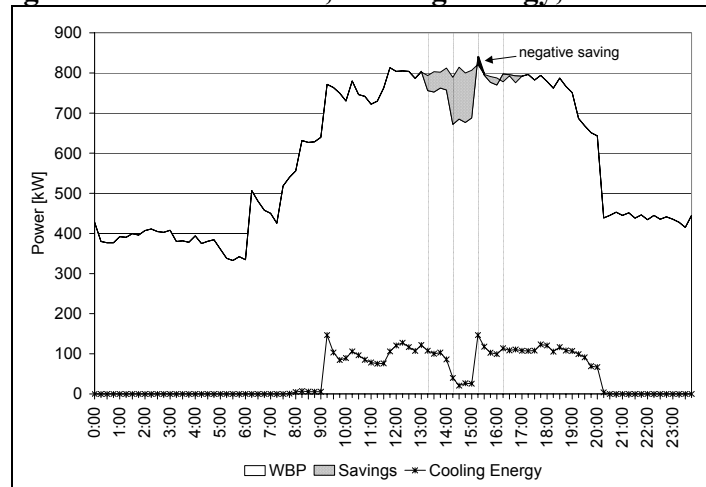
Zone temperatures were also collected at this site. Although the zone temperatures were anticipated to rise due to the shed period, average zone temperature changes were within 1°F during the shed. Since the building has a large thermal mass (building mass and books), the zone temperature change might be moderated due to the thermal mass effect. There was no complaint from occupants during the shed.

Summary of Results

Figure 7 shows the result summary for all sites by the component level method. The shed kW is averaged over each 1-hour price signal period. Site C (government office) achieved the highest shed of the five sites (240 kW, 10%). Site A (supermarket) achieved the maximum shed per unit of floor area (W/ft^2) (0.83 kW/ft^2). Site D (pharmaceutical laboratory) achieved the largest demand saving percentage in WBP (21%).

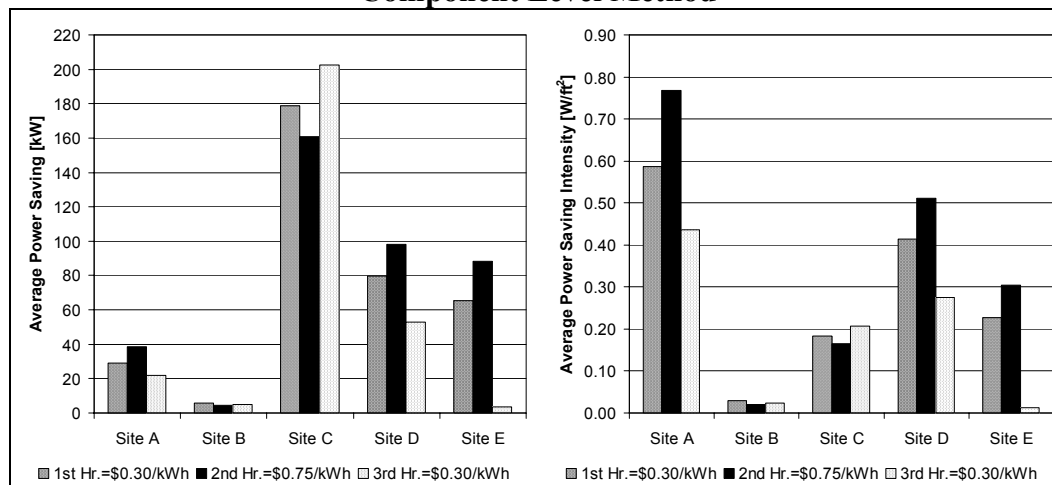**Figure 7. Average Hourly Shed kW and W/ft^2 by Price Signal Level – Component Level Method**

Figure 8 shows the comparison of total demand savings calculated by the whole-building method and the component method globally for the five buildings. The maximum aggregated

savings were 519 kW (11% of WBP) by the whole-building method, and 477 kW (10% of WBP) by the component method. The demand savings by the two methods were similar. The savings dropped off at 3:00 pm because of rebound cooling demand from $0.75/kWh to $0.30/kWh.

Figure 8.   Savings by Whole-Building and Component Method
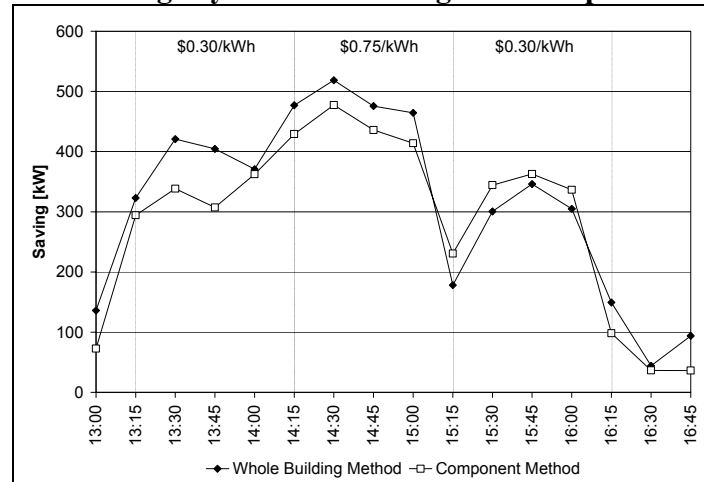
Summary and Future Directions

This paper reviewed measurement and saving evaluation methods of the Auto-DR test, and analyzed the results of the test using the methods. Saving results by the whole-building method and the component method were similar.   The results suggest that the weather normalized whole-building electric loads provide a reasonable measurement method. Whole building data are much easier to collect and are more readily available than end-use and component data. We did not compare the weather-normalized whole-building analysis method with the flat 10-day average baseline used in many DR evaluations. Previous work has shown that methods that do not account for weather can have significant bias for commercial buildings (KEMA-Xenergy, 2003).

The controllable component baseline method should be carefully chosen based on equipment operation schedule, and weather-sensitivity of the component. If the component is weather-sensitive, OAT regression should be considered. However, if the other factors affect on the load and the OAT regression model doesn't fit the actual load, alternate baseline methods, such as the prior time load should be developed.

Total demand savings from the five sites were 477 to 519 kW (10 to 11% of WBP, 0.28 to 0.30 W/ft^2) for the whole-building and component baseline method respectively. Site E showed an increase in demand at the end of the shed caused by returning shed components back to normal operation. This resulted in producing higher peak demand than normal operation. Although only one site showed this trend in the test, this trend can be a common issue for the other sites in warmer weather condition. The shed strategies need to be reconsidered to avoid the risk of higher demand charge, and modified if necessary.

The electric demand savings were relatively small because the tests were conducted in November and the strategies were not aggressive. Greater savings can be expected if the tests are conducted in warmer weather, though occupants' comfort issues including zone temperature rise may also increase. The research reported above will continue in 2004. New themes to be explored will include evaluation of measurement system and Auto-DR technology costs, review

of results in warmer weather, simplifying measurement techniques, and evaluation of the above techniques for additional buildings and a broader set of demand shedding strategies.

Acknowledgements

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