Short Term Notification Demand Response Measures in Office Buildings in a Hot and Dry Climate

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ABSTRACT

Demand response (DR) is a load curtailment strategy strongly advocated by electric utilities nationwide to tide over periods when grid usage is likely to reach/exceed its maximum capacity. It essentially involves notifying commercial customers in advance and incentivizing them to reduce their consumption voluntarily during such peak periods. In essence, this notification can be either short term with a lead time of 2-3 hrs, or long term (12-24 hour notification). The demand-side curtailment measures which a customer can implement under the former are fewer and, often, not transparent. In this paper, we present the results of a simulation study which investigated the effect of various short notification DR measures and their resulting impact on indoor occupant comfort. Two DOE prototype commercial buildings, a medium size office building (53,600 sq. ft.) and a large size office building (498,600 sq. ft.) were simulated under the hot and dry climate of Phoenix, AZ using the detailed building energy simulation program, EnergyPlus V6.0.0,. The peak diurnal period selected was 12:00-18:00 hours (6 hour window). Analysis of the weather file led us to select two hot peak days, one reflective of the summer high-peak (15th July) and another of the mid-peak (29th June). The impact of building thermal mass as well as several other measures such as reducing lighting levels, increasing thermostat set points, adjusting supply air temperature, resetting chilled water temperature was studied. Subsequently the simulation results were distilled and summarized in tabular form according to the different combinations of load reduction measures needed to achieve different levels of DR reductions along with the associated percentage values of people dissatisfied (PPD). The approach described in this paper is likely to be better adopted by building owners and utility operators contemplating DR response since it allows them to evaluate alternative sets of measures and their comfort consequences for different magnitudes of load reduction. This methodology can be extended to other buildings and climates.

PROBLEM STATEMENT

Electric utilities are being increasingly challenged to meet peak loads during summer due to consistent load growth over the years at one end and high cost of installing additional generation power plants on the other. Therefore, being able to reduce peak loads when grid usage is likely to reach its maximum capacity (which occur for only a few hours during a small number of days in the year) is critically important. Demand response (DR) is a process, being aggressively pursued by electric utilities, whereby advance notification is given to customers along with incentives to implement short-term load reduction measures meant to reduce facility electricity use over a few hours. Such reductions taken over a large number of buildings can allow utilities to tide over the few critical peak hours, improve electrical system reliability and reduce electricity supply cost (Chen, 2008).

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DR measures need to be distinguished from demand-shifting measures which are implemented on a diurnal basis for much of the year. Electric utilities offer time-of-day electric energy and demand rates to incentivize such demand-shifting or demand shedding practices (Motegi et. al., 2007). Here, shift in diurnal demand profile is achieved by consuming electricity at an off-peak time (e.g. shifting the energy usage time from peak afternoon to night time during summer months) to benefit from the time-of-use electric rates. This can be achieved by active means, such as precooling the building thermal mass and controlling the indoor temperature ramp-up appropriately, or by passive means such as installing thermal ice energy storage.

The implementation of both DR and demand-shifting measures needs proper building operation. Poor operation and maintenance (O&M) of buildings can result in 10 to 30 percent excess energy use (PNNL, 2011). Thus, it is important to work with building owners and operators to improve operation and maintenance practices. Only then is it likely that such load reduction practices will lead to increased energy efficiency, lower energy costs, longer equipment life, and enhanced occupant satisfaction.

OBJECTIVE AND SCOPE

The objective of this paper is to describe a methodology which we feel would be acceptable to building owners wishing to evaluate different DR strategies in commercial buildings. A shift in focus between this paper and others (for example, Gu et al., 2011) is to try to identify sets of DR measures which are likely to result in preset reductions in peak load (for example, 5% or 10% or 20%) and their corresponding impact on occupant thermal comfort. The building owner can then decide which level of DR measures to implement by evaluating the associated occupant impact and the effort needed to practically implement them in his/her facility. In some ways, this paper is similar to that by Norford et al. (1998) which suggested a knowledge base approach of actionable measures which a building operator can undertake under real-time electricity rates which vary hourly

LITERATURE REVIEW

Reddy et al. (2004) describe the benefits of multi-building load aggregation and load curtailment measures in commercial buildings. The load curtailment measures selected in their study are load reduction measures and not load shifting measures. They studied the effect of reducing lighting and equipment electric density levels, changing the thermostat and cold deck settings and changing the ventilation rates during the occupied hours.

Newsham et al. (2006) have studied the effects of temperature and lighting ramp downs on the occupants comfort levels. They mention that rapid lighting intensity reductions of up to 20% can remain undetected by occupants. Furthermore, they suggest that a slower rate of reduction may enable a higher percentage of reduction.

Yin et al. (2010) studied the potential impact of building size, thermal mass, climate and DR strategies on demand savings in commercial buildings. They used a precooling strategy to study the impact of building thermal mass and size. The impact of three types of control strategies: linear, step and exponential temperature reset, on the peak demand reduction in a prototypical commercial building was analyzed. Thermal comfort analysis was done to determine the effects of these strategies on the occupancy comfort levels. This research involved buildings with low, medium and high thermal mass. They also studied demand shifting strategy; however they did not investigate any load reduction strategies.

The impact of most commonly used DR control strategies on peak electricity reduction was studied by Gu et al. (2011). Their study included small, medium and large size office and retail buildings. Five geographical regions were chosen to study climate specific variations in the results. The effect of several control strategies was studied during different prototype days of the year. The prototype days selected were designated as Summer Peak, Summer Mild, Summer Low, Fall Cool High, Winter Peak, Winter Mild, Winter Low, and Fall Heat High.

BUILDING DESCRIPTION AND DR MEASURES

Since the DR measures will be building specific, the selection of which type of buildings and their exact geometry, construction and HVAC system specifications and building operation are important issues. Due to the transparency and widespread acceptance, it was decided to select the ASHRAE 90.1 prototype building simulation models developed by Pacific Northwest National Laboratory (PNNL) in support of DOE's Building Energy Codes Program which cover 80% of the commercial building floor area in the U.S. Simulation of these buildings is best done using the detailed building energy simulation platform EnergyPlus (U.S. Department of Energy, 2011) since the simulation codes for these buildings are available from the web as open source and free downloads. More specifically, for this study the medium size office building and the large size office building prototypes were selected and simulated under the hot and dry climate of Phoenix, Arizona. Pertinent building details are assembled in Table 1.

Table 1. Details of the Two DOE- PNNL Office Building Prototypes Selected

Specifications	Medium	Large
Area	53,000 sq.ft.	498,600 sq.ft.
Dimensions	163.8 ft x 109.2 ft	240 ft x 160 ft
Aspect Ratio	1.5	1.5
Number of floors	3	12 + basement
Window to wall ratio	33%	40%
Windows	Evenly distributed on all sides	Evenly distributed on all sides
Type of construction	Steel-frame walls	Pre-cast 8 in. heavy concrete
Perimeter zone depth	15 ft	15 ft
Perimeter to Core Areas	Perimeter 40% and Core 60%	Perimeter 33% and Core 67%
Zoning	4 exterior + core	4 exterior + core
Total number of zones	15	60
Heating System	Gas furnace	Gas boiler
Cooling System	Packaged A/C unit	Two water cooled centrifugals
Air Distribution	VAV terminal boxes with elec. Reheat coil	VAV terminal boxes with hot water reheat coil
Internal loads	As per ASHRAE 90.1	As per ASHRAE 90.1

This study investigated short-time notification DR strategies used to reduce peak demand consumption during fixed time window near on-peak period in commercial buildings in hot and dry climates like Arizona. The literature review indentified the following DR strategies: Lighting power density reduction (LPDR): 10%, 20% and 30% LPD reduction per hour for peak hours, thermostat set-point setback (TSS): 3.5 ^{0}C zone thermostat temperature increase is divided over 6 hour peak period window, supply air temperature adjustment (SATA): maximum supply air temperature was increased by 5 ^{0}C over peak hour window, and chilled water temperature reset (CWTR) chilled water temperature was increased by a total of 5 ^{0}C in stepped pattern over the peak demand window. Finally SATA and CWTR were also studied limiting fan and pump mass flow rates constant to the speed found just prior to the start of the peak demand window. Effect of these strategies were first investigated individually, and then in all the different combinations. Strategies such as LPDR and TSS are suitable for both building types, while SATA and CWTR strategies are only applicable to buildings served with central plant only (in our case, the large office building). The last two strategies were quite complex as they involved fans and pumps as well.

PEAK REDUCTION SIMULATION RESULTS

The effects of various DR strategies on DOE prototypes for the medium size office building and the large size office building were simulated using EnergyPlus for two days of the year under the various DR strategies described above. For this study summer peak (15th July) and summer mid peak (29th June) were selected from an analysis of the Typical Mean year (TMY) climate record for Phoenix, AZ (see Khanolkar, 2012 for details). The diurnal peak period was taken to be a fixed time window from 12:00 to 18:00 hours (consistent with the local electricity utility rate schedule). Two different envelope constructions were simulated (steel frame and heavy concrete construction) so as to study the effect of thermal mass. However, the study showed that impact of thermal mass on peak demand reduction was not significant, and therefore this was not considered .EnergyPlus also allows indoor occupant thermal comfort to be analyzed as well. In all the simulations, percent reduction in building electric load due to the DR strategy/strategies as compared to the base case during the peak demand period was determined.

Medium office building: LPDR, TSS, and all strategies combined were simulated for high-peak (07/15) and mid-peak (06/29) day and the results summarized in Figure 1.

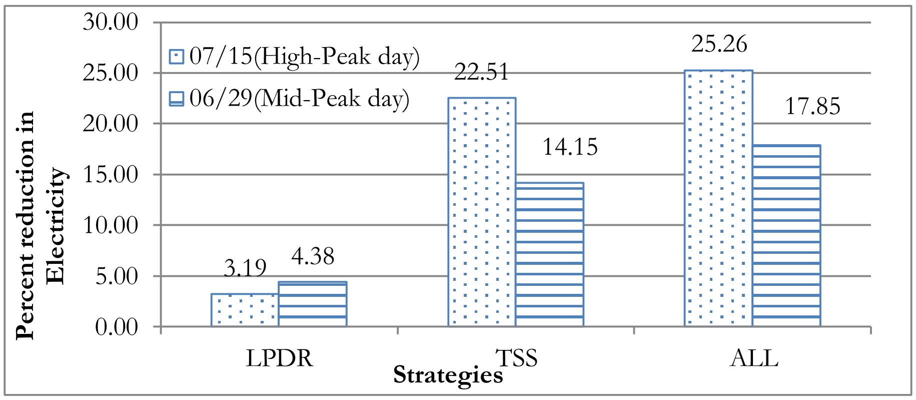


Figure 1 *Percent reductions in electricity consumption for medium office building*

Large office building: Control strategies are quite involved and complex and required investigation of many different demand reduction strategies compared to the relatively simpler ones for medium office building. LPDR, TSS, SATA and CWTR are the base strategies which were evaluated on the large office building. Different combinations of these base strategies were simulated incrementally to study the interaction between these strategies (Figure 2).

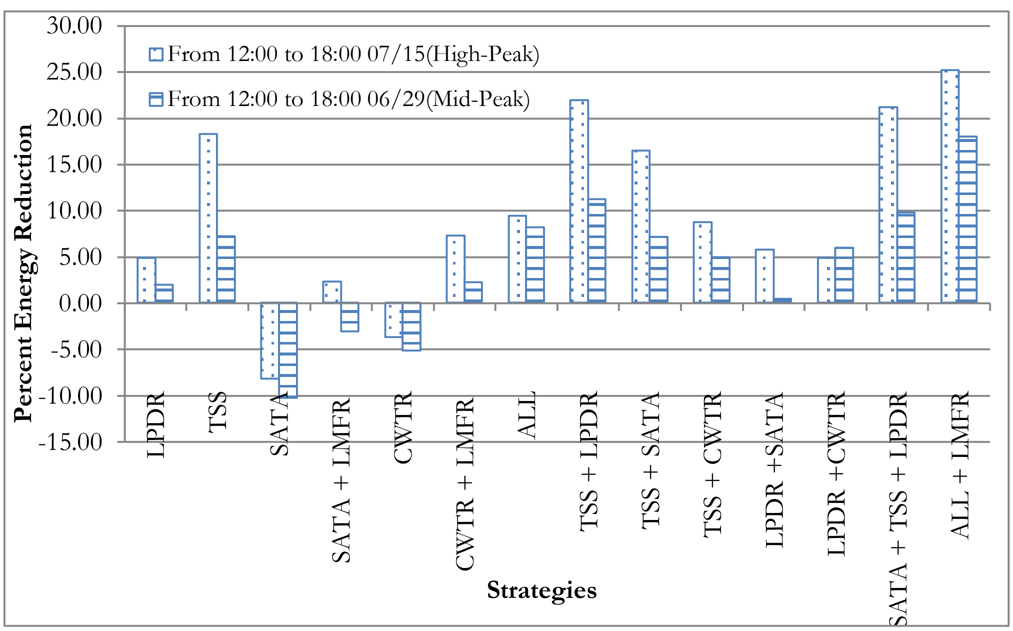


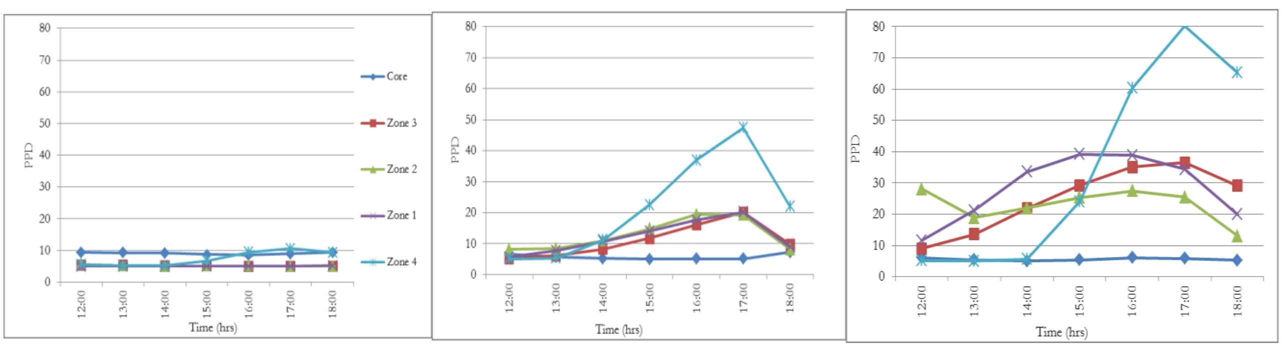
Figure 2 *Percent reductions in electricity consumption for large office building*

THERMAL COMFORT ANALYSIS

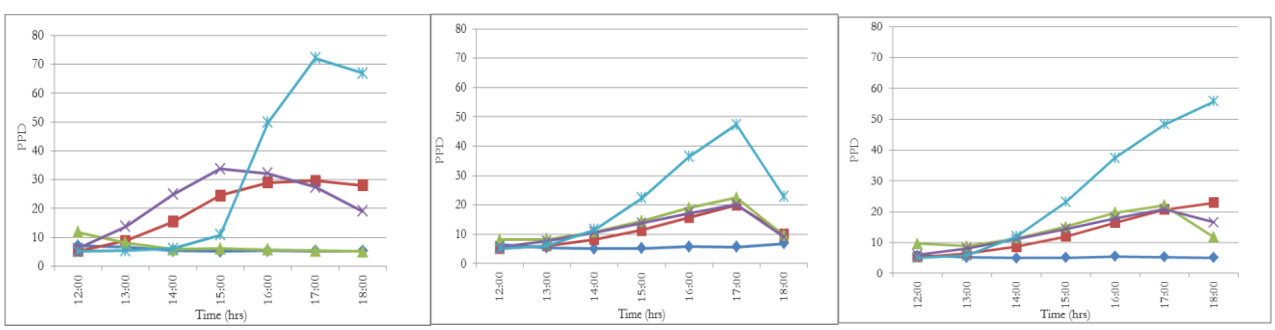
DR strategies are likely to compromise indoor occupant thermal comfort and it is very important to study this effect. Thermal comfort analysis for high-peak summer day is presented here in terms of occupant discomfort which is likely to be more severe in the summer months. The Fanger comfort model is used in this study to assess occupants' thermal comfort (Fanger, 1970). It relies on two indices, the predicted mean vote (PMV) and the predicted percent dissatisfied (PPD), and the relevant description is provided in ASHRAE Standard 55 (2004). Basically, DR strategies resulting in PPD values less than 20% would be acceptable building operation strategies to consider and adopt.

Medium office building: From the analysis it is clear that the PPD for all the control strategies is in the range of 5-15% except one zone facing the west side of the building. Therefore from the PMV and PPD analysis it is clear that the strategies selected in this study are reasonable DR strategies for this medium office building.

Large office building: For the large office building base case, we note that PPD is in the range of 5-12%. The SATA strategy and strategies involving SATA result in high occupants discomfort levels (5-40%). For all the other strategies the discomfort levels are in the approximately in the range of 5-30%. Zone facing west always has higher percentage of people uncomfortable; therefore alternate arrangements are required for this one zone when DR strategies are implemented.



a) Base case b) TSS strategy c) SATA strategy



d) CWTR strategy e) All strategies combined f) All strategies combined

Figure 3 *Large office building: Fanger PPD for different hours of the peak period during the high-peak day. LPDR graph is same as base case in figure (a). Difference between (e) and (f) is that the former applies to the case when the fan and pump mass flow rates are not restricted while frame (f) applies to the case when they are restricted.*

ANALYSIS RESULTS AND RECOMMENDATIONS

The results for medium (packaged roof top unit) and large office buildings for high-peak day are tabulated in Tables 2 and 3 respectively. For example, from Table 2 one can surmise that if 20-25% demand reduction is desired, then the TSS strategy alone can achieve this level with the associated PPD being in the 5-15% range for all the zones (except one). We can make the following recommendations to building owners and operators:

1. DR management is a very effective process to reduce peak hour energy consumption for fixed time window. It can give up to 25% peak load reductions in large office buildings served with VAV system and in medium office building served with packaged air conditioning unit.
2. Lighting power density reduction is an effective strategy to meet the peak demand energy reduction requirements. Lighting power density reduction varied from 90%, 80% to 70%, and as the percent of LPD reduced, the load reduction amount increased linearly. Lighting power density has no impact on the occupants' thermal comfort levels. However, it obviously has impact on the occupants' visual comfort but visual comfort analysis is not supported by EnergyPlus, so no analysis could be performed in that regard.
3. Thermostat set-point setback strategy gave highest load reduction compared to all individual strategies (up to 18% in large office and up to 23% in medium office building). But it also resulted in increased thermal occupant discomfort levels.
4. Supply air temperature adjustment and chilled water temperature reset strategies when used individually result in a comfort penalty and the total electric load increased as the fan and pump flow rate increased.
5. If fan speed is held constant, the supply air temperature adjustment strategy gives small load reductions. However, at the same time, this strategy greatly increases occupant discomfort. Therefore this strategy by itself is not recommended.

Table 2. Recommendations for Building Operators for Medium Office Building for High-Peak Day

% OF LOAD REDUCTION EXPECTED	DR STRATEGIES	RANGE OF FANGER PPD:	ZONE REQUIRING ATTENTION*
2-5%	LPDR 10%, 20%, 30%	5-8%	None
20-25%	TSS	5-15%	5-36%
25-30%	ALL	5-15%	5-35%

* PPD values are too high in one zone

Table 3. Recommendations for Building Operators for Large Office building for High-Peak Day

% OF LOAD REDUCTION EXPECTED	DR STRATEGIES	RANGE OF FANGER PPD	ZONE REQUIRING ATTENTION*
2-5%	LPDR 10%, 20%	5-12%	None
	SATA + LMFR	5-40%	5-80%
5-10%	LPDR 30%	5-12%	None
	LPDR+CWTR	5-25%	5-72%
	LPDR+SATA	5-36%	5-78%
	TSSR+CWTR	5-23%	5-62%
	CWTR+ LMFR	5-32%	5-72%
10-15%	ALL without LMFR	5-22%	5-47%
15-20%	TSSR+SATA	5-33%	5-75%
	TSSR	5-20%	5-45%
20-25%	SATA+TSSR+LPDR	5-22%	5-47%
	TSSR+LPDR	5-20%	5-45%
25-30%	ALL + LMFR	5-23%	5-56%

* PPD values are too high in one zone

6. Chilled water temperature holding fan and pump flow rate (speed) constant gives good load reduction and the discomfort levels are smaller compared to the supply air temperature adjustment strategy.
7. It is observed that in most of the cases single control strategy did not provide maximum load reductions. Combinations of various strategies gave impressive savings (for example, TSSR+LPDR saved more compared to just TSSR.
8. All the strategies combined together can result in the most load reduction.
9. Certain DR strategies such as supply air temperature adjustment and chilled water temperature reset can result in highest discomfort levels but the discomfort levels reduce if these strategies are combined with thermostat set-point setback.
10. The thermal comfort analysis revealed that discomfort levels in a zone facing west were always higher compared to other zones. This warrants some alternative type of load curtailment (e.g. permanent or temporary shades, blinds etc.).

SUMMARY AND CONCLUSIONS

Some of the pertinent conclusions are listed below.

1. More load reduction can be achieved on summer high-peak days as compared to summer mid-peak days.
2. Higher percent reductions have been achieved for the medium sized building compared to the large one.
3. Thermostat set-point setback is found to be the best DR strategy among all other individual strategies. When all strategies are combined, one can of course obtain the highest energy savings.
4. Supply air temperature adjustment and chilled water temperature reset strategies should not be performed individually without holding the fan and pump flow rate constant.
5. Supply air temperature adjustment strategy gives minimal energy savings and had the highest occupants' discomfort level.
6. Lighting power density gives reasonable savings and did not impact occupant thermal comfort level. However, no visual comfort analysis can be performed in EnergyPlus so that aspect could not be investigated.

This study has been performed for a medium office building with packaged air conditioning unit and large office with distributed chiller systems. The results from this study ought to apply directly to buildings with similar geometry and HVAC configuration. However, this study focuses on summer months of a very hot location such as Phoenix, AZ. Identical buildings in locations with milder summers can yield different results, and would need similar studies. Of general interest is the methodology of simulating a building for evaluating different DR strategies and then summarizing the results in a form which we feel is most appropriate and helpful for building owners to decide on specific DR measures to implement.

ACRONYMS

ALL	=	All strategies combined without limiting mass flow rate
ASHRAE	=	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CWTR	=	Chilled Water Temperature Reset
DOE	=	Department of Energy
DR	=	Demand-Response
HVAC	=	Heating, Ventilating and Air Conditioning
LMFR	=	Limiting Mass Flow Rate
LPDR	=	Lighting Power Density Reduction

O&M	=	Operation and Maintenance
PNNL	=	Pacific Northwest National Laboratory
SATA	=	Supply Air Temperature Adjustment
TMY	=	Typical Meteorological Year
TSS	=	Thermostat Set-point Setback
VAV	=	Variable Air Volume

REFERENCES

ASHRAE Standard 90.1-2004 (2004). "Energy Standard for Buildings except Low Rise Residential Buildings", American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA

ASHRAE Standard 55-2004 (2004). "Thermal environmental conditions for human occupancy," American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA

Chen, A. (2008). "Automated Demand Response: How the internet helps the electricity grid in California" http://www.lbl.gov/Science-Articles/Archive/sabl/2008/Feb/ADR.html

EnergyPlus V6.0.0, U S Department of Energy http://apps1.eere.energy.gov/buildings/energyplus/

Fanger, P. O. (1970). Thermal Comfort. Copenhagen: Danish Technical Press.

Gu, L., Raustad, R., and Basarkar, M., (2011). "Short-Term Curtailment of HVAC Loads in Buildings", ASHRAE Research Project 1390-RP UCF/FSEC 20128171, American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA

Khanolkar, A. (2012). "Short-Term Reduction of Peak Loads in Commercial Buildings in a Hot and Dry Climate", MS Thesis, The Design School, Arizona State University, May.

Motegi, N., Piette, M.A., Watson, D.S., Kiliccote, S. and Xu, P. (2007). "Introduction to commercial building control strategies and techniques for demand response". Lawrence Berkeley National Laboratory report LBNL-59975. May. Avaiable from http://drrc.lbl.gov/pubs/59975.pdf

Newsham, G.R., Donnelly, C. Mancini, S., Marchand, R.G., Lei, W., Charles, K.E. and Veitch, J.A., (2006). "The effect of ramps in temperature and electric light level on office occupants": A literature review and a laboratory experiment. Proc. 2006 ACEEE Summer Study on Energy Efficiency in Buildings Pacific Grove, CA;4-252-4-264

Norford, L.K., Englander, S.L. and Wiseley, B.J. (1998). "Demonstration Knowledge Base to Aid Building Operators in Responding to Real-Time-Pricing Electricity Rates", ASHRAE Transactions vol. 104(1), American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA

Pacific Northwest National Laboratory. (2011). http://eere.pnnl.gov/building-technologies/

Reddy, T.A., Lukes, J.K. and Norford, L.K., (2004). "Benefits of Multi-Building Electric Load Aggregation: Actual and Simulation Case Studies", ASHRAE Transactions, vol. 110(2), American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA

Yin, R., Kiliccote, S., Piette, M.A. and Parrish, K. (2010). "Scenario Analysis of Peak Demand Savings for Commercial Buildings with Thermal Mass in California" by LBNL, Proceedings of the 2010 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA.