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EVALUATION OF DEMAND SHIFTING STRATEGIES WITH THERMAL MASS IN TWO LARGE COMMERCIAL BUILDINGS

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ABSTRACT

Building thermal mass can be used to reduce the peak cooling load. For example, in summer, the building mass can be pre-cooled during non-peak hours in order to reduce the cooling load in the peak hours. As a result, the cooling load is shifted in time and the peak demand is reduced. The building mass can be cooled most effectively during unoccupied hours because it is possible to relax the comfort constraints.

While the benefits of demand shift are certain, different thermal mass discharge strategies result in different cooling load reduction and savings. The goal of an optimized discharge strategy is to maximize the thermal mass discharge and minimize the possibility of rebounds before the shed period ends. A series of field tests were carefully planned and conducted in two commercial buildings in Northern California to investigate the effects of various precooling and demand shed strategies. Field tests demonstrated the potential of cooling load reduction in peak hours and importance of discharge strategies to avoid rebounds. EnergyPlus simulation models were constructed and calibrated to investigate different kind of recovery strategies. The results indicate the value of pre-cooling in maximizing the electrical shed in the on-peak period. The results also indicate that the dynamics of the shed need to be managed in order to avoid discharging the thermal capacity of the building too quickly, resulting in high cooling load and electric demand before the end of the shed period. An exponential trajectory for the zone set-point during the discharge period yielded good results and is recommended for practical implementation.

INTRODUCTION

The principle of pre-cooling and demand limiting is to pre-cool buildings at night or in the morning during off-peak hours, storing cooling in the building thermal mass and thereby reducing cooling loads during the peak periods. Savings are achieved by reducing on-peak energy and demand charges. The potential for utilizing building thermal mass for cooling load shifting and peak demand reduction has been demonstrated in a number of simulation, laboratory, and field studies (Braun 1990, Ruud et al.

1990, Conniff 1991, Andresen and Brandemuehl 1992, Mahajan et al. 1993, Morris et al. 1994, Keeney and Braun 1997, Becker and Paciuk 2002, Xu et al. 2003).

A series of field tests were carefully planned and conducted in two commercial buildings in Northern California to investigate the effects of various precooling and demand shed strategies. Field tests demonstrated the potential of cooling load reduction (25~50%) in peak hours and importance of discharge strategies to avoid rebounds (Xu et al., 2005).

However, since only limited tests were conducted over a short period, there were several important issues that were not addressed in the field tests.

It is not clear what would happen if the temperatures were reset in the peak hours without pre-cooling. One possibility is that the cooling load reduction will be nearly as much as with pre-cooling.

The effects of nocturnal pre-cooling are still unclear. Night pre-cooling appeared to produce very modest effects in the field tests. In theory, the effects during the following morning should be more significant than in the afternoon. In fact, there are contradictory reports in the literature of tests of the effect of nocturnal cooling on the afternoon period (Ruud et al 1990) (Mahajan et al. 1993).

The importance of recovery strategies was realized at the end of the field tests when recovery was observed to be a problem on the hot days. However, there was no opportunity to test any of these strategies in the field. There are two temperature reset sequences worthy investigating, namely the linear reset, in which the temperature increases at a constant rate to the maximum temperature over the shed period, and exponential reset, in which the temperature increases faster in the beginning and slower in the end. It is important to understand the building response under these two strategies and compare their advantages and disadvantages.

Therefore EnergyPlus simulations were used in this study to help understand more about the buildings' dynamics and evaluate various strategies. EnergyPlus, DOE's successor to DOE-2, was used for the simulation work. Compared to DOE-2,

EnergyPlus has a number of advantages. It solves for the building cooling load and mechanical system response simultaneously, which is a significant advantage for demand response studies, where the zone temperatures are not always at their set-point. In addition, the time-step can be significantly less than one hour – fifteen minute time-steps were used in this study.

In this study, the simulation model was constructed first and then the measured data were used to calibrate the model. It is difficult to simulate building operation exactly and match the utility data hour by hour. Since the main focus of the study was to evaluate different building control strategies, the initial models were debugged and the parameters were adjusted till the hourly simulation profile matched the data collected in the field.

Six simulations were conducted for each building:

- 1) *Baseline*. The simulation is based on normal building operation.
- 2) *Zonal reset only*. There is no pre-cooling. The zone temperature set point is increased by a few degrees during the on-peak period.
- 3) *Pre-cooling and zonal reset*. Pre-cool the buildings during the morning off-peak period and reset the zone temperature up by few degrees during the on-peak period.
- 4) *Extended pre-cooling and zonal reset*. Pre-cool the building starting from midnight and continue throughout the morning until the start of the on-peak period, then reset the zone temperature up by few degrees during the peak period.
- 5) *Pre-cooling and linear zonal reset*. Pre-cool the building as in Strategy 3 then increase the zone temperatures linearly to the new on-peak set-point.
- 6) *Pre-cooling and exponential temperature reset*. Pre-cool the building as in Strategy 3 then increase the zone temperatures exponentially to the new on-peak set-point.

SIMULATION STUDIES: TEST SITE I

The first building selected for the study is a medium-sized governmental office building located in Santa Rosa, CA. The floor area is ~80,000 ft² and about half of the space is for offices and half for courtrooms. It has three stories with moderate structural mass, having 6” concrete floors and 4” exterior concrete walls. The office area has a medium furniture density and standard commercial carpet on the floor. The building has a window-to-wall ratio of 0.67, with floor-to-ceiling glazing on the north and south façades and significantly smaller

glazing fractions on the east and west. The windows have single-pane tinted glazing. The internal equipment and lighting load are typical for office buildings. The total number of occupants in the office areas is approximately 100 (400ft²/person).

The building has independent HVAC systems for the west wing and the east wing. On the west wing (office side), there are three 75-ton, 30-year old air-cooled chillers. Two dual-duct VAV (variable air volume) air handlers deliver conditioned air to the zones. On the east side, there are two 60-ton, 10-year old air-cooled chillers with three single duct VAV air handlers. There is one constant-speed water pump for each chiller. All the chillers have two stage compressors. The supply and return fans for the dual duct system are controlled by variable frequency drives (VFD). The single duct system has constant speed fans with inlet vane controls. There are ~ 50 thermal zones in the building. The building is fully equipped with digital direct control (DDC), but had no global zone temperature reset strategies implemented before the study.

Model Description

The EnergyPlus model is based on the mechanical system layout and zoning of the building. The west side of the building is divided into six zones, two zones per floor. There are two AHUs, each serving three zones. The air distribution system is a dual duct VAV system with a deadband of four degrees between the zone heating and cooling set-points. Test site I has a dual duct system, while test site II has a single duct VAV system. We choose one building with dual duct system and the other building of test site II. The return air flows through ducts located in plenums above the occupied spaces. The geometry information was collected from the scanned architecture drawings in AutoCAD. The lighting power density and equipment load were estimated during inspections of the building.

Simulation Scenarios

Figures 1 and 2 show the temperature set-point profiles and operating hours for the simulations performed to determine the effect of the nocturnal pre-cooling and morning pre-cooling, respectively. By comparing the electrical demand of zonal reset with and without pre-cooling, the impact of pre-cooling can be determined. By comparing the electrical demand of pre-cooling with zonal reset to extended pre-cooling with zonal reset, the effects of night pre-cooling can be determined.

Simulation Results

Figure 3 shows the simulated chiller power for a hot summer day for various pre-cooling strategies. The outside air temperature profile for the simulated hot summer day is similar to those of the hot test days.

Zonal reset only. Zonal reset without pre-cooling produces an immediate cooling load shed of almost the same magnitude as that produced after pre-cooling. However, the shed does not last as long as after pre-cooling. The chiller power increases more quickly and rises to a higher level.

Pre-cooling with zonal reset. Compared with the baseline, the chiller power is a bit higher in the morning before the peak period. However, during the peak period, the chiller power is significantly less than that observed without pre-cooling. The cooling load, and hence the electrical demand, is moved from the on-peak period in the afternoon to the off-peak period in the morning.

Extended pre-cooling with zonal reset. The shed during the on-peak period is almost identical to the shed obtained using the morning-only pre-cooling strategy. The extended pre-cooling shifts the morning cooling load a bit, but not as much as expected. Note that there is no chiller power consumption during the night because the outside air temperature is low enough that chiller operation is not needed in order to meet the supply air temperature set-point. During the on-peak period, the extended pre-cooling decreases the cooling load by a very small amount compared to morning-only pre-cooling. This agrees with our experiment data collected from the site. The effects of extended pre-cooling in this building are very limited.

Figure 4 shows the simulation results of various set-point trajectories during the on-peak period. Notice that in the simulation results shown in Figure 3, the chiller comes back on in the afternoon and creates a second peak. The more ideal scenario is to charge the thermal mass more smoothly and to create a flat power profile in the afternoon. Figure 4 shows the chiller power over a 24 hour period for various demand discharge strategies. Notice that the integrated cooling load shed is almost same for all the strategies, which is to be expected since the heat capacity is unchanged.

Pre-cooling and linear zonal reset. Compared to the morning pre-cooling with zonal reset, the chiller power varies more smoothly. The shed is not as drastic as the instant reset but there is still a little rebound just before the end. However, the electrical power profile is much improved.

Pre-cooling and exponential zonal reset. This strategy achieves the best power profile of all the scenarios. The power is essentially constant during the on-peak period and there is no “rebound”.

SIMULATION STUDIES: TEST SITE II

The second test site, is an office building located at Mather Field, near Sacramento, California. It is a 84,000square foot, Class A office building. The building was built in 2001. It has two stories with moderate structural mass, having 4in (0.1m) concrete floors and 8in (0.2m) exterior concrete walls. The office area has a medium furniture density and standard commercial carpet on the floor. The building has a window-to-wall ratio of 0.5. The windows are single-pane glazing with green tint.

Model Description

The building has two floors and two rooftop package units. The building was divided into ten zones, five zones on each floor. On each floor, there is an interior zone and four exterior zones facing north, south, east, and west. The lighting power density and equipment load were estimated during inspections of the building. The air distribution system is single duct VAV.

The simulation scenarios are identical to those in Test site I. Six cases were simulated to identify the effects of the morning pre-cooling, night pre-cooling and various recovery strategies as showed in Figure 1 and 2.

Simulation results

Figure 5 and 6 show the simulation results for Test site II. The outside air temperature profile for the simulated hot summer day is similar to those of the hot test days. Since rooftop units are used in this building, it is essential to separate the fan power usage and compressor power usage. Two plots were made under each scenario. One is the total electricity power and the other is the cooling load.

Figure 5 and 6 shows the rooftop unit total electricity and cooling load under various pre-cooling strategies. The total electricity power agrees well with the field results for the morning pre-cooling with zonal reset test.

Zonal temperature reset only. Compared with pre-cooling strategies, the shed is not as deep and does not last as long as the pre-cooling strategies. Zonal reset without pre-cooling produces an immediate load shed of smaller magnitude than that produced after pre-cooling. The shed does not last as long as after pre-cooling and the chiller power rises to a higher level.

Morning pre-cooling with zonal reset. In the morning period, both the total power and the cooling load are slightly higher than the baseline. When the set-point is increased at 12 pm, the total power and the load are each immediately reduced by about 50%.

However, the shed does not last very long; the temperature increase quickly and the total power and the load reach new peaks at about 4 pm.

Extended pre-cooling with zonal reset. In the morning period, the electrical load is only slightly lower than with morning-only pre-cooling. In the on-peak period, the magnitude of the shed is significantly greater than with morning-only pre-cooling and the rebound is significantly reduced.

The main result is that extended pre-cooling produces significantly deeper shedding, at the expense of substantial energy use during the night, resulting in a significant energy penalty. This result for the test site II matched well with the results for the test site I, where both the simulation results and the field tests showed little or no benefit from extending the pre-cooling period. This result should be investigated further to determine the critical factor producing the difference in response and verify that the result is not spurious.

Figure 7 and 8 show comparisons of various temperature-reset strategies. As was found for the test site I, the load profile for the exponential profile is the best, producing an essentially constant load and the lowest peak demand.

CONCLUSION

The simulation results for both buildings confirmed the results of the field tests that increasing the zone temperature set-point by four degrees can reduce chiller electricity consumption by about 33% and HVAC electricity consumption by about 25% over a four hour shed, even on hot days. The results also indicate the value of pre-cooling in maximizing the electrical shed in the on-peak period. By lowering the zone temperature by two degrees in the morning off-peak period, the on-peak shed resulting from raising the set-point by four degrees is increased by about 50%. Whether or not pre-cooling is used, the dynamics of the shed need to be managed in order to avoid charging the thermal capacity of the building too quickly, resulting in high cooling load and electric demand before the end of the shed period. An exponential trajectory for the zone set-point during the shed yielded good results and is recommended for practical implementation.

The simulation results also indicate that the effect of the extended pre-cooling can vary significantly. The result for test site I was that there is almost no effect, which is what was observed in the field tests. For test site II, nocturnal pre-cooling increased the shed by about 30%, though with a significant off-peak energy consumption penalty. Further work is required to determine the key building and HVAC

system characteristics that determine the effect of nocturnal pre-cooling on on-peak electricity consumption.

ACKNOWLEDGMENT

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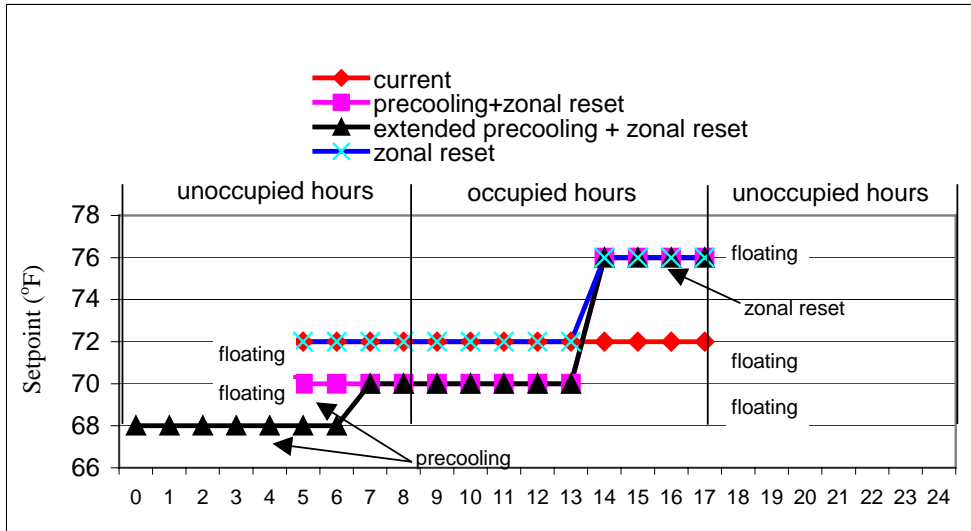


Figure 1 Pre-cooling and zonal reset strategies used in the simulation

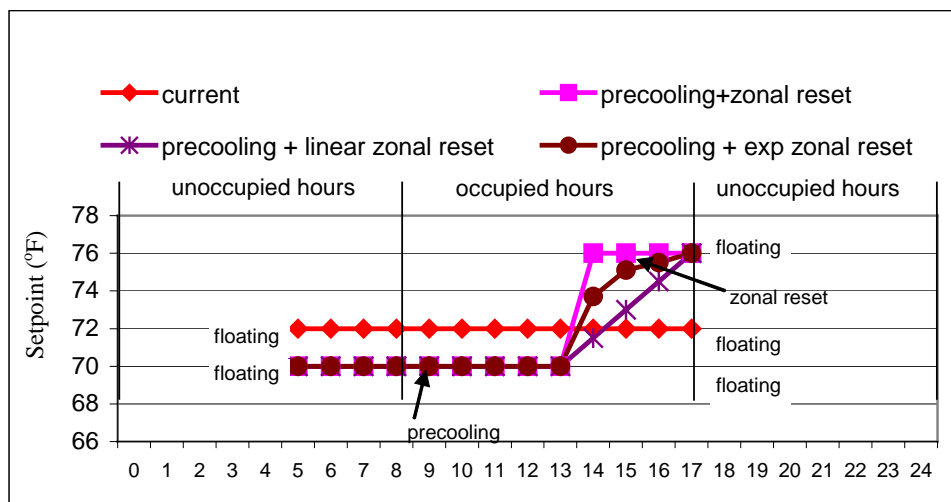


Figure 2 Demand limiting and recovery strategies used in the simulation

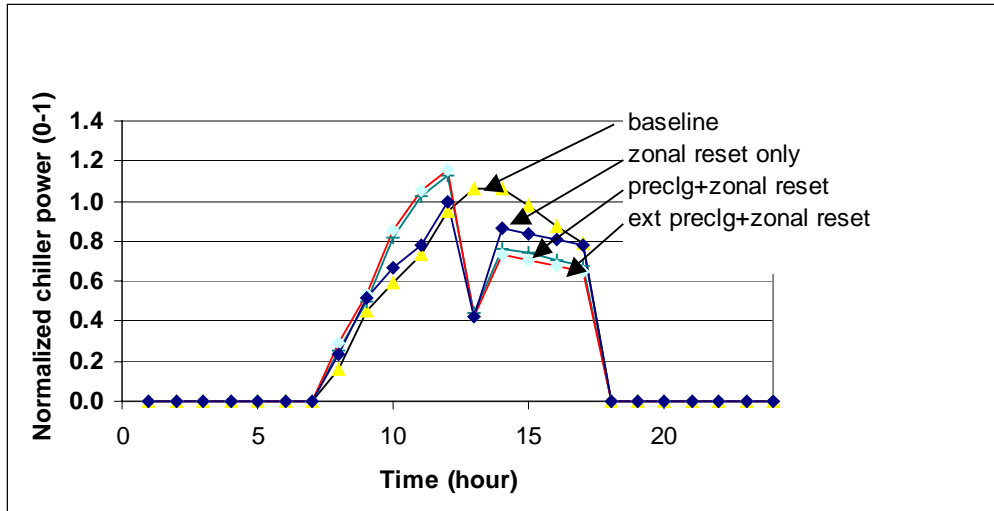


Figure 3 Simulated chiller power under various pre-cooling strategies (Test site I)

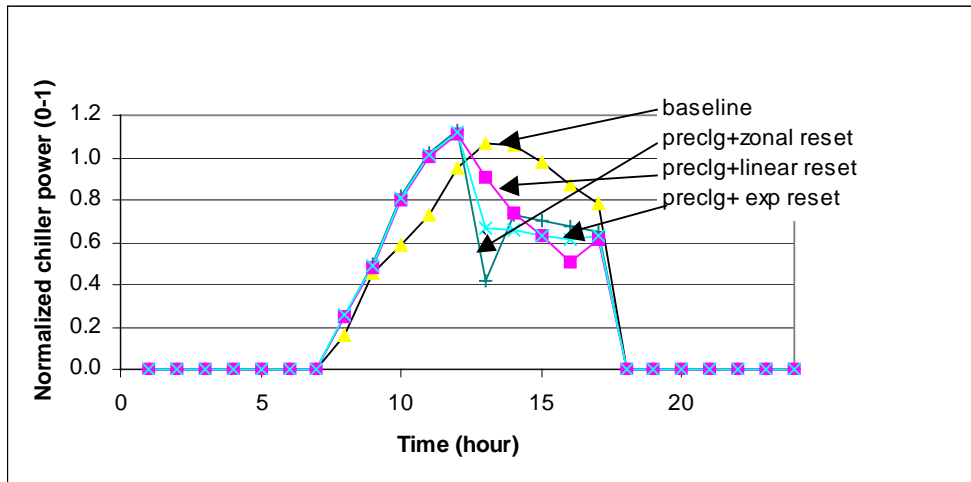


Figure 4 Simulated chiller power under various zonal reset strategies (Test site II)

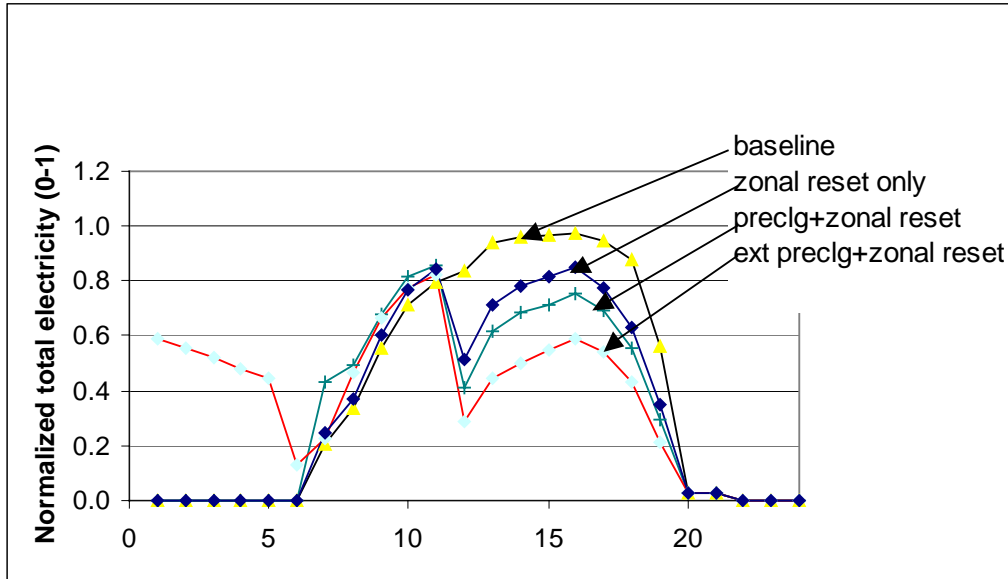


Figure 5 Rooftop unit electricity demand under various pre-cooling strategies (Test Site II)

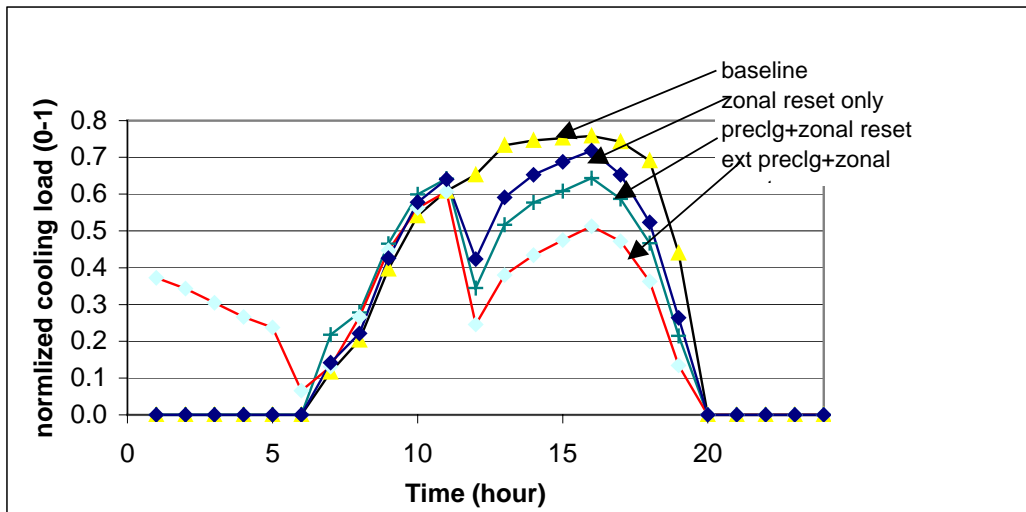


Figure 6 Rooftop unit cooling load under various pre-cooling strategies (Test site II)

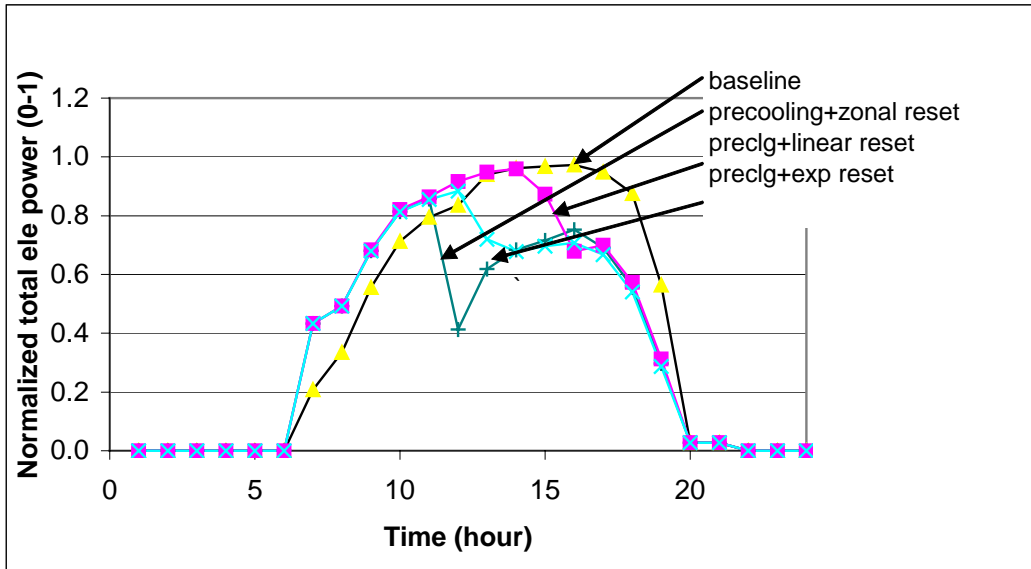


Figure 7 Rooftop unit total electricity consumption for different temperature-reset strategies (Test site II)

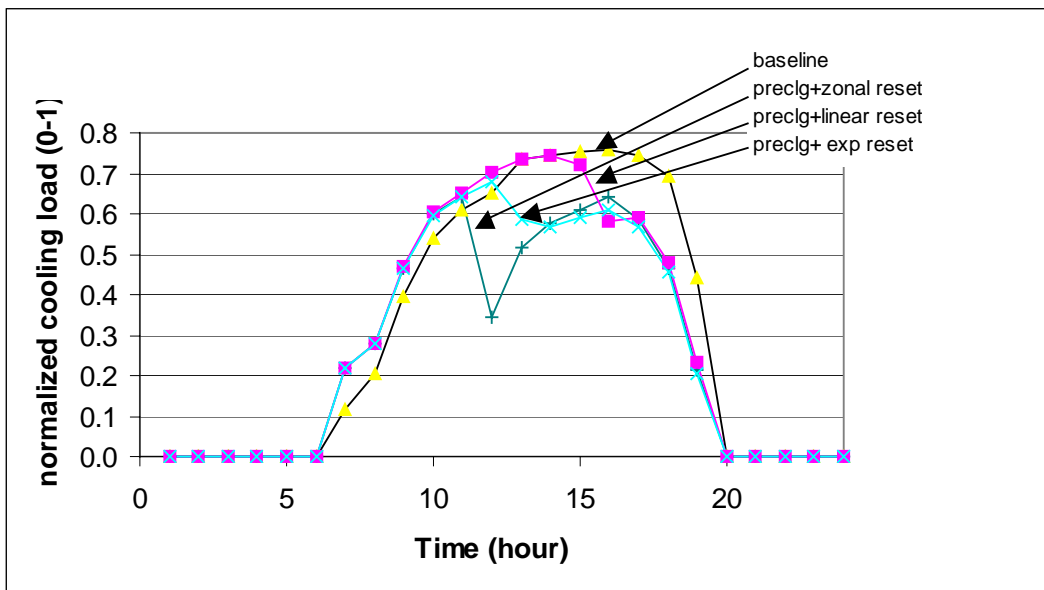


Figure 8 Rooftop unit cooling load under various pre-cooling strategies (Test Site II)