Introduction to Commercial Building Control Strategies and Techniques for Demand Response

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

What follows is the final report for the Statewide Auto-DR Collaboration Project, 500-03-026, conducted by Lawrence Berkeley National Laboratory. The report is entitled "Introduction to Commercial Building Control Strategies and Techniques for Demand Response." This project contributes to the Energy Systems Integration Program.

For more information on the PIER Program, please visit the Energy Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Energy Commission's Publications Unit at 916-654-5200.

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Abstract

Demand Response (DR) is a set of time-dependent program activities and tariffs that seek to reduce electricity use or shift usage to another time period. DR provides control systems that encourage load shedding or load shifting during times when the electric grid is near its capacity or electricity prices are high. DR helps to manage building electricity costs and to improve electric grid reliability.

This report provides an introduction to commercial building control strategies and techniques for demand response. Many electric utilities have been exploring the use of critical peak pricing (CPP) and other demand response programs to help reduce summer peaks in customer electric loads. This report responds to an identified need among building operators for knowledge to use DR strategies in their buildings. These strategies can be implemented using either manual or automated methods.

The report compiles information from field demonstrations of DR programs in commercial buildings. The guide provides a framework for categorizing the control strategies that have been tested in actual buildings. The guide's emphasis is on characterizing and describing DR control strategies for air-conditioning and ventilation systems. There is also good coverage of lighting control strategies. The guide provides some additional introduction to DR strategies for other miscellaneous building end-use systems and non-component-based DR strategies.

The core information in this report is based on DR field tests in 28 non-residential buildings, most of which were in California, and the rest of which were in New York State. The majority of the participating buildings were office buildings. Most of the California buildings participated in fully automated demand response field tests.

Executive Summary

Introduction

Demand Response (DR) is a set of time-dependent program activities and tariffs that seek to reduce or shift electricity usage to improve electric grid reliability and manage electricity costs. DR strategies provide control methodologies that enhance load shedding or load shifting during times when the electric grid is near its capacity or electricity prices are high. Many electric utilities have been exploring the use of critical peak pricing (CPP) and other demand response programs to help reduce summer peaks in customer electric loads. Recent evaluations have shown that customers have limited knowledge of how to operate their facilities to reduce their electricity costs under CPP (Quantum and Summit Blue 2004).

Purpose

The purpose of this report is to provide an introduction to commercial building control strategies and techniques for demand response. While energy efficiency measures have been widely understood by many audiences including facility managers, building owners, control contractors, utility program managers, auditors, and policy makers, there are not many documents introducing frameworks or guidelines for measures and strategies to participate in demand response programs.

Commercial buildings have been only minor participants in demand response programs. This report is designed to be an initial introduction to the technical capabilities of existing building equipment and systems and their ability to provide demand response control strategies. While the focus of the guide is on DR, we have found that the process of developing DR control strategies can also help identify strategies for energy efficiency during daily building operations.

Project Objectives

The report is a unique guide that compiles information from actual field demonstrations of DR programs in commercial buildings. The guide provides background technical information necessary to identify and enable demand response control strategies. The guide is intended for use by building professionals including facility managers, building owners, control contractors, building engineers, utility personnel, and auditors.

Project Outcomes

The guide provides a framework for categorizing the control strategies that have been tested in actual buildings. The guide's emphasis is on characterizing and describing DR control strategies for air-conditioning and ventilation systems, plus lighting control strategies. The guide provides some additional introduction to DR strategies for other miscellaneous building end-use systems and non-component-based DR strategies. These strategies can be implemented using either manual or automated methods.

The core information in this report is based on DR field tests in 28 non-residential buildings, most of which were in California, and the rest of which were in New York State. The majority of the participating buildings were office buildings. Most of the California buildings participated in fully automated demand response field tests.

Heating, Ventilating, and Air Conditioning (HVAC). HVAC systems can be an excellent resource for DR savings for the following reasons. First, HVAC systems comprise a substantial portion of the electric load in commercial buildings. Second, the "thermal flywheel" (thermal storage) effect of indoor environments allows HVAC systems to be temporarily unloaded without immediate impact on the building occupants. Third, it is common for HVAC systems to be at least partially automated with energy management and control systems (EMCS). To provide reliable, repeatable DR control, it is best to pre-plan and automate operational modes that will provide DR savings. The use of automation reduces the labor required to implement DR operational modes when they are signaled.

HVAC-based DR strategies recommended for a given facility vary based on building type and condition, mechanical equipment, and EMCS. Based on these factors, the best DR strategies are those that achieve the aforementioned goals of meeting electricity demand-savings targets while minimizing negative impacts on the occupants of the buildings or the processes that they perform. This guide discusses the following DR strategies for HVAC systems, which are best suited to achieve these goals:

- Global Temperature Adjustment of Zones, and
- Systemic Adjustments to the Air Distribution and/or Cooling Systems.

It is often difficult to estimate the demand savings achieved by HVAC strategies, because the building's HVAC electric load is dynamic and sensitive to weather conditions, occupancy, and other factors. However, previous research has found that HVAC demand as well as demand savings tend to have positive correlation with outside air temperature (OAT).

Lighting. DR strategies for lighting can also be effective in reducing peak demand. On a hot summer day when daylight is in abundance, daylit and/or over-lit buildings are the best candidates for lighting demand savings. Since lighting produces heat, reducing lighting levels will also reduce the cooling load within the space (Sezgen and Koomey 1998). Lighting DR strategies tend to be simple and depend widely on wiring and controls infrastructures. However, since lighting has safety implications and the strategies tend to be noticeable, they should be carried out selectively and carefully, considering the tasks in the space and ramifications of reduced lighting levels for the occupants.

DR control capability of lighting systems is generally determined by the characteristics of the lighting circuit and the control system. Following is the list of lighting DR strategies discussed in this guide in increasing order of sophistication:

- Zone switching

- Fixture switching
- Lamp switching
- Stepped dimming
- Continuous dimming

Miscellaneous Equipment. There is also demand savings potential for certain other equipment in both commercial and industrial buildings. Equipment or processes with the demand saving potentials discussed in this report are fountain pumps, anti-sweat heaters, electric vehicle chargers, industrial process loads, cold storage, and irrigation water pumps.

Non-Component-Specific Strategies. Other effective DR strategies focus on controls settings rather than on specific equipment. Such strategies highlighted in this report include demand limit strategy and signal-level response strategy.

Conclusions

HVAC systems can be an excellent resource for DR shed savings because; 1) HVAC systems create a substantial electric load in commercial buildings, 2) the thermal flywheel effect of indoor environments allows HVAC systems to be temporarily unloaded without immediate impact to the building occupants, and 3) it is common for HVAC systems to be at least partially automated with EMCS systems.

For HVAC DR strategies, global temperature adjustment of zones is the priority strategy that best achieves the DR goal. In contrast, systemic adjustments to the air distribution and/or cooling systems can be disruptive to occupants. DR strategies that slowly return the system to normal condition (rebound avoidance) should be considered to avoid unwanted demand spikes caused by an immediate increase of cooling load.

Lighting DR strategies tend to be simple and provide constant, predictable demand savings. Since lighting produces heat, reducing lighting levels may reduce the cooling load and/or increase the heating load within the space. The resolution of lighting controls tends to be lower than that of HVAC controls. Also lighting systems are often not automated with EMCS. These issues can be major obstacles for automation of lighting DR strategies.

If a DR strategy can be achieved without any reduction in service, the strategy should be considered as permanent energy efficiency opportunity rather than a temporary DR strategy. That is, it should be performed on non-DR days as well. The process of commissioning should be applied to each phase of DR control strategy application, including planning, installation, and implementation to make sure the goal of DR control is achieved.

Recommendations

The information in this report should be disseminated to key personnel who are involved in DR implementation including facility managers, building owners, controls contractors, and auditors. Disseminating this information will help provide a common understanding of DR control strategies and development procedures to enable these strategies. The report is not an exhaustive list of all DR strategies. Further research is needed to better understand the peak demand reduction potential and capabilities of these strategies for various building types in different climates and occupancy patterns. One specific technical development needed is to explore the design and operation of simplified peak electric demand savings estimation methods and tools. Current auditors and building engineers have widely varying methods to estimate peak demand reductions for various strategies.

Benefits to California

This guide is based primarily on case studies in California and is intended to help streamline the DR control strategy implementation process and increase successful participation in DR programs in California. Peak demand reduction and demand response are key parts of the state's energy policies.

1. Introduction

1.1. Background and Overview

Demand Response (DR) is a set of time-dependent program activities and tariffs that seek to reduce or shift electricity usage to improve electric grid reliability and manage electricity costs. DR strategies provide control methodologies that enhance load shedding or load shifting during times when the electric grid is near its capacity or electricity prices are high. Many electric utilities have been exploring the use of critical peak pricing (CPP) and other demand response programs to help reduce summer peaks in customer electric loads. Recent evaluations have shown that customers have limited knowledge of how to operate their facilities to reduce their electricity costs under CPP (Quantum and Summit Blue 2004).

1.2. Objectives

The purpose of this report is to provide an introduction to commercial building control strategies and techniques for demand response. While energy efficiency measures have been widely understood by many audiences including facility managers, building owners, utility program managers, auditors, and policy makers, there are not many documents introducing frameworks or guidelines for measures and strategies to participate in demand response programs. Commercial buildings have been only minor participants in demand response programs. This report is designed to be an initial introduction to the technical capabilities of existing building equipment and systems and their ability to provide demand response control strategies. While the focus of the guide is on DR, we have found that the process of developing DR control strategies can also help identify strategies for energy efficiency during daily building operations.

This report will help understand technical aspects of demand response control strategies. HVAC systems are often complex combinations of components with minimal sensor points, limited trend logging, and poorly-commissioned sequences of operation. The process of developing DR control strategies will provide valuable peak demand savings in addition to new insights for improving energy efficiency during daily building operations. The report is the first guide that compiles information from actual field demonstrations of DR programs in commercial buildings. The guide provides the technical information necessary to install demand response control strategies for audiences including facility managers, building owners, and auditors.

1.3. Research Scope

This report provides an introduction to commercial building control strategies for demand response that have been field-tested in actual commercial buildings. These strategies can be implemented using either manual or automated control methods. The authors compiled information from actual field demonstrations in commercial buildings that have participated in DR programs in California and New York. Thus, the guide provides a framework for categorizing control strategies that have been tested in actual buildings. The guide emphasizes strategies for air-conditioning and ventilation systems. There is also ample coverage of lighting control strategies. In addition, the guide provides some introduction to DR strategies for other building end-use equipment. It also discusses non-component-based DR strategies.

The report is a unique guide that compiles information from actual field demonstrations of DR programs in commercial buildings. The guide provides background technical information necessary to identify and enable demand response control strategies. The guide is intended for use by building professionals including facility managers, building owners, control contractors, building engineers, utility personnel, and auditors. It may also be of interest to researchers, energy planners, and policy makers.

The demand response control strategies discussed in this guide would be recommended for either semi- or fully-automated DR, though they may be used for manual DR as well. See Section 1.6 on **Levels of Automation for DR** for definitions of DR automation types. Lawrence Berkeley National Laboratory (LBNL) has been conducting a series of research projects and demonstrations of fully-automated DR strategies (referred to as *LBNL Auto-DR*) (Piette et al. 2005a, 2005b, and 2006). This report is based on the cumulative experiences and findings from the LBNL Auto-DR demonstration studies along with the other case studies referenced in this report.

The core information in this guide is based on DR field tests in 28 non-residential buildings, most of which were in California. DR data from the Energy Commission's Enhanced Automation case studies in California were also evaluated (CEC 2006a), along with case studies from New York (NYSERDA 2006). Case studies to date have emphasized certain types of buildings, while other building types have not yet been studied. The majority of the participants have been office buildings. Other building types include several retail sites, a supermarket, public assembly buildings, a cafeteria, a post office, a museum, a high school, data centers, and laboratory buildings. The sample did not include any hotel or healthcare buildings, but many of the strategies discussed may be applicable to these building types. Most of the California buildings participated in fully automated demand response field tests.

It is also important to consider the HVAC systems that the case studies and demonstration buildings used. Built-up variable air volume (VAV) systems with central cooling plants dominate the sample, although many of the smaller buildings use rooftop packaged unit systems. Many of the less-common HVAC systems were not included in the case studies. This report did not identify any water-source heat pump or gas cooling sites that have implemented DR strategies.

This guide focuses on summer peak demand reduction strategies, although lighting DR strategies can be utilized to reduce winter demand as well. Most of the examples introduced in this report are based on case studies in the northern or central California region, which has a mild or hot-and-dry climate. This report does not include careful consideration of the application of DR to facilities in hot and humid climates.

This guide is intended as a starting point for organizing and presenting such information. Although the information is based on a limited number of buildings, the authors compiled the existing case study data because of the need for organized information on this subject. The information in this guide has been evaluated by several professional engineers and energy analysts to bring building HVAC and controls theory into the discussion of DR strategies.

1.4. Benefits to California

This guide is based primarily on case studies in California and is intended to help streamline the DR control strategy implementation process and increase successful participation in DR programs in California. Peak demand reduction and demand response are key parts of the state's energy policies.

1.5. Report Organization

This section discusses the guide's background, objectives, organization, and definitions, terms, and concepts. Section 2 provides an overview of the characteristics of demand response control strategies. These control strategies are presented in four categories: HVAC, lighting, miscellaneous equipment, and non-end-use-specific measures. In Section 3, ten HVAC strategies, four lighting strategies, six miscellaneous equipment strategies, and two non-end-use-specific strategies are described in detail along with their system requirements and sequences of operation. The appendices provide more detailed descriptions and case study examples of each strategy. Section 4 discusses commissioning and the EMCS data collection procedure; measurement and verification of demand response strategies is very important to achieve successful demand response. Statistical findings from the DR strategy case studies are also introduced in this section.

This report reviewed DR strategies that have been demonstrated in actual buildings in previous research activities, including;

- Enhanced Automation - California Energy Commission (CEC 2006a)
- Real-Time Price Response Program - Independent System Operator New England (ISO New England 2003)
- Automated Demand Response - Lawrence Berkeley National Laboratory (LBNL) (Piette 2005a, 2005b)
- Automated Critical Peak Pricing - LBNL (Piette 2006)
- Demand Shifting with Thermal Mass - LBNL (Xu 2004, 2006)
- Peak Load Reduction Program - New York State Energy Research and Development Authority (NYSERDA 2006 and Smith 2004)
- New York Times - LBNL and New York Times (Kiliccote 2006)
- Demand Response Program Evaluation - Quantum Consulting and Summit Blue Consulting (Quantum and Summit Blue 2004)

1.6. Building Operation and Energy Management Framework

This section provides background information for various energy and demand control activities. It also provides definitions of terms and concepts used in this guide.

During the past few decades, knowledge and use of practices to minimize energy consumption in commercial building design and operations has been improved to achieve greater levels of energy efficiency. Related to reduction of energy use is energy cost minimization. Electricity cost minimization in building operations requires close attention to the structures of electricity tariffs, which consider the time and the quantity of electricity used. Electricity pricing structures can be complex, including time-of-use charges, demand ratchets, peak-demand charges, and other related features. New demand response programs and tariffs that utilities or independent system operators (ISO) offer provide greater incentives to consider the use of sophisticated building operational and control strategies that reduce electricity use during occasional events. Following are three definitions for building design and operational control strategies. Table 1 provides insight into the motivations, design, and operation of these three strategies (Kiliccote 2006).

Energy Efficiency and Conservation: Energy efficiency lowers energy use while providing the same level of service. **Energy conservation** reduces unnecessary energy use. Both energy efficiency and conservation provide environmental protection and utility bill savings. **Energy efficiency measures** can permanently reduce peak demand by reducing overall consumption. In buildings this is typically done by installing energy efficient equipment and/or operating buildings efficiently. Energy-efficient operations, a key objective of new building commissioning and retro-commissioning (for existing buildings), require that building systems operate in an integrated manner.

Table 1. Demand side management terminology and building operations

	Efficiency and Conservation (Daily)	**Peak Load Management (Daily)**	**Demand Response (Dynamic Event Driven)**
Motivation	Economic Environmental protection Resource availability	TOU savings Peak demand charges Grid peak	Price (economic) Reliability Emergency supply
Design	Efficient shell, equipment, systems, and control strategies	Low power design	Dynamic control capability
Operations	Integrated system operations	Demand limiting Demand shifting	Demand shedding Demand shifting Demand limiting
Initiation	Local	Local	Remote

Peak Load Management: Daily peak load management has been conducted in many buildings to minimize the impact of peak demand charges and time-of-use rates. Typical peak load management methods include demand limiting and demand shifting.

Demand Limiting refers to shedding loads when pre-determined peak demand limits are about to be exceeded. Demand limits can be placed on equipment (such as a chiller or fan), systems (such as a cooling system), or a whole building. Loads are restored when the demand is sufficiently reduced. This is typically done to flatten the load shape when the monthly peak demand is pre-determined. **Demand shifting** is achieved by changing the time that electricity is used. Thermal energy storage is an example of a demand shifting strategy. Thermal storage can be achieved with active systems such as chilled water or ice storage, or with passive systems such as pre-cooling of building mass. In California, **time dependent valuation (TDV)**[1] is also in use for building energy code compliance calculations required by the state building energy code (Title 24) to take into account the time that electricity is used during the year (CEC 2005). TDV acknowledges that some efficiency measures reduce summer peak electric demand more than others.

Demand Response: Demand response is dynamic and event-driven and can be defined as short-term modifications in customer end-use electric loads in response to dynamic price and reliability information. Demand response programs may include dynamic pricing and tariffs, price-responsive demand bidding, contractually obligated and voluntary curtailment, and direct load control or equipment cycling. As discussed above, **Demand limiting and shifting** can be utilized for demand response. DR can also be accomplished with **demand shedding,** which is a temporary reduction or curtailment of peak electric demand. Ideally a demand shedding strategy would maximize the demand reduction while minimizing any loss of building services.

Figure 1 illustrates concept of typical electric load shapes for each energy/demand control activity described above.

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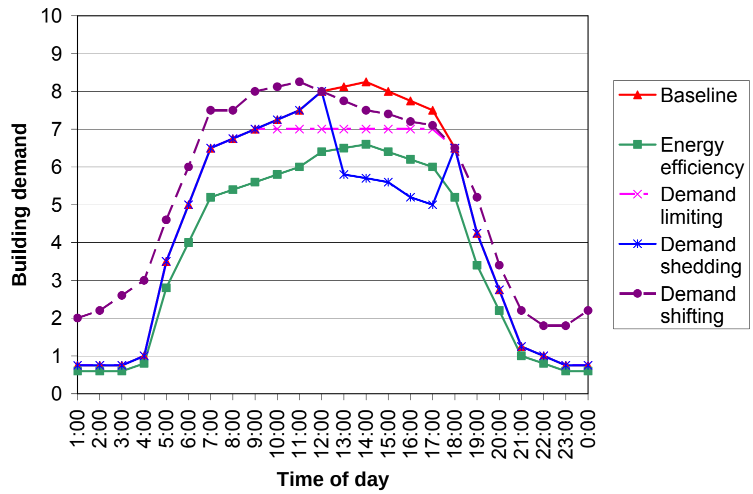
[1] Time dependent valuation (TDV) is an energy cost analysis methodology that accounts for variations in cost related to time of day, seasons, geography, and fuel type. In California, under TDV the value of electricity differs depending on time-of-use (hourly, daily, seasonal) and the value of natural gas differs depending on season. TDV is based on the cost for utilities to provide the energy at different times.



* This chart is conceptual; the data are not from actual measurements.

Figure 1. Examples of load shapes

Levels of Automation for DR: Varying levels of automation for DR can be defined as follows. **Manual Demand Response** involves a labor-intensive approach such as manually turning off or changing comfort set points at each equipment switch or controller. **Semi-Automated Demand Response** involves a pre-programmed load shedding strategy initiated by a person via centralized control system. **Fully-Automated Demand Response** does not involve human intervention, but is initiated by an Energy Management Control System (EMCS) in a home, building, or facility through receipt of an external communications signal, receipt of which initiates pre-programmed shedding strategies.

Recent evaluations have shown that customers have limited knowledge of how to operate their facilities to reduce their electricity costs under critical peak pricing or CPP (Quantum and Summit Blue 2004). While lack of knowledge of how to develop and implement DR control strategies is a barrier to participation in DR programs like CPP, another barrier is the lack of automation in DR systems. Most DR activities are manual and require people to first receive emails, phone calls, and pager signals, and secondly for people to act on these signals to execute DR strategies (Piette 2006).

1.7. Terms and Concepts for DR Strategies

The terms defined below describe key concepts of demand response control strategies. These terms are used throughout this report.

Reduction in service: Demand response strategies achieve reductions in electric demand by temporarily reducing the level of service in the facility. HVAC and lighting are the systems most commonly adjusted to achieve demand response savings in commercial buildings. The goal of demand response strategies is to meet the demand savings targets while minimizing any negative impacts on the occupants of the buildings or the processes that they perform.

Occupant satisfaction: Occupant satisfaction should be maintained by adjusting DR strategies to minimize the reduction in service, so that the occupants do not notice the change in service (detectability), or at least so that the occupants can accept the changes (acceptability). Many studies have addressed the effect of temperature changes or lighting changes on occupant detectability, acceptability, and task performance. Newsham et al. conducted an extensive literature search on these studies (Newsham 2006).

One common question regarding DR strategies is: If you can use a strategy for a short period, why not use it all the time? Even if the occupants do not notice the reduction in service, the occupants' productivity may be higher when the space conditions are closer to the occupants' desirable conditions. Differences between the impacts of short-term and long-term space condition changes are yet unknown. Daily demand savings associated with reduction in service should be considered carefully. See **Links to retro-commissioning** below for discussion of related topics.

Shared burden: DR strategies that share the burden evenly throughout the facility are least likely to have negative effects on building occupants. For example, if it were possible to reduce lighting levels throughout an entire facility by 25% during a DR event, impacts to occupants might be minimal. However, turning off all of the lights in one quadrant of an occupied space would not be acceptable. In HVAC systems, strategies that reduce load evenly throughout all zones of a facility are superior to those that allow certain areas (such as those with high solar gains) to substantially deviate from normal temperature ranges. By combining demand savings from shed in each component of HVAC and lighting systems (and other loads, if available), the impact on each component is minimized and the demand savings potential is increased.

Closed-loop control: Comfort is maintained in modern buildings through the use of closed loop controls. Sensors are used to measure important parameters such as temperature, and actuators adjust dampers or valves to maintain the desired setpoints. The effect of the valve or actuator on the controlled zone or system is measured by the sensor, hence *closing the (control) loop*. Control sub-systems for which there is no feedback from sensors are known as *open loop* controls.

To maintain predictable and managed reductions of service during DR events, strategies should maintain the use of closed loop control wherever possible. However, closed loop control may become an obstacle to achieve demand savings when the final target parameter cannot be changed through centralized control. (For example, pneumatic control systems cannot change zone setpoints from centralized control, while typical direct digital control systems can.) For instance, if supply air temperature is raised in a closed loop control system to reduce chiller demand, the fan speeds up to deliver more air to satisfy the zone setpoints and fails to shed HVAC demand, unless the zone setpoints are increased.

Granularity of control: For the purposes of DR control in buildings, the concept of *granularity* refers to the amount of floor area covered by each controlled parameter (e.g.

temperature). If the space has many zones that can be separately controlled, the control strategy is considered highly granular. In HVAC systems, the ability to easily adjust the temperature setpoint of each occupied space is a highly granular way to distribute the DR shed burden throughout the facility. Less granular strategies such as making adjustments to chillers and other central HVAC equipment can provide effective shed savings, but can cause temperature in some zones to drift out of control. Granularity of control can also allow building operators to create DR shed behaviors that are customized for their facility. An example would be to slightly increase all office zone temperature setpoints, but leave computer room setpoints unchanged.

Resolution of control: Higher resolution of control increases the flexibility to adjust the level of DR control within a desirable range. Higher resolution of control also enhances the capability of ramping up the change of DR control parameters. HVAC parameters can often be controlled with high resolution; in many systems temperature setpoints can be adjusted by as little as 0.1°F. Although some modern fluorescent dimming ballasts can adjust individual lamps light output in 1% increments, most commercial lamp ballasts are only capable of turning lamps on or off.

Rebound: At the end of each DR event, the affected systems must return to normal operation. When lighting strategies are used for DR, normal operation is regained by simply re-enabling all lighting systems to their normal operation. Lights come back on as commanded by time clocks, occupancy sensors, or manual switches. There is no reason for lighting power to jump to levels that are higher than normal for that period.

However, without special forethought, HVAC systems tend to use extra energy following DR events to bring systems back to normal conditions. Extra energy is used to remove heat that is typically gained during the reduced service levels of the DR event. This post DR event spike is known as *rebound*. To minimize the chance of high demand charges and to reduce negative effects to the electric grid, rebound should be minimized through use of a graceful return to normal strategy. The simplest case is where the DR event ends or can be postponed until the building is unoccupied. If this is not possible, strategies that allow HVAC equipment to slowly ramp up or otherwise limit power usage during the post-DR period should be used.

Links to retro-commissioning: Assuming the HVAC and lighting systems are already operated to achieve optimal occupant satisfaction and minimize energy consumption in their normal operation, the implementation of DR may cause a reduction in service. However, there are many cases in reality where the systems are not operated optimally. In these cases, it may be possible to reduce electric demand without reduction in service. If a facility finds such a strategy, it should be considered a permanent energy efficiency opportunity rather than a temporary DR strategy, and should be performed on non-DR days as well.

Planning a DR strategy can be a good opportunity to examine the sequence and parameters of building control. While facility managers may be concerned about deviations from current operation only for energy efficiency, they may be more motivated if the goal is both energy efficiency and DR because the occupants can be more permissive under a DR situation in many cases. Once confirmed that the strategy does not negatively impact the level of service, the strategy can be operated on a daily basis.

The LBNL Auto-DR studies found several cases where DR strategies merely impacted the level of service and incorporated the strategies in their daily operation (Piette et al. 2005a, 2005b, 2006). In one example, a duct static pressure reset strategy was used for a building with pneumatic zone controls. Through this effort to develop short-term DR strategies, the duct static pressure was reset to operate lower during all operating hours. In another case, reduction in service actually improved occupant comfort or productivity in some zones that were over-cooled during normal operation. These cases can be viewed as classic retro-commissioning opportunities, identified through the process of developing DR strategies. In other instances, when examining electric load shapes, the team found equipment, such as fans or process equipment, running unnecessarily at night.

In addition, if systems in a facility are operating poorly due to design or commissioning issues, it may be more difficult to implement effective DR strategies. For example, if zones are over-cooled due to excessive minimum airflows or low supply air temperatures, raising zone temperature setpoints during a DR event will not save energy.

DR strategy commissioning: The process of commissioning should be applied to each phase of DR control strategy application including planning, installation, and implementation to make sure that the goal of DR control -- to maximize demand savings and minimize impact to occupants -- is achieved. The commissioning procedure and key issues are described in Section 4.1.

Design of DR control strategies would ideally take place during the new construction commissioning phase and be incorporated into the commissioning process. A demonstration of this concept is being planned at the New York Times Headquarters building (Kiliccote et al. 2006).

2. Demand Response Strategy Overview

This section provides an overview of demand response control strategies. These strategies are categorized into four areas: HVAC, lighting, miscellaneous equipment, and non-component-specific measures. The details of each strategy are described in the following section.

2.1. HVAC Systems

HVAC systems can be an excellent resource for DR shed savings for several reasons. First, HVAC systems create a substantial electric demand in commercial buildings, often more than one third of the total demand. Second, the *thermal flywheel* effect of indoor environments allows HVAC systems to be temporarily unloaded without immediate impact to the building occupants. Third, it is common for HVAC systems to be at least partially automated with EMCS.

However, there are significant technical challenges to using commercial HVAC systems to provide DR savings. These systems are designed to provide ventilation and thermal comfort to the occupied spaces. Operational modes that provide reduced levels of service or comfort are rarely included in the original design of these facilities. To provide reliable, repeatable DR sheds it is best to pre-plan and automate operational modes that will provide DR savings. The use of automation reduces labor costs associated with the implementation of DR operational modes.

HVAC-based DR strategies recommended for a given facility vary based on the type and condition of the building, mechanical equipment, and EMCS. Based on these factors, the best DR strategies are those that achieve the aforementioned goals of meeting electric demand savings targets while minimizing negative impacts on the occupants of the buildings or the processes that they perform. The following DR strategies are prioritized to achieve these goals:

- Global Temperature Adjustment of Zones
- Systemic Adjustments to the Air Distribution and/or Cooling Systems

It is often difficult to estimate the demand savings that will be achieved by HVAC strategies, because HVAC cooling load is dynamic and sensitive to weather conditions, occupancy, and other factors. However, previous research has found that the HVAC demand and its demand savings tend to have positive correlation with outside air temperature (OAT).

In all field tests that used HVAC-based DR strategies, upon initiation of DR events, temperatures in occupied zones drifted from normal levels at rates well within the acceptable rate of change specification allowed in ASHRAE Standard 55-2004 (ASHRAE 2004). DR strategies used to return HVAC systems to normal operation should also be designed to limit the rate of temperature change so as to not exceed the ASHRAE standard. DR strategies that slowly return the system to normal condition have the additional benefit of limiting rebound.

HVAC strategies can be categorized by the system targeted for control modification. These include zone control, air distribution, and central plant, in order of recommended priority. Where practical, DR strategies that use temporary modifications to zone temperature setpoints are recommended. This recommendation is based on maximizing DR shed savings effectiveness while minimizing the potential for occupant discomfort.

Figure 2 shows the basic concept of the HVAC DR strategy decision tree.

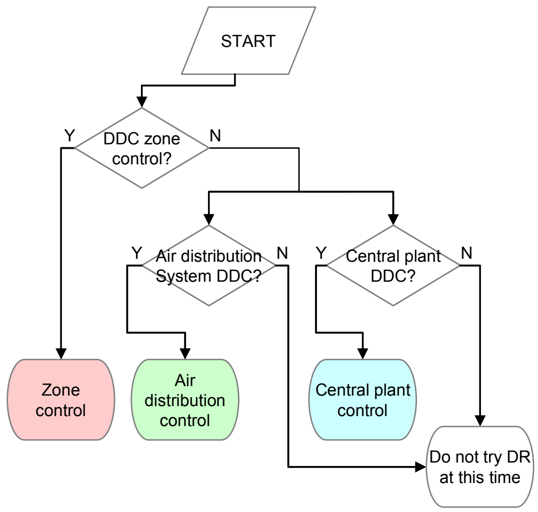


Figure 2. HVAC DR strategy decision tree

Building HVAC types

Building HVAC types are characterized using the following four primary system attributes and the secondary attributes listed in Table 2.The primary attributes are (1) constant air volume (CAV) or variable air volume (VAV), and (2) central plant with chilled water system or packaged units. Applicable DR strategies depend on these system types. Applicability based on these attributes is described in each strategy section. Many of the less-common HVAC systems, including water source heat pumps and gas cooling systems, are not included in this study.

Table 2. Building HVAC types

Type	Primary system attribute	Secondary system attribute
Type A	CAV system with central plant (CAV-Central)	Single zone / multi-zone Single duct / dual duct With reheat / without reheat Type of chiller
Type B	VAV system with central plant (VAV-Central)	Single duct / dual duct With reheat / without reheat Type of chiller
Type C	CAV system with package units (CAV-Package)	Single zone / multi-zone Single duct / dual duct With reheat / without reheat
Type D	VAV system with package units (VAV-Package)	Single duct / dual duct With reheat / without reheat

CAV: Constant air volume VAV: Variable air volume

Table 3 provides short definitions of DR strategies and their applicability by building HVAC type. One can find a building HVAC type that is the closest to one's building, and look for those strategies that are appropriate. Even if the HVAC type matches, the strategies listed here may or may not be feasible, depending on the control attributes of your building.

Table 3. HVAC demand response strategies

Category	DR Strategy	Definition	A	B	C	D
Zone control	Global temperature adjustment	Increase zone temperature setpoints for an entire facility	X	X	X	X
	Passive thermal mass storage	Decrease zone temperature setpoints prior to DR operation to store cooling energy in the building mass, and increase zone setpoints to unload fan and cooling system during DR.	X	X	X	X
Air distribution	Duct static pressure decrease	Decrease duct static pressure setpoints to reduce fan power.		X		X
	Fan variable frequency drive limit	Limit or decrease fan variable frequency drive speeds or inlet guide vane positions to reduce fan power.		X		X
	Supply air temperature increase	Increase SAT setpoints to reduce cooling load.	X	X	X	X
	Fan quantity reduction	Shut off some of multiple fans or package units to reduce fan and cooling loads.	X	X	X	X
	Cooling valve limit	Limit or reduce cooling valve positions to reduce cooling loads.	X	X		
Central plant	Chilled water temperature increase	Increase chilled water temperature to improve chiller efficiency and reduce cooling load.	X	X		
	Chiller demand limit	Limit or reduce chiller demand or capacity.	X	X		
	Chiller quantity Reduction	Shut off some of multiple chiller units.	X	X	*	*
Rebound avoidance	Slow recovery	Slowly restore HVAC control parameters modified by DR strategies.	**	**	**	**
	Sequential equipment recovery	Restore HVAC control to equipment sequentially within a certain time interval.	**	**	**	**
	Extended DR control Period	Extend DR control period until after the occupancy period.	**	**	**	**

* The strategy can be applied to package systems by reducing shutting off some of the compressors.

** Applicability of rebound avoidance strategies is determined by the DR strategies selected.

Zone control strategies – Global Temperature Adjustment

This strategy requires zone level direct digital control (DDC) that can be easily programmed to respond globally to demand response commands. Some control system manufacturers provide products that enable the zone setpoints of all thermostats to be changed globally by one parameter. This software feature is known as global temperature adjustment (GTA). For control systems that do not offer GTA as a standard feature, it can usually be programmed during the installation or retrofit process, at a cost somewhat higher than if it were a standard feature. This strategy has proven to be an effective and minimally-disruptive technique for achieving HVAC demand response.

Air distribution strategies

In systems for which global temperature adjustment of zones is not an option (such as those that are not DDC), strategies that make temporary adjustments to the air distribution or mechanical cooling systems can be employed to enable demand response. If the HVAC (fans, chillers, or both) is a constant volume system (without VAV), direct control of the equipment may be considered.

If the HVAC system is VAV, a combination of multiple parameter controls can be considered. Within a closed loop system, fans and chillers always try to maintain the required set points by changing HVAC parameters. For example, a supply air temperature (SAT) increase might reduce chilled water flow to save cooling energy, but fan power might rise to increase airflow to maintain cooling zone set points at the VAV boxes (which try to compensate for warmer supply air by supplying more air). To achieve a demand reduction, the fan and chiller control strategies may require simultaneous modifications. One may want to limit or fix the chilled water supply temperature, and simultaneously limit or fix the variable frequency drive (VFD) percentage to reduce fan power.

While effective in achieving load reductions, the use of systemic adjustments to air distribution systems and/or mechanical cooling systems for DR purposes has some fundamental drawbacks. In these strategies, the DR burden is not shared evenly between all the zones. Centralized systemic HVAC DR shed strategies can allow substantial deviations in temperature, airflow, and ventilation rates in some areas of a facility. Centralized systemic changes to the air distribution system and/or mechanical cooling systems allow zones with low demand or those that are closer to the main supply fan to continue to operate normally and hence these zones do not contribute toward load reduction in the facility. Zones with high demand, such as the sunny side of the building or zones at the ends of long duct runs, can become starved for air. After a VAV box is fully opened, its zone setpoint is no longer under control. Increased monitoring of occupied areas should be conducted when using these strategies.

Cooling strategies

Most modern centrifugal, screw, and reciprocating chillers have the capability of reducing their power demands. This can be done by raising the chilled water supply temperature setpoint or by limiting the speed, capacity, number of stages, or current draw of the chiller. The number of chillers running can also be reduced in some plants. As mentioned above, reducing the central plant load can typically achieve larger demand savings than can be achieved by reducing the air distribution load. These strategies may cause some air distribution load increases, which are usually more than compensated for by central plant load reductions.

Rebound avoidance strategies

As mentioned in section 1.7, HVAC systems tend to experience rebound, using extra energy following DR events in order to bring systems back to normal conditions. To minimize the chance of high demand charges and to reduce negative effects on the electric grid, rebound should be minimized through use of a gradual return to the normal strategy. The simplest case is where the DR event ends or can be postponed until the building is unoccupied. If this is not possible, strategies that allow HVAC equipment to slowly ramp up or otherwise limit power usage during the return to normal state should be used.

2.2. Lighting Systems

On a hot summer day when daylight is abundant, daylit and/or over-lit buildings are the best candidates for demand reduction using the lighting system. Since lighting produces heat, reducing lighting levels will also reduce the cooling load within the space and allow the HVAC strategies to work for extended periods of time. Research has shown that each kWh of lighting savings can also provide additional cooling savings by reducing the cooling load. This savings varies in quantity by building type and characteristics, climate zone, and season of the year. An LBNL study estimated that, on a national annual average, 1 kWh lighting savings induces 0.48 kWh cooling savings for existing commercial buildings (Sezgen and Koomey 1998).

Lighting demand shed strategies tend to be simple and depend widely on wiring and controls infrastructures. However, since lighting is typically associated with health and safety and the shed strategies tend to be visible, they have to be carried out selectively and carefully considering the tasks perfomed in the space and ramifications of reduced lighting for the occupants. Typically, the resolution of lighting controls tends to be lower than that of HVAC controls. Also, lighting systems are often not automated with EMCS. These issues can be major obstacles for automation of lighting DR strategies, although lighting strategies are popularly used in manual DR.

Estimating the demand savings potential of lighting strategies depend on how the demand savings are achieved. Demand response control capability of lighting systems is generally determined by the characteristics of lighting circuit and control system. There are two ways to implement demand response control with lighting, *absolute reduction* and *relative reduction***.** Absolute reduction is achieved by programming preset lighting level for times when demand response is required. This may be configured in many different ways based on the lighting control strategies, i.e. half the fixtures on, one third of the lamps in each fixture on, or all lamps at 70% of full light output.

The problem with an absolute reduction approach is that it does not yield any savings or may even increase lighting electricity consumption if the lighting levels are the same as or lower than the preset levels at the time demand response is initiated. Therefore, although this approach is easy to implement with current lighting control systems, the demand savings estimate varies depending on the building use and occupancy.

Relative reduction means reducing loads with respect to the level of lighting at the time of demand response. Instead of reducing to a preset level, a certain percent reduction over the current value is achieved during a demand response event. Implementation requires that the light output from the lamp or power output from the ballast is communicated back to the lighting control system, so central closed loop control is required. Systems with such sophisticated controls tend to be newer and more expensive. The decision to implement absolute or relative lighting reduction depends on the building lighting infrastructure, the lighting use in the building, and the capabilities of the installed lighting control system.

Following is a list of lighting DR strategies in increasing order of sophistication.

- Zone switching
- Fixture switching
- Lamp switching
- Stepped dimming
- Continuous dimming

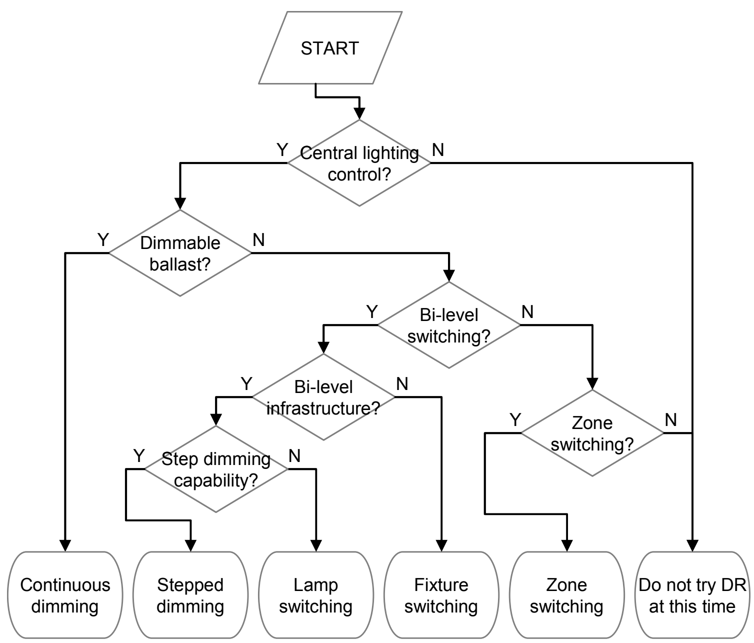


Figure 3. Lighting DR strategy decision tree

Figure 3 presents a decision tree to assist in strategy development. Each strategy is described in detail in section 3 below.

Control strategy planning procedure

While the decision tree in Figure 3 shows the decision process, within a facility it is common to find various vintage of equipment and control systems for lighting, as retrofits tend to happen in stages depending on the varying tasks and their lighting requirements within the spaces. It is important to start with the reflected ceiling plan of a facility to understand the zones, circuits, and control infrastructures. Granularity of controls describes how much floor area is covered by a given control parameter such as a photosensor. Less granular strategies affect more occupants and tend to be more disruptive. More granular strategies require well-designed and well-implemented infrastructures and allow occupants to better accept DR strategy implementation.

2.3. Miscellaneous Equipment

DR can target other equipment besides HVAC and lighting. If the equipment is independent from any critical operation, the sequence of control does not require such careful consideration. One issue of shedding miscellaneous equipment is that this equipment is often not connected to the EMCS but rather is operated stand-alone. In commercial buildings, the demand response potential of miscellaneous equipment shed is usually insignificant compared to HVAC or lighting shed. On the other hand, in industrial sites, significant demand reduction can be achieved by temporally unloading process loads without jeopardizing the process or product quality

2.4. Non-Component-Specific Control Strategies

The demand response control strategies mentioned above can be controlled in a sophisticated manner with the use of an advanced EMCS. Combination of DR strategies are programmed in the EMCS to coordinate appropriate strategies based on various conditional parameters such as outside air temperature, whole building demand level, or electricity price level. These strategies may require a high level of programming effort.

2.5. Strategies Used in Case Studies

Table 4 and Table 5 summarize the DR strategies used during 4 years in the LBNL Auto-DR studies and the other case studies. The list contains 56 participants (35 commercial and 9 industrial buildings). All 40 LBNL project sites implemented the strategies as fully-automated DR, while the other case studies used either manual or semi-automated DR.

Table 4. DR strategies used in LBNL Auto-DR studies (fully-automated)

	Participation				HVAC														Lighting					Other		
Building use	2003	2004	2005	2006	Global temp. adjustment	Duct static pres. Increase	SAT Increase	Fan VFD limit	CHW temp. Increase	Fan qty. reduction	Pre-cooling	Cooling valve limit	Boiler lockout	Fan-coil unit off	Electric humidifier off	Chiller demand limit	Slow recovery	Extended shed period	Common area light dim	Office area light dim	Turn off light	Dimmable ballast	Bi-level switching	Anti-sweat heater shed	Fountain pump off	Non-critical process shed
Office	●	●			X																					
Office		●			X																					
Office		●																	X		X					
Office		●			X																					
Office		●			X			X	X	X															X	
Office		●				X													X	X	X	X				
Office		●	●	●	X												X									
Office		●	●	●	X												X									
Office			●	●			X																			
Office			●	●	X	X																				
Hi-tech office		●	●	●	X	X	X			X									X	X	X	X				
Hi-tech office				○																	X					
Office, data center	●	●	●	●		X	X	X	X			X														
Office, data center			●		X						X															
Office, lab		●			X								X	X					X	X		X				
Office, lab			●	●	X	X	X		X			X	X					X								
Office, lab			●	●	X		X																			
Office, lab			●	●	X		X																			
Research facility		●								X					X											
Cafeteria, auditorium	●	●								X																
Archive storage		●			X																					
Library	●	●				X		X				X														
Highschool			●	●	X						X															
Junior Highschool				○	X						X															
Detention facility				●	X																					
Retail			●	●	X					X									X				X			
Retail				●	X					X																
Retail				●	X					X																
Retail				●	X					X																
Furniture retail			●	●	X																					
Furniture retail				○	X																					
Supermarket	●																		X				X	X		
Supermarket				○																			X			
Supermarket				○																			X			
Supermarket				○																			X			
Museum			●	●	X						X															
Distribution center		●	○	○												X	X									
Manufacture, office				○	X																X					
Bakery				●																						X
Material process		●																								X

* Some sites participated in 2003 or 2004 study stopped due to ineligibility to participate in CPP.
* In the Participation column, ● indicates the year of participation, and ○ indicates that the site was in the process of developing the DR strategies indicated in columns to the right.

Table 5. DR strategies used in case studies (manual or semi-automated)

		HVAC										Lighting					Other			
Building use	Rerefenced studies	Global temp. adjustment	Duct static pres. Increase	SAT Increase	Fan VFD limit	CHW temp. Increase	Fan qty. reduction	Pre-cooling	Fan-coil unit off	Chiller demand limit	Chiller qty. reduction	Common area light dim	Office area light dim	Turn off light	Dimmable ballast	Bi-level switching	Non-critical process shed	Elevator cycling	Shut off cold storage	Wwater pump peak shift
Office	Quantum	X			X	X														
Office	Quantum	X	X		X	X				X		X		X						
Food process	Quantum										X	X		X						
Glass process	Quantum																X			
Chemical repackage	Quantum						X					X		X						
Packing & cold storage	Quantum											X		X			X		X	
Packing & cold storage	Quantum																X		X	
Retail	NYSERDA											X				X				
Cement process	NYSERDA																X			
Office	NYSERDA				X	X												X		
Irrigation	NYSERDA																			X
Lumber process	SCE														X					
Office	SCE	X													X					
Office	DOE Project	X		X				X	X			X	X	X	X					
Library	ISO New England											X		X						

Figure 4 illustrates the number of sites for each strategy used. The most popular strategy used was global temperature adjustment, of which nearly half of the listed sites used. Duct static pressure increase and SAT increase were the second-most popular strategies.

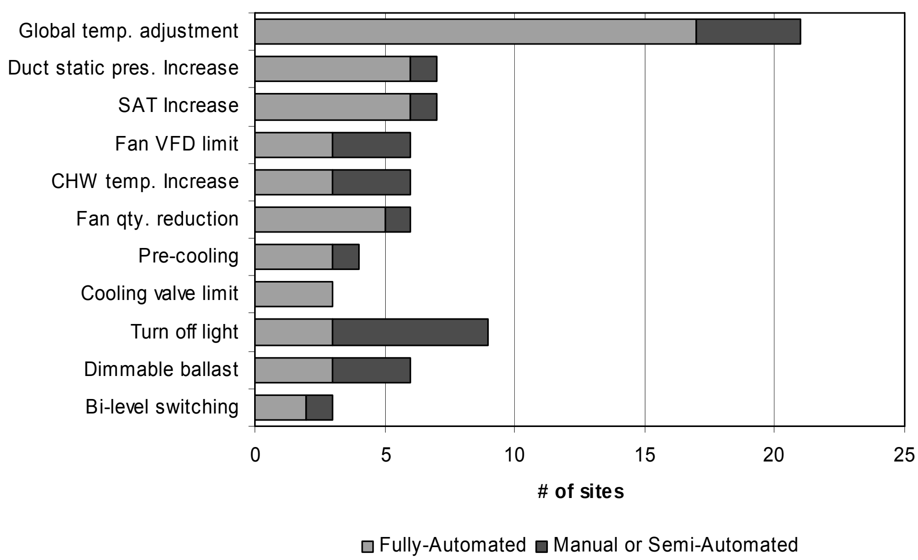


Figure 4. Frequency of DR strategies

3. Demand Response Strategy Detail

This section describes the details of the system operation methods of demand response strategies. Each strategy is explained with system requirements, sequence of operation and specific issues to consider. The information is first summarized in table form and then explained below.

3.1. HVAC Systems

This section describes the details of HVAC DR control strategies. Table 6 through Table 15 summarize the key information on the strategy, and the details are explained below the table. Definitions of items in the table are listed below,

- **Definition** – Brief definition of the DR control strategy.
- **HVAC type** – Applicable HVAC types as defined in Table 2.
- **Target loads** – HVAC system component or equipment whose electric load is targeted to be reduced by the DR strategy.
- **Category** – DR approach: demand shed, demand shift, or demand limit as defined in Section 1.6.
- **System applicability** – HVAC or control system characteristics required to use the DR strategy.
- **Sequence of operation** – Detailed sequence of operation used to program the EMCS to implement the DR control strategy.
- **EE potential** – Potential of achieving savings from energy efficiency as well as DR by applying the DR strategy during regular practice outside of DR events.
- **Rebound** – Risk of rebound peak and necessity of rebound avoidance strategy from applying the DR strategy.
- **Cautions** – Miscellaneous issues to be considered when the DR strategy is applied to mitigate and avoid any risks.
- **Applied sites** – Number and building type of the LBNL Auto-DR participant sites that applied the DR strategy. *None* indicates the DR strategy was not implemented at the LBNL Auto-DR sites, but was used in some other case studies or at an ex-candidate site that implemented the strategy but could not automate it.

3.1.1. Global temperature adjustment

Table 6. Conditions for global temperature adjustment (GTA)

Definition	Increase zone temperature setpoints for an entire facility.
HVAC type	All
Target loads	Air distribution, cooling
Category	Demand shed
System applicability	1. DDC zone control 2a. Global temperature adjustment (GTA) capability at zone level, or 2b. Capability to program GTA at each VAV box.
Sequence of operation	Option 1: Absolute setpoint adjustment Globally adjust (increase) all zone cooling setpoints to a common value (e.g. 76°F), T_c°F Globally adjust (decrease) or leave unchanged all zone heating setpoints to a common value (e.g. 68°F), T_h °F (T_c: DR mode cooling setpoint, T_h: DR mode heating setpoint)
	Option 2: Relative setpoint adjustment Globally adjust (increase) all zone cooling setpoints by a common differential temperature from their prior setpoint (e.g. 2°F), T_c°F Globally adjust (decrease) or leave unchanged all zone heating setpoints by a common differential temperature from their prior setpoint (e.g. 2°F), T_h°F (T_c: DR mode cooling setpoint, T_h: DR mode heating setpoint)
EE potential	Some occupants may be more comfortable during DR events. This would indicate making permanent changes to the setpoints.
Rebound	Rebound avoidance strategy required.
Cautions	Adjust zone temperature setpoints in multiple steps if a long shed duration is required.
Applied sites	15 office buildings, 6 retail stores, 2 laboratory facilities, 2 schools, 1 manufacturing facility, 1 museum, 1 archive storage, 1 detention facility

Global Temperature Adjustment (GTA) of occupied zones is a strategy that allows commercial building operators to easily adjust the space temperature setpoints for an entire facility by one command from one location. Typically, this is done from a screen on the human machine interface (HMI) to the EMCS. In field tests, GTA was shown to be the most effective and least objectionable strategy of the HVAC DR strategies tested (Piette et al. 2005a, 2005b, and 2006). It is most effective because it reduces the load of all associated air handling and cooling equipment. It is least objectionable because it shares the burden of reduced service level evenly between all zones. GTA-based DR strategies can be implemented either automatically based on remote signals or manually by building operators.

GTA is typically implemented by broadcasting a signal from the central EMCS HMI server to all the endpoint space temperature control devices distributed throughout the facility. Upon receipt of a global signal from the central EMCS server, the final space temperature control devices interpret the signal and react accordingly. (For example, the global signal for DR Mode Stage-1 means to increase space cooling setpoints 3°F and to decrease space heating setpoints 3°F). Final space temperature control devices suitable for GTA include: 1) space temperature controllers that adjust VAV terminal box dampers (e.g. VAV boxes), 2) space temperature controllers that adjust hot water heating coil valves or chilled water cooling coils (e.g. fan coil units, CAV multi-zone heating, and cooling coil valves) and 3) space temperature controllers that adjust the capacity of heat pumps or direct expansion (DX) units.

To avoid an unwanted increase in heating energy, heating setpoints (if any) should remain the same or be reduced during GTA mode. Otherwise, raising cooling setpoints could also raise heating setpoints, and may cause heating operation to be started.

GTA may be implemented on either an absolute or relative basis. Absolute setpoint adjustment of GTA allows the operator to set the space temperature setpoints for the entire facility to absolute values (e.g. heating setpoints at all final space temperature control devices = 68°F and cooling setpoints at all final space temperature control devices = 76°F). Relative setpoint adjustment of GTA allows the operator to adjust the space temperature setpoints for the entire facility to new values that are offset from the current values by a relative amount (e.g. heating setpoints at all final space temperature control devices decrease 2°F from current values and cooling setpoints increase 2°F from current values).

While being implemented, the rate of increase in temperature in the spaces should comply with the temperature drift rate allowed under ASHRAE Standard 55 as outlined in the Figure 5:

ASHRAE 55-2004, Paragraph 5.2.5.2 Change in Temperature
Time Period
2 ºF -15 minutes
3 ºF - 30 minutes
4 ºF - 1 hour
5 ºF - 2 hours
6 ºF - 4 hours

Figure 5. Temperature drift rate allowed under ASHRAE Standard 55

Several manufacturers offer GTA as a standard feature in their EMCS products. EMCS without the GTA feature can adjust space temperature setpoints in each zone individually, but not globally. Adjusting each zone individually is too time-consuming and error-prone for DR purposes. In field tests, sites that used EMCS products from these vendors provided some of the largest sheds and required the least amount of set-up labor.

For sites that have EMCS controlled space temperature zones, but lack GTA, it can typically be added in the field. To add GTA to an existing site, each EMCS zone controller must be programmed to "listen" for a global GTA command from the central EMCS system. In addition, the central system must be programmed to send GTA commands to all relevant zone controllers on the EMCS digital network. Typically GTA commands are sent in a global broadcast to all controllers simultaneously.

Manufacturers offer different types of VAV zone setpoint configuration methods. The following two examples are common VAV zone setpoint configurations.

1. Define zone cooling setpoints and zone heating setpoints separately.
2. Define the midpoint between zone cooling setpoints and zone heating setpoints and the width of the *deadband.*[2] Increasing the deadband makes cooling setpoints higher and heating setpoints lower. Raising the midpoint makes both cooling and heating setpoints higher. Figure 6 shows the change in the deadband and required airflow change in a VAV system. [3] Increasing the cooling setpoints reduces the required airflow.

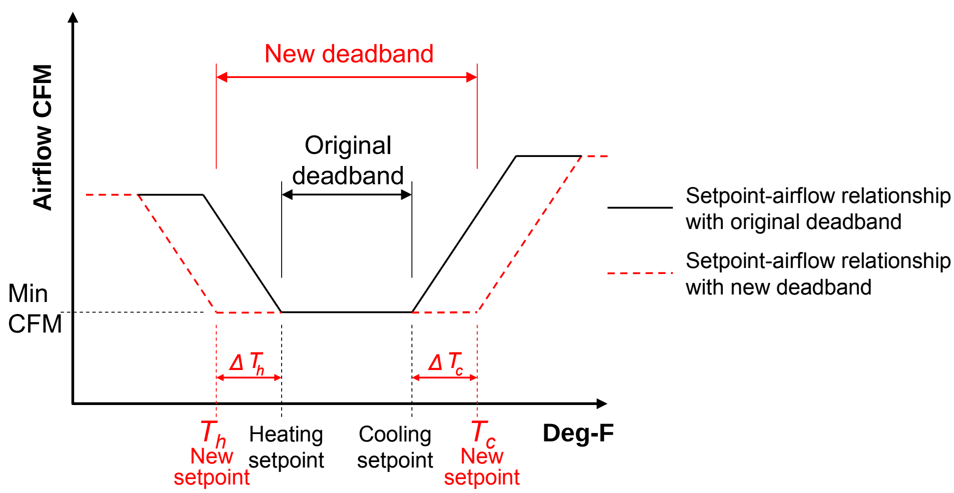


Figure 6. Zone setpoints deadband

[2] Deadband in the context of zone temperature control has two definitions; 1) the temperature range between actuation and de-actuation of the cooling or heating system, and 2) the temperature range where no cooling or heating (beyond that required to provide fresh air) is provided. Although the first definition has been historically used, the second definition is also commonly used. This report uses the second definition.

[3] Figure 5 shows proportional control for illustrative purposes. Most zone controllers use proportional and integral control algorithms.

If GTA of zones is available, it is the recommended HVAC DR strategy for commercial buildings. In field tests, sites that used HVAC DR strategies other than GTA usually did so because that feature was not available at the site. Reasons that GTA was not available include: 1) Space temperature was not controlled by the EMCS (e.g. use of pneumatic controls in occupant zones), and 2) Space temperature was controlled by the EMCS, but the space temperature controllers did not include the GTA feature.

While the GTA strategy reduces the service level of the occupied spaces, it does so using a closed-loop control strategy in a highly granular fashion. This causes the DR shed burden to be evenly shared between all building occupants and keeps all zones under control. Since none of the zones are starved for airflow, there is no risk of ventilation rates dropping below specified design levels.

Sometimes if the HVAC systems are oversized and the chillers are not controlled by the percentage of zones asking for cooling, the GTA strategy has to be combined with supply air temperature reset. One typical example is a building with multiple rooftop units, where the compressors are controlled not by how many zones are directly asking for cooling, but by meeting the supply air temperature setpoints. If the units are oversized or the minimum supply air flow rate is too high, GTA may not work and the zone temperatures will not follow the new setpoints because of the excessive cooling provided by the minimum air flow. In that case, the SAT setpoint has to be increased about 3~5^{o}F in the GTA period to reduce the minimum cooling delivered by the HVAC system.

The GTA strategy works well with most built-up HVAC systems, where typically the chillers shut off if the percentage of zones that ask for cooling is less than a predefined threshold. In GTA, if no zones ask for cooling once the new setpoint is above the current zone temperatures, the chillers normally shut off automatically. Sometimes, instead of being completely shut off, the chillers will only be reduced to a partial capacity, to maintain cooling for some "hot spots" that are poorly balanced or otherwise overloaded.

Thermal zones that are poorly designed or poorly balanced can also pose challenges due to overcooling. If minimum fresh air requirements are overcooling many zones, shed savings from a GTA DR strategy alone may not be effective. This problem can be solved by increasing the supply air temperature in addition to raising the zone temperature setpoints.

Demand savings components of GTA

Demand savings by the GTA strategy consists of two parts, ***steady-state savings*** and ***transient savings***. When zone setpoints are raised, cooling is turned off or reduced to its minimal operation until zone temperatures reach the new setpoints (transient savings). After zone temperatures are stabilized at the new setpoints, the cooling load is still lower than the baseline cooling load due to a smaller difference between zone setpoints and OAT (steady-state savings).

Transient savings can be achieved by the thermal mass storage effect of building structure mass, including floor slab and interior-and-exterior walls, furniture, and other materials. When zone setpoints are increased by the GTA strategy, the thermal mass components have stored cooling energy. The thermal mass cools down the indoor air and displaces the cooling load until it runs out of stored cooling energy. Duration of transient savings can widely vary depending on factors including building structure, outside air flow rate, internal heat gain, and solar heat gain through windows.

Figure 7 illustrates a conceptual diagram of demand savings (not actual field data) by the GTA strategy with zone setpoint (ZT set point) increase from 72°F to 76°F. The zone temperture (ZT read) is also shown. A case study of this strategy is introduced in Appendix A, section A.1.

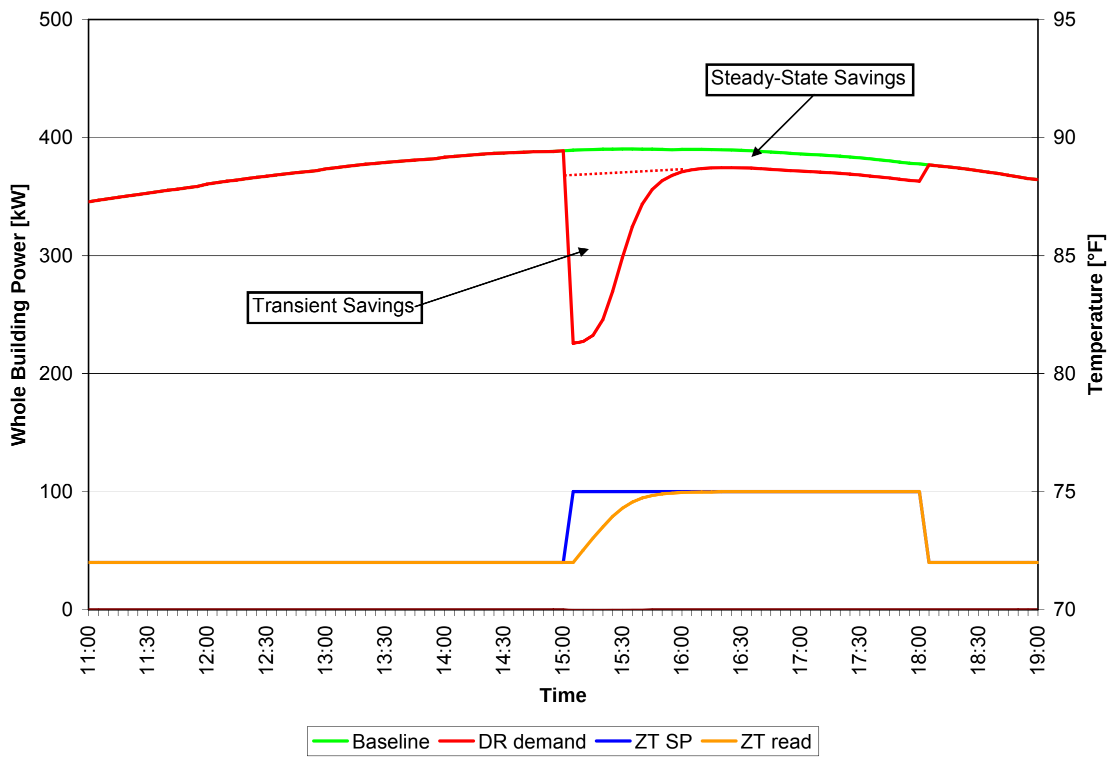


Figure 7. Conceptual diagram of demand savings for typical HVAC-based demand response strategy

3.1.2. Passive thermal mass storage

Table 7. Conditions for passive thermal mass storage

Definition	Decrease zone temperature setpoints during off-peak hours prior to a curtailment to store cooling energy in the building mass, and then increase zone setpoints to unload fan and cooling system during a curtailment.
HVAC type	All
Target loads	Air distribution, cooling
Category	Demand shift or demand shed
System applicability	1. DDC zone control 2a. Global temperature adjustment (GTA) capability at zone level, or 2b. Capability to program GTA at each VAV box. 3. Medium to high building mass.
Sequence of operation	Decrease zone temperature setpoints by ΔT_{c1} °F prior to a curtailment. Increase zone temperature setpoints by ΔT_{c2}°F during a curtailment.
EE potential	Occasionally produces total energy usage savings in mild climates, especially when nighttime free ventilation cooling is used. However, total energy usage may increase depending on climate, building type, and pre-cooling schedule.
Rebound	Rebound avoidance strategy required.
Cautions	This strategy is applicable to day-ahead DR programs, where the event notification is sent on the day before. If the event notification is on the same day, there is not sufficient time to store enough cooling energy. The passive thermal mass storage control is very complicated and has to be done properly. Testing, adjusting, and balancing control schedules are recommended in the preparation phase. Avoid over-cooling during the pre-cooling period to prevent cold complaints from occupants.
Applied sites	1 office building, 1 museum

Pre-cooling the thermal mass of the building can be used to reduce the peak load. For example, in summer, the building mass can be cooled during non-peak hours 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.

Thermal mass control strategies differ in the way they store and release heat from the mass. The building mass may be cooled by natural or mechanical ventilation, with or without mechanical cooling. Pre-cooling can be performed either during the unoccupied hours or during the occupied non-peak hours, usually in the morning. In climates with a large diurnal temperature swing, it may be possible to pre-cool the building mass without mechanical cooling.

If there is sufficient pre-cooling and the daytime cooling load is relatively low, it may be possible for the indoor air temperature to remain within the comfort range during the peak hours without any mechanical cooling. Cooling energy stored in the mass can be discharged during the peak hours by either zonal temperature reset or demand limiting the cooling plant and distribution system (Xu 2004). A detailed simulation study of the passive thermal mass storage strategy is summarized in Appendix A, section A.2 (Braun et al. 2001).

3.1.3. Duct static pressure decrease

Table 8. Conditions for duct static pressure decrease

Definition	Decrease duct static pressure (DSP) setpoints to reduce fan power.
HVAC type	B (VAV-Central), D (VAV-Package)
Target loads	Air distribution, cooling (occasionally)
Category	Demand shed
System applicability	1. All zone control systems including pneumatic and DDC 2. DDC for air handling unit
Sequence of operation	Lower DSP setpoints by *X*%.
EE potential	Tuning DSP setpoints can save fan power consistently without a reduction in service.
Rebound	Rebound avoidance strategy required.
Cautions	Less airflow for some zones that may cause ventilation rates to drop below specified design levels.
Applied sites	5 office buildings, 1 library

For VAV systems, duct static pressure (DSP) is typically measured in the supply duct. The EMCS modulates the speed of the fan or the position of inlet guide vanes (IGV) to maintain defined DSP setpoints at the measured locations. The normal DSP setpoints should be high enough to provide enough pressure for each terminal VAV box to function properly. Typically DSP is measured at a single location about two-thirds of the way down the duct system. The DSP setpoints are set to fixed values that are high enough to meet the needs of the box of greatest demand during design conditions. During less demanding conditions energy may be wasted due to losses associated with the DSP setpoints being higher than necessary to meet demands of VAV boxes.

Fan energy and cooling energy can be reduced during DR events by reducing the DSP setpoints. This strategy is effective for three reasons:

1. Unless the building has been recently commissioned, the normal DSP setpoints are often higher than necessary. By reducing the DSP setpoints, some shed savings is provided without any reduction in comfort or service to the occupants.
2. Additional shed savings occur when the DSP setpoints are set low enough to cause some VAV terminal boxes to starve from lack of air pressure. This reduction in service causes less air flow through the fans. When airflow drops below levels necessary to cool the space, the electric load on the cooling system also drops. However, there is some risk of ventilation rates dropping below specified design levels in some areas using this strategy.
3. When airflow drops below levels necessary to cool the space, the electric load on the cooling system also drops.

Details of the controls behavior of this strategy are discussed in Appendix A, section A.3.

3.1.4. Fan variable frequency drive limit

Table 9. Conditions for fan variable frequency drive limit

Definition	Limit or decrease fan variable frequency drive (VFD) speed or change position of IGV) to reduce fan power.
HVAC type	B (VAV-Central), D (VAV-Package)
Target loads	Air distribution, cooling (occasionally)
Category	Demand shed
System applicability	1. Applicable to all zone control systems including pneumatic and DDC without GTA feature. 2. DDC for air handling unit 3. Supply fans have VFD or IGV.
Sequence of operation	**Option 1: VFD limit (absolute)** Limit supply fan VFD to X% of normal condition, or limit IGV opening to provide the same result.
	Option 2: VFD reduction (relative) Limit supply fan VFD at ΔX% lower than A% (pre-DR mode), or limit IGV opening to provide the same result.
EE potential	If DSP setpoints are set too high, the VFD limit will decrease DSP and save fan power without reduction in service.
Rebound	Rebound avoidance strategy required.
Caution	Less airflow for some zones that may cause ventilation rates to drop below specified design levels.
Applied sites	2 office buildings, 1 library

Like duct static pressure setpoint reduction described above, this DR strategy is relevant to fans with variable frequency drives (VFD). During a curtailment, the speed of the VFD is limited to a fixed value. To be effective, the fixed value must be lower than if it were allowed to operate under normal closed loop conditions. This fan speed limiting saves energy for the same reasons as DSP setpoint reduction. Its effect on the air distribution systems and associated occupied zones is somewhat less predictable because of the open-loop nature of the control. Fan speed limits may be useful as part of other DR strategies such as cooling system adjustments described below. This strategy may also be used on fans with inlet guide vanes.

The VFD limit can be programmed in the following two ways. The first option (absolute limit) is to apply a fixed percentage limit to the VFD. If the VFD is limited to 70%, the fan cannot speed up more than the limit. One disadvantage of this option is that the demand savings totally depend on where it was operated. If a supply fan was running at 100% VFD, a 50% limit may cause significant change in its operation. On the other hand, if a supply fan was operated at 40% VFD, a 50% limit will not shed any demand at all. This option is adequate when the fans normally run at fairly constant speed. The second option (relative reduction) is to lock the VFD at a fixed percentage lower than the VFD% prior to the curtailment. Detail of this strategy is discussed in Appendix A, section A.4.

3.1.5. Supply air temperature increase

Table 10. Conditions for supply air temperature reset

Definition	Increase supply air temperature (SAT) setpoints to reduce cooling load.
HVAC type	A (CAV-Central), C (CAV-Package) (B (VAV-Central), D (VAV-Package with additional measures)
Target loads	Cooling. May increase air distribution load slightly.
Category	Demand shed
System requirement	1. Applicable to all zone control systems including pneumatic and DDC without GTA feature. 2. DDC for air handling unit
Sequence of operation	Increase supply air temperature (SAT) by *X* °F. For VAV, lock fan VFD or IGV at the position prior to DR operation.
EE potential	If the building has a large reheat load, this strategy will save reheat energy.
Rebound	Rebound avoidance strategy required.
Caution	For a VAV system, cooling demand shed will not be achieved until some VAV boxes begin to starve. It is hard to predict the SAT increase that will result in demand savings. A series of tests is recommended prior to actual implementation.
Applied sites	4 office buildings, 2 laboratory facilities

For a CAV system, increasing SAT saves mechanical cooling energy. In packaged direct expansion units and heat pumps, the savings will be achieved at each unit by reducing compressor load. For air handlers with cooling coils, the savings will occur at the central cooling plant. As the temperature difference between mixed air and supply air becomes smaller, the fan requires less chilled water flow.

For a VAV system, locking the fan VFD or IGV at the position prior to the DR operation is required to prevent a fan power increase. Cooling demand savings will not be achieved until some VAV boxes begin to starve. Therefore, there will be a time lag between the strategy initiation and the achievement of demand shed. Unless the VFD or IGV positions are locked, airflow will increase to deliver more air to the zones. Then fan power will increase while cooling load does not decrease, resulting in a net demand increase. Details of controls behavior for this strategy are discussed in Appendix A, section A.5.

In addition to the cooling demand savings, this strategy will reduce reheat load for both VAV and CAV systems if the building has a large reheat load.

3.1.6. Fan quantity reduction

Table 11. Conditions for fan quantity reduction

Definition	Shut off some of multiple fans or direct expansion units to reduce fan and cooling load.
HVAC type	A (CAV-Central), C (CAV-Package)
Target loads	Air distribution, cooling
Category	Demand shed
System requirement	1. Open floor space with multiple air handling or package units, or 2. Multi-fan single-duct system where GTA feature is not available.
Sequence of operation	Shutdown part of multiple supply fans or package units. **Multiple CAV fans**: Prevent any offline fans from starting up to make up the shut-off load. **VFD fans**: Limit VFD% of remaining supply fans at the position prior to curtailment.
EE potential	None
Rebound	Rebound avoidance strategy required.
Caution	Significant reduction of airflow is expected if the building has only few fans in the system. Make sure that the remaining fans can supply the required airflow to all zones. Low airflow can cause the pollutant level to rise in the conditioned space.
Applied sites	4 office buildings, 1 retail store

This strategy reduces air distribution demand by shutting off some of the fans or package units. Depending on the quantity of fans in the system, this can be a very disruptive strategy for the conditioned space. This strategy will increase cooling load of the remaining fans or package units to make up for those that are shut off. This strategy is primarily recommended for constant volume systems. Though not impossible to implement for VAV systems, this is not recommended, since less disruptive strategies are available.

In a CAV system, if the some fans are offline before DR operation is started, these fans should be prevented from starting up to make up for the load of the fans that are shut off. In a VAV system, the VFD or IGV for the remaining fans should be locked to prevent the fans from speeding up. For both systems, it is critical that the remaining fans satisfy ventilation requirements of the conditioned space.

The applicability of this strategy depends on the design airflow level and the occupancy level during the DR period. If the fans deliver too low a level of airflow to the occupied space during normal operation, this strategy may cause a shortage of fresh air. If the building has only a few fans in the system, shutting off one fan may cause significant airflow reduction due to low control resolution. This strategy should be applied with careful consideration.

A case study of this strategy is introduced in Appendix A, section A.6.

3.1.7. Cooling valve limit

Table 12. Conditions for cooling valve limit

Definition	Limit or reduce cooling valve positions to reduce cooling load.
HVAC type	A (CAV-Central), B (VAV-Central with additional measures)
Target loads	Chiller demand. Chilled water pump demand if variable speed drive (VFD) pump.
Category	Demand shed
System requirement	1. DDC for air distribution 2. Chilled water temperature setpoint is not optimized by feedback from zones or fans.
Sequence of operation	**Option 1: Cooling valve limit** Limit cooling valve position to *X*% open.
	Option 2: Cooling valve position reduction Limit cooling valve position to *ΔX* % lower than *A*%. (*A*%: cooling valve percentage open prior to a curtailment)
	VAV system: Limit supply fan VFD or IGV at the position prior to a curtailment.
EE potential	None
Rebound	Rebound avoidance strategy required.
Caution	Cooling valve limit must not be set lower than the threshold to shut off chiller operation. For cooling load savings, lock the supply fan VFD or IGV in position to prevent the fans from speeding up.
Applied sites	2 office buildings, 1 library

For air handling unit (AHU) systems with chilled water, the chilled water flow is controlled by modulating the cooling valve positions to maintain the supply air temperature setpoints. By limiting or closing the cooling valve positions, this strategy reduces chilled water flow and saves electric demand at the central plant. It is important to make sure that the cooling valve limits are not set lower than the threshold to shut off chiller operation.

In CAV systems, if the chilled water temperature setpoints are constant without any feedback from zones or fans, cooling load is reduced by limiting or closing the cooling valves. AHUs may lose control of the SAT setpoints due to the shortage of chilled water.

In VAV systems, AHUs also begin to lose control of the SAT setpoints due to shortage of cooling. Unless the VFD or IGV are locked, the fans speed up to increase airflow to deliver more air to the zones. The SAT cannot be maintained even with the increased airflow, but the same amount of cooling will be delivered to the zones until some VAV boxes start to starve. The chilled water return temperature will rise due to the increased airflow, resulting in increased chiller operation and no cooling load savings. Therefore, locking the fan VFD or IGV at their positions prior to the DR operation is required to achieve demand savings.

A case study of this strategy is introduced in Appendix A, section A.7.

3.1.8. Chilled water temperature increase

Table 13. Conditions for chilled water temperature increase

Definition	Increase chilled water temperature to reduce cooling load.
HVAC type	A (CAV-Central), B (VAV-Central)
Target load	Chiller demand
Category	Demand shed
System applicability	DDC for central plant
Sequence of operation	Increase chilled water supply temperature by *X* °F. VAV system: Lock fan VFD or IGV in position prior to curtailment.
EE potential	Raising chilled water temperature increases chiller efficiency. Until the AHU loses control of the SAT setpoints, total HVAC power can be reduced without a reduction in service.
Rebound	Rebound avoidance strategy required.
Caution	For cooling load savings, lock the fan VFD or IGV in position to prevent the fans from speeding up. If the chilled water temperature setpoints are already optimized properly, a chilled water temperature increase strategy may cause inefficient operation.
Applied sites	3 office buildings

By increasing chilled water discharge temperature, chiller power can be reduced due to the increased efficiency. Most chillers perform at higher efficiency at a higher chilled water discharge temperature. However, if chilled water pumps or AHUs are variable volume, the distribution energy increases under this strategy to deliver more chilled water or air. Unless the variable volume components are locked, the demand savings will depend on the trade-off between the reduced chiller electric demand from increased chiller efficiency and the increased distribution electric demand from fans and pumps.

The best practice of chilled water temperature optimization is to maintain the highest temperature before air handling units begin to lose control of the SAT setpoints. Chilled water temperature reset based on outside air temperature is also a popular optimization strategy. However, the majority of existing HVAC systems do not have proper chilled water temperature optimization strategies. Therefore, the chilled water temperature increase strategy may have energy efficiency potential as well as demand savings.

By raising chilled water temperature, chilled water flow delivered to AHU will be increased to maintain the same amount of cooling energy. This will cause variable volume chilled water pumps to speed up and increase their demand, while constant volume pumps will not increase their demand. Fan operation will not be affected until the chilled water flow reaches its maximum limit and the AHU begins to lose the SAT setpoints. Until then, no reduction of cooling service would be anticipated.

Once the AHU loses the SAT setpoints due to a shortage of chilled water flow, CAV systems begin to lose zone control. For VAV systems, fans speed up to satisfy zone setpoints. It is recommended to lock the fan VFD or IGV positions to prevent fans from speeding up, to achieve larger demand savings. VAV dampers begin to open wider until they satisfy the required airflow, or reach their 100% open position. When the airflow rate reaches the maximum limit, reduction of service may occur in some zones.

3.1.9. Chiller demand limit

Table 14. Conditions for chiller demand limit

Definition	Limit or reduce chiller demand or capacity.
HVAC type	A (CAV-Central), B (VAV-Central)
Target loads	Cooling
Category	Demand shed
System applicability	1. DDC for central plant 2. Chiller demand limit or capacity limit is available. 3. For VAV system, DDC for air distribution
Sequence of operation	**Option 1: Chiller demand limit** Limit chiller demand at *X*% **Option 2: Chiller demand reduction** Limit chiller demand at *ΔX* % lower than the demand provided by the cooling valve position of the pre-DR mode
	Prevent offline chillers from starting up to make up the reduced cooling load. VFD pumps: Limit chilled water pump speed to that prior to curtailment. VAV systems: Limit fan VFD% speed to that prior to curtailment.
EE potential	None
Rebound	Rebound avoidance strategy required.
Caution	Severe reduction of cooling may occur if large percent of demand limit is applied. Impact on zone temperatures is hard to predict. . For demand savings, lock the pump speed at the state prior to DR. In VAV systems, lock the fan VFD or IGV in position to prevent the fans from speeding up.
Applied sites	1 distribution center

The chiller demand limit strategy saves cooling demand by directly controlling the chiller compressor. If the chillers are operated nearly at full load, this strategy is beneficial just by limiting the demand at the most efficient part-load operation. If the chiller was already running under the assigned demand limit (for Option 1), no change would occur in this strategy.

The chiller compressor adjusts its capacity based on the chilled water supply temperature. By limiting its demand capacity, the chiller system can no longer maintain the chilled water supply temperature setpoint at high loads. Then cooling valves at AHUs open wider and request more chilled water flow to maintain the SAT. For a constant volume chilled water system, the pump power will not increase. For a variable volume system, the chilled water pump speeds up to increase chilled water flow to maintain the SAT. However, when this strategy is employed, regardless of the increase in the chilled water flow, the chiller cannot provide more cooling than the demand limit allows. Therefore, the more the chilled water flow increases, the higher the chilled water supply temperature becomes. Thus, the pump power increase will not provide more space cooling; therefore the pump speed should be locked at the state prior to DR.

AHUs begin to lose control of the SAT setpoints due to a shortage of cooling. Then CAV systems begin to lose zone control. In VAV systems, unless the VFD or IGV are locked, the fans speed up to increase airflow to deliver more air to the zones. The SAT cannot be maintained even with the increased airflow and begin to lose zone control, because amount of cooling capacity is limited. Therefore, locking fan VFD or IGV at the position prior to the DR operation is required to achieve demand savings. Chillers that are not operated when the DR operation is initiated must remain offline.

3.1.10. Chiller quantity reduction

Table 15. Conditions for chiller quantity reduction

Definition	Shut off some of multiple chiller units.
HVAC type	A (CAV-Central), B (VAV-Central)
Target loads	Cooling
Category	Demand shed
System requirement	Central plant with multiple chillers
Sequence of operation	Shut off some operating chillers. Prevent offline chillers from starting up to make up the reduced cooling load. **VFD pumps**: Limit chilled water pump speed to that prior to curtailment. **VAV systems**: Limit fan VFD% speed to that prior to curtailment.
EE potential	None
Rebound	Rebound avoidance strategy required.
Caution	Remaining chillers may run at lower efficiency if they begin to run at full-load, which may result in a net demand increase. Impact on zone temperatures is hard to predict. For demand savings, lock the pump speed at the state prior to DR. In VAV systems, lock the fan VFD or IGV in position to prevent the fans from speeding up.
Applied sites	None

If the chiller demand limit strategy discussed above is not available, shutting off some chillers can be an alternative strategy. To apply this strategy, the central plant has to have multiple chiller units. A larger number of chillers are preferred to have better control resolution. It is important to consider carefully which chillers are usually operated, and which chillers should be shut off during DR. Lack of the careful planning may result in either no demand savings or severe reduction in service. This strategy can be very disruptive due to significant reduction of cooling supply. If the remaining chillers run at full load, lower chiller efficiency may result, which may cause a net demand increase.

By shutting off some of the chillers, the central plant can no longer maintain the chilled water temperature setpoint when the operating chillers reach full-load. Then cooling valves at the AHUs open wider and request more chilled water flow to maintain the SAT. For constant volume chilled water systems, the pump power will not increase. For variable volume systems, the chilled water pump will speed up to increase chilled water flow to maintain the SAT. However, regardless of the increase in the chilled water flow, chillers cannot provide any more cooling than their total full-load capacity. Therefore, the more the chilled water flow increases, the higher the chilled water supply temperature becomes. Thus, this pump power increase will not provide more space cooling, and therefore the pump speed should be locked at its state prior to DR.

Once the operating chillers reach full load, the AHUs begin to lose control of the SAT setpoints due to the shortage of cooling. Then CAV systems begin to lose zone control. In VAV systems, unless VFD or IGV are locked, the fans speed up to increase airflow to deliver more air to the zones. The SAT cannot be maintained even with the increased airflow and zone control begins to be lost, because the amount of cooling capacity is limited. Therefore, locking the fan VFD or IGV at their positions prior to DR operation is required to achieve demand savings.

3.1.11. Rebound avoidance strategies

A rebound avoidance strategy should be considered for each HVAC DR strategy that has a risk of having a rebound peak at the end of the DR period. There are several types of strategies to avoid rebound.

Slow recovery strategy

Slow recovery strategies slowly recover the target parameter that was controlled in the DR strategy. If the GTA strategy is applied, the zone setpoints should be gradually restored to the normal setpoints.. If the fan VFD limit strategy is applied, the fan VFD limit should be gradually shifted up. The setpoints should be changed linearly or step-by-step in short increments. Some facilities extend the DR event into "unoccupied" periods where the setpoints are higher than the "occupied" period setpoints and therefore do not need to gradually lower the setpoint A case study of this strategy is introduced in Appendix A, section A.8.

Sequential equipment recovery

If many pieces of equipment are controlled by a DR strategy, the rebound peak can be suppressed by restoring the original control setpoints for each piece of equipment one by one at certain time intervals. For example, for global temperature adjustment, the normal zone setpoints can be restored for each VAV box one by one. Similarly, for fan quantity reduction, fans can be restored one by one. Although constant volume equipment do not speed up, sequential equipment recovery should be applied to strategies that control constant volume equipment. Sequential equipment recovery can disperse the short-duration start-up spikes and avoid a huge in the whole building demand spike.

Extended DR control period

Although a slow recovery strategy is very critical to maximize the demand response program benefit, the EMCS programming for the strategy can be very complex or may not be possible for many conventional EMCSs. An alternative method to avoid a rebound peak is to extend DR control until the end of the building's occupancy schedule. This strategy may be applied to office buildings and retail stores that close around 5 or 6 p.m. A case study of this strategy is introduced in Appendix A, section A.9.

3.2. Lighting Systems

In this section, conditions for each lighting DR strategy are first presented in table format (Table 16 through Table 19) followed by discussion.

3.2.1. Zone switching

Table 16. Conditions for zone switching

Definition	Switching off luminaires in an entire zone.
Lamp type	Any (except high-intensity discharge (HID) lamps if full light output is needed when lights are turned back on).
System applicability	Availability of daylighting in affected zones. Separate zoning of luminaires in common spaces such as a lobby, corridor, or cafeteria.
Sequence of operation	Switch off lighting in an entire zone.
Target loads	Lighting. May decrease cooling load and/or increase heating load.
Category	Demand shed
EE potential	None
Rebound	Rebound avoidance strategy required for all lamps, especially HID lamps.
Cautions	Visible, may disrupt work. Do not use in high-security areas.
Applied sites	3 office buildings

A zone switching strategy switches off luminaires where daylight is available. Since this is simple on/off control, it is quite noticeable for occupants, especially if the zone size is large. This strategy can be adequately applied to common spaces such as lobby, corridor, and cafeteria, if daylight is present. It may not be appropriate for open office spaces even where they are daylit because of its possibility to disrupt work. Zone switching may not be useful in private offices or other areas where there is already an occupancy sensor.

To avoid rebound, when the event is over, turn lamps back on in groups rather than all at once. Most high-intensity discharge (HID) lamps require a warm-up period of several minutes to reach full brightness after they are turned on. In areas where full light output is needed right away this may be inconvenient, although if daylight is already present the warm-up time may not be noticeable.

3.2.2. Luminaire/lamp switching

Table 17. Conditions for luminaire/lamp switching

Definition	Luminaire Switching: Switching off a percentage of luminaires. Lamp Switching: Switching off various fractions (e.g. one-half, one-third, two-thirds) of lamps within a luminaire.
Lamp type	Fluorescent or incandescent
System applicability	Wiring and circuiting of fixtures that allow for separate luminaire or lamp switching
Sequence of operation	Switch off a portion of the luminaires or lamps in luminaires.
Target load	Lighting. May decrease cooling load and/or increase heating load.
Category	Demand shed
EE potential	None.
Rebound	No capability for slow recovery.
Caution	Visible, may disrupt work.
Applied sites	2 retail stores

Luminaire switching depends on how the fixtures are circuited and lamp switching depends on how each lamp/ballast combination is wired. California's Title 24 building energy standards require multiple lighting level control for all enclosed spaces 100 square feet or larger with connected lighting load over 0.8 watts per square foot with more than one light source. With multilevel switching, each office occupant is provided with two wall switches near the doorway to control their lights. In a typical installation, one switch would control 1/3 of the fluorescent lamps in the ceiling lighting system, while the other switch would control the remaining 2/3 of the lamps. This allows four possible light levels: Off, 1/3, 2/3 and Full lighting. Because it has been required by the building standards since 1983, multilevel switching is common in California office buildings (LBN 1998). The 2005 compliance manual for the Title 24 standards (CEC 2006b) indicates that multilevel lighting control can be achieved in a variety of ways such as:

- Separately switching on alternative rows of fixtures (luminaire switching). Typically an electronic ballast drives each luminaire. When each ballast in a row is connected to the same circuit with the ballasts in alternating rows, turning off one circuit results in turning off alternating rows of fixtures, as shown in Figure 8. For example, this is often implemented in pendant-mounted fixtures in rows in school buildings.

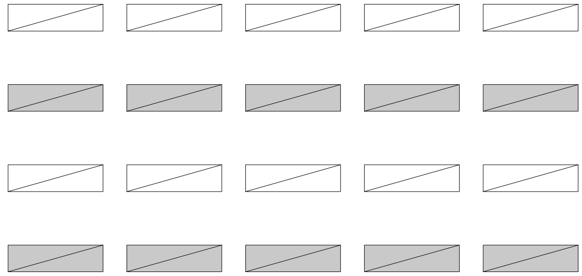


Figure 8. Luminaire switching – alternate rows of luminaires

- Separately switching on every other luminaire in each row (luminaire switching), as shown in Figure 9. Since this wiring scheme is less common than the wiring scheme of Figure 8, rewiring may be required to achieve this pattern.

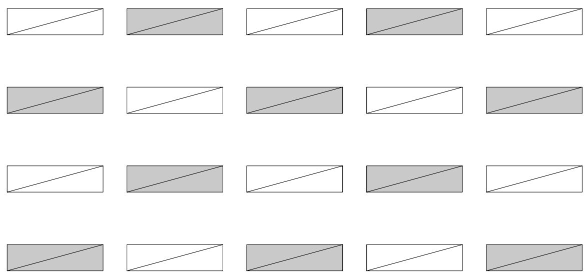


Figure 9. Luminaire switching – every other luminaire in each row

- Switching the middle lamps of three-lamp fixtures independently of the outer lamps (lamp switching). The wiring for a three-lamp fixture can be done in one of two ways: 1) Two ballasts are installed; i.e. one of them drives the inner lamp and the other drives the outer lamps. 2) Fixtures share ballasts (tandem wiring); i.e. two inner lamps of two fixtures are connected to a two-lamp ballast and the four outer lamps of two fixtures are connected to a four-lamp ballast. Both wiring schemes, shown in Figure 10, deliver the same operation for this strategy. (The second option may be preferable because it uses fewer ballasts and the total wattage per luminaire is slightly lower. However, the luminaire layout must be conducive to luminaires sharing a ballast; i.e. luminaires must be close enough together to allow the tandem wiring).

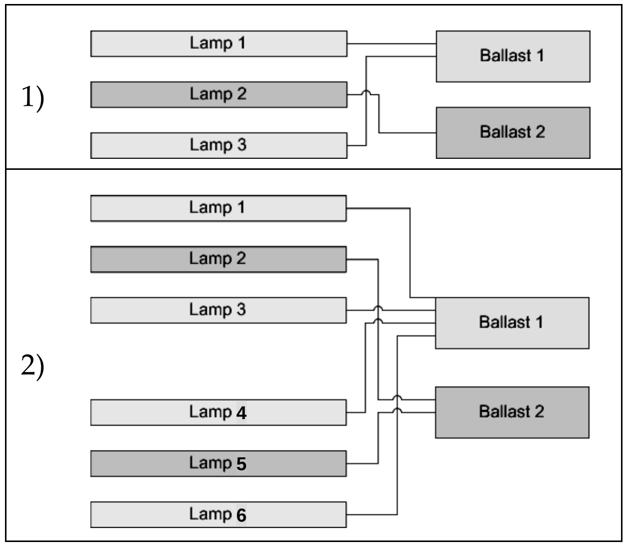


Figure 10. Lamp switching - middle lamps of three-lamp fixtures

- Separately switching lamps in each luminaire (lamp switching). In two- or four-lamp fixtures, each half of the lamps can be driven by a separate ballast or ballast combinations and switched off independently. Figure 11 shows this configuration for two-lamp and four-lamp fixtures.

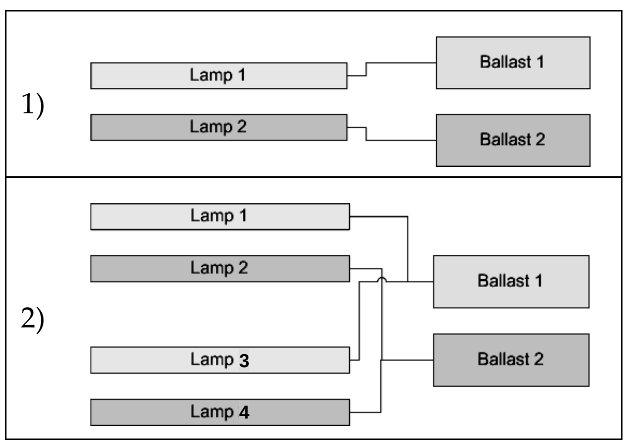


Figure 11. Lamp switching – lamps in each luminaire

3.2.3. Stepped dimming

Table 18. Conditions for stepped dimming

Definition	Dimming a fixture in discrete steps using lamp switching
Lamp type	Fluorescent, incandescent
System applicability	Fixture wiring that allows for two or three lighting levels.
Sequence of operation	Switch off a portion of the lamps in luminaires.
Target load	Lighting. May decrease cooling load and/or increase heating load.
Category	Demand shed
EE potential	Only when replacing existing fixtures that do not have dimming ballasts
Rebound	No capability for slow recovery. Stepping up the lighting level to recover the original level may be even more disruptive to occupants than switching immediately back to the original level.
Caution	Visible, may disrupt work.
Applied sites	None.

Stepped-dimming ballasts are typically enclosed in a fluorescent luminaire with two or three lamps and regulate the lighting level by switching one of two (bi-level dimming), or one, two or three lamps (tri-level dimming) incrementally through use of on/off switch controls. Stepped dimming was a popular energy-saving retrofit solution for applications where existing fixtures were not equipped with dimming ballasts. Their function is essentially the same as that of the ballasts in the lamp switching strategies discussed above; stepped-dimming ballasts are transitional devices that were used before the lamp switching wiring methods shown in the luminaire/lamp switching strategy became popular. Stepped-dimming can be operated on a time-of-day schedule or on a sensed quantity of daylight.

3.2.4. Continuous dimming

Table 19. Conditions for continuous dimming

Definition	Dimming lamps using dimmable ballasts.
Lamp type	Fluorescent, HID
System applicability	Dimmable ballasts
Sequence of operation	1. Absolute reduction: Dim to a preset level, or 2. Relative reduction: Dim a certain percent of the current light level.
Target load	Lighting. May decrease cooling load and/or increase heating load.
Category	Demand shed
EE potential	Fully utilize daylighting where applicable.
Rebound	May want to come gradually back to full light level to avoid disturbing the visual environment.
Caution	Design according to ballast dimming capability (some ballasts do not dim below a certain light level).
Applied sites	3 office buildings

Dimmable ballast control is the best way to shed lighting for demand response because it is gradual and therefore not usually noticeable by the occupants. With dimming ballasts, some dimming would already be occurring, but this strategy may increase it during the DR event.

Depending on the control system, a continuous dimming strategy may be able to implement relative reduction, instead of absolute reduction (Rubinstein 2006). Relative reduction requires that the light output from the lamp or power output from the ballast is communicated back to the lighting control system, so centrally closed loop control is required. Systems with such sophisticated controls tend to be newer and more expensive.

As an additional control option, the light level can be gradually lowered so that occupants will not notice the change. A study by Lighting Research Center (LRC) on their load shedding ballast states that a 30% light level reduction over 10 seconds is not noticeable (Akashi 2002).

3.3. Miscellaneous Equipment

Fountain pumps

Exterior or interior fountains serve mainly for visual comfort, though a they have some evaporative cooling effect. Since fountains are mostly located in common space, shutting down fountains may not cause much discomfort to the occupants. Though it varies widely depending on pump size, potential demand savings is about 3 to 10 kW for each pump.

Anti-sweat heaters

Cold display cases with glass doors in grocery stores usually have small *anti-sweat heaters* to keep moisture from forming. Some of them can be controlled by a thermostat or humidistat based on the room air temperature or humidity. Turning off the anti-sweat heaters for short period of time may not cause any significant service loss to the display cases. Potential demand savings is about 5 to 10 kW for a typical supermarket (30,000 to 50,000 ft^2). However, if anti-sweat heaters are controlled by humidistat, this strategy may not save much demand in a dry climate because the air does not contain much moisture. Savings may not result by curtailing anti-sweat heaters in a supermarket with a dehumidification system, since during normal operation the room humidity may not become high enough to turn on the anti-sweat heaters.

Electric vehicle chargers

Regardless of when vehicles are used the next time, electric vehicle chargers usually charge vehicles whenever the vehicles are plugged into them until the batteries are fully charged. When the batteries are fully charged, most chargers shut off or ramp down to trickle charger mode. If the vehicle will not be used until the end of the day or the next day, charging it is not necessary during a DR event. There are some charger systems designed to take advantage of time-of-use rates during normal operation. This technology can be used for DR operation as well. The electric demand for a Class-1 electric vehicle charger is usually up to 2 kW, and that of a Class-2 electric vehicle charger is up to 6.5 kW.

Industrial process loads

Some process equipment loads can be shut off during a DR period without spoiling the process or product quality. For example, a material process plant might shut off transfer pumps during a DR period. Because the process has a buffer tank, the processed material is stored in the tank for short period of time. Once the DR period ends, the transfer pumps restart and transfer the material in the buffer tank to the storage tank. Another example is a cement process plant that shuts off rock crushers. During a DR event, the rock crushers are run before the DR period, so that they will have enough crushed rock until the end of the DR period. Both of the above cases use demand shift techniques. If the buffer tank is filled, or crushed rock runs out, the equipment must be restarted even during the DR period. Other strategies that do not use demand shift, such as air compressor shed, are also available, but careful consideration is required not to spoil the industrial processes.

Cold storage

A large segment of agricultural and food processing plants have cold storage equipment. The refrigeration load for cold storage can be shed during a DR period by increasing the storage temperature setpoints or unloading chillers. It is possible to shed cold storage load without spoiling the product by keeping an acceptably-high limit of storage temperature and limiting the length of exposure time to the higher temperature. A pre-cooling strategy may be a suitable option for cold storage. Unlike commercial building spaces, cold storage areas usually have much lower internal and external heat gains, so the thermal mass storage effect lasts longer than it does in commercial building spaces (Quantum and Summit Blue 2004).

Elevator cycling

If a building has multiple elevators, some of the elevators can be shut off or cycled during the DR period. This strategy is considered a demand shift strategy because it does not save energy consumption if occupants wait for the remaining elevators. Part of a large office building in New York City used this strategy and shut down two elevators in each passenger bank as well an escalator (NYSERDA 2006).

Irrigation water pumps

Water delivery systems that have large-scale water tanks can store sufficient amounts of water to satisfy their customers during a curtailment. This large storage capacity provides the flexibility to pump and store water before it is needed. This strategy will contribute to significant water pump demand savings without reduction in service. A water measurement system integrated with the pump control system is required to analyze water reserves and ensure that a proper water supply is available even during a curtailment (NYSERDA 2006).

3.4. Non-Component-Specific Strategies

Non-component-specific strategies are means of control of the single or multiple DR strategies introduced so far.

3.4.1. Demand limit strategy

Many advanced EMCS have the capability to minimize the whole building peak demand from exceeding a pre-specified peak *demand limit* (Piette 1991). This strategy has been utilized for daily peak load management for many years. Demand limit strategy is a supervisory control algorithm that manages a combination of single or multiple DR control strategies. When the whole building demand exceeds a warning level, the EMCS deploys strategy #1. If the whole building demand still exceeds the warning level, strategy #2 is deployed, and so on. Thus, whenever the demand hits the warning level, the whole building demand is suppressed by a combination of sequential strategies. Strategies that have a lower impact on occupants' comfort should come first, and strategies that have more impact should come later. When the demand goes below the lower deadband level, the last strategy should be deployed. For any strategy that may have a risk of causing a rebound peak, slow recovery strategies must be considered.

Demand limit strategy has been considered as a method to avoid high demand charges during normal operation, rather than as a demand response strategy. However, depending on the structure of demand response programs, demand limit strategy can be a very useful tool to achieve desired kW savings. For example, *demand bidding programs*[4] offered by many utility companies require curtailing a preset kW demand against a baseline defined by each utility. If the EMCS has a function to develop dynamic demand limit setpoints based on the baseline, the demand limit target can be set as shown in Equation 1, so that the desired demand savings can always be achieved.

Equation 1

[Demand limit target] = [Baseline] – [Desired demand savings]

[4] A demand response program where participants submit bids for a proposed level of curtailment. For accepted bids, participants receive a credit equal to the product of the energy reduction and the market price plus a participation bonus.

3.4.2. Price-level response strategy

Real time pricing, a type of price-based demand response program or tariff, provides a dynamic electricity price to motivate customers to shift or reduce consumption during high-cost periods. To relate the level of the electricity price to the depth (aggressiveness) of DR strategy control, electricity price information can be used as a control parameter. Figure 12 shows an example of DR strategy control based on electricity price change. In this example, global temperature adjustment, the zone setpoints are increased linearly with correlation to the electricity price until the maximum allowed zone setpoints are reached. Control parameters used for DR strategies, such as duct static pressure, fan VFD%, chiller demand limit percent, or light level, can be controlled in this manner. The electricity price, or any other dynamic value, can be used as an external input. The input should be translated to an analog signal (e.g. 4-20 mA or 0-10 V) so that the EMCS can receive the input directly. The controls capability based on this input may require a similar level of controls resolution. For example, zone setpoints can be related to electricity price level as shown in Figure 12 since zone setpoints can be adjusted at 1°F or lower resolution, while an on/off lighting switching strategy cannot be controlled to such fine resolution.

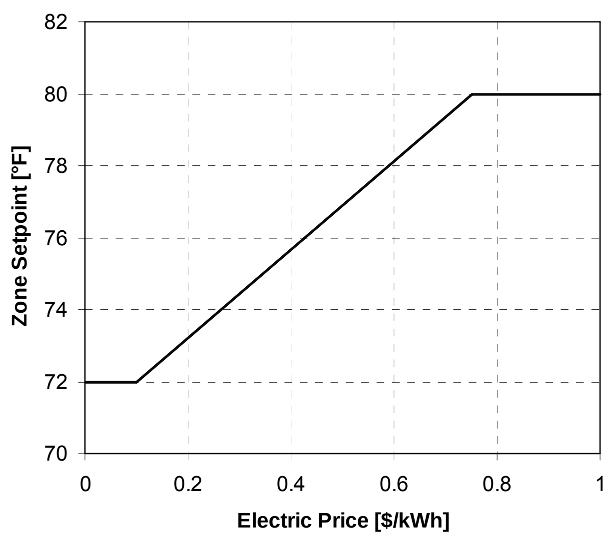


Figure 12. Example of price-level zone setpoint control

4. Implementation of DR Strategies

This section discusses procedures and issues to be considered during the process of DR control strategy planning, installation, and implementation.

4.1. DR Strategy Development and Commissioning

The process of commissioning should be applied to each phase of DR control strategy application, including planning, installation, and implementation. This will ensure the goal of DR control, to maximize demand savings while minimizing impact to occupants, is achieved. This process should be supervised by a "coordinator." A "coordinator" can be a controls contractor, a building facility management team, or a third-party agent. The following steps should be taken to achieve successful DR strategy operation.

1. **Initial site inspection**. At the beginning of the DR strategy planning, the coordinator collects all the necessary information on the site process to minimize redundancy. The necessary data include building type, building floor area, HVAC and lighting system profiles, EMCS profiles, and historical electricity demand data.
2. **DR strategy sequence of operation**. In coordination with the coordinator, facility managers, controls contactors, and other key personnel, DR strategies are planned with respect to system applicability, impact to occupants, desired demand savings, and other relevant factors. Each planned DR strategy needs to be written as a detailed control sequence of operation so that controls contractors can understand exactly what they need to do with EMCS programming and additional hardware installation if necessary.
3. **Demand savings potential estimation.** The coordinator makes a preliminary estimate of demand saving potential to estimate the benefits of participating in the DR program and to justify the project cost. While estimation of demand savings from lighting DR strategies can be relatively simple, demand savings from HVAC DR strategies are complicated by various factors. Development of a simplified simulation tool for demand savings estimation from different DR strategies is desired.
4. **Performance monitoring plan**. Along with the DR strategy sequence of operation, EMCS data collection should be also planned in advance by the facility management team. EMCS trend data are helpful to evaluate the success of DR strategies. Table 20 lists EMCS data points that are recommended for collection for DR strategy diagnosis.
5. **Proof-of-concept manual test**. It is recommended that facility management team perform a manual DR strategy demonstration test as a proof-of-concept. The coordinator should supervise the test and analyze the trend data after the test. If the demand savings by the DR strategies are weather dependent, such a test should preferably be conducted on a warm day that can represent a DR event day (at least 85°F or higher). If operational problems or complaints occur even though the

sequence of operation is successful, the strategies should be reconsidered. The test results should be compared with the preliminary demand savings potential estimation. If there is difficulty conducting both a demand savings estimation and a manual test, at least one of them should be performed (manual test is preferred). Obstacles to a manual test include seasonal weather conditions, concerns about distracting occupants without a real DR situation, and lack of sophisticated controls to perform a manual test (e.g. hundreds of zone setpoints cannot be changed simultaneously without automation).

6. **DR strategy proposal**. Based on the DR strategy sequence of operation developed in the previous step, the controls contractor develops a project proposal for the client.

7. **DR strategy installation**. When the project proposal is accepted by the facility manager, the controls contractor starts the EMCS programming and hardware installation as specified in the proposal.

8. **Post-installation test.** When the DR strategy installation is completed, the facility manager tests the strategies to 1) confirm that the strategies work correctly as specified in the sequence of operation, and 2) verify the demand savings potential as estimated in the calculation and pre-installation test. Confirmation of correct operation is more critical, and may be done on a cool day with a shorter duration than actual DR events. EMCS trend data should be collected during the test. After the test, the coordinator should check the EMCS data, especially for the modified parameters, to see if the controls change occurred as planned. If it did not occur, the EMCS programming should be revisited.

9. **M&V for DR events**. Measurement and verification efforts should be continued by the coordinator during the actual curtailment as well. If the post-installation test was conducted before the hot summer season, the reduction in service can be larger and the demand savings can be widely different during the real curtailment than in the test. The DR operation should be carefully reviewed especially until the first or second curtailment is completed. The facility manager should calibrate the strategies to maximize demand savings while minimizing impact to occupants.

Completing all the steps above may take several months or more, depending on the effort required for coordinating the process among facility managers, controls contractors, and upper management decision-makers. It is important to prepare DR strategies well in advance before the peak summer season arrives.

Table 20. Recommended data collection points

Whole building	Whole building power demand	
HVAC system	Zone control	Zone temperature Zone setpoint temperatures VAV damper position VAV airflow Reheat valve position
	Air distribution	Supply air temperature Return air temperature Outside air temperature Outside air damper position Fan power Fan status Fan VFD percent Fan airflow Duct static pressure
	Central plant	Chiller power Chiller status Chilled water supply temperature Chilled water return temperature Chilled water flow Cooling tons
Lighting system	Lighting power Light levels	
Other equipment	Power of target equipment Status of target equipment	
Weather	Outside air temperature Outside air humidity	

4.2. Notification to Occupants

One of the issues of DR implementation is whether the facility managers should notify their occupants of the potential adjustments in site conditions from DR. The LBNL Auto-DR studies included both participants who notified their occupants about DR and those who did not notify them.

4.2.1. No notification

One of the most common reasons not to notify occupants is to avoid unnecessary concern among occupants. When occupants are notified of an upcoming DR event, some may overreact and increase complaints. In one case where the facility manager notified occupants of the DR event in advance, some occupants complained that the zone temperature was too high. However, later the facility manager found out that the DR control had failed and there was actually no affect on the zone temperature. In later DR events the facility manager did not notify the occupants and received no complaint call even when the DR strategies were successfully operated (LBNL Auto-DR demonstration 2004). No notification may work well if detectability of the DR strategy is low.

4.2.2. Notification

On the other hand, some facility managers prefer to inform the occupants about upcoming DR events. One of the common reasons to notify occupants is to avoid upsetting occupants. In this occasion, notification works well if detectability of the DR strategy is high but still within in an acceptable level (i.e. the occupants will notice the reduction in service but can accept it). In one case, when the facility manager did not notify the occupants of a DR event, some occupants inquired about increased temperature or reduced lighting because they concerned that the HVAC or lighting systems had malfunctioned. Once they were told that it was part of DR effort and not equipment failure, they understood and the inquiry calls stopped (LBNL Auto-DR demonstration 2004). In a unique example, the facility group announced a DR event the day before and requested employees to wear tropical outfits. They declared the DR event "Aloha Day" and employees apparently enjoyed the temporary warm space condition (LBNL Auto-CPP demonstration 2006).

4.3. Factors that influence demand savings achievement

This section describes demand savings achieved by DR strategies with some example data from the LBNL Auto-DR studies. These studies covered DR events for eleven buildings in 2003 and 2004. Demand savings achieved by DR strategies vary, especially for HVAC DR strategies, depending on various factors. It is difficult to estimate demand saving potential by an HVAC DR strategy until it is tested. Even within the same building, demand savings will vary widely depending on weather conditions. Table 21 summarizes the factors that influence HVAC demand savings. On the other hand, lighting DR strategies generally provide consistent, predictable demand savings. Lighting demand savings can be influenced by daylight (if the strategy uses dimmable ballast control with daylight feedback) or occupant behavior (if the strategy can be controlled or disabled by the occupants).

Table 21. Demand savings influence factors

Building factors	System factors	Strategy factors	Weather factors
Building use Building size Structure type Level of occupancy	HVAC type Efficiency Control type Commissioning	Depth of shed Area% controlled Duration of curtailment	Outside air temperature Outside air humidity Solar radiation

Figure 13 shows maximum demand savings intensity (W/ft²) categorized by shed strategy for one of the LBNL Auto-DR tests. The test was performed on November 5, 2004, a relatively cool day with maximum average outside air temperature (OAT) of 66°F in the site locations. Of the 9 sites shown in the chart, these methods were used to calculate the demand savings from their DR strategies:

- 5 sites (A, B, D, G, and H) used the whole building baseline method,
- 3 sites (C, E, and F) used HVAC end-use metering data, and
- 3 sites (I, E, and F) used lighting end-use metering.

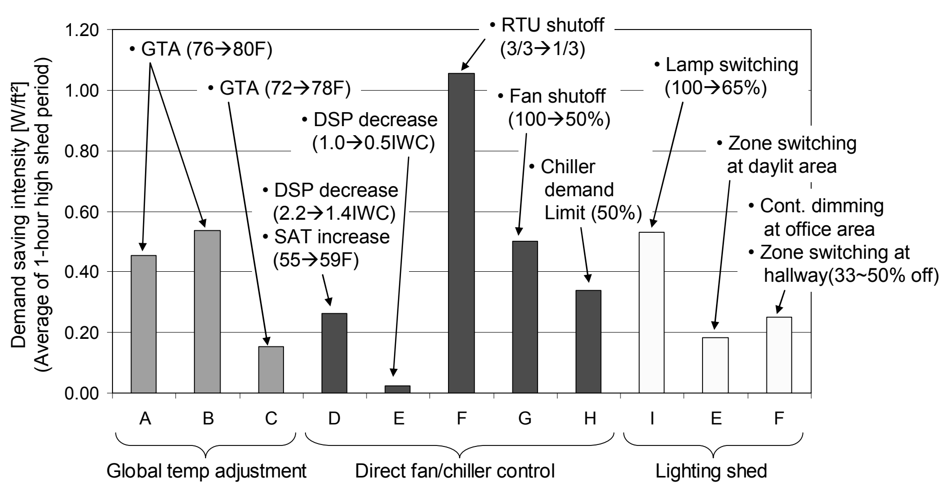


Figure 13. Demand savings intensity by shed strategy (W/ft^2)

The limited case study results of the buildings in the LBNL study shown in Figure 13 do not guarantee the level of demand savings for each DR strategy. Depending on the factors mentioned above, the demand savings can be either larger or smaller than those shown. Since these results are from intermediate seasons (fall and spring), demand savings by some HVAC DR strategies can be larger than the results shown in the charts.

Figure 14 shows the average demand savings (CPP high price period 3 p.m. to 6 p.m.) versus outside air temperature for six sites, including four offices and two retail stores. The results vary building by building. While Office A, Office C, and Retail B seem to have positive correlation between OAT and demand savings, Office B, Office D, and Retail A do not show correlation. In the charts, P means probability of linear correlation between the average demand savings and OAT.

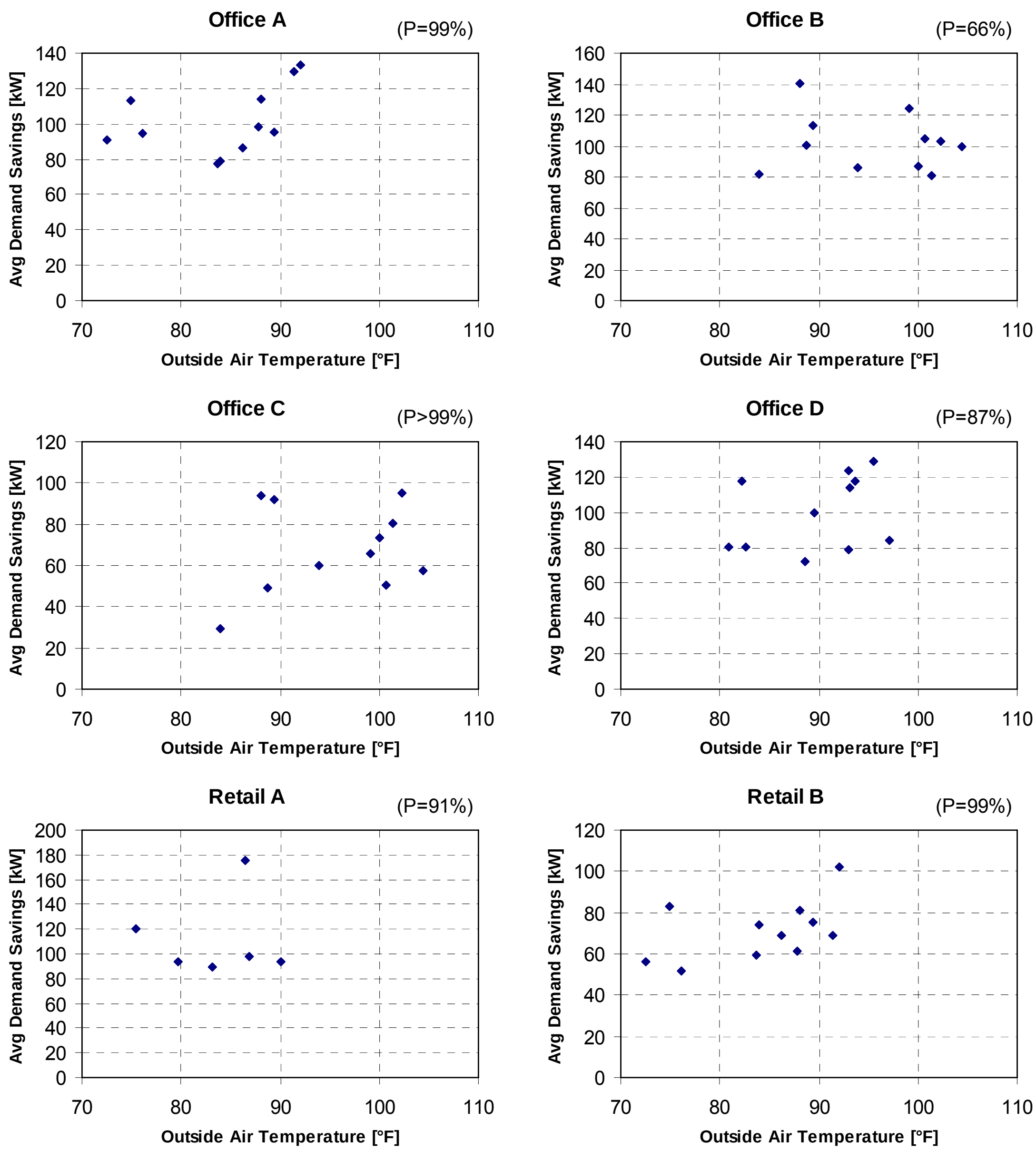


Figure 14. OAT vs. average demand savings

Table 22 lists the results of paired sample t-tests for OAT vs. demand savings shown in Figure 14 (significance level α = 0.05). The demand savings at three sites out of six showed statistically significant correlation with OAT. The weather dependency of demand savings varies widely depending on many factors including the building's system profile and the DR strategies chosen. Further investigation should be conducted with a larger set of sample data.

Table 22. Statistical significance of OAT vs. demand savings

Sites	DR strategies	Sample size	Probability	Statistical significance
Office A	GTA, CHW valve limit, etc	11	97%	Yes
Office B	GTA	11	4%	No
Office C	GTA	11	100%	Yes
Office D	RTU shutdown, Lighting, etc	11	79%	No
Retail A	GTA	5	87%	No
Retail B	GTA, RTU shutdown	11	100%	Yes

Figure 15 shows the correlation between outside air temperature (OAT) and average whole building power demand for an office building for a high-price period (3 p.m. to 6 p.m.) for 11 events in 2006. This building utilized GTA strategy with two-level increase for a rooftop unit (RTU) system with VAV. The high-price period average of the adjusted OAT regression baseline and CPP baseline of the event days are also plotted. Regression lines are projected for the actual demand of non-event days and event days separately. As shown, the regression line of non-event day actual demand has positive linear correlation, as well as does the regression line of event day actual demand. Though the event day demand line is slightly steeper than the non-event day line, the two regression lines are approximately parallel. This indicates that the average demand savings were nearly constant regardless of OAT at this building. The adjusted OAT regression model baseline shows a higher estimate than the actual days' regression line. Since the noon-time load of the actual event days was closer to the adjusted model than the regression estimate, we assume that the adjusted model is more accurate in this case. The average demand savings based on the adjusted OAT regression model were approximately constant over the series of events. This chart also indicates that CPP baselines were nearly constant, because CPP baseline is an average of the building demand for non-event days. On the CPP event days the OAT was higher than that of any non-event days.

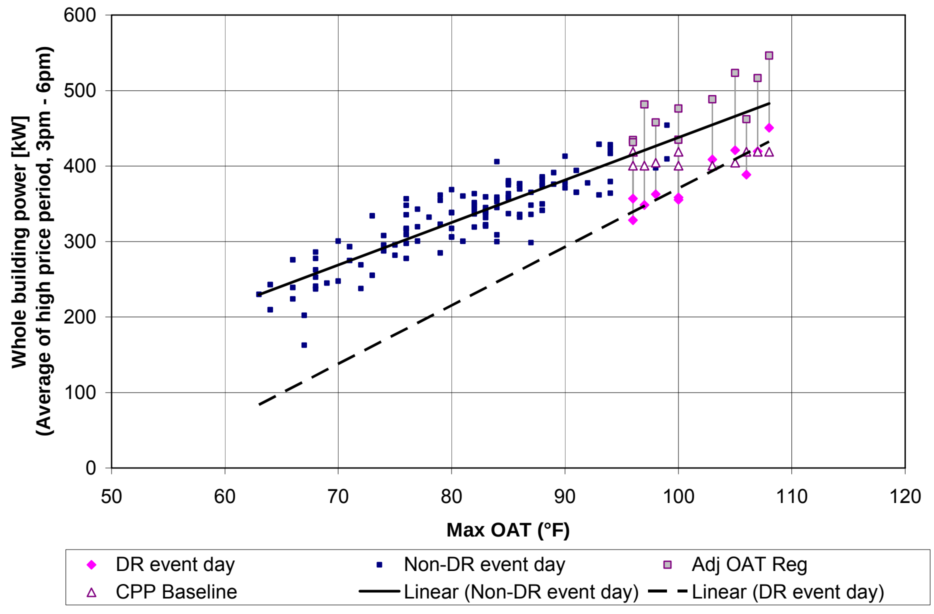


Figure 15. Whole-building hourly demand vs. OAT and demand sheds

5. Discussion and Conclusions

5.1. Discussion

This section addresses key issues that were not pursued in this report. These issues can form a future research agenda.

Hot and humid climates

Most of the examples introduced in this report are based on the results from the LBNL Auto-DR studies. The studies were performed in the northern California region, which does not have a hot and humid climate. Thus, this report does not include careful consideration of application of DR to facilities in hot and humid climates. While lighting DR strategies are mostly independent of climate, further field investigation in diverse climate conditions should be considered for HVAC DR strategies.

Demand savings potential in different seasons

The focus of the report was to introduce DR strategies for summer peak demand reduction. However, although a DR event is likely to occur on a high-temperature day, an unexpected event in electric grid conditions or a temporary electricity price increase can be triggered by factors other than temperature. In such cases, the demand savings potential for seasons other than summer should also be investigated for HVAC DR strategies.

Short hours versus long hours

As DR programs evolve into more dynamic and real-time strategies, a variety of DR program options will emerge, including short-hours and long-hours events. This report does not specifically indicate the difference between the short-hours and long-hours events. A short-hours event may be triggered by a sudden contingency in the electric grid and may require short-term but aggressive demand savings. On the other hand, a long-hours event may be triggered by an electricity price change or other factors and may require long-term but moderate demand savings. Characteristics of a DR strategy may better suit either short-hours or long-hours events or be applicable for both. Currently major California investor-owned utilities (IOUs) offer Critical Peak Pricing (CPP), which has a DR period of 6 hours, and Demand Bidding Program (DBP), which has a customizable DR period of 2 to 8 hours. DR strategies and the depth of DR control should be carefully investigated with relation to their duration to maximize demand savings achievement, minimize impact to occupants, and maximize financial incentive benefits from the DR programs.

Demand savings estimation tool

As mentioned throughout this report, the demand savings can widely vary depending on numerous influential factors. It would be useful to have a simplified calculation tool for demand savings estimation. The tool should be examined by comparing it against actual case studies and detailed building simulation models. Development of a simplified estimation tool for various types of DR strategies is recommended. Part of this development was initiated in passive thermal mass storage cooling research area (Xu 2006). A series of discussions has been conducted among LBNL researchers and DR auditors regarding simplified calculation methods to be used in utility incentive applications for DR technology installations. These efforts need to be coordinated and expanded.

5.2. Conclusions

The conclusions of this report are summarized below.

- The goal of DR strategies is to meet electric demand savings targets while minimizing negative impacts on the occupants or the processes that they perform.
- HVAC systems can be an excellent resource for DR shed savings because:
  - HVAC systems create a substantial electric load in commercial buildings,
  - The thermal flywheel effect of indoor environments allows HVAC systems to be temporarily unloaded without immediate impact to the building occupants, and
  - It is common for HVAC systems to be at least partially automated with EMCS systems.
- For HVAC DR strategies, global temperature adjustment of zones is the priority strategy that best achieves the DR goal. In contrast, systemic adjustments to the air distribution and/or cooling systems can useful for DR, but care must be taken to prevent disruption to occupants.
- DR strategies that slowly return the system to normal conditions (rebound avoidance) should be considered to avoid unwanted demand spikes caused by an immediate increase of cooling load.
- Lighting DR strategies tend to be simple and provide constant, predictable demand savings. Since lighting systems produce heat, reducing lighting levels may reduce the cooling load and/or increase the heating load within the space.
- Major obstacles for automation of lighting DR strategies are:
  - the resolution of lighting controls tends to be lower than that of HVAC controls, and
  - lighting systems are often not automated with EMCS.
- If a DR strategy can be achieved without any reduction in service, the strategy should be considered as a permanent energy-efficiency opportunity rather than a temporary DR strategy. That is, it should be performed on non-DR days as well. An added benefit of DR is that these energy-efficiency opportunities can often be discovered through development and implementation of DR control.

- The process of commissioning should be applied to each phase of DR control strategy application, including planning, installation, and implementation to make sure the goal of DR control is achieved.

5.3. Recommendations

This information should be disseminated to key personnel who are involved in DR implementation including facility managers, building owners, controls contractors, and auditors. Disseminating this information will help provide a common understanding of DR control strategies and development procedures to enable these strategies. Readers should note that the report is intended as a starting point for organizing and presenting such information, not an exclusive list of all DR strategies. Further research is needed to better understand the peak demand reduction potential and capabilities of these strategies for various building types in different climates and occupancy patterns. Additionally, research is needed in characterizing the capabilities of EMCSs for enabling DR and matching DR technologies and strategies with existing DR program rules for delivering optimized demand savings. One specific technical development needed is to explore the design and operation of simplified peak electric demand savings estimation methods and tools. Current auditors and building engineers have widely varying methods to estimate peak demand reductions for various strategies.

Among specific technical development efforts, development of a simplified demand saving estimation tool is recommended, as mentioned in the Discussion section. These efforts should be conducted as streamlined research.

5.4. Benefits to California

This guide is based primarily on case studies in California and is intended to help streamline the DR control strategy implementation process and increase successful participation in DR programs in California. Peak demand reduction and demand response are key parts of the state's energy policies.

References

Akashi, Y., J. Neches, and A. Bierman. 2002. *Energy saving load-shedding ballast for fluorescent lighting systems: Occupant's dimming requirements*. Lighting Research Center, Rensselaer Polytechnic Institute. Troy, NY. Draft report available at http://www.lrc.rpi.edu/researchTopics/reducingBarriers/resources.asp. Accessed December 11, 2006.

ASHRAE. 2004. *ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. Item #: 330-6854-04. ISBN: 1041-2336. Atlanta GA.

Braun, J.E., K.W. Montgomery, and N. Chaturvedi. 2001. *Evaluating the Performance of Building Thermal Mass Control Strategies.* International Journal of Heating, Ventilating, Air-Conditioning and Refrigeration Research, Vol. 7, No. 4, pp. 403-428. October.

CEC. 2006a. California Energy Commission. "Enhanced Automation – Case Studies." Sacramento CA. Available at http://www.energy.ca.gov/enhancedautomation. Accessed November 10, 2006.

CEC. 2006b. *Nonresidential Manual for Compliance with the 2005 Energy Efficiency Standards.*CEC 400-2005-006-CFM, Revision 3. Sacramento CA. September. Available at http://www.energy.ca.gov/title24/2005standards/index.html. Accessed December 19, 2006.

ISO (Independent System Operator) New England. 2003. "Real-Time Price Response Program Case Study - Wesleyan University." July 22. Available at http://www.iso-ne.com/genrtion_resrcs/dr/broch_tools. Accessed November 10, 2006.

Kiliccote, S., M.A. Piette, and G. Hughes. 2006. "Dynamic Controls for Demand Response in New and Existing Commercial Buildings in New York and California." Presented at the ACEEE 2006 Summer Study on Energy Efficiency in Buildings: Less is More: En Route to Zero Energy Buildings, Asilomar, Pacific Grove CA, August 13–18.

LBNL. 1998. *The Usefulness of Bi-Level Switching; Original Technical Note*. Lawrence Berkeley National Laboratory, Lighting Systems Group. LBNL-44281. Berkeley CA.

NYSERDA (New York State Energy Research and Development Authority). "Peak-Load Program Case Studies." Albany NY. Available at http://www.nyserda.org/programs/PeakLoad/peakload_case_studies.asp Accessed November 10, 2006.

Piette, M. A.1991. *Leaning Experiences with Controls to Reduce Electrical Peak Demands in Commercial Buildings*. Centre for the Analysis and Dissemination of

Demonstrated Energy Technologies, Analysis Series No. 7. Sittard, Netherlands. August.

Piette, M.A., O. Sezgen, D.S. Watson, N. Motegi, and C. Shockman. 2005a. *Development and Evaluation of Fully Automated Demand Response in Large Facilities*. Lawrence Berkeley National Laboratory. CEC-500-2005-013. LBNL-55085. Berkeley CA, January. Available at http://drrc.lbl.gov/drrc-pubs1.html. Accessed November 10, 2006.

Piette, M.A., D.S. Watson, N. Motegi, N. Bourassa, and C. Shockman. 2005b. *Findings from the 2004 Fully Automated Demand Response Tests in Large Facilities*. Lawrence Berkeley National Laboratory. CEC-500-03-026. LBNL-58178. Berkeley CA, September. Available at http://drrc.lbl.gov/drrc-pubs1.html. Accessed November 10, 2006.

Piette, M.A., D.S. Watson, N. Motegi, S. Kiliccote, and P. Xu. 2006. *Automated Critical Peak Pricing Field Tests: Program Description and Results*. Lawrence Berkeley National Laboratory. LBNL- 59351. Berkeley CA, April. Available at http://drrc.lbl.gov/drrc-pubs4.html. Accessed December 3, 2006.

Quantum Consulting Inc. and Summit Blue Consulting, LLC. 2004. *Working Group 2 Demand Response Program Evaluation – Program Year 2004 Final Report.* Prepared for Working Group 2 Measurement and Evaluation Committee. Berkeley CA and Boulder CO, December 21. Available at http://www.energy.ca.gov/demandresponse/documents/. Accessed November 10, 2006.

Rubinstein, F., and S. Kiliccote. 2006. *Demand Responsive Lighting: A Scoping Study.* Lawrence Berkeley National Laboratory. Berkeley CA, November. Review Draft.

Sezgen, O. and J. Koomey. 1998. *Interactions between Lighting and Space Conditioning Energy Use in U.S. Commercial Buildings*. Lawrence Berkeley National Laboratory. LBNL-39795. Berkeley CA.

Smith, C, G. Epstein and M. D'Antonio. 2004. "Demand Response Enabling Technologies and Case Studies from the NYSERDA Peak Load Reduction Program." Presented at the ACEEE 2004 Summer Study on Energy Efficiency in Buildings: Breaking Out of the Box, Asilomar, Pacific Grove, CA, August 22–27.

Xu, P., P. Haves, M.A. Piette, and J. Braun. 2004. "Peak Demand Reduction from Pre-Cooling with Zone Temperature Reset in an Office Building." Presented at the ACEEE 2004 Summer Study on Energy Efficiency in Buildings: Breaking Out of the Box, Asilomar, Pacific Grove, CA, August 22–27. LBNL-55800. Available at http://drrc.lbl.gov/drrc-pubsall.html. Accessed December 19, 2006.

Xu, P., P. Haves, M.A. Piette, and L. Zagreus. 2006. *Demand shifting with Thermal Mass in Large Commercial Buildings (Field Tests, Simulations and Audits)*. Lawrence Berkeley National Laboratory. CEC-500-2006-009. LBNL-58815. Berkeley CA, January. Available at http://drrc.lbl.gov/drrc-pubsall.html. Accessed December 19, 2006.

Glossary

AHU	Air handling unit
CAV	Constant air volume
CEC	California Energy Commission
CHW	Chilled water
CPP	Critical peak pricing
DBP	Demand bidding program
DDC	Direct digital control
DR	Demand response
DSP	Duct static pressure
DX	Direct expansion
EMCS	Energy management and control system
GTA	Global temperature adjustment
HMI	Human machine interface
HVAC	Heating, ventilating, and air conditioning
IGV	Inlet guide vanes
IOU	Investor-owned utility
ISO	Independent system operator
IWC	Inch water column
LBNL	Lawrence Berkeley National Laboratory
LRC	Lighting Research Center
NYSERDA	New York State Energy Research and Development Authority
OAT	Outside air temperature
PIER	Public Interest Energy Research
PMV	Predicted mean vote
RTU	Roof-top unit
SAT	Supply air temperature
TDV	Time dependent valuation
TMY	Typical meteorological year
VAV	Variable air volume
VFD	Variable frequency drive

Introduction to Commercial Building Control Strategies and Techniques for Demand Response

Appendices

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DR Strategies for HVAC Systems

Appendix A: DR Strategies for HVAC

This section provides additional technical details on HVAC DR strategies that are not covered in the main report. Although section 4.3 of the main report discusses statistical data from actual demand saving results, it does not clearly identify the demand savings results for some strategies, for reasons such as irregular whole building load shape, lack of sub-metering, or the application of multiple DR strategies. This appendix contains some actual demonstration results, which clearly illustrate the effects of the strategies. Table A.1 is a summary of the strategies discussed in this appendix.

Table A.1. Summary of DR strategies

Category	DR Strategy	Technical Details	Case Study
Zone control	Global temperature adjustment	X	X
	Passive thermal mass storage	X	
Air distribution	Duct static pressure decrease	X	
	Fan variable frequency drive limit	X	X
	Supply air temperature increase	X	
	Fan quantity reduction		X
	Cooling valve limit		X
Central plant	Chilled water temperature increase		
	Chiller demand limit		
	Chiller quantity reduction		
Rebound avoidance	Slow recovery		X
	Sequential equipment recovery		
	Extended DR control period		X

A.1. Global Temperature Adjustment (GTA)

Case Study

Site Name	2530 Arnold (Martinez CA), government office
DR Strategy	**Moderate Price (12:00 p.m. - 3:00 p.m.)** ▪ Zone setpoint increased 2°F (76°F to 78°F) **High Price (3:00 pm - 6:00 pm)** ▪ Zone setpoint increased 4°F (80°F)
Event Date	9/22/2005 (Max OAT: 82°F)

Figure A.1. Whole building power (global temperature adjustment) - 2530 Arnold shows the whole building power and baselines[1] of the building on a DR event day. This site used GTA, which has two levels of step increase (Pattern #1). The whole building demand dropped 100 kW immediately after the moderate price period started (transient savings). After about an hour the whole building demand increased and stabilized around 50 kW lower than the baseline (steady-state savings). This indicates that it took an hour to increase zone temperature from 76°F to 78°F with no cooling or a minimum level of cooling. 350 kW of whole building demand was required to maintain a 78°F setpoint, while 400 kW was required to maintain a 76°F setpoint.

When the high price period started, the demand dropped again from 350 kW to 300 kW (transient savings). After about an hour the whole building demand slightly increased. Around this time the whole building demand began to decrease towards the end of the occupancy period. The building did not have a rebound peak because the occupancy period ended at nearly the same time as the end of the curtailment period.

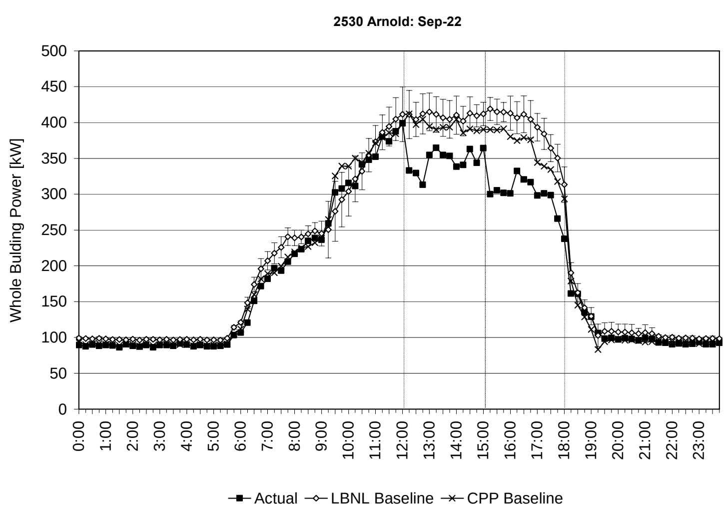

Figure A.1. Whole building power (global temperature adjustment) - 2530 Arnold

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[1] LBNL's OAT regression baseline model and PG&E's CPP baseline (highest 3 days of the last 10 non-event working days) are plotted.

A.2. Passive Thermal Mass Storage

This section summarizes the results of a simulation analysis of passive thermal mass storage strategy conducted by Purdue University (Braun et al. 2001). Several thermal mass pre-cooling and discharge strategies were examined in the simulation.

Table A.2 shows details of the building for which the simulation model was developed. The simulation tool was used to estimate cooling season operation for a variety of DR strategies, utility rates, and locations. For these simulations, typical meteorological year (TMY) data were used for all locations. The acceptable range of occupied zone air temperatures was considered to be between 69°F to 77°F. This range was based on comfort studies specific to the field site (Keeney and Braun 1997).

Table A.2. Simulation building description

Building use	Headquarters office building
Building profile	• 1.4 million ft^2, 4-story • Heavy-weight concrete structure, energy-efficient windows • Total of 3,600 ton chillers, AHU with VAV, total 1,200,000 cfm • Occupancy period 7 a.m. to 5 p.m.
DR Strategy	Pre-cooling

Figure A.2. Weekday hourly zone temperature setpoints for night setup, light, moderate, and extended pre-cooling strategies shows zone setpoint temperature variations for four strategies where the on-peak occupied setpoint was held constant at 73°F. *Night setup* was the baseline used for comparing the alternative strategies. The *light pre-cooling* and *moderate pre-cooling* strategies are simple strategies that pre-cool the building at a fixed setpoint of 67°F prior to occupancy and then maintain a fixed discharge setpoint in the middle of the comfort range, 73°F, during occupancy. The light pre-cooling begins at 3 a.m., whereas moderate pre-cooling starts at 1 a.m. The *extended pre-cooling* strategy also starts at 1 a.m. and attempts to maintain the thermal mass cooled until the onset of the on-peak period. In this case, the setpoint at occupancy is maintained at the lower limit of comfort, 69°F, until the on-peak period begins at 9 a.m. At this point, the setpoint is raised to the middle of the comfort range (73°F).

Figure A.3 shows the simulated cooling loads for a sample day in mid-July in Chicago for each of the strategies. For all three strategies, night setup resulted in very little cooling during the unoccupied period, with a peak ocurring in the middle of the night. The cooling requirement was relatively flat during the day, with a second peak near the end of the occupied period. Each of the pre-cooling strategies resulted in reduced cooling requirements throughout the occupied period, particularly in the early morning. The greater the pre-cooling, the greater the on-peak period load reduction. For each strategy, although the on-peak <u>total</u> cooling requirement was reduced significantly, the peak cooling requirement during the on-peak period was only marginally reduced. These strategies tended to discharge the mass relatively early during the on-peak period.

The peak loads could be reduced further if up to the upper limit of comfort range were used throughout the on-peak occupied period.

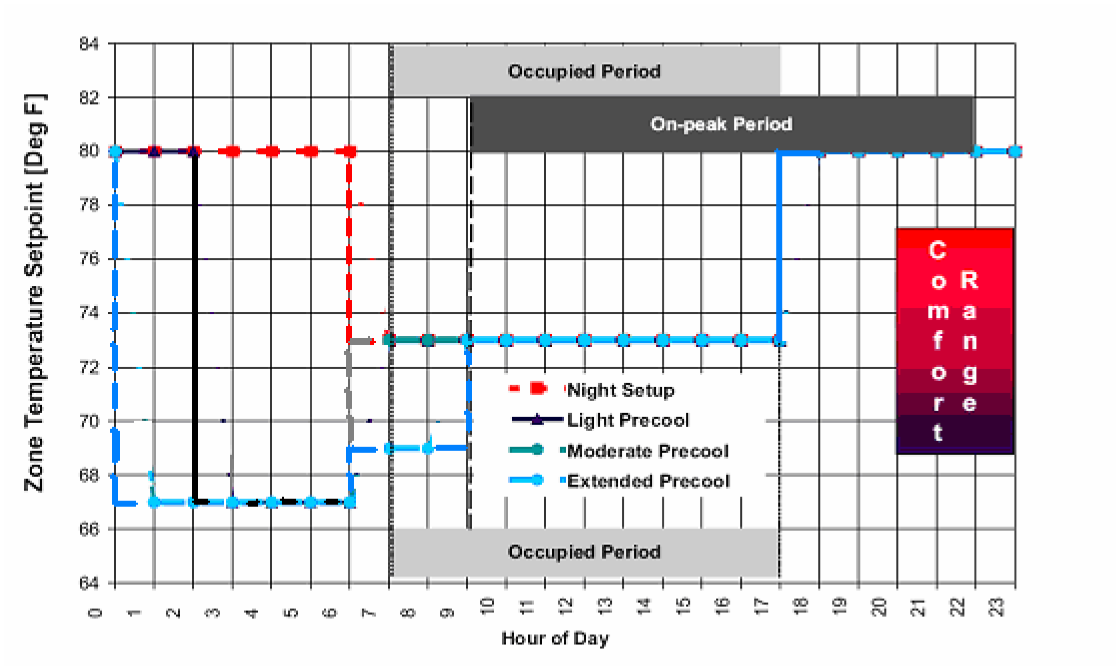

Figure A.2. Weekday hourly zone temperature setpoints for night setup, light, moderate, and extended pre-cooling strategies

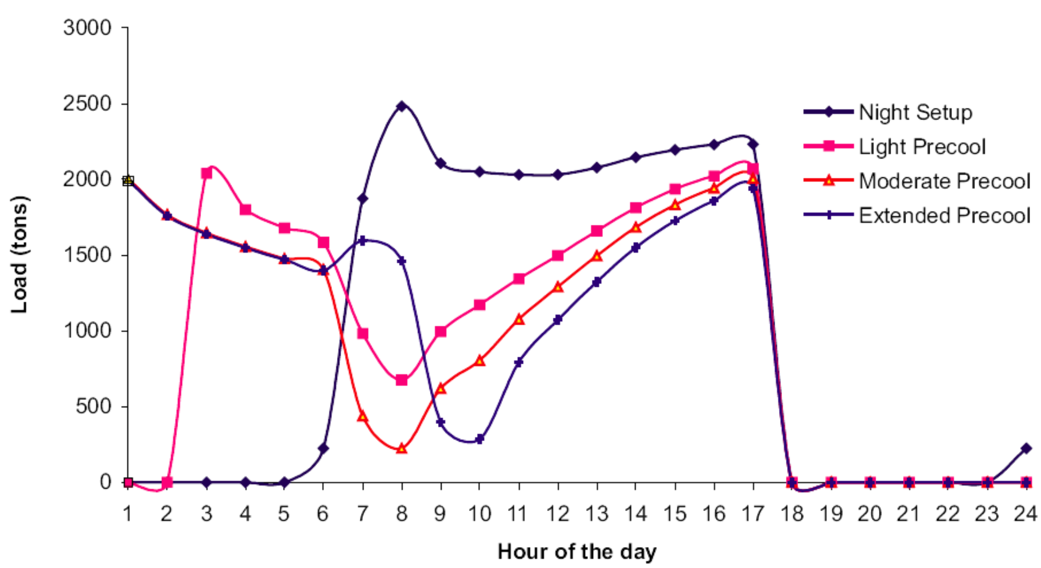

Figure A.3. Cooling load profiles for night setup, light, moderate, and extended pre-cooling strategies

Figure A.4 shows two additional strategies that have the same pre-cooling characteristics as the *extended pre-cooling* strategy, but that use the entire comfort range during the on-peak occupied period. The *maximum discharge* strategy attempts to discharge the mass as quickly as possible following the onset of the on-peak period. In this case, the setpoint is raised to the upper limit of comfort within an hour after the on-peak period begins. The maximum discharge strategy maximizes storage efficiency and load shifting but is not necessarily optimal in terms of peak load reduction. It tends to lead to low loads during the morning and a peak during the late afternoon. *Linear rise* strategies were also investigated as a means of leveling the load to further reduce peak loads. The *slow linear rise* strategy raises the setpoint linearly over the entire on-peak occupied period (nine hours in this case), whereas the *fast linear rise* strategy raises the setpoint over four hours.

Figure A.5 shows cooling load profiles for the night setup, maximum discharge, and linear rise strategies for the same day in mid-July. The maximum discharge strategy resulted in the lowest on-peak period total load. It also had a slightly lower peak load than the linear rise strategies during the on-peak period (after 9 am). The fast linear rise strategy had a flatter on-peak load profile but had its peak at the onset of the on-peak period. It is interesting to note that both the maximum discharge and the fast linear rise strategies resulted in minimum chiller loading at the onset of the on-peak period.

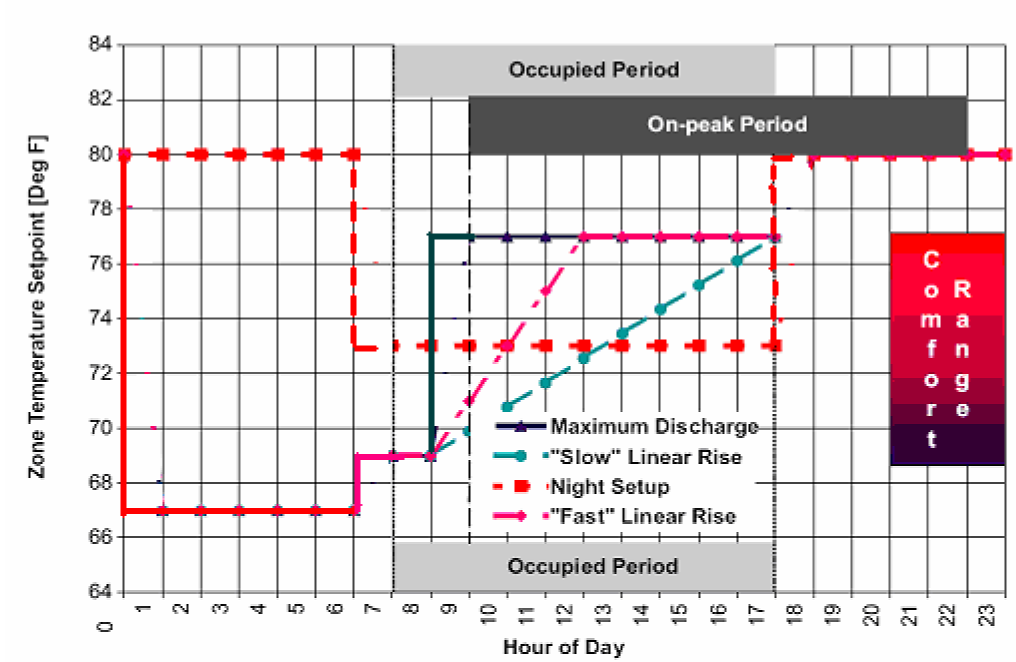

Figure A.4. Weekday hourly zone temperature setpoints for night setup, maximum discharge, and linear temperature rise strategies

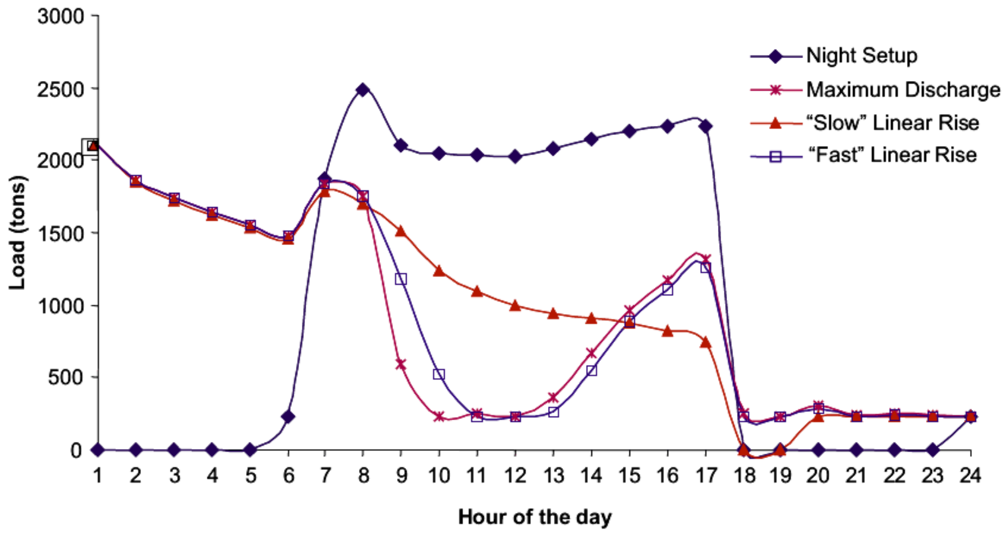

Figure A.5. Cooling load profiles for night setup, maximum discharge, and linear temperature rise strategies

A.3. Duct Static Pressure Decrease

This section describes the principle of controlling fan behavior using the *duct static pressure (DSP) decrease* strategy. Figure A.6 illustrates the concept of fan system parameter behavior when the DSP decrease strategy is applied. The fan characteristics curves based on the fan laws[2] and duct system characteristics are defined here (assuming fan size, gas density, and mechanical efficiency do not change during the DR strategy operation):

- ***fan curve***: Shows the relation between total pressure and airflow rate determined by fan VFD.
- ***system curve***: Shows the relation between total pressure and airflow rate determined by duct system resistance (from ducts and VAV dampers).
- ***power curve***: Shows the relation between airflow rate and fan power.

In the figure, the airflow rate and total pressure of the fan system are originally positioned at *point* ⓐ on ***fan curve 1*** as their normal settings. When the DSP setpoint is decreased, the system shifts from ***system curve 1*** to ***system curve 2***. Under this strategy, the fan variable frequency drive (VFD) speed is decreased to adjust the DSP, which causes conditions to shift from ***fan curve 1*** to ***fan curve 2***. The variable air volume (VAV) dampers open wider to deliver the same airflow rate for the lower DSP condition. The pressure-airflow relationship is stabilized with airflow rate and total pressure at *point* ⓑ on ***fan curve 2***, as shown. Power decreases as the fan speed is decreased and system conditions move from ***power curve 1*** to ***power curve 2***. The demand savings achievement by this strategy is represented by the shift from *point* ⓐ to *point* ⓑ on the power curves.

If the DSP setpoint is too low to deliver enough air to some zones, the VAV boxes at these zones will open 100% and starve for air. Even if some VAV boxes are starving, the fan VFD will not speed up as long as the DSP setpoint is maintained. If the DSP setpoint is not met, then the airflow rate becomes lower than required to maintain comfort in the space. This reduction in airflow reduces the chilled water flow to maintain the supply air temperature. Consequently, cooling demand is saved under such conditions, but airflow may fall below design levels in some zones. Therefore, careful consideration to avoid a shortage of fresh air supply should be taken in selecting a DSP setpoint.

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[2] The fan laws relate the performance variables for any dynamically-similar series of fans. The variables are fan size, rotational speed, gas density, volume flow rate, pressure, power, and mechanical efficiency (ASHRAE System and Equipment Handbook 18.4).

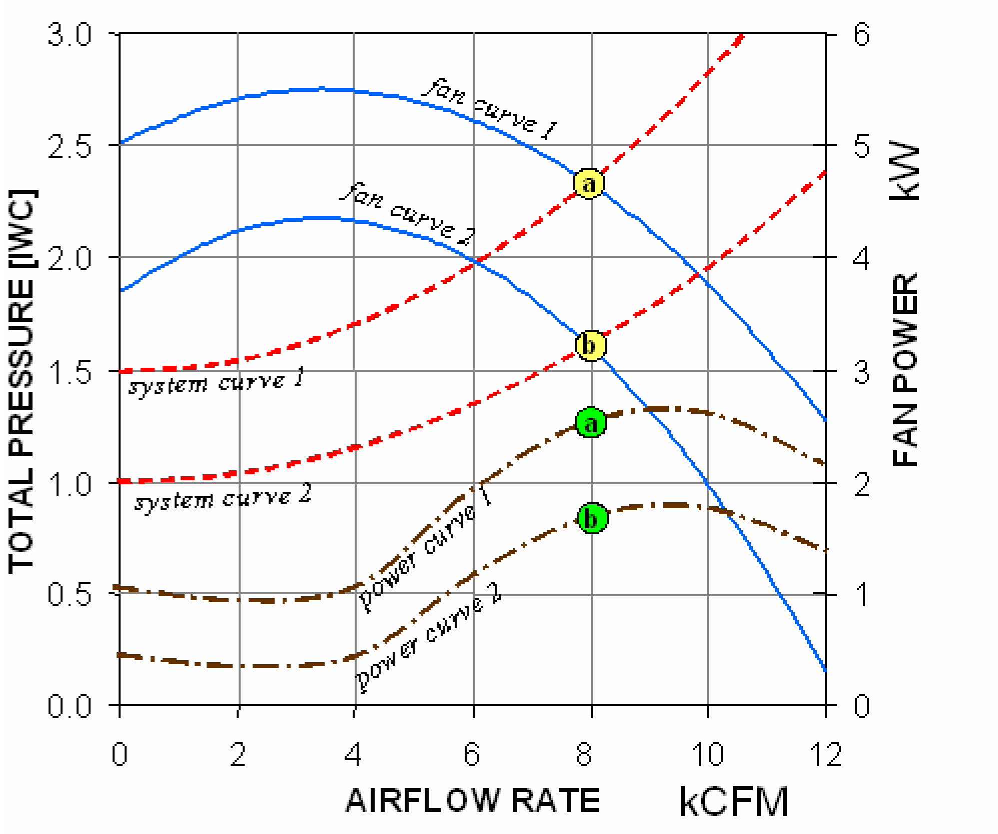


Figure A.6. Fan performance curve for DSP decrease strategy

A.4. Fan VFD Limit

This section describes the principle of controlling fan control behavior by the *fan variable frequency drive (VFD) limit* strategy. Figure A.7 illustrates the concept of fan system parameter behavior when the fan VFD limit strategy is applied. In the figure, the airflow rate and total pressure of the fan system are originally positioned at *point* ⓐ on f***an curve 1*** as their normal settings. When fan speed is lowered by the DR control, system conditions shift from ***fan curve 1*** to ***fan curve 2***. To maintain the duct static pressure (DSP) setpoint the system conditions have to be on ***system curve 1***. When the strategy is applied the total fan pressure moves to *point* ⓑ on ***fan curve 2***, with a corresponding reduction in airflow rate. On the fan power side, when the fan speed is lowered the system moves from ***power curve 1*** to ***power curve 2***. Due to the airflow rate reduction the fan power is reduced to *point* ⓑ on ***power curve 2***.

However, the VAV boxes are not satisfied with the reduced airflow and start opening the damper positions. From this point, the system can no longer maintain the DSP setpoint, because the fan speed is locked. The condition rides on ***fan curve 2*** as the DSP decreases while the airflow increases. In the figure, conditions move from ***system curve 1*** towards ***system curve 2*** (DSP 1.0 IWC (inches water column)), and the airflow rate is satisfied at *point* ⓒ on ***system curve 2***. The demand savings is represented by ⓐ – ⓒ on the fan power curves.

If the VFD limit is too low to maintain sufficient DSP, the VAV boxes at some zones open 100% and starve for air. Even if some VAV boxes are starving, the fan VFD will not speed up because the fan speed is locked, causing DSP to drop. This strategy may provide essentially the same result as the DSP decrease strategy. However, when the fan VFD limit strategy is used, the resulting DSP cannot be predicted, while DSP can be specified with the DSP decrease strategy.

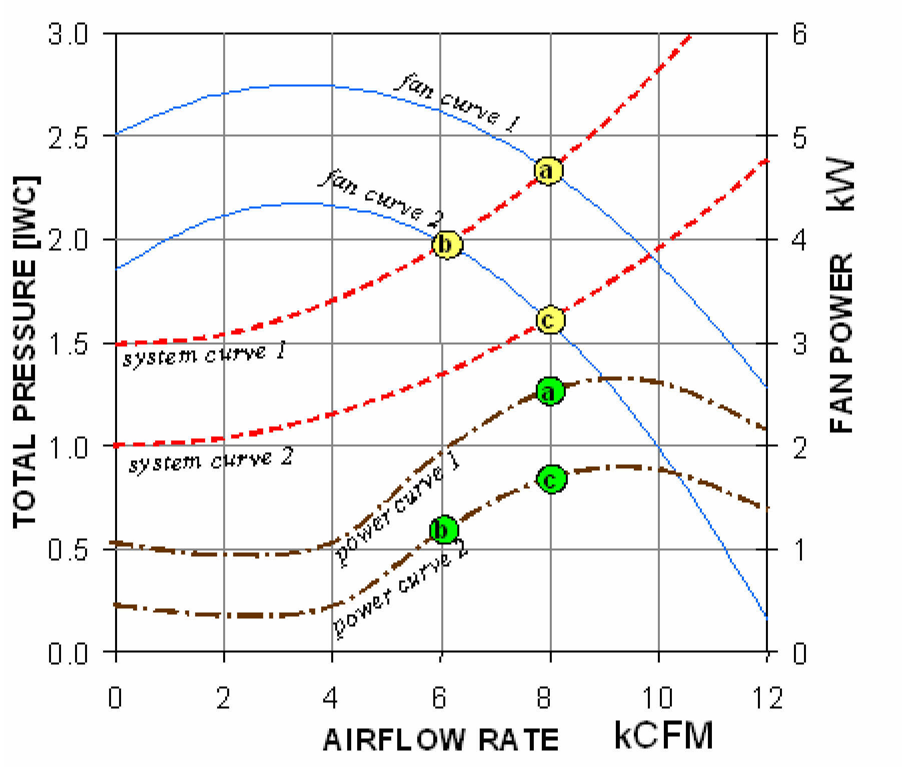


Figure A.7. Fan performance curve for fan VFD limit strategy

Case Study

Site Name	**UC Santa Barbara (Santa Barbara CA), Library**
DR Strategy	**Moderate Price (1:15 p.m. - 2:15 p.m., 3:15 p.m. - 4:15 p.m.)** Supply fan VFD 70% limit Economizer 100% open **High Price (2:15 p.m. - 3:15 p.m.)** Supply fan VFD 60% limit Duct static pressure reset 0.4 IWC (partial) Heating/cooling valve closed
Event Date	11/19/2003 (Max OAT: 69 °F)

Figure A.8 shows the fan power demand of a university library that employed the fan VFD limit strategy in a mixture of multiple strategies. The fan power shed was mostly accomplished by the fan VFD limit strategy. During normal operation most fans were operated at 100% VFD. During the moderate price period the fan VFD was limited to 70% achieving approximately 17% fan power reduction. During the high price period the fan VFD was lowered to 60% resulting in approximately 35% of fan power shed compared to the baseline operation.

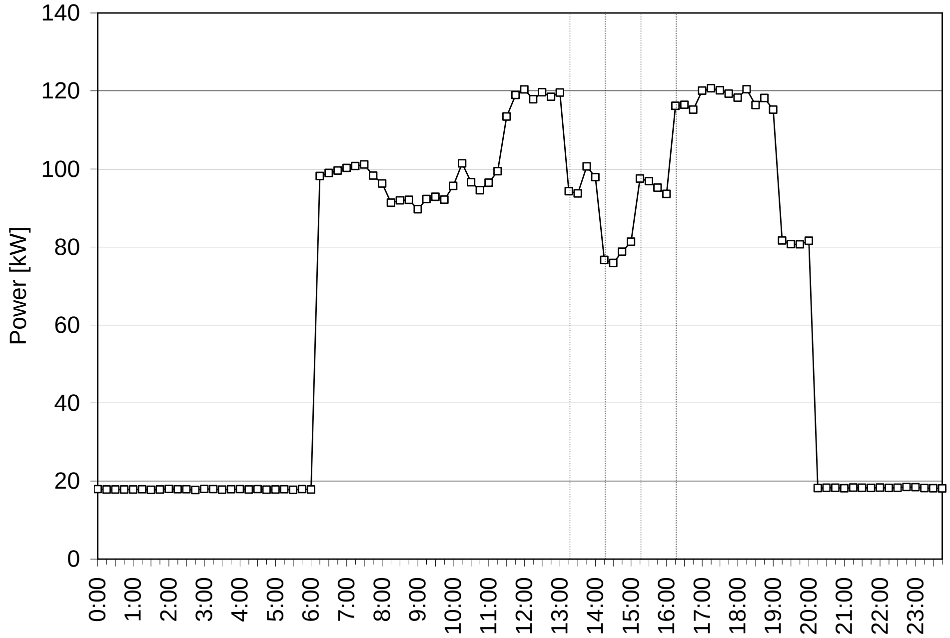


Figure A.8. Fan power (fan VFD limit) - UCSB

A.5. Supply Air Temperature Increase

This section describes the controls behavior for the supply air temperature (SAT) increase strategy for VAV systems. When the SAT is raised, the VAV boxes require more airflow and open the dampers wider. This causes the DSP to drop. The fan speeds up to maintain the DSP setpoint resulting in a fan power increase. Therefore, locking the fan VFD or IGV at their positions prior to curtailment is required to avoid a significant fan power increase. However, even when the fan VFD or IGV is locked, the airflow increases until it satisfies the VAV boxes (when DSP is lowered airflow rate can increase even without increasing fan speed). Along with the airflow increase, the fan power may or may not increase depending on its location on the power curve (no power reduction is expected). Therefore, fan power demand savings cannot be achieved by this strategy.

The increased airflow requires the same amount of chilled water flow as would be required at the original SAT setting. Therefore, this strategy will not save or may even increase fan power demand, nor will it save chiller power demand, while the DSP setpoint is maintained.

To achieve cooling demand savings, the SAT setpoint has to be raised until the VAV system loses control of the DSP setpoint. As in the fan VFD limit strategy, when some VAV boxes open 100% and begin to starve for air, the DSP setpoint can no longer be maintained if the VFD is locked. Then the airflow rate becomes smaller than required. This reduction in airflow reduces the chilled water flow to maintain the SAT. Consequently, the cooling demand is saved.

For reheat load reduction an SAT increase strategy will be beneficial for both CAV and VAV systems. If the building has a large reheat load, since many VAV boxes are running at minimum damper position, the airflow increase caused by the SAT increase will be minimal. Technically, the same amount of cooling energy will be reduced as reduced reheat energy.

The best practice for reheat control for a VAV system is to increase the SAT until the first VAV box damper goes to the fully-open position. If the building is operated in this manner the SAT increase will cause some VAV boxes to starve immediately. If the SAT is controlled at a fixed temperature, the SAT increase may not cause a significant zone temperature increase if most of the VAV boxes are operated below 100% open. If the building tends to have a large reheat load, fine tuning of this strategy results in worthwhile demand savings without a severe reduction in service.

A.6. Fan Quantity Reduction

Case Study

Site Name	**Roche Pharmaceutical (Palo Alto CA),** **Office, Auditorium, and Cafeteria**
DR Strategy	**Moderate Price (1:15 p.m. - 2:15 p.m., 3:15 p.m. - 4:15 p.m.)** ▪ Auditorium - supply fans off (50%) **High Price (2:15 p.m. - 3:15 p.m.)** ▪ Auditorium - supply fans off (50%) ▪ Cafeteria - supply fans off (50%) ▪ Office - supply fans off (50%)
Event Date	11/19/2003 (Max OAT: 66°F)

A pharmaceutical laboratory campus used fan quantity reduction for its DR strategy at three buildings -- an office, an auditorium, and a cafeteria. Half of the constant volume AHUs were turned off for 3 hours in the auditorium and for 1 hour in the cafeteria and the office. Figure A.9 shows the whole building power (not including the cooling demand) and the aggregated OAT regression baseline of all three buildings. The levels of demand shed due to the different price signals can be clearly seen in the demand profile. After the first $0.30/kWh signal at 1 p.m., the whole building power dropped by 71 kW at 1:15 p.m. from the implementation of the fan quantity reduction strategy in the auditorium. After the $0.75/kWh signal at 2 p.m., the demand dropped further by 57 kW at 2:15 p.m. when half the fans were also shut off in the cafeteria and the office. Roche achieved maximum 164 kW demand savings (28%) from 2:45 p.m. to 3:00 p.m. After the end of the moderate price signal at 3:00 p.m., the cafeteria and office fans were returned to 100% operation, while half the auditorium fans remained shut off.

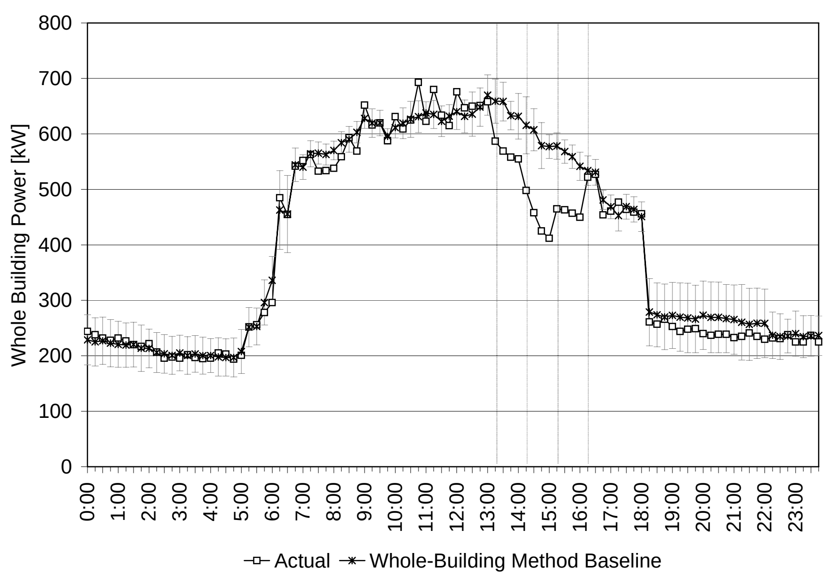


Figure A.9. Total whole building power (fan quantity reduction) - Roche

A.7. Cooling Valve Limit

Case Study

Site Name	**UC Santa Barbara (Santa Barbara CA), Library**
DR Strategy	**Moderate Price (1:15 p.m. - 2:15 p.m., 3:15 p.m. - 4:15 p.m.)** ▪ Supply fan VFD 70% limit ▪ Economizer 100% open **High Price (2:15 p.m. - 3:15 p.m.)** ▪ Supply fan VFD 60% limit ▪ Duct static pressure reset 0.4 IWC (partial) ▪ Heating/cooling valve closed
Event Date	11/19/2003 (Max OAT: 69°F)

Cooling valve limit was another strategy employed by the university library. Chilled water is supplied from a campus-wide chilled water network, and during the DR event the cooling valve was completely shut off to reduce chiller demand at the central plant. The fan was kept operating at lower speed to deliver fresh air to zones.

Figure A.10 shows the library's cooling demand, which was calculated from chilled water consumption at the library and the ratio of the central chiller plant electric demand to total chilled water supply Btu/h. Cooling power dropped significantly at the beginning of the high price period because of the strategy. However, the cooling power demand had a rebound peak at the end of the shed period and was greater than the baseline demand for that time period. A rebound avoidance strategy should be considered when this strategy is applied.

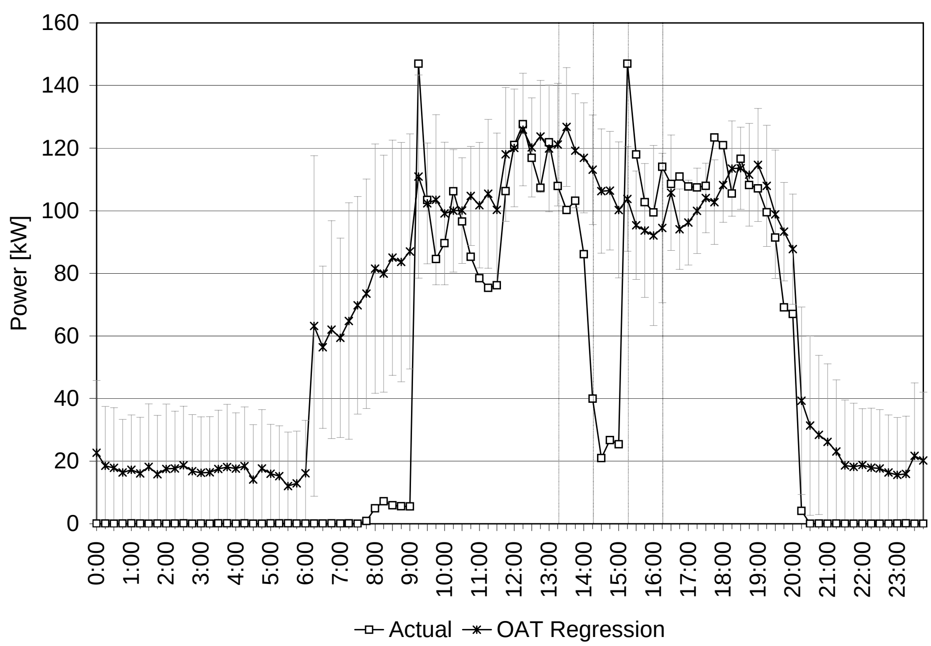


Figure A.10. Cooling demand (cooling valve limit) - UCSB

A.8. Slow Recovery Strategy

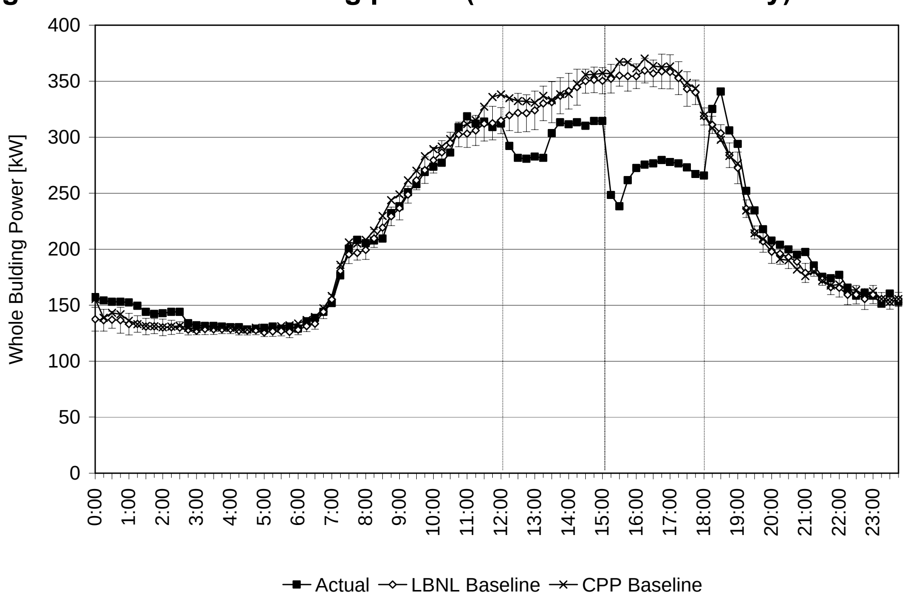
This section introduces a case study of the slow recovery strategy, one of the rebound avoidance strategies.

Case Study

Site Name	**Echelon (San Jose CA), Corporate headquarters office**
DR Strategy	**Moderate Price (12:00 p.m. - 3:00 p.m.)** ▪ Hallway lighting turned off where ambient light present ▪ Daylit office lights turned off ▪ Inner office lights dimmed to 20% **High Price (3:00 p.m. - 6:00 p.m.)** ▪ 1 of 3 RTU turned off ▪ DSP reduced from 1.5" to 0.8" ▪ SAT increased from 55 to 65°F **Rebound avoidance** ▪ Ramp-up DSP in 0.2 IWC increments every 5 minutes (manual)
Event Dates	10/13/2005 (Max OAT: 83 °F), 10/25/2005 (Max OAT: 69 °F)

Figure A.11 shows the whole building power and OAT regression baselines of an office building that employed a set of HVAC DR strategies for the high price period. Due to limitation of the control system's capability, the rebound peak avoidance strategy was not programmed for the first test. After the DR period, all the HVAC operations were set back to normal at once, and this caused rebound peak.

Figure A.11. Whole building power (without slow recovery) - Echelon



For the second test, to avoid the high rebound peak right after the shed period, the operator did manual slow recovery by ramping up the duct static pressure from 0.8 IWC to 1.5 IWC in increments of 0.2 IWC every 5 minutes. It took about 20 minutes to get the DSP back to normal. The building operator also manually ramped down the supply air temperature from 65°F to 55°F gradually over 30 minutes after the end of DR period. Figure A.12 shows the whole building power of the site when the slow recovery strategy was applied. Use of this strategy mitigated the high rebound peak.

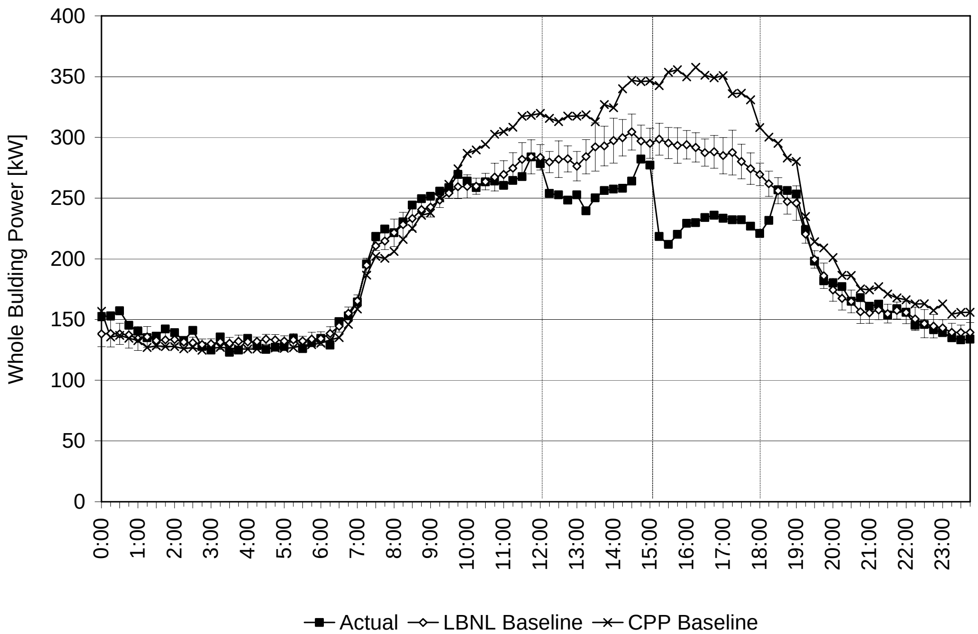


Figure A.12. Whole building power (with slow recovery) - Echelon

A.9. Extended DR Control Period

This section introduces a case study of the extended DR control period strategy, one of the rebound avoidance strategies.

Case Study

Site Name	Alameda County Water District (Fremont CA), Office
DR Strategy	**Moderate Price (12:00 p.m. - 3:00 p.m.)** ▪ Boiler disabled ▪ CHW setpoint raised to 50°F ▪ Current limiting to 70% ▪ SAT increased from 55°F to 65°F for AHUs 1, 2, 3, and Lab AHU ▪ DSP setpoint decreased from 1.5" to 1.0" ▪ Zone setpoint increased to 75°F **High Price (3:00 p.m. - 6:00 p.m.)** ▪ Zone setpoint increased to 78°F **Rebound Avoidance** ▪ Extend shed control 2 hours (until 8 p.m.)
Event Date	9/29/2005 (Max OAT: 87°F), 10/6/2005 (Max OAT: 75°F)

Figure A.13 shows the whole building power and OAT regression baselines of an office building that employed multiple HVAC DR strategies. At the beginning of the demonstration this site did not have any rebound avoidance strategy programmed. At the end of the DR period a high rebound peak occurred due to the sudden recovery of HVAC operation.

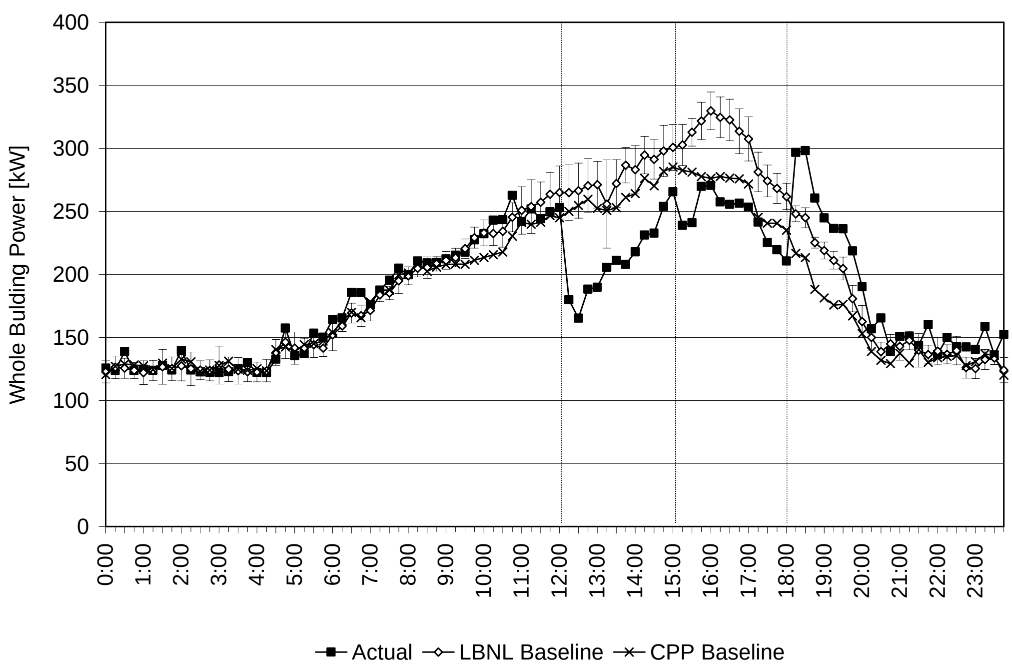


Figure A.13. Whole building power (without extended DR period) - ACWD

After experiencing the rebound peak during the first test, the building operator added an extended DR control period. Since the occupants start to leave around 6 p.m., the operator assumed that there would be no significant impact on occupant comfort even if the DR strategies were continued after the end of the work day. The new sequence of operation initiated the original DR strategies when the DR event was triggered and continued the strategies until 8 p.m.

Figure A.14 shows the demonstration results after implementation of the extended DR period strategy. For this event all the strategies were successfully operated and rebound peak did not occur.

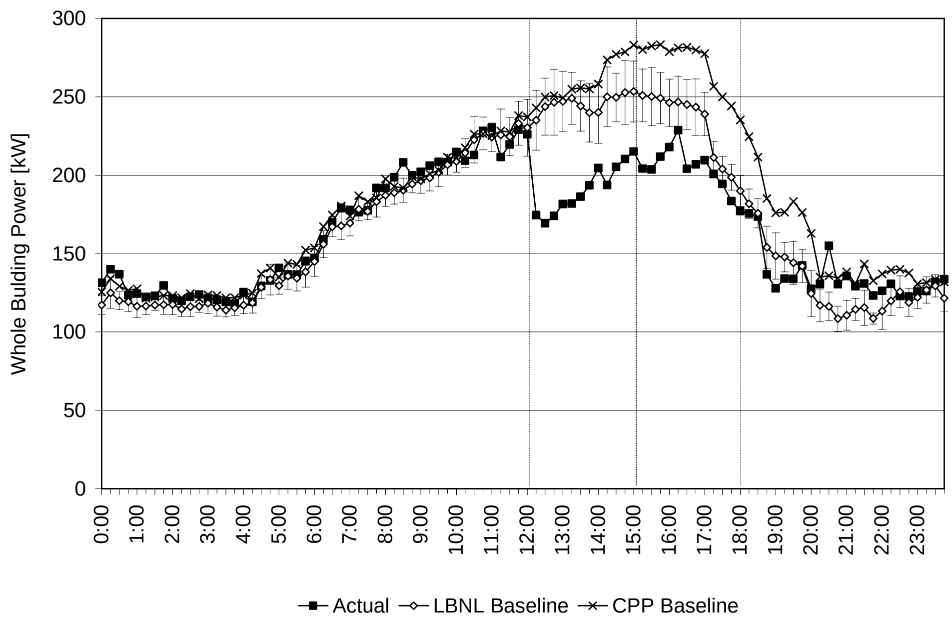


Figure A.14. Whole building power (with extended DR period) – ACWD

References

ASHRAE 2004. ASHRAE Handbook – HVAC Systems and Equipment. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. 18.4. Atlanta GA.

Braun, J.E., K.W. Montgomery, and N. Chaturvedi. 2001. *Evaluating the Performance of Building Thermal Mass Control Strategies.* International Journal of Heating, Ventilating, Air-Conditioning and Refrigeration Research, Vol. 7, No. 4, pp. 403-428. October.

Keeney, K.R. and J.E. Braun. 1997. *Application of Building Precooling to Reduce Peak Cooling Requirements*. ASHRAE Transactions, Vol.103, No.1, pp. 463-469.

Appendix B

Summary of DR Strategies

Appendix B: Summary of DR Strategies

This section summarizes the DR control strategies chosen for each participation site in the LBNL Auto-DR studies over three years (Piette et al. 2005a, 2005b, 2006) and other case studies (see section 1.5 of the main report).

B.1. DR Strategies of LBNL Auto-DR Studies

Table B.1 summarizes the DR strategies chosen for the Auto-DR participant sites in 2003 and 2004. Albertsons, Bank of America, OFB, Roche and UCSB participated in the 2003 and 2004 studies and rest of the sites in the table participated in the 2004 study.

In these tests the moderate price period was from 1 p.m. to 2 p.m. and from 3 p.m. to 4 p.m. The high price period was from 2 p.m. to 3 p.m. The strategies chosen for the moderate price period were continued during the high price period, with greater increase or decrease of parameter setpoints chosen for the moderate price period.

Table B.1. DR strategies by site for LBNL Auto-DR studies, 2003 and 2004

Site Name	Moderate Price	High Price
300 Capitol Mall - Office	► CHW temp increase 44°F → 47°F ► GTA cooling 1.5°F increase ► Supply fan VFD lock ► Fountain pump off ► Fan quantity reduction at loading deck ► Zone switching at lobby	► CHW temp increase → 55°F ► GTA cooling 3°F increase
Albertsons - Supermarket	► Bi-level switching 35% off at store area	► Anti-sweat door heater in night-mode
B of A - Office, Data Center	► SAT reset 55°F → 59°F ► DSP decrease 2.2" → 1.8"	► SAT reset → 59°F ► DSP decrease → 1.4"
Cal EPA - Office	► DSP decrease 1.0" → 0.5"	► Zone switching in daylit space
CETC - Research Lab	► Unload chiller and cool with ice storage ► Fan quantity reduction (2 AHU off) ► Electric humidifier off	
Cisco - Office, Data Center	► GTA cooling 2°F increase ► Boiler pump off & stairwell fan coils off ► Zone switching in daylit space ► Zone switching in stairwell, lobby, hallway	
50 Douglas - Office	► GTA cooling 76°F → 78°F	► GTA cooling → 80°F
Summit Center - Office	► GTA cooling 76°F → 78°F	► GTA cooling → 80°F
Echelon - Office	► GTA cooling individually setup by zones ► Continuous dimming at office	► RTU quantity reduction (2 of 3 off) ► Zone switching in common area ► Bi-level switching up to 50% off in hallway
450 Golden Gate - Federal Office	► GTA cooling 72°F → 74°F ► GTA heating 70°F → 68°F	► GTA cooling → 78°F ► GTA heating → 66°F
NARA - Federal Archive Storage	► GTA cooling 75°F → 76°F ► GTA heating 70°F → 68°F	► GTA cooling → 78°F ► GTA heating → 66°F
Oakland Federal - Office	► GTA cooling 72°F → 76°F ► GTA heating 70°F → 68°F	► GTA cooling → 78°F ► GTA heating → 66°F
Kadant - Material Processing	► Transfer pump off	
Monterey - Office	► Bi-level switching 33% off at lobby	

Table B.1. DR strategies by site for LBNL Auto-DR studies, 2003 and 2004 (continued)

Site Name	Moderate Price	High Price
OSIsoft - Office	► GTA cooling 72°F → 76°F ► GTA heating 70°F → 68°F	► GTA cooling → 78°F
Roche - Office, Cafeteria	► Supply fan quantity reduction (50%) in Bldg-A	► Supply fan quantity reduction (50%) in Bldgs-B&C
UCSB - Library	► Supply fan VFD limit 70%	► Supply fan VFD limit 60% ► DSP decrease 0.4" (partial) ► Heating/cooling valve closed
USPS - Distribution Center	► Chiller demand limit 75%	► Chiller demand limit 50%

CHW: chilled water, GTA: global temperature adjustment, VFD: variable frequency drive
SAT: supply air temperature, DSP: duct static pressure, RTU: rooftop unit

Table B.2 summarizes the DR strategies chosen for the Auto-DR participant sites in 2005. The major additions from the 2003 and 2004 studies were passive thermal mass storage and rebound avoidance strategies. In the table, pre-cooling for passive thermal mass storage and other strategies started prior to the DR period and are noted as "Pre-event" in the Moderate Price column. Rebound avoidance strategies are noted as "Rebound" in High Price column.

Table B.2. DR Strategies by site for LBNL Auto-CPP study, 2005

Site Name	Moderate Price	High Price
ACWD - Office, Lab	► Boiler disabled ► CHW temp increase → 50°F ► Cooling valve limit 70% ► SAT increase 55°F → 65°F ► DSP decrease 1.5" → 1.0" ► GTA cooling → 75°F	► GTA cooling → 78°F ► ***(Rebound)*** *Extended DR control period 2 hours (until 8 p.m.)*
B of A - Office, Data Center		► DSP decrease 2.2" → 1.4" ► Fan VFD lock 3 minutes after DSP decrease ► CHW temp increase 5°F at secondary loop ► Cooling valve lock at AHU
Chabot - Museum	► ***(Pre-event)*** *Free cooling when OAT is below 62°F. Pre-cooling until noon at 70°F average zone temperature.* ► GTA cooling → 74°F (4/3°F/h step-by-step)	► GTA cooling → 78°F (4/3°F/h step-by-step)
2530 Arnold - Office	► GTA cooling 76°F → 78°F	► GTA cooling → 80°F ► ***(Rebound)*** *Sequential recovery: VAV boxes released one by one over a short interval*
50 Douglas - Office	► GTA cooling 76°F → 78°F	► GTA cooling → 80°F ► ***(Rebound)*** *Sequential recovery: VAV boxes released one by one over a short interval*
Echelon - Office	► Zone switching at hallway with ambient light ► Zone switching in daylit spaces ► Continuous dimming 20% off in offices	► RTU quantity reduction (1 of 3 off) ► DSP decrease 1.5" → 0.8" ► SAT increase 55°F → 65°F
Irvington - High School	► ***(Pre-event)*** *GTA 72°F until 11:50 a.m. for pre-cooling* ► GTA cooling → 78°F	► Turn off HVAC system at 2:50 pm (school closes at 3 pm)
Gilead 300 - Office	► ***(Pre-event)*** *Shed control starts at 11 a.m.* ► SAT increase 55°F → 65°F.	► Same as moderate price
Gilead 342 - Office, Lab	► ***(Pre-event)*** *Shed control starts at 11 a.m.* ► SAT increase 55°F → 65°F ► GTA cooling → 75°F (70 - 75°F normal)	► Same as moderate price
Gilead 357 - Office, lab	► ***((Pre-event)*** *Shed control starts at 11 a.m.* ► SAT increase 55°F → 65°F ► GTA cooling → 75°F (70 - 75°F normal)	► Same as moderate price

Table B.2. DR strategies by site for LBNL Auto-CPP study, 2005 (continued)

Site Name	Moderate Price	High Price
IKEA - Retail	► GTA cooling 2°F increase	► GTA cooling → 76°F
LBNL OSF - Office, Data Center	► ***(Pre-event)*** *GTA 0 to 2°F in morning for pre-cooling* ► GTA cooling 2 - 6°F increase	► GTA cooling up to 6°F increase
Oracle - Office	► DSP decrease 20%	► GTA cooling 3°F increase
Target - Retail	► RTU quantity reduction (3 of 12 off; Increased to 5 on Oct 6th to end of summer)	► Bi-level switching 1/4 off in sales area
USPS - Distribution Center	► Chiller demand limit 80%	► Chiller demand limit 65% ► ***(Rebound)*** *Slow recovery: increase chiller demand limit by 5% every 15 minutes*

B.2. DR Strategies of Other Case Studies

This section summarizes the DR strategies chosen in the other case studies listed in section 1.5 of the main report. Due to lack of data, technical details of some of the strategies, including whether control setpoints were in normal or DR mode, were not included. These DR strategies were either manually or semi-automatically operated.

Table B.3. DR strategies by site for other case studies

Building	HVAC	Lighting	Others
Facility - Office	► Fan VFD limit 40, 60, or 80% ► GTA cooling ► CHW temp decrease		
Facility 2 - Office	► GTA cooling ► Chiller demand limit ► Shut off one condenser water pump ► CHW temp increase 3 to 5°F ► Fan VFD limit to minimum speed ► DSP decrease	► Bi-level switching ► Zone switching in common area	
Facility 3 - Food Processing	► Chiller quantity reduction: 40 & 60-ton chiller, 10 &20-ton chillers in packaging room, chillers in freezer warehouse	► Zone switching in daylit area including central warehouse and second floor packaging area	► Shut off 150-hp mixers (1 of 2)
Facility 4 - Glass Processing			► Shut off air compressors, glass transfer equipment motors, dissolver, conveyors, mixers, fans, and tank farm pumps
Facility 5 - Chemical Pepackaging	► Unload two 20-ton package unit in production area	► Bi-level switching 40% off in production area	
Facility 6 - Packaging & Cold Storage		► Main building lighting reduction (details unknown)	► Shut off cold storage and selected process and packing lines from noon to 2:30 p.m.
Facility 7 - (Packaging & SCold storage)			► Shut off cold storage for maximum allowed period without spoilage ► Shed misc. process loads

Table B.3. DR strategies by site for other case studies (continued)

Building	HVAC	Lighting	Others
New York Times Building - Office	► GTA level 1: 74 → 76.5°F ► GTA level 2: 76.5 → 78.5°F ► Reduce perimeter fan boxes to 30% capacity from 2 p.m. to 6 p.m. ► ***(Pre-event)*** *SAT decrease 54°F until 2 p.m. for pre-cooling* ► SAT increase 59.5°F from 2 p.m. until 6 p.m.	► Level 1: Continuous dimming to 50% in core, 70% in PC-dominated interior and perimeter zones ► Level 2: Continuous dimming to 50% in core, 70% in interior zones, and 0% in perimeter zones	
Home Depot - Retail		► Bi-level switching 1/2 off in sales area and display light	
Rockefeller Center - Office	► CHW temp increase ► Fan VFD reduction		► Elevator & escalator cycling
Lafarge Building Materials - Material Process			► Shut off rock crushers
MCWA - Irrigation			► Irrigation pump peak shifting
Wesleyan University		► Turn off unnecessary lighting	► Turn off unnecessary equipment
Ganahl Lumber - Lumber Processing		► Continuous dimming	
LA County - Office	► GTA cooling	► Continuous dimming	

References

Piette, M.A., O. Sezgen, D.S. Watson, N. Motegi, and C. Shockman. 2005a. *Development and Evaluation of Fully Automated Demand Response in Large Facilities*. Lawrence Berkeley National Laboratory. CEC-500-2005-013. LBNL-55085. Berkeley CA, January. Available at http://drrc.lbl.gov/drrc-pubs1.html. Accessed November 10, 2006.

Piette, M.A., D.S. Watson, N. Motegi, N. Bourassa, and C. Shockman. 2005b. *Findings from the 2004 Fully Automated Demand Response Tests in Large Facilities*. Lawrence Berkeley National Laboratory. CEC-500-03-026. LBNL-58178. Berkeley CA, September. Available at http://drrc.lbl.gov/drrc-pubs1.html. Accessed November 10, 2006.

Piette, M.A., D.S. Watson, N. Motegi, S. Kiliccote, and P. Xu. 2006. *Automated Critical Peak Pricing Field Tests: Program Description and Results*. Lawrence Berkeley National Laboratory. LBNL- 59351. Berkeley CA, April. Available at http://drrc.lbl.gov/drrc-pubs4.html. Accessed December 3, 2006.

Appendix C

Case Study of Advanced Demand Response

Appendix C: Case Study of Advanced Demand Response

This section presents a unique case study of commissioning of DR control strategies that was planned from the new construction system design phase. In 2005 Lawrence Berkeley National Laboratory (LBNL) researchers worked with the design of the new New York Times Headquarters building in Manhattan to integrate control of lighting and shading devices, to commission the lighting systems, and to develop DR strategies and DR controls specifications for the building. LBNL developed a detailed energy simulation model to design the optimal DR strategy[3].

C.1. DR Strategies Plan at New York Times Headquarters

The building systems and the owner's preferences provided a framework and identified constraints for DR strategy development. The owner requested that any common equipment, such as the chiller plant, and common spaces would be exempt from DR work. In addition, the DR strategies would be implemented floor-by-floor depending on occupancy and other priorities. DR control strategies were initially proposed as follows:

- **HVAC system**: Increase the cooling setpoint 3°F for moderate demand reduction and an additional 3°F for further demand reduction. The 3°F change was proposed as a starting point for the simulations. Iterations of the temperature gradient were expected depending on the simulated temperatures within the zones.
- **Lighting system**: Employ two stages of lighting control. Stage 1 involved lowering the lighting power in all perimeter daylight configuration zones by 70% and in all zones close to the central core by 50%. During Stage 2 perimeter lights were turned off. Anytime the lighting system reached 10% output it was automatically turned off.

A detailed energy simulation model was used to evaluate dynamic DR control strategies during the new construction design process. A custom version of the EnergyPlus [4] program was developed by NaturalWorks [5] and utilized for this simulation. The modeling and simulation effort was conducted in two phases that involved some iteration. In the first phase, a basic building model was developed and a limited set of DR strategies was simulated, such as window shade control (control angle of window shades to optimize daylighting and solar heat gain) and global temperature adjustment (GTA). To refine the model the owner and LBNL researchers assisted in providing accurate estimation parameters.

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[3] This section is a summary of a paper presented at the 2006 ACEEE Summer Study (Kiliccote 2006).

[4] EnergyPlus is a building energy simulation program for modeling building heating, cooling, lighting, ventilating, and other energy flows.

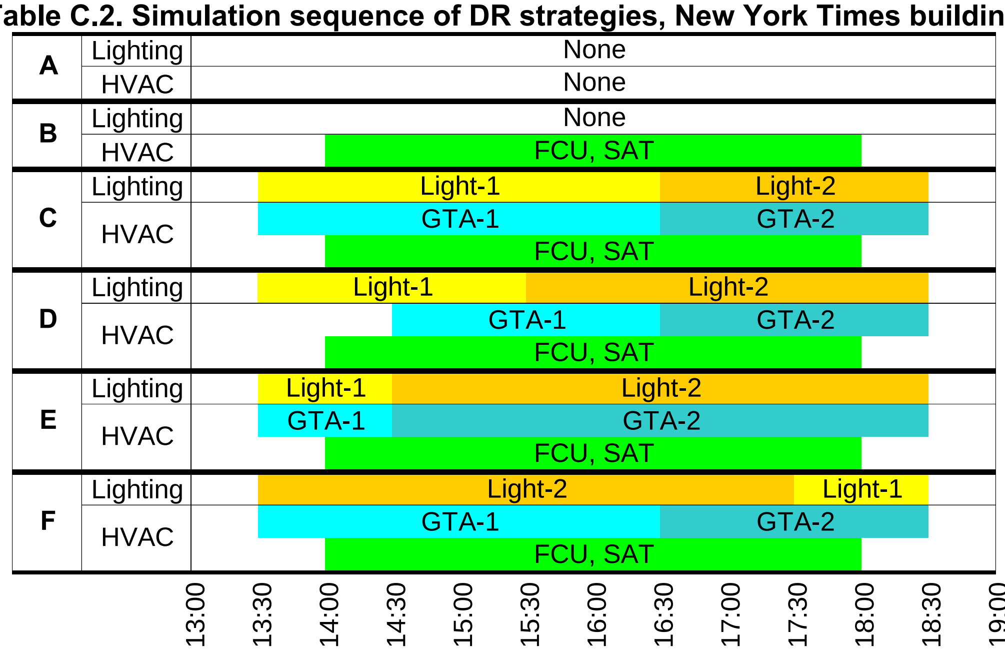
[5] NaturalWorks (San Diego CA) offers consultancy and research services in the field of building physics. http://www.natural-works.com

During the second phase NaturalWorks delivered a more complete model including the ability to simulate lighting shed strategies. For lighting management during DR events the space is divided into three zones based on use and daylight availability: core, interior, and perimeter. The model included two strategies for the lighting system, two levels for GTA setup, and two additional HVAC strategies: 1) decrease supply air temperature (SAT) for thermal mass pre-cooling until 2 p.m. and increase SAT during the demand peak period, and 2) reduce fan coil units' capacity on the perimeter. Table C.1 lists the DR strategies modeled in the simulations. These DR strategies were combined in six different operation schedules described in Table C.2.

Table C.1. DR strategies for second phase simulation, New York Times building

Type	Strategies	Definition
HVAC	GTA-1	Cooling setpoint increase to 76.5°F
	GTA-2	Cooling setpoint increase to 78.5°F
	FCU	Reduce perimeter fan coil units to 30% capacity from 2 p.m. to 6 p.m.
	SAT	SAT 54°F for pre-cooling until 2 p.m. and then raised to 59.5°F
Lighting	Light-1	Reduce lighting power to 50% in core zone and to 70% in PC dominated interior and perimeter zones
	Light-2	Reduce lighting to 50% in core, to 70% in interior zones, and off in perimeter zones

Table C.2. Simulation sequence of DR strategies, New York Times building



C.2. Preliminary Results of Simulation Study

Figure C.1 displays the preliminary results from the simulation model analysis. This chart shows the baseline with overnight pre-cooling and the demand profile of the building under pattern F, the DR sequence shown to provide the most demand savings in the most recent simulation results. Demand savings estimated from this simulation was approximately 600 kW. The simulation study also revealed that the overnight pre-cooling strategy should be refined. The results indicate that morning pre-cooling may be as effective as overnight pre-cooling while consuming less energy.

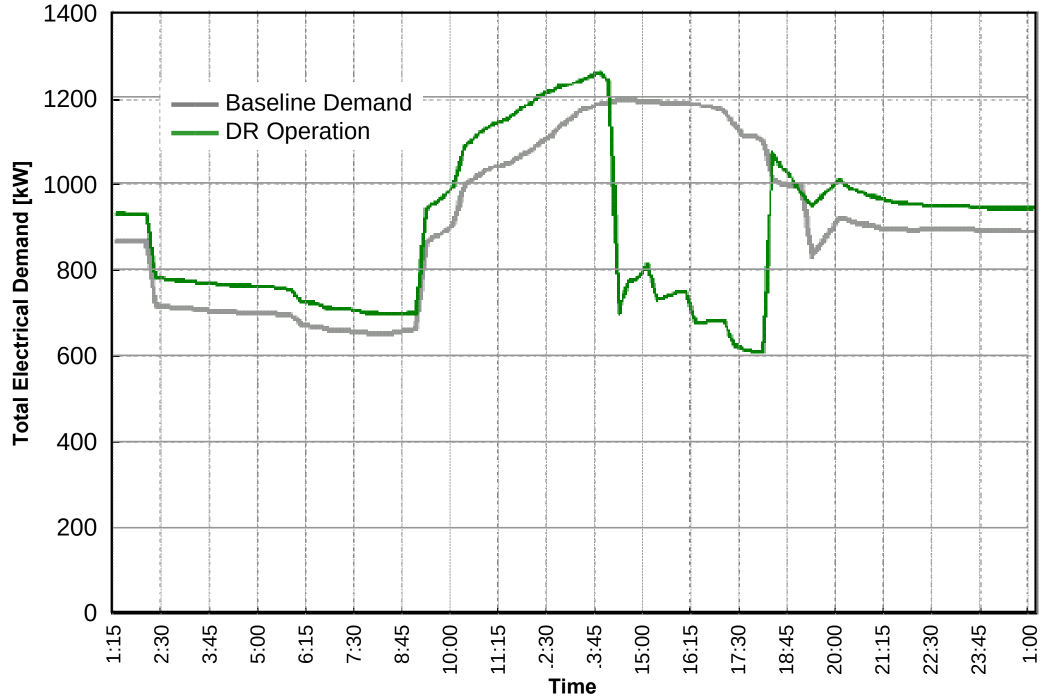


Figure C.1. Total demand profile of occupied floors, New York Times building

For any building, the owner must decide how aggressively the DR strategies will be implemented, based in part on occupant comfort. The current simulation results display potential demand savings but do not provide occupant comfort indicators. NaturalWorks has planned to examine predicted mean vote[6] (PMV) and temperatures in the building that will provide indicators of conditions in the space under different sequences of operation. Further simulation studies are needed to provide more accurate estimates for the owner to make a decision on the most efficient DR strategies.

The study also examined the financial impact of the demand response activities in different scenarios.

C.3. Conclusion

DR strategy planning from the early phase of new construction design can reduce the risk of missing effective DR strategies or programming unwanted strategies. Performing building simulations will reduce costs and efforts to manually demonstrate the effect of DR strategies and/or to reprogram the EMCS. Analysis of the combination of demand, energy, comfort, and economics is important to achieve the best DR strategy for any building.

[6] The average comfort vote predicted by a theoretical index for a group of subjects when subjected to a particular set of environmental conditions.

References

Kiliccote, S., M.A. Piette, and G. Hughes. 2006. "Dynamic Controls for Demand Response in New and Existing Commercial Buildings in New York and California." Presented at the ACEEE 2006 Summer Study on Energy Efficiency in Buildings: Less is More: En Route to Zero Energy Buildings, Asilomar, Pacific Grove CA, August 13–18.