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Demand Response and Building Energy Simulation

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Sponsored by California Energy Commission

What is Demand Response?

- **Definition of Demand Response (DR):** Changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.
- The estimated minimum amount of power electricity consumers demand on a day-to-day basis is called the baseload.
- Demand for electric power is highest in the afternoon and early evening. The periods when demand is greatest are called peak usage times.
- Dynamic pricing, time-of-use rates (TOU) and upgrading to smart grid technology are all examples of demand response programs that could reduce energy consumption, reduce power outages and reduce wholesale energy costs.
- DR addresses peak demand (kW) and not overall consumption (kWh).
- Ultimately, with successful DR, fewer power plants are needed.

Demand Response Research Center

- The California Energy Commission's Public Interest Energy Research (PIER) program's Demand Response Research Center (DRRC) is led by Lawrence Berkeley National Laboratory; http://drrc.lbl.gov/

- The main objective of the DRRC is to develop, prioritize, conduct, and disseminate research that develops broad knowledge that facilitates DR

- "Demand Shifting with Thermal Mass" is one of the research projects conducted by DRRC; it investigates the methods and effects of shifting electrical energy usage in small and large commercial buildings using various pre-cooling strategies

Demand Response Research Center

1. Electric Systems and Strategic Issues

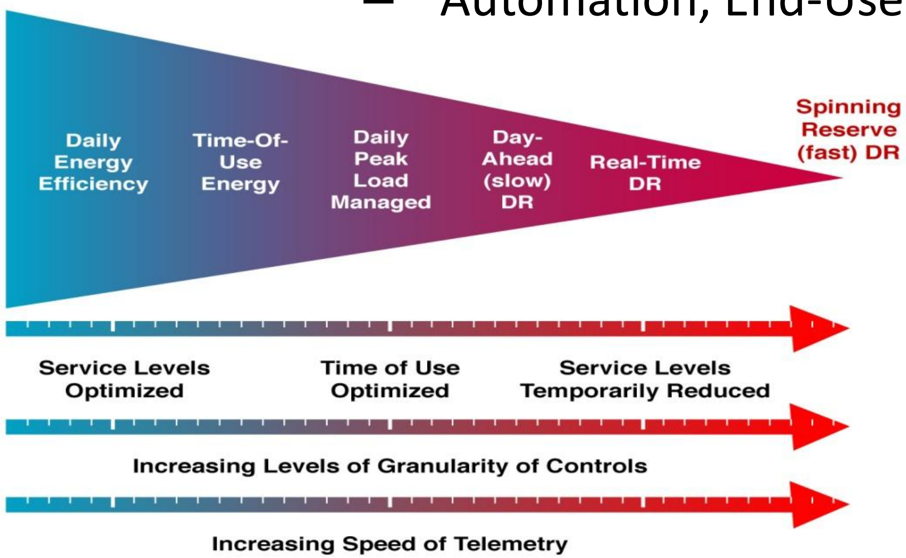
- Valuing Demand Response
- Dynamic Tariffs, Rate Design, Ancillary Services
- Communications and Telemetry

2. Buildings

- Automation, Communications and Control
- End-Use Control Strategies and Models
- Behavior–response to dynamic tariffs

3. Industry

- Automation, End-Uses and Controls



DRRC Research Portfolio

Automated Demand Response

- Initial Research 2002
- Pilots 2003-06
- Commercialization 2007-2009
  - Open Source DR Automation Server 2009
  - AutoDR Dynamic Pricing 2009

CAISO
- Demo Lab
- Participating Load Pilots

Renewables and DR

DR and Ancillary Services Pilot

Load as a Resource 2011

Microgrids and DR

EVs and DR

Seattle City Light 2009-10

ZigBee Harmonization 2009

Residential Energy Display Survey 2010-11

Emerging Technologies

HAN Evaluation

Building Energy Monitoring

Initiate Standards Donate to OASIS, UCAIug 2007

NiST 2009

OpenADR Alliance 2010

Technical Strategies

- Pre-Cooling 2003-2009
- DR Quick Assessment Tool
- Dimmable Lighting 2006-2009
- Small C/I AutoDR SCE 2009
- PCT Radio Coverage 2008
- AutoDR Price Mapping Demo 2009
- Open Source DR Automation 2009
- Wireless Protocol OpenADR 2009

Case Studies

- Case Studies Industrial, Ag, Water
- DR at UC Campus 2008-2009
- Refrigerated Warehouses, Wastewater
- Industrial Controls
- Bell Carter Green Energy Mgmt. 2008-2010
- DR for Data Centers
- Integrated Audits

Related Pricing and Behavior

- DR Pricing / Rates Scoping 2006
- DR Rates 2008
- Behavior
  - TOU 2007
  - CPP Small C/I
- DR Decision, Information, Control 2008-2010

D2G Test Lab

OpenADR is becoming a National Standard

Research initiated by LBNL/ DRRC
(California Energy Commission PIER)

Pilots and field trials
- 2003: Developments, tests
- 2004: Scaled-up tests, relay
- 2005-06: CPP/ Auto-CPP (PG&E)

OpenADR Commercialization
(PG&E, SCE, and SDG&E)

First official OpenADR v1.0 specification by LBNL/CEC*

1. OpenADR standards
2. Pilots and field trials
- Wholesale markets (CAISO)
- Pacific-NW (Winter DR)
3. International demos.

2002 2003 2004 2005 2006 2007 2008 2009 2010 2011

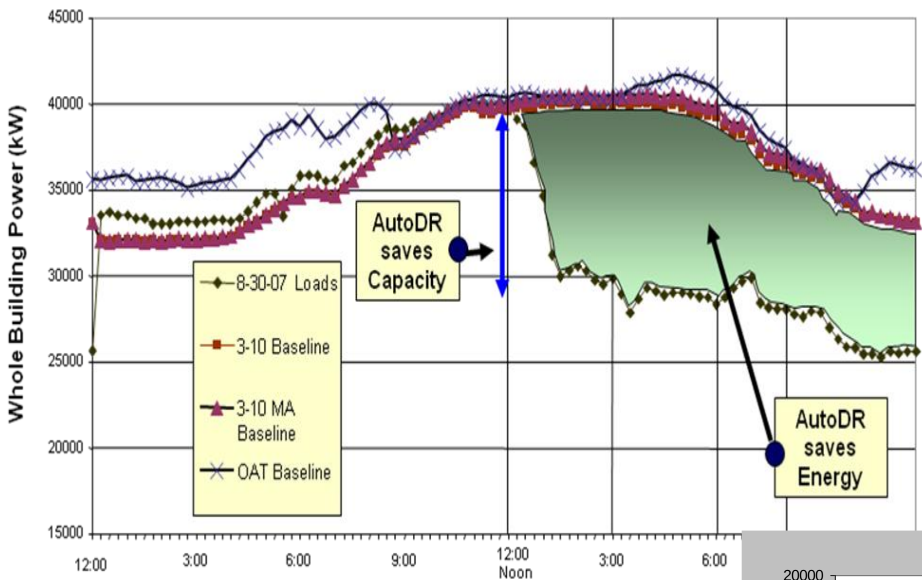
1. OpenADR donated to OASIS and UCAIug
- UCA OpenADR Taskforce formed
- OASIS EI TC formed
2. NIST Smart Grid, PAP 09
3. Honeywell Smart Grid
- ARRA 80MW Auto-DR w/ SCE

Over 250 MW of DR in California from AutoDR

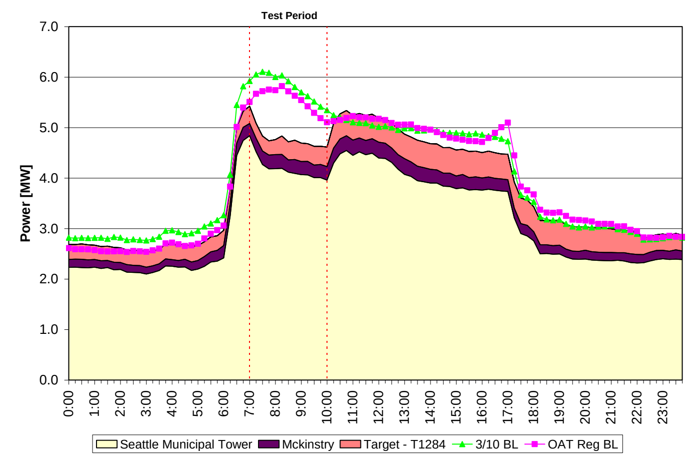
***OpenADR v1.0:** http://openadr.lbl.gov/

Historic focus on Seasonal Grid Stress

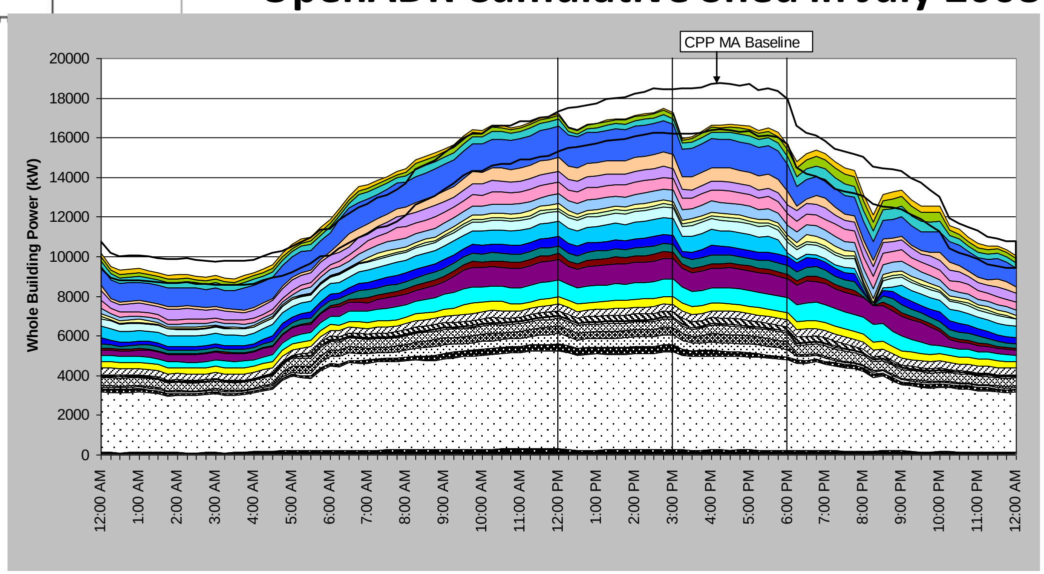
OpenADR PG&E Demand Bid Test Day



OpenADR Northwest Test on Cold Morning

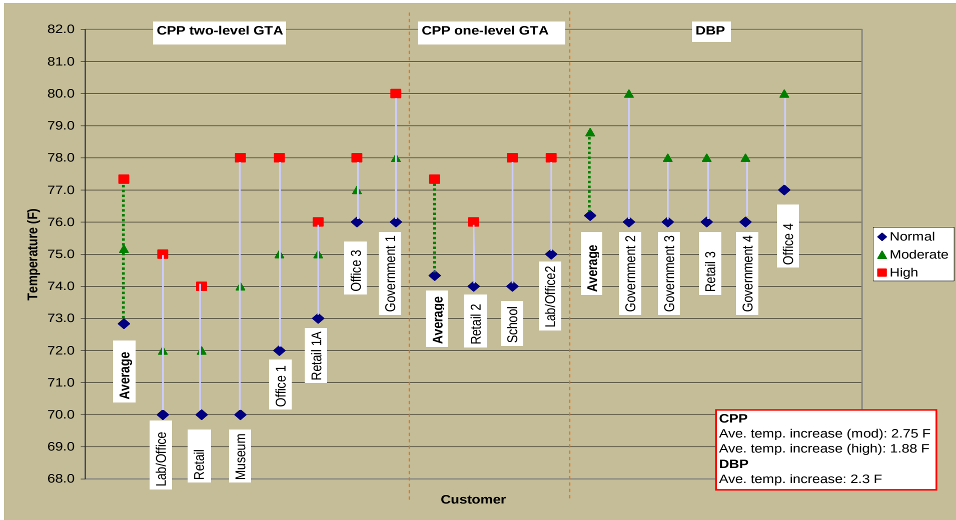


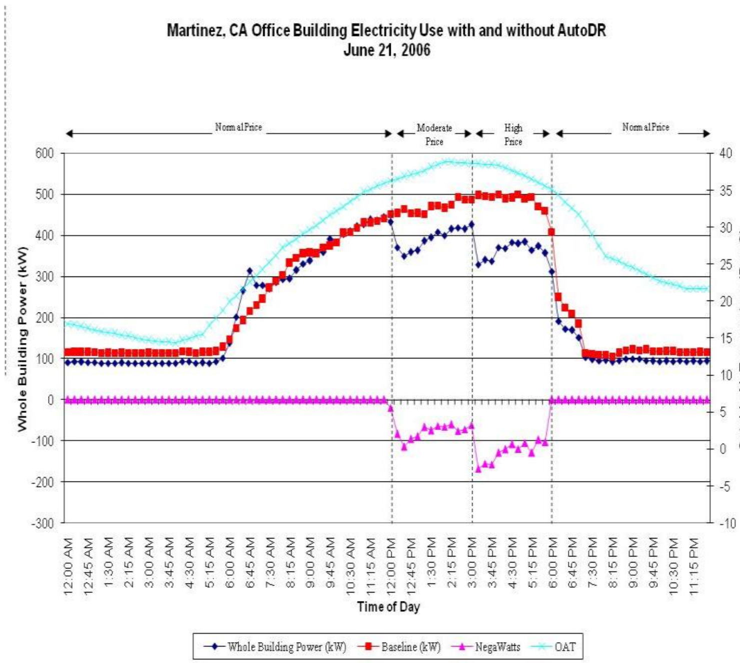
OpenADR Cumulative Shed in July 2008



Extensive R&D on baselines
Future directions ancillary services

DR Control Strategies Evaluated in Previous Research





	Building use	HVAC											Lighting					Other
		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	Slow recovery	Extended shed period	Common area light dim	Office area light dim	Turn off light	Dimmable ballast	Bi-level switching	Non-critical process shed
ACWD	Office, lab	X	X	X		X			X	X		X						
B of A	Office, data center		X	X	X	X			X									
Chabot	Museum	X						X										
2530 Arnold	Office	X									X							
50 Douglas	Office	X									X							
MDF	Detention facility	X																
Echelon	Hi-tech office	X	X	X			X						X	X	X	X		
Centerville	Junior Highschool	X						X										
Irvington	Highschool	X						X										
Gilead 300	Office			X														
Gilead 342	Office, Lab	X		X														
Gilead 357	Office, Lab	X		X														
IKEA EPaloAlto	Furniture retail	X																
IKEA Emeryville	Furniture retail	X																
IKEA WSacto	Furniture retail																	
Oracle Rocklin	Office	X	X															
Safeway Stockton	Supermarket																X	
Solectron	Office, Manufacture	X													X			
Svenhard's	Bakery																	X
Sybase	Hi-tech office														X			
Target Antioch	Retail	X					X											
Target Bakersfield	Retail	X					X											
Target Hayward	Retail	X					X						X				X	
Walmart Fresno	Retail	X															X	

In Summary DRRC is …

- **Continuing to pursue its vision:**
  - Efficiency and demand response fully integrated under a unified default tariff / incentive structure.
  - All customers, all load participates.
  - Major appliances come "DR Ready" from the factory.
  - All buildings are "DR Enabled" .
  - Full automated system integration between generators, distributors and customers.

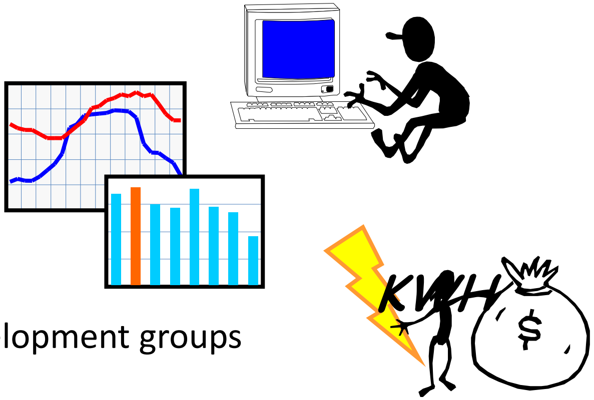
- **Expanding research:**

Basic Research

- Load Analysis methods, DR forecasting algorithms, DR impact analysis methods, physical and statistical modeling of resources etc.

Applied Research

- Tools and Guides
- Residential Energy Display Systems
- Technologies for Small Commercial Customers
- Distribution Automation integration with DR
- Renewables and DR integration
- Collaboration with IOUs, national and international research and development groups



- **Seeking collaboration opportunities**

Introduction to DRQAT

- **DRQAT** (Demand Response Quick Assessment Tool) is a tool for simulating large commercial buildings developed by LBNL
- It is a user-friendly "wrapper" around the **EnergyPlus** building energy simulation program.
- Large commercial buildings differ from small commercial building in terms of building materials and size, HVAC equipment, and utility rates
- It uses **prototypical models** of buildings and HVAC equipment
- Allows the user to specify a relatively small number of important parameters in order to determine a **quick assessment** of a range of demand response strategies
- The critical outputs are predictions of **energy demand, utility costs, and occupant comfort**

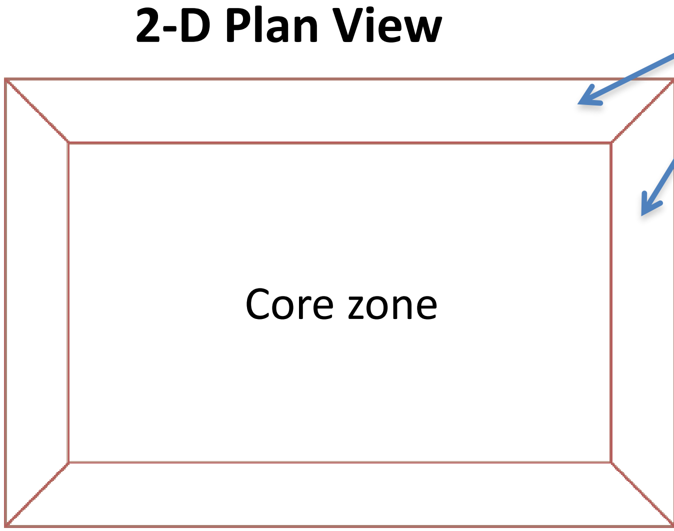
DRQAT Prototype Models

- DOE reference models of office and retail buildings
- Parameters modified to meet California Title 24 energy and building code
  - Building envelope and window thermal properties
  - Minimum outdoor air flow rate requirements
  - Cooling plant performance parameters
- EnergyPlus auto-sizing adjusts cooling plant capacity to meet design-day weather conditions

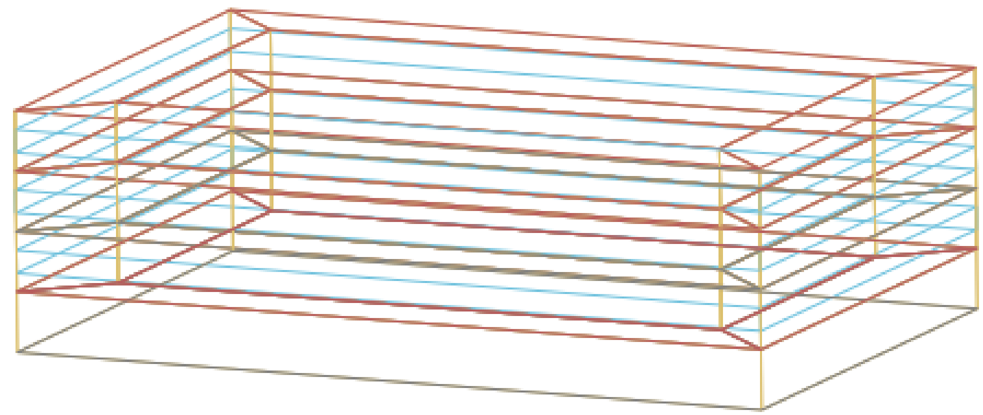
Prototypical Office Building Model

Perimeter zones

2-D Plan View

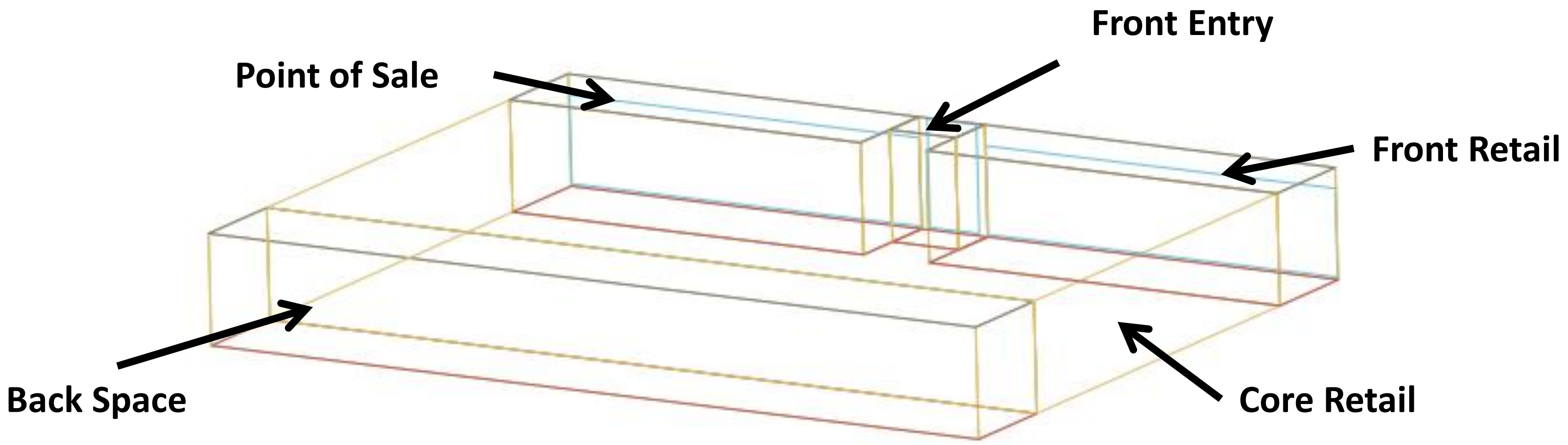


3-D View



- **HVAC Model Description**
  - **Electric Chiller + VAV system**
  - **Rooftop Unit + VAV system**
  - **Airflow and capacity are auto-sized by EnergyPlus**

Prototypical Retail Building Model

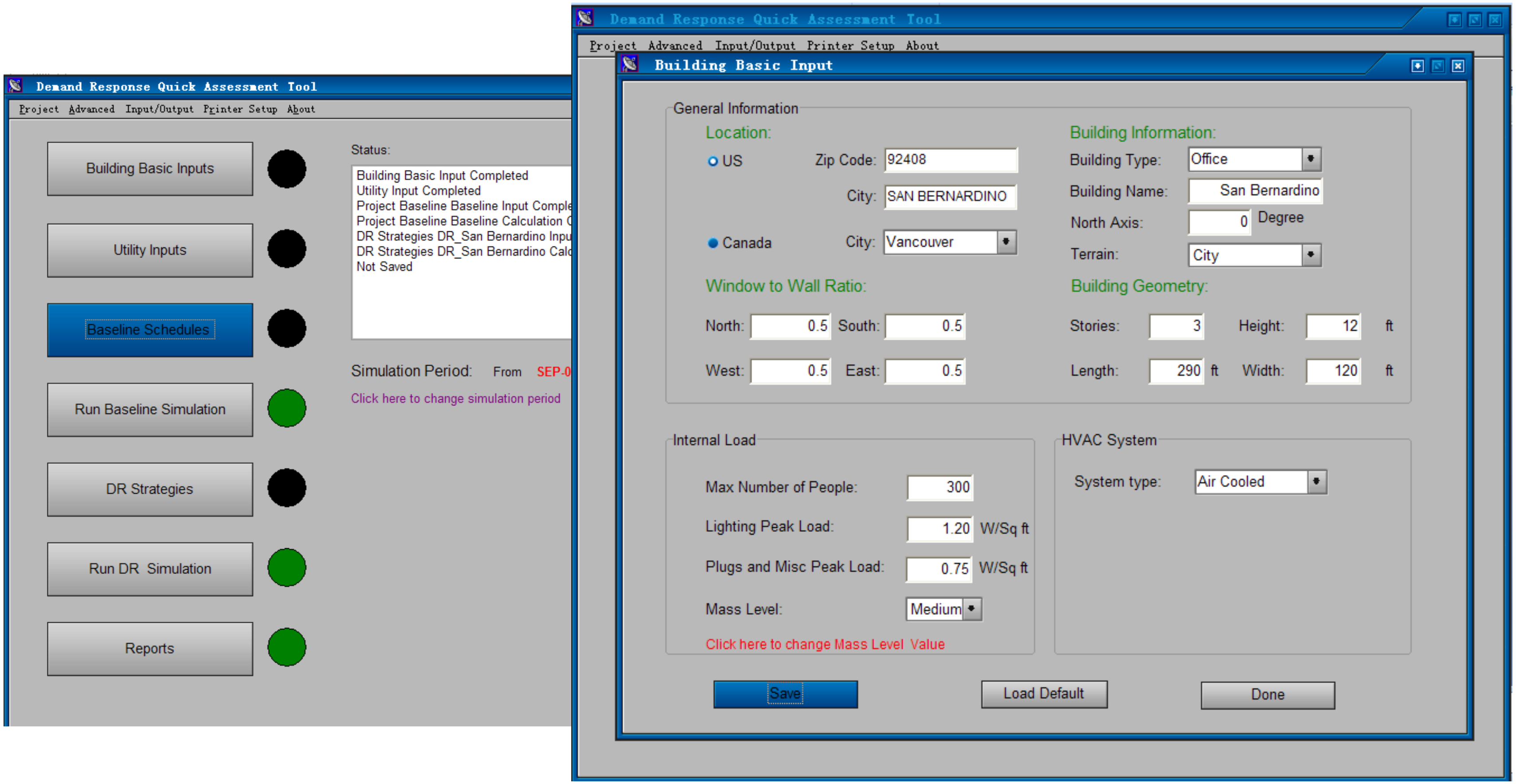


- **HVAC Model Description**
  - **Electric Chiller + VAV system**
  - **Rooftop Unit + VAV system**
  - **Airflow and capacity are auto-sized by EnergyPlus**

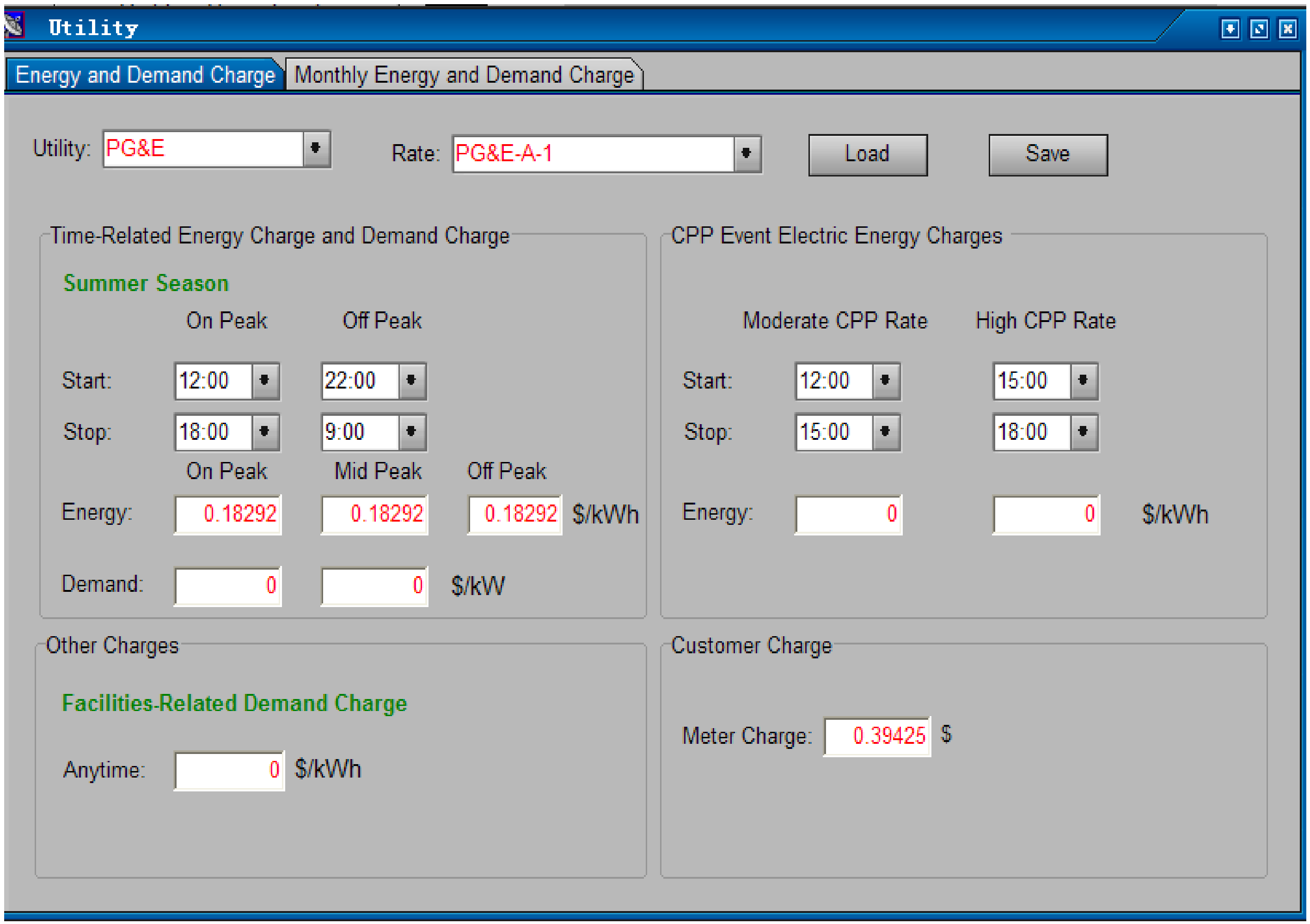
DRQAT Building Inputs/Outputs

- DRQAT Inputs
  - Building construction parameters
  - Utility rates—All California rates are pre-programmed; user can enter custom utility rate structures
  - Cooling system parameters
  - Internal loads—lights, plug, occupancy—peak values and hourly schedules
  - DR strategies—changes to settings and schedules to implement on DR days
  - Weather data (OAT, solar radiation, RH) from typical meteorological year (TMY3), which is not average, but most frequent temperature for a given hour on a given day for past 30 years
- DRQAT Outputs
  - Demand reduction
  - Cost savings
  - Occupant comfort
- DRQAT advanced users experienced with EnergyPlus can do more with the EnergyPlus input and output files generated by DRQAT.

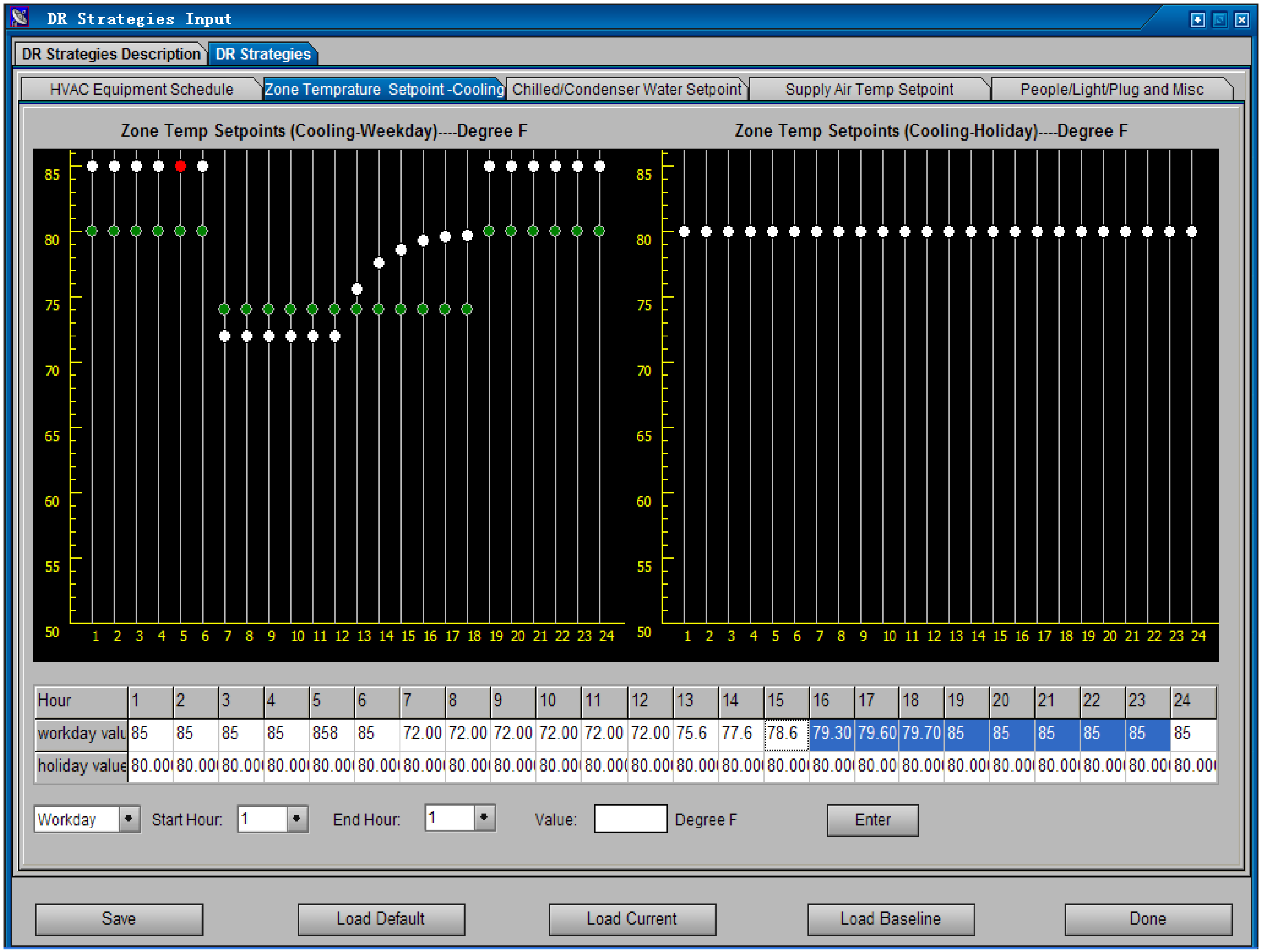
DRQAT Building Inputs



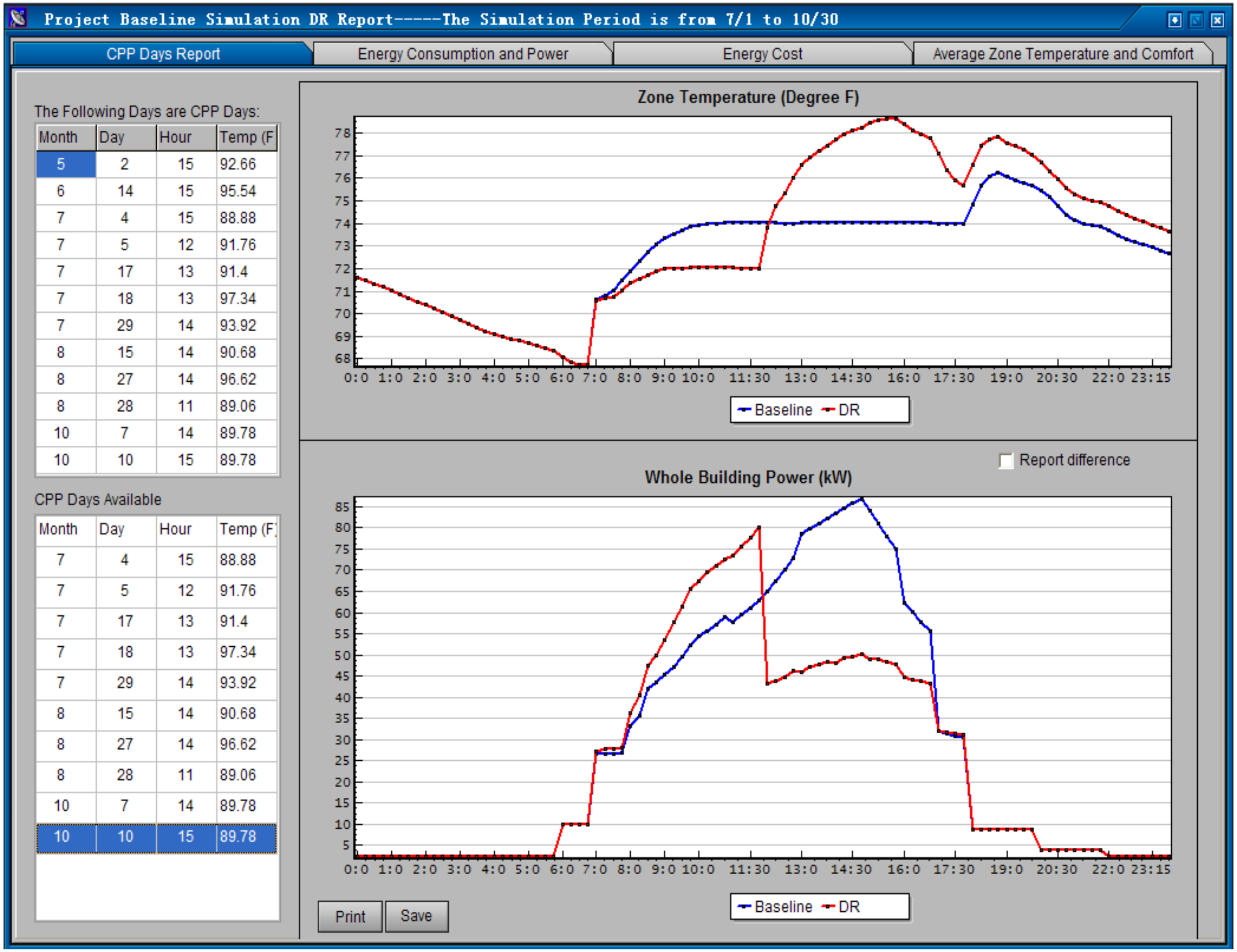
DRQAT – Utility Inputs



DRQAT – Zone Temp Schedule



DRQAT – Output of Average Zone Temp and Whole Building Electric Demand



The Following Days are CPP Days:

Month	Day	Hour	Temp (F
5	2	15	92.66
6	14	15	95.54
7	4	15	88.88
7	5	12	91.76
7	17	13	91.4
7	18	13	97.34
7	29	14	93.92
8	15	14	90.68
8	27	14	96.62
8	28	11	89.06
10	7	14	89.78
10	10	15	89.78

CPP Days Available

Month	Day	Hour	Temp (F)
7	4	15	88.88
7	5	12	91.76
7	17	13	91.4
7	18	13	97.34
7	29	14	93.92
8	15	14	90.68
8	27	14	96.62
8	28	11	89.06
10	7	14	89.78
10	10	15	89.78

DRQAT Performance

- Utility (PG&E) compared DRQAT predicted demand reductions to the actual measured demand reductions at ~40 commercial buildings

- The average demand reduction over a season predicted by DRQAT was within 5% for 85% of the sites.

DRQAT Input Data Sources

Data Collection → Input data into the model →

- Building plans
- Utility Data

On- Site Surveys

- Building Envelope and Thermal Mass
- Lighting System
- Plug Loads
- HVAC System
- Building occupants

DRQAT Model Inputs

Data Collection → **Input data into the model** →

Building Construction

Location, Window to Wall Ratio,
Building Geometry.

HVAC System

HVAC System Characteristics,
Operation Schedules

Building Basic Input

Internal Load

Lighting & Plug Power Densities and
Operation Schedule,
Occupaant Number & Schedule

Internal Surface Mass Level

High, Medium and Low

DRQAT Model Calibration

Input Data into the Model → **Calibration** →

1. **Enter the actual weather data measured at or near the building into the model;**

2. **Compare the simulated energy consumption to the measured energy usage data; monthly utility bills and hourly data**

Model Calibration Criteria

Input Data into the Model → Calibration →

1. Acceptable tolerance for monthly data calibration

Index	Monthly
MBE	±5%
CV(RMSE)	±15%

ASHRAE's GUIDELINE 14-2002 FOR MEASUREMENT OF ENERGY AND DEMAND SAVINGS

2. Daily and hourly agreement

Index	Daily	Hourly
MBE	±10%	±20%

* ±20% for a minimum of 20 out of 24 hours for each day
* MBE: Mean bias error
* CV(RMSE): Coefficient of Variation of the Root Mean Square Error

Steps Following Calibration

Calibration → Refine the model

↓

Confirm the baseline model

↓

DR simulation

↓

Calculate Saving

↓

Report

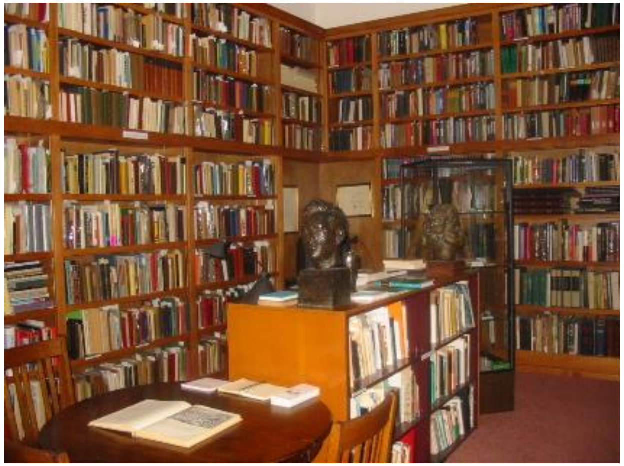
Optimal Pre-cooling Strategy Study

- Pre-cooling refers to a demand response strategy that uses a building's thermal mass to shift demand from peak afternoon periods to earlier in the day.
- Pre-cooling is done by lowering the building's temperature set-points in the morning (typically 5 AM to 12 PM).
- The demand savings are achieved by raising the building's temperature set-points in the afternoon.
- Key to success is meeting the demand reduction goal while not making the occupants too cold in the morning and/or too hot in the afternoon.
- Studies of optimal temperature adjustment strategies (e.g. single step, multiple step, exponential increase) and key building parameters have been conducted

Building Thermal Mass

- **Thermal Capacity**
  - **Primarily determined by the mass of construction materials (exterior & interior walls, roof, floor) and internal mass**
- **Thermal Mass in Prototypical Model**

Thermal Mass level

Low	Medium	Heavy
		

Simulation and Field Test of 11 Buildings

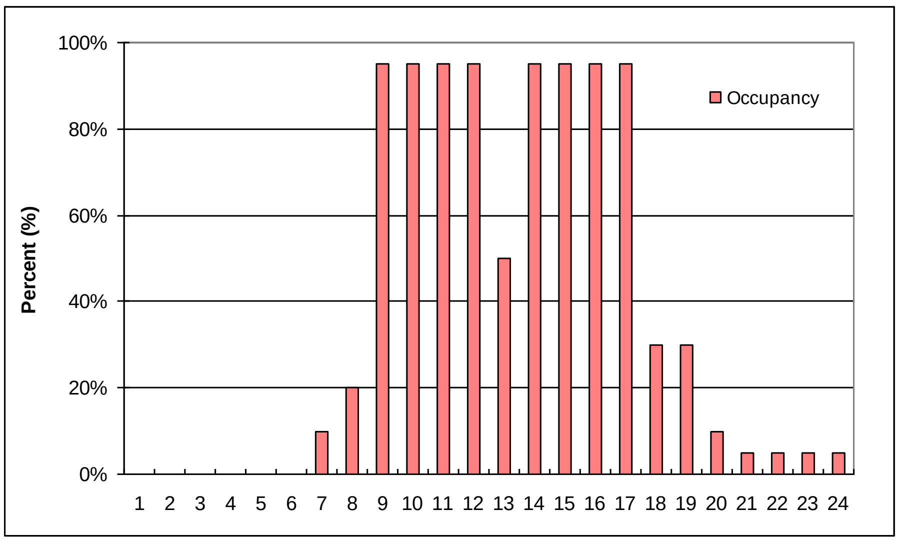
Building Construction Inputs

BUILDING BASIC INPUT – INITIAL VALUE								
SITE NO.	SITE NAME	**GROSS (SQ FT)**	**LENGTH (FT)**	**WIDTH (FT)**	**FLOOR HEIGHT (FT)**	**WWR_SN**	**WWR_EW**	**BUILDING ORIENTATION**
#1	Two Carnegie Plaza	68,955	300	115	12	0.50	0.50	45
#2	One Carnegie Plaza-A	62,800	300	105	12	0.50	0.50	315
#3	One Carnegie Plaza -B	38,808	270	70	12	0.50	0.50	45
#4	One Vanderbilt	73,730	205	90	12	0.25	0.25	315
#5	One Parkside	70,069	175	100	12	0.60	0.60	0
#6	Lakeside Tower	112,717	210	90	12	0.60	0.60	0
#7	Two Parkside	80,750	250	110	12	0.40	0.40	0
#8	Three Carnegie Plaza	83,698	420	100	12	0.40	0.40	45
#9	Brier Corporate Center	104,501	350	100	12	0.40	0.40	45
#10	Vanderbilt Plaza	119,035	200	150	12	0.40	0.40	0
#11	Inland Regional Center	81,079	350	115	12	0.30	0.30	45

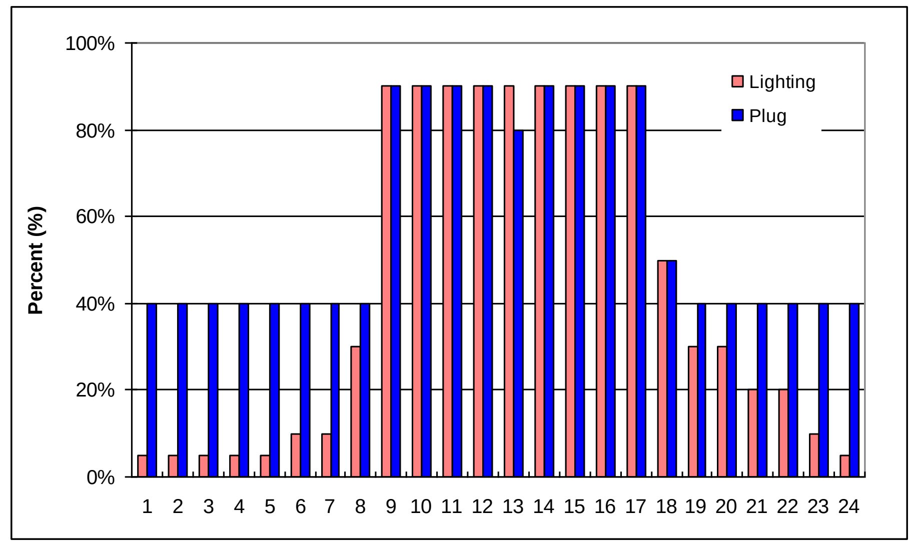
Initial Model Parameters

- Internal loads densities
  - Occupancy – 390 sqft per person
  - Lighting—Estimated from building type and year built, using Title 24
    - 1.8 W/sqft for oldest and 1.2 W/sqft for newest
  - Plug load—0.75 W/sqft
- Internal load schedules were set to match actual building operating hours
- Interior mass was set to medium unless otherwise specified in owner surveys

Internal Load Schedules



Occupancy



Lighting and Equipment

Initial HVAC System Parameters

- Water-Cooled (Central chiller) and Air-Cooled (Package DX Units)
- Air Distribution Type – VAV
- Normal Zone Temperature Set Points – 77° F
- Operating Schedules – Site survey or demand profile (measured data)

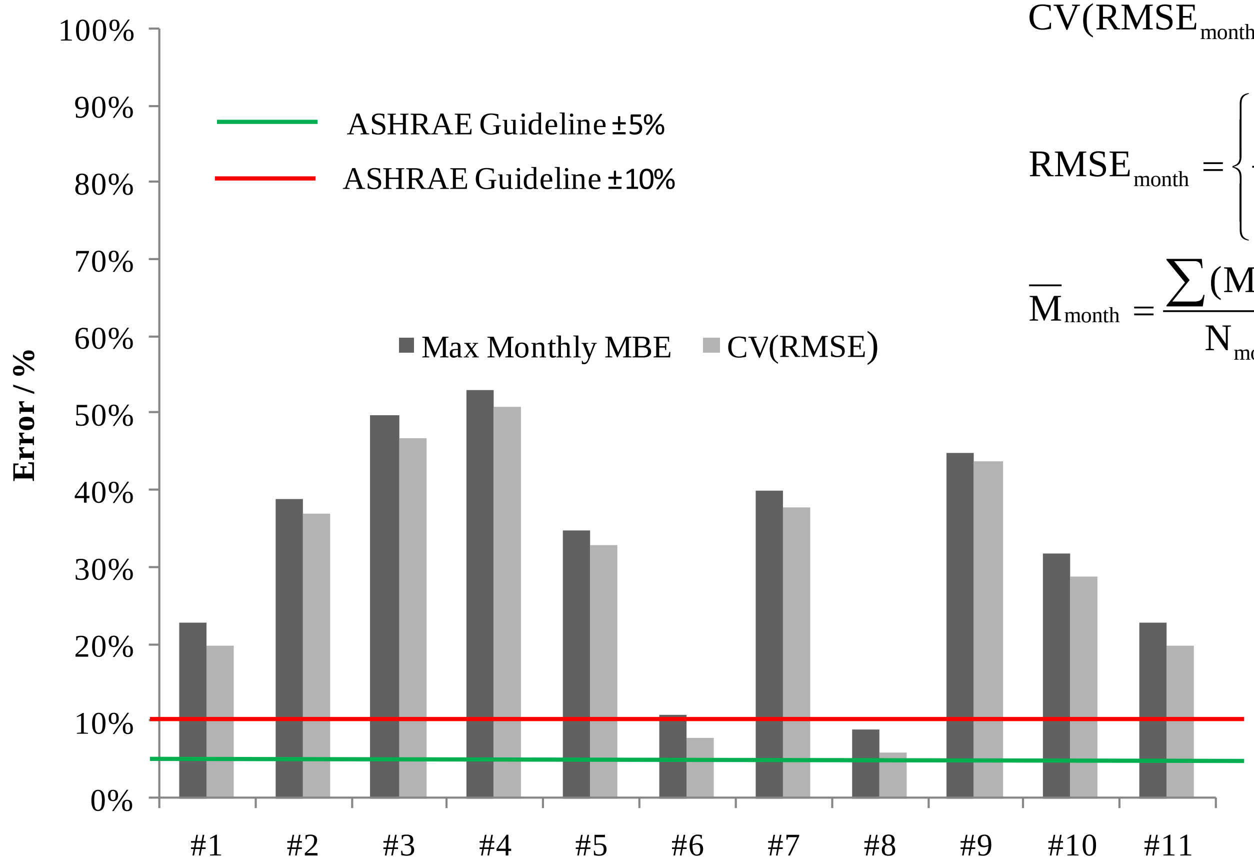
Initial Simulation Results

$$\mathrm{MBE}_{\mathrm{month}}(\%) = \left[\frac{(\mathrm{M}-\mathrm{S})_{\mathrm{month}}}{\mathrm{M}_{\mathrm{month}}}\right] \times 100\%$$

$$\mathrm{CV}(\mathrm{RMSE}_{\mathrm{month}})(\%) = \left[\frac{\mathrm{RMSE}_{\mathrm{month}}}{\overline{\mathrm{M}}_{\mathrm{month}}}\right] \times 100\%$$

$$\mathrm{RMSE}_{\mathrm{month}} = \left\{\frac{\left[\sum_{\mathrm{month}} (\mathrm{M}-\mathrm{S})^2_{\mathrm{month}}\right]}{\mathrm{N}_{\mathrm{month}}}\right\}^{1/2}$$

$$\overline{\mathrm{M}}_{\mathrm{month}} = \frac{\sum(\mathrm{M}_{\mathrm{month}})}{\mathrm{N}_{\mathrm{month}}}$$



Simulation Model Adjustments

- Weather data – Replace the TMY weather file with actual weather data measured at or very near the buildings

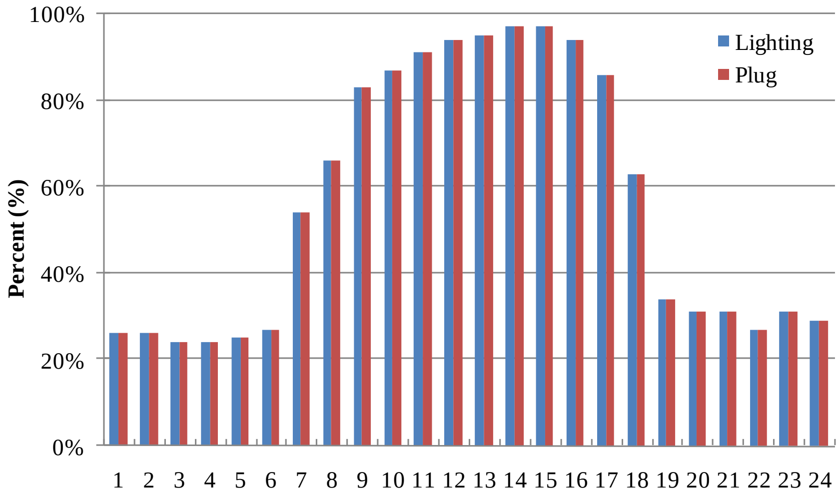
- Internal loads – Adjust lighting and equipment densities and operating schedules
  - Use the whole building electrical data to estimate the magnitudes of the internal densities and shapes of the operating schedules
  - Schedule any special circumstances in to the model. In this case, he cooling plants were locked out when the outside temperature was lower than 55° F so that schedule was added to the model

Internal load adjustments

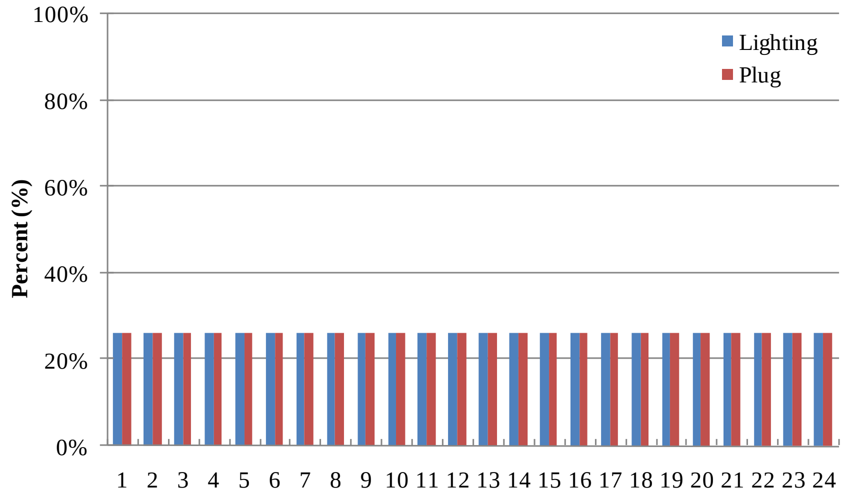
Site No.	Year Constructed	Lighting Density (w/sq ft)	Plug Load Density (w/sq ft)	
			Initial	After calibration
#1	1990	1.60	0.75	***0.75***
#2	1988	1.60	0.75	***1.50***
#3	1988	1.60	0.75	***1.50***
#4	1988	1.60	0.75	***1.80***
#5	1993	1.60	0.75	***1.40***
#6	1990	1.60	0.75	***0.90***
#7	2001	1.20	0.75	***1.50***
#8	2003	1.20	0.75	***0.60***
#9	2005	1.10	0.75	***1.40***
#10	2002	1.20	0.75	***1.00***
#11	1994	1.60	0.75	***1.00***

Adjusted internal load schedules for Bldg. 8

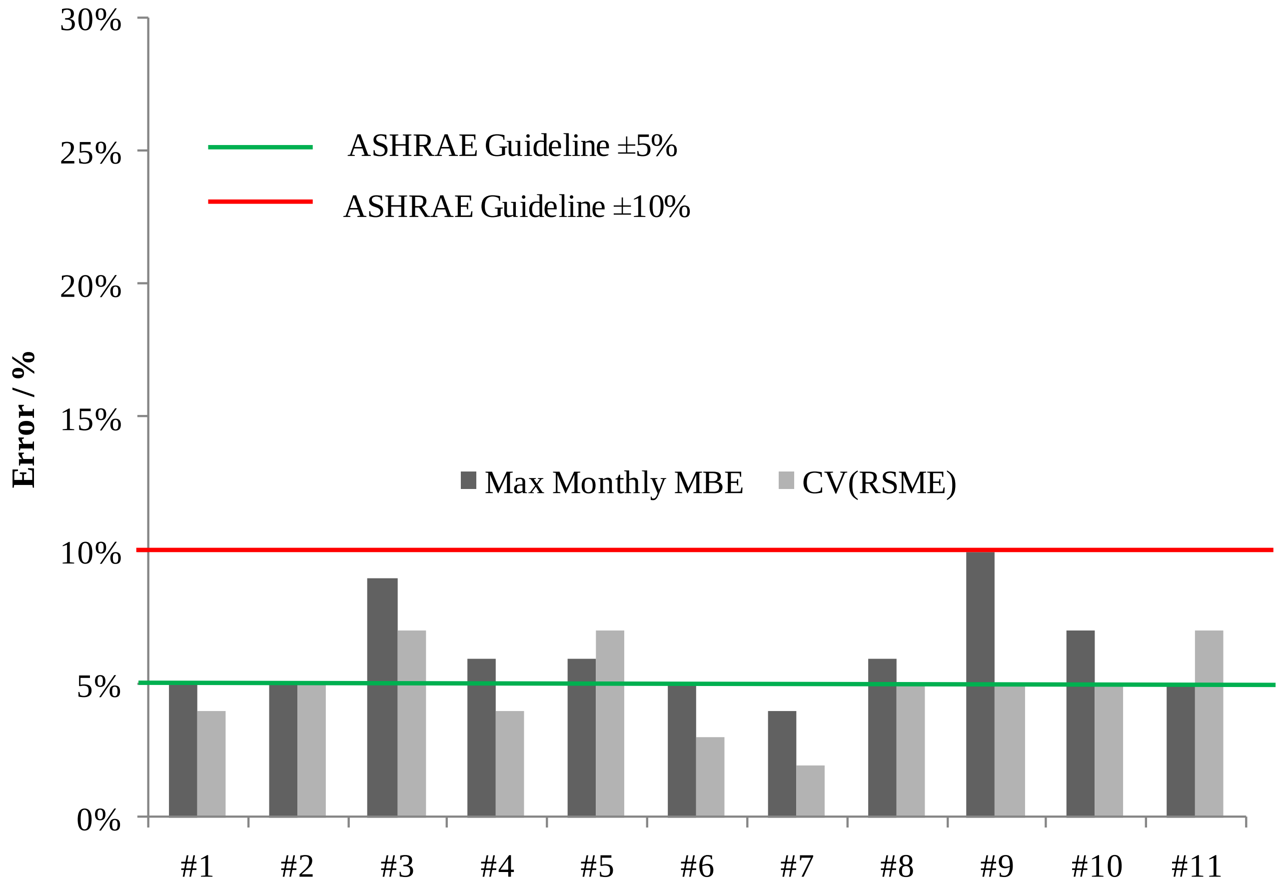
Weekdays



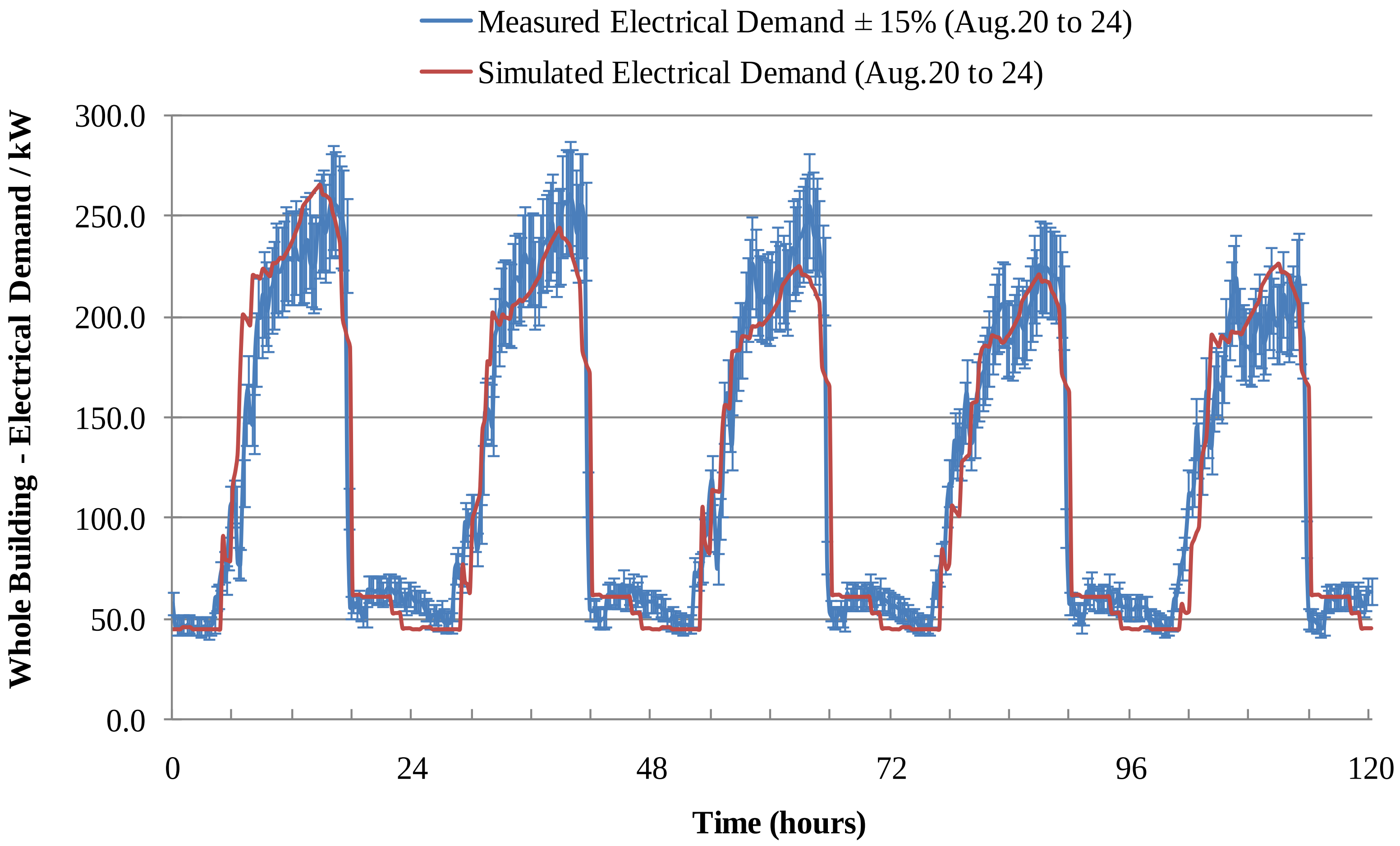
Weekend and Holiday



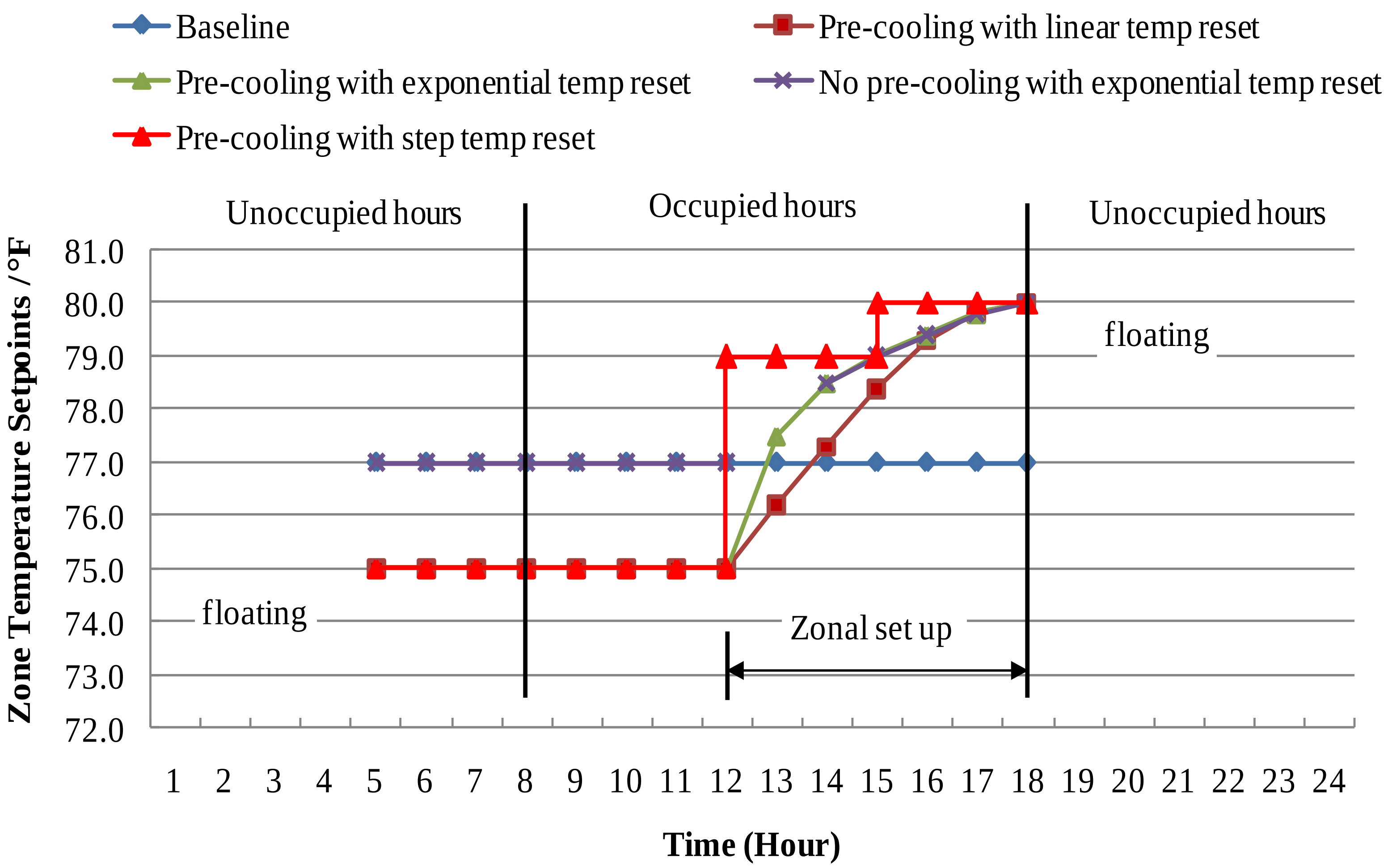
Adjusted Model Performance—Monthly



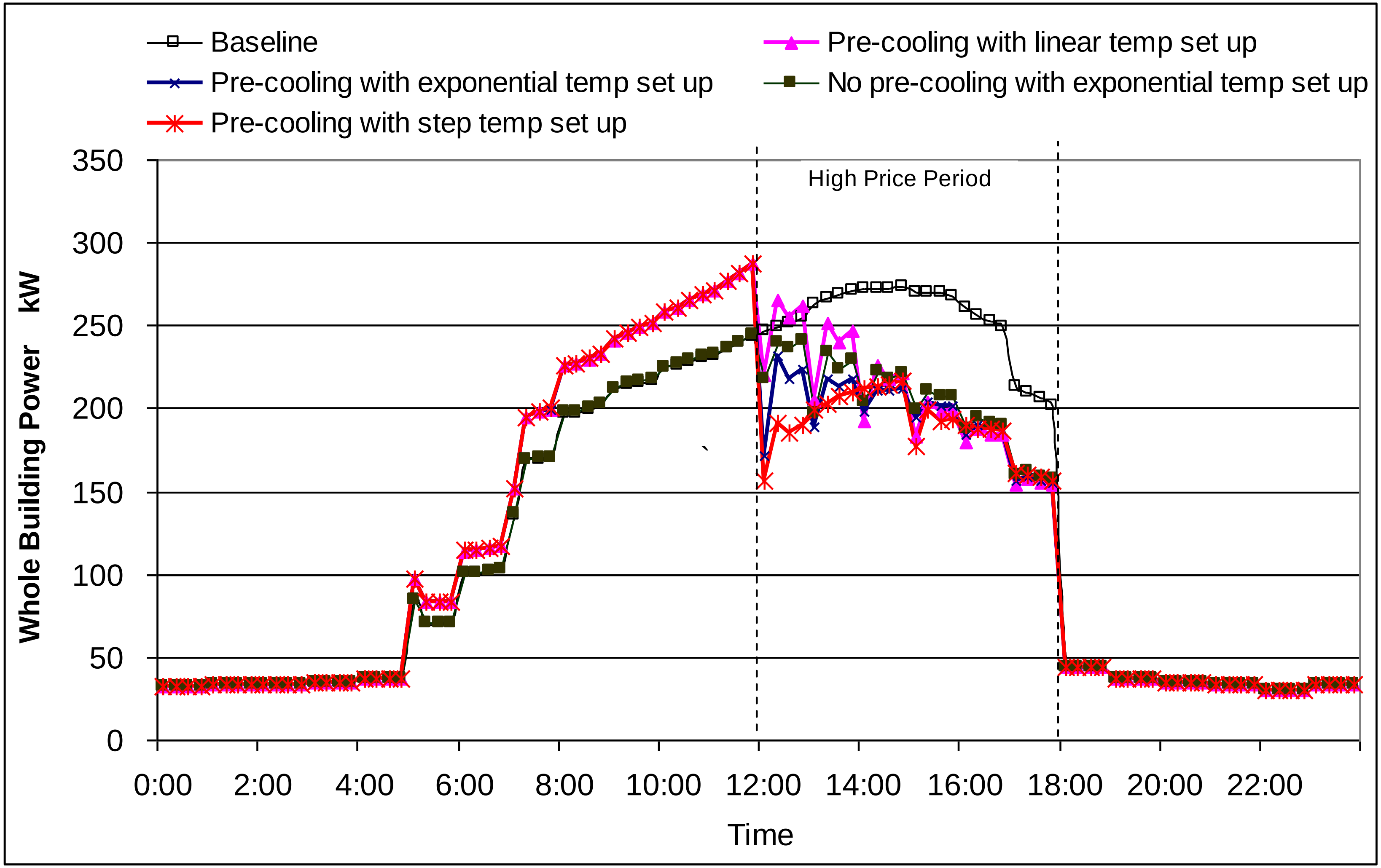
Adjusted Model Performance—Daily



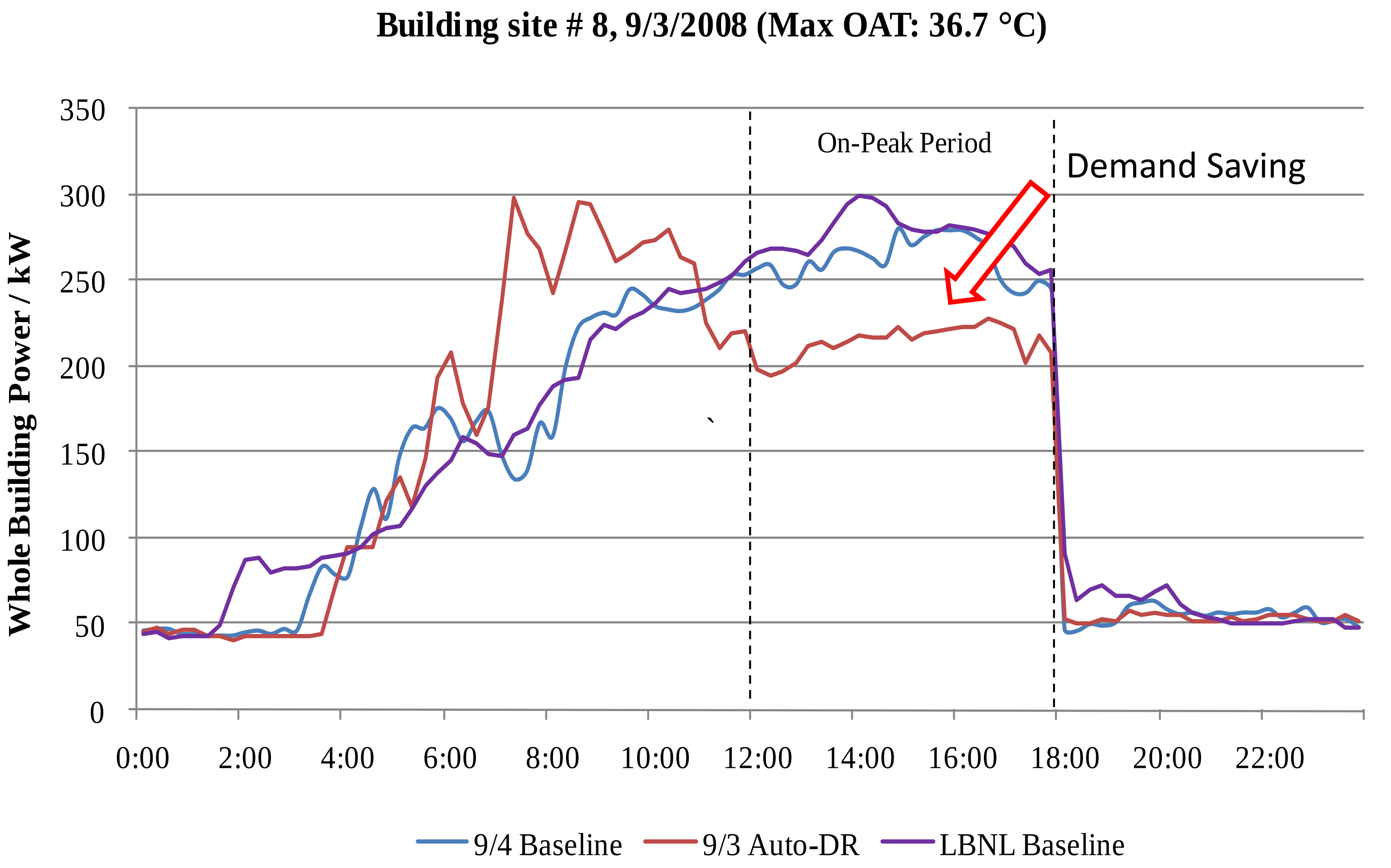
Pre-cooling Strategies



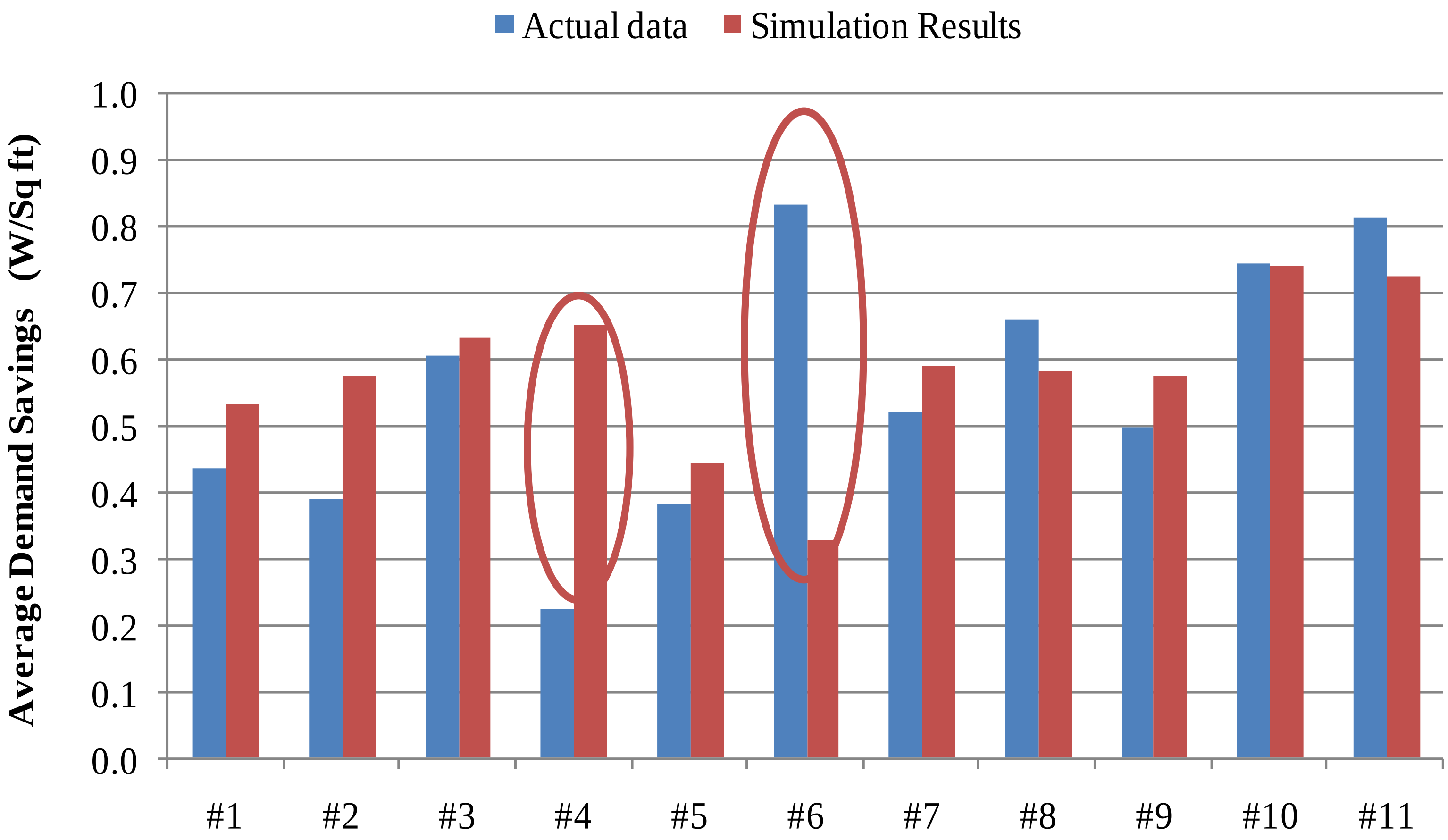
Simulations of Pre-cooling Strategies



Measured Pre-cooling Implementation

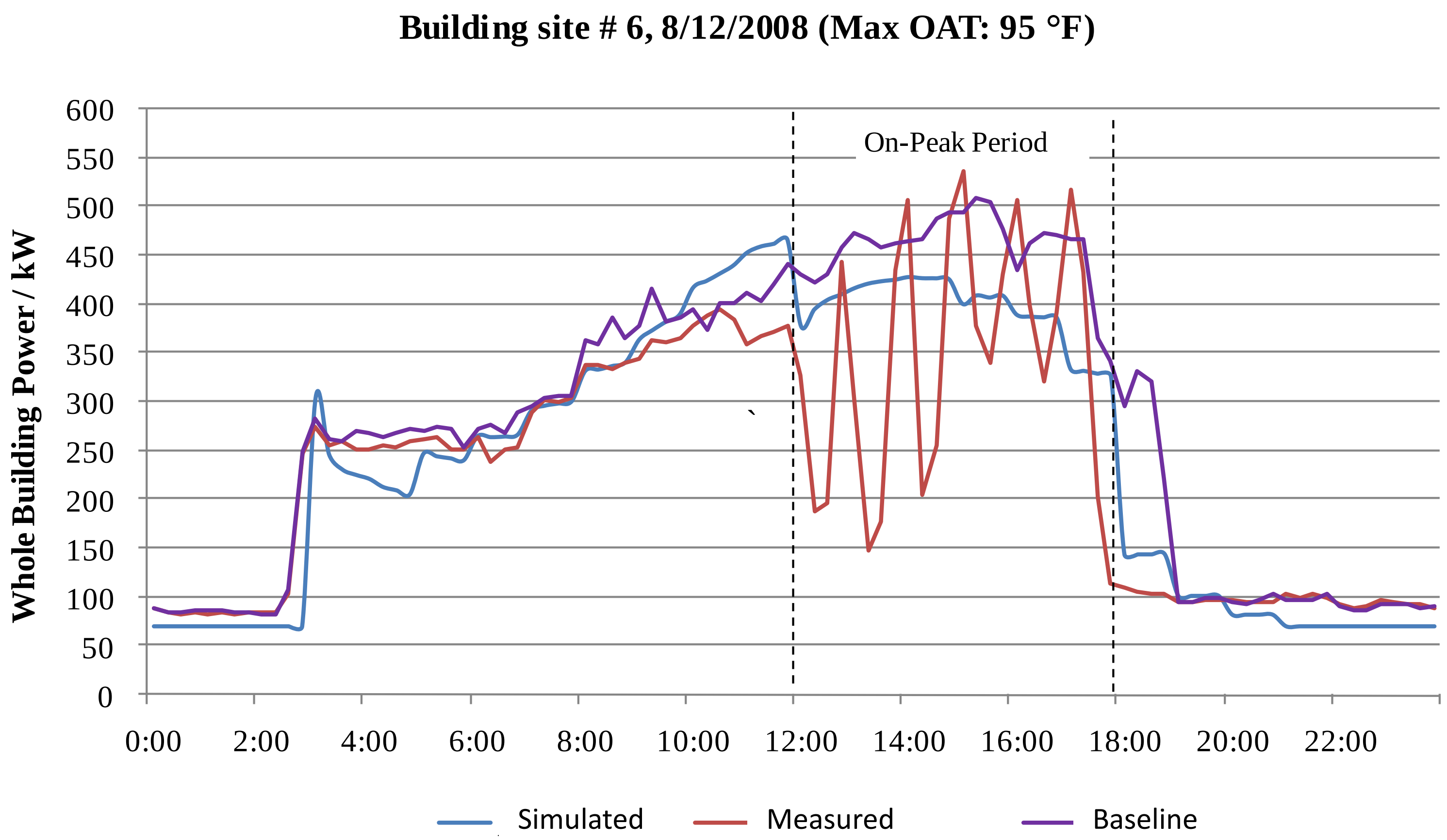


Predicted vs. Measured Demand Savings



Pre-cooling Field Test Analysis

Discrepancy between Measured and Simulated Demand Savings in Site #6



DRQAT Model Adjustments in Two Steps

1a. Use actual weather data

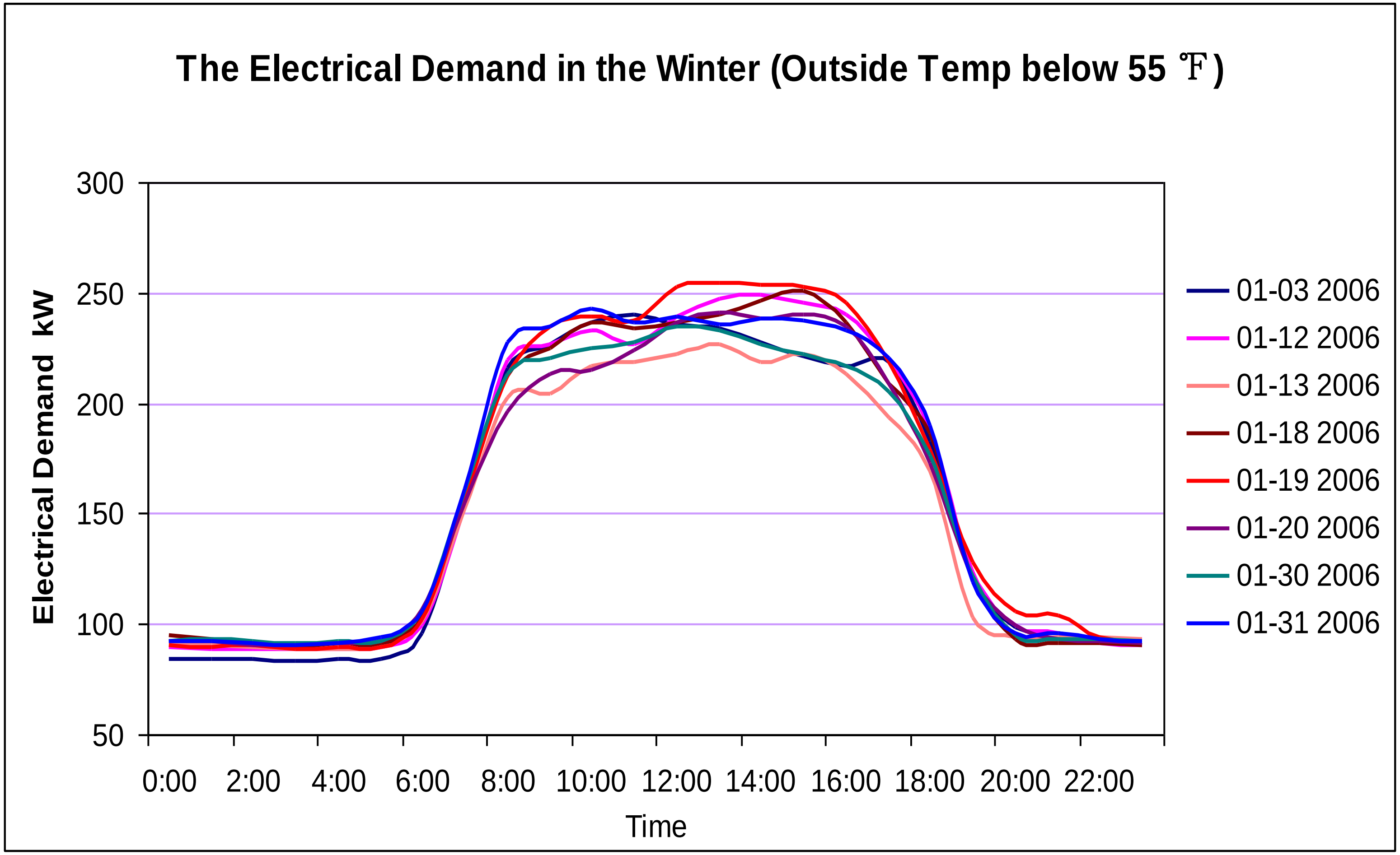
1b. Model input adjustments

- Building information
- Lighting & plug load power densities, operating schedules
- Occupant number, operating schedules
- HVAC system characteristics
- Plant equipment characteristics

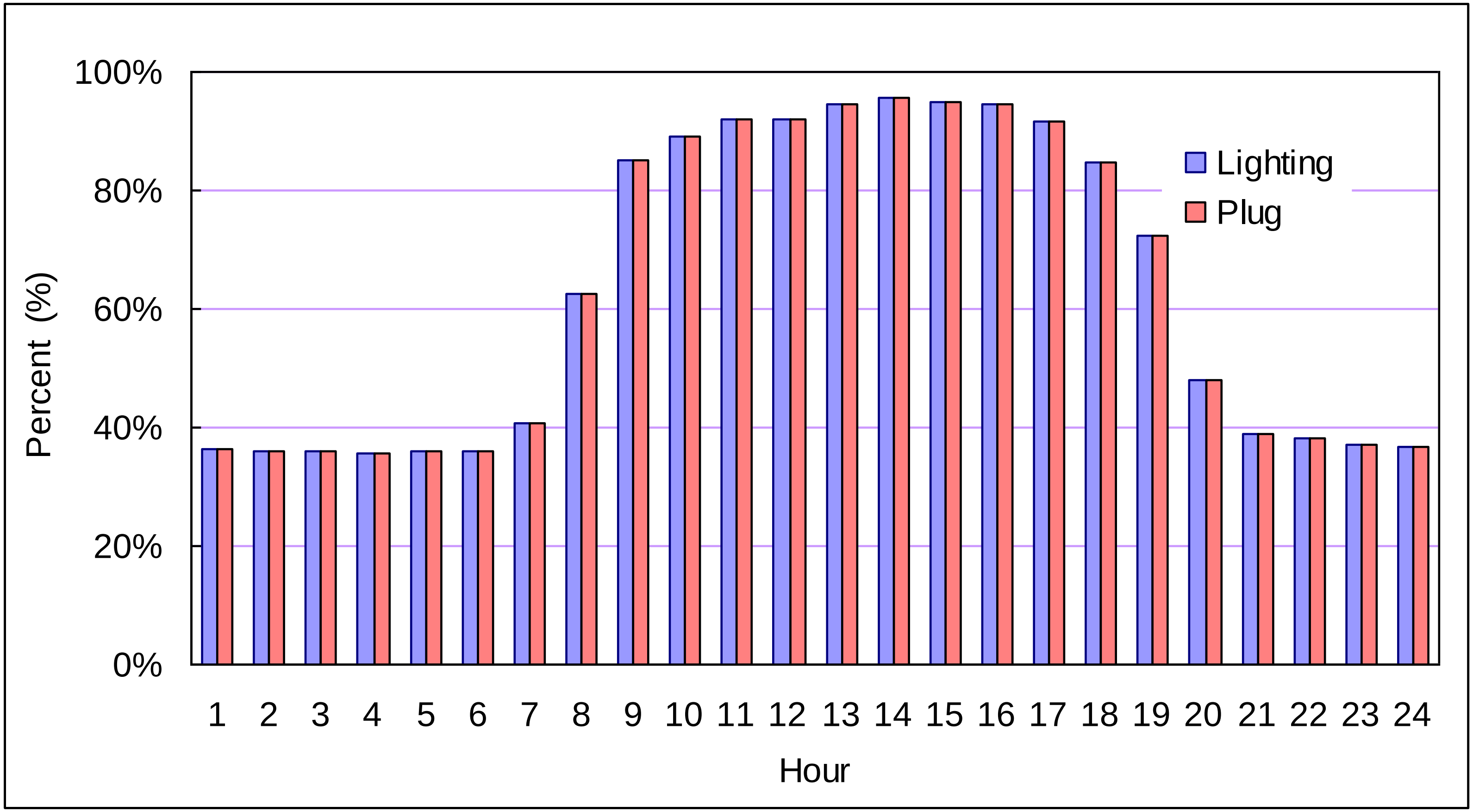
2. Model input adjustments based on Step 1 model outputs

- Using DRQAT zone temperature output check if set-points are met and maintained
- If not increase zone sizing factor, which will increase simulated cooling capacity

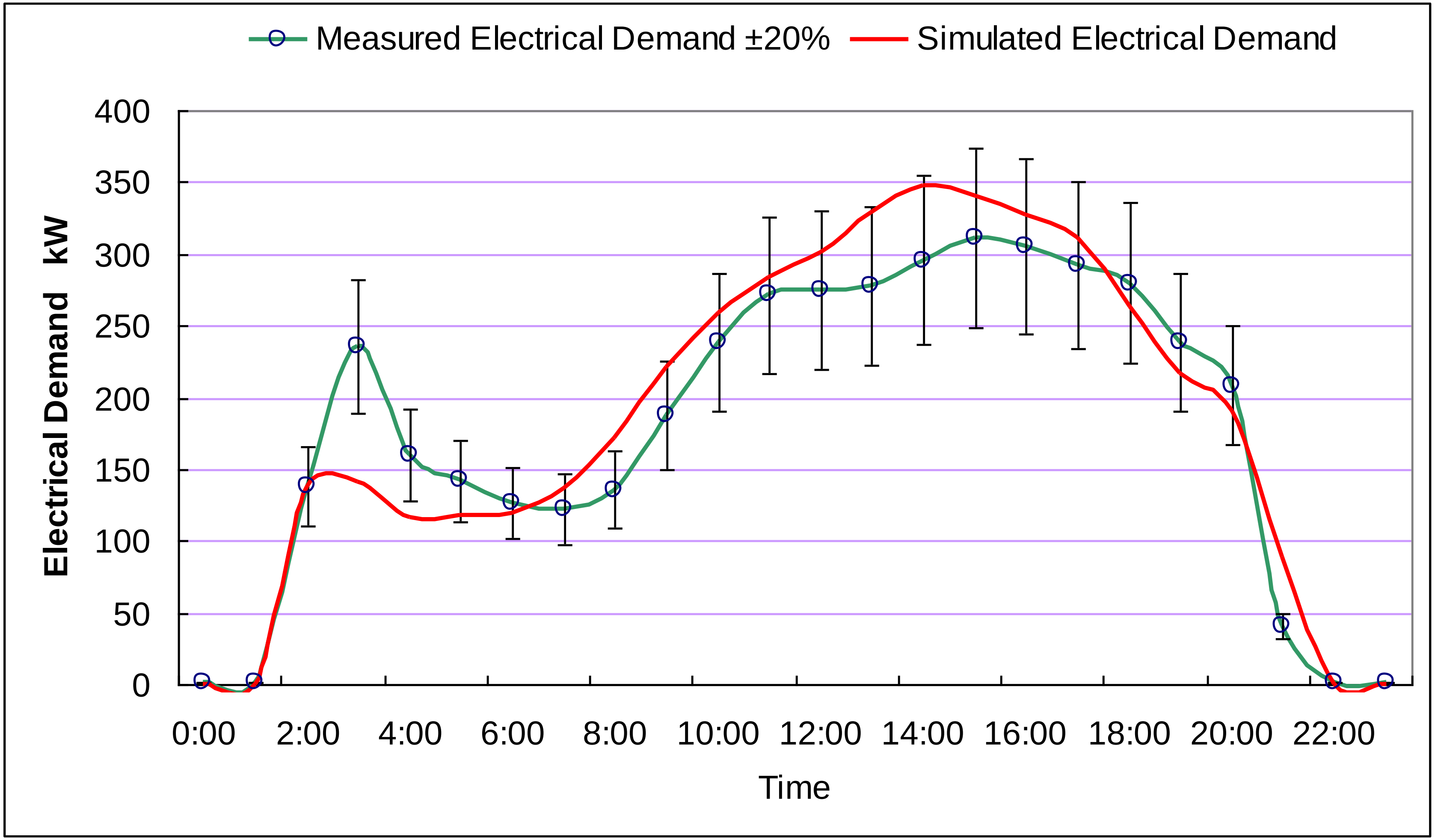
Winter Electric Demand to Adjust Lighting and Plug Load Density and Schedule



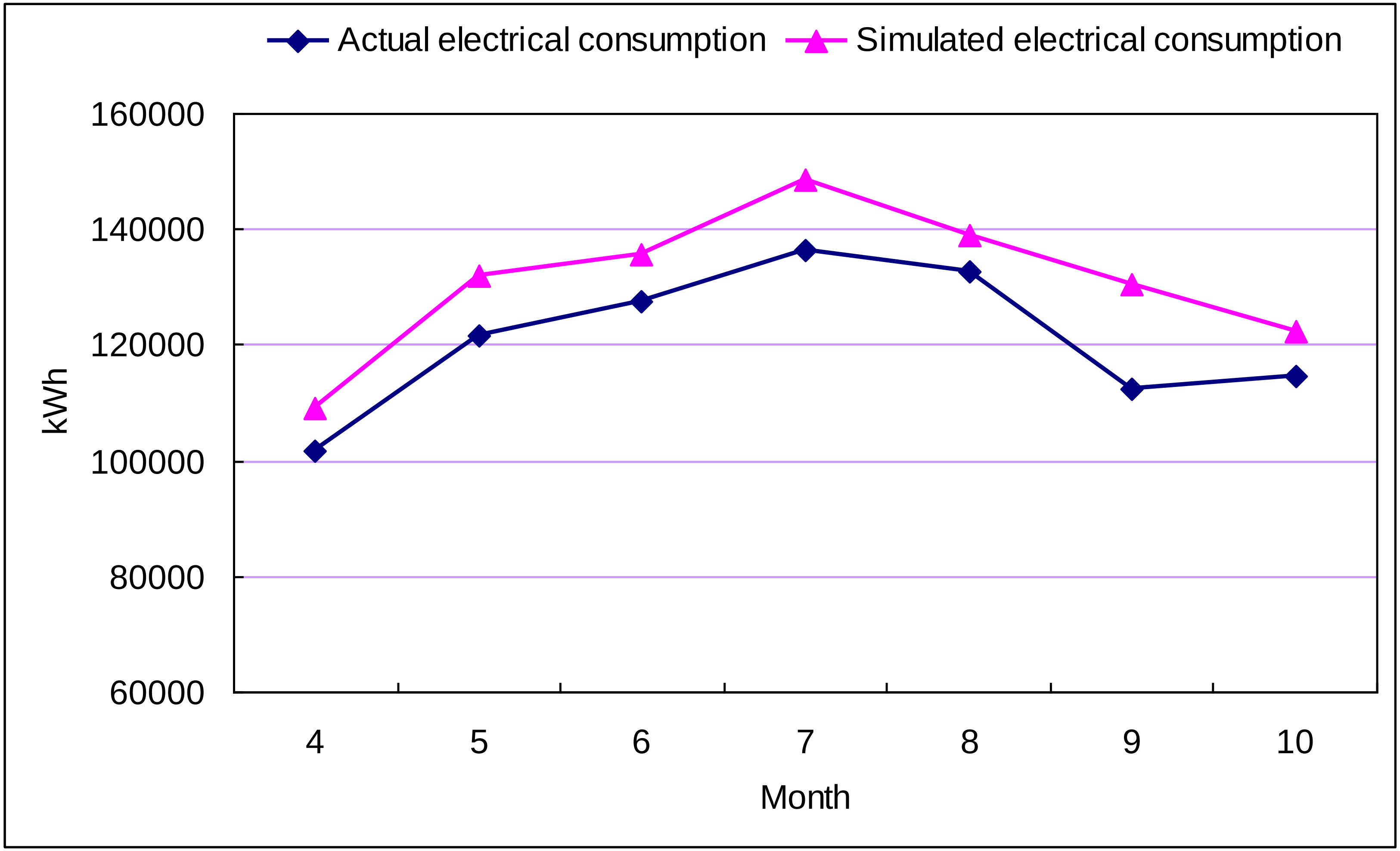
Adjusted lighting & plug load densities and schedules



Compare Step 1 Adjusted Model to Measured Loads



Compare DRQAT Step 1 Model Monthly Energy Consumption Predictions to Measured Data



DRQAT Model Adjustments—Step 2

1a. Use actual weather data

1b. Model input adjustments

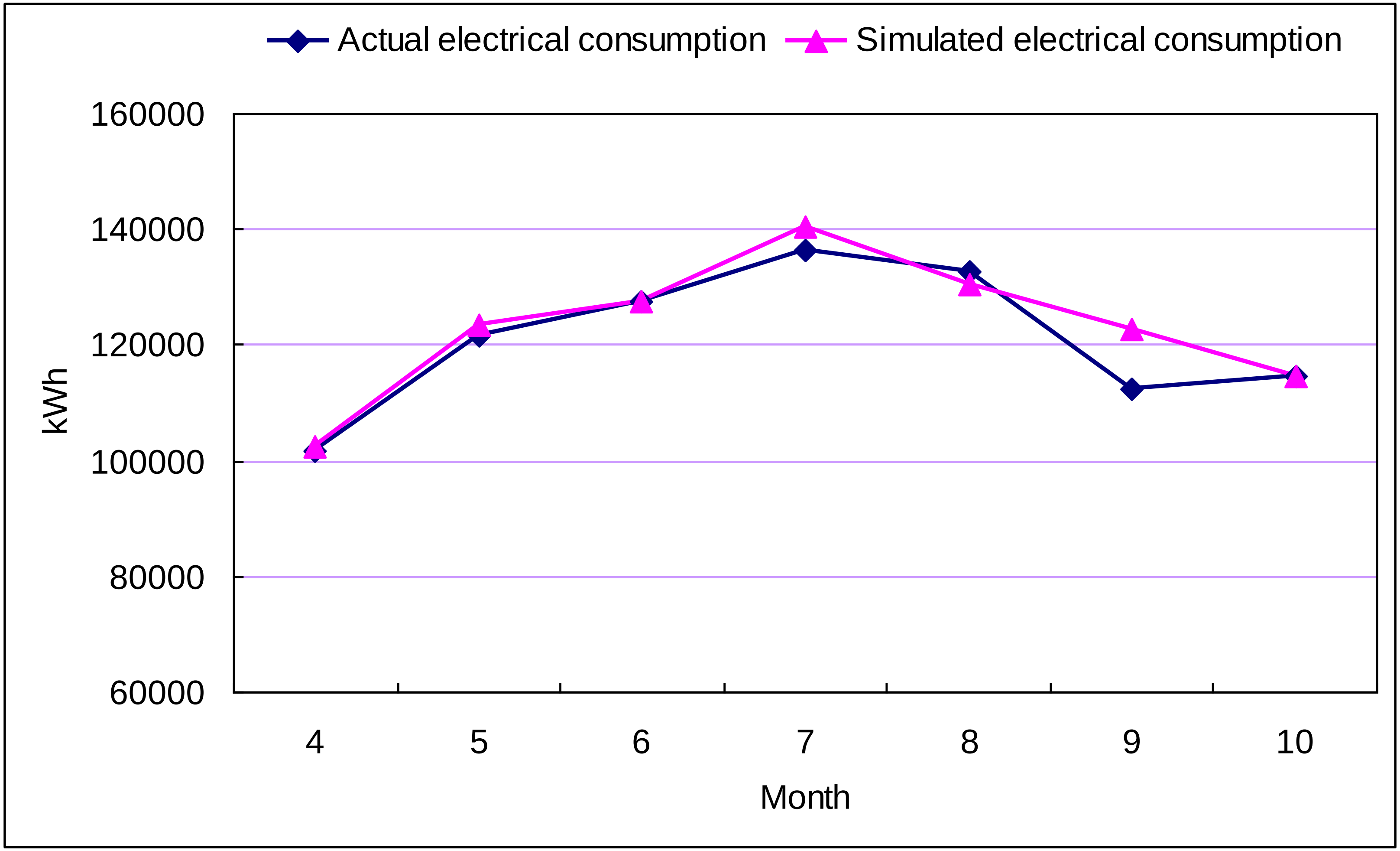
- Building information
- Lighting & plug load power densities, operating schedules
- Occupant number, operating schedules
- HVAC system characteristics
- Plant equipment characteristics

2. Model input adjustments based on Step 1 model outputs

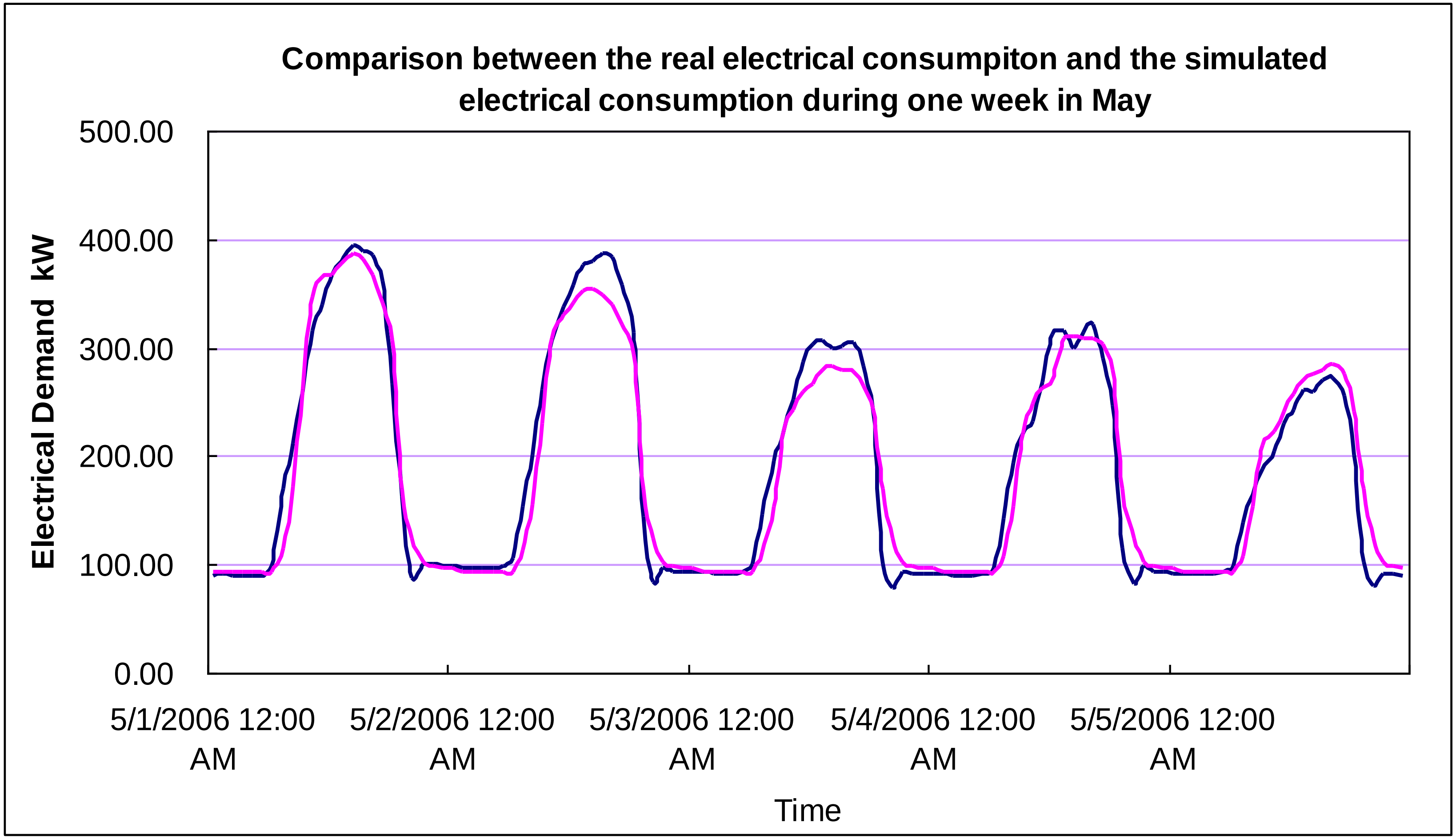
- Using DRQAT zone temperature output check if set-points are met and maintained
- If not increase zone sizing factor, which will increase simulated cooling capacity

Simulated zone temperatures unable to reach set-point

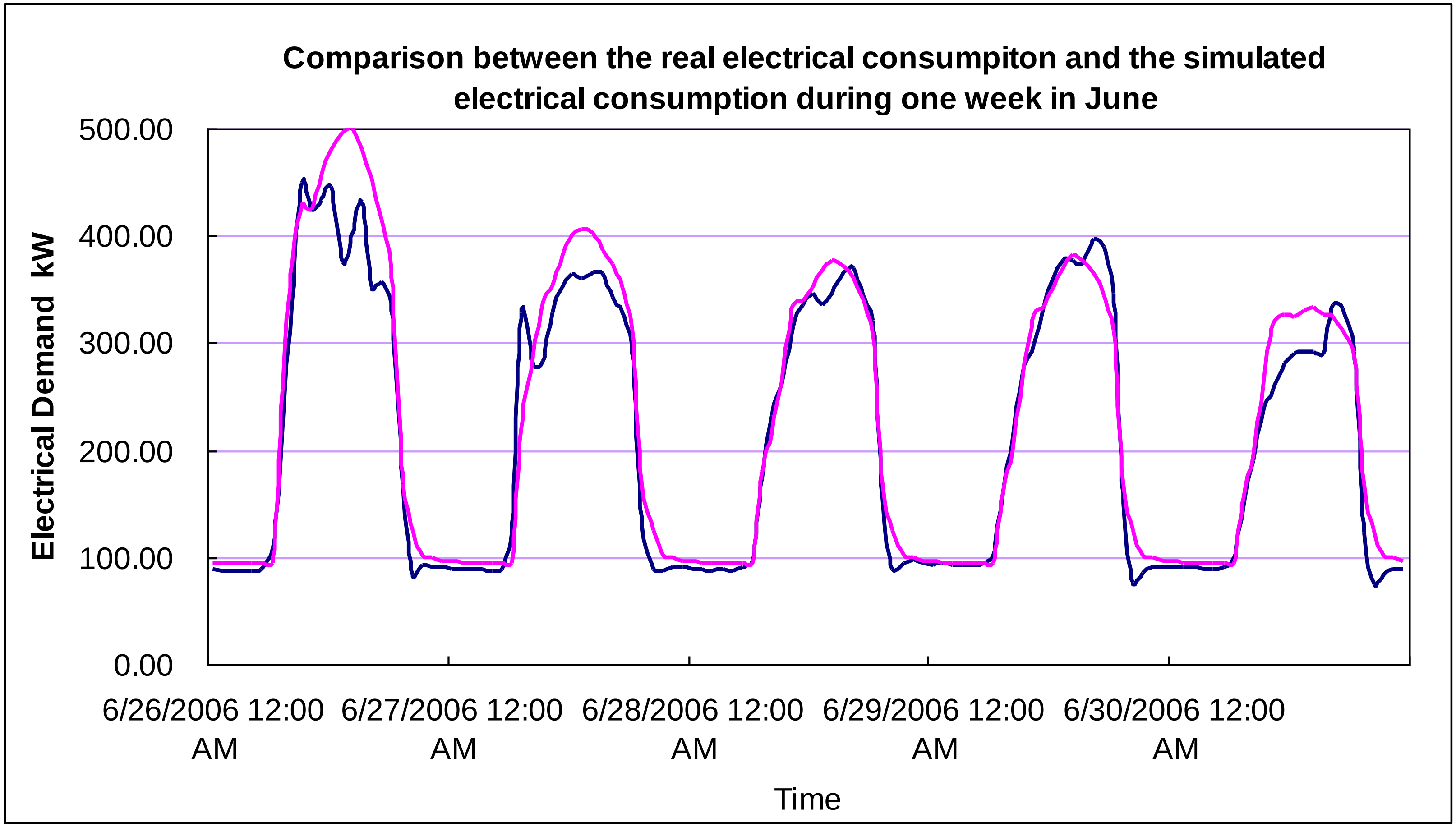
Compare DRQAT Step 2 Model Monthly Energy Consumption Predictions to Measured Data



Daily electrical demand comparison in May



Daily electrical demand comparison in June



Conclusions

- Demonstrated how to optimize and verify pre-cooling strategies for the office buildings in hot climate zone with the assistance of Demand Response Quick Assessment Tool (DRQAT)
- The field test results indicated that the pre-cooling strategies were able to reduce the peak demand as expected on Auto-DR test days (15~30% throughout the summer period)
- The demand shed predicted by the adjusted DRQAT models match well with the actual data on Auto-DR days when HVAC equipment were operated properly

Lessons Learned

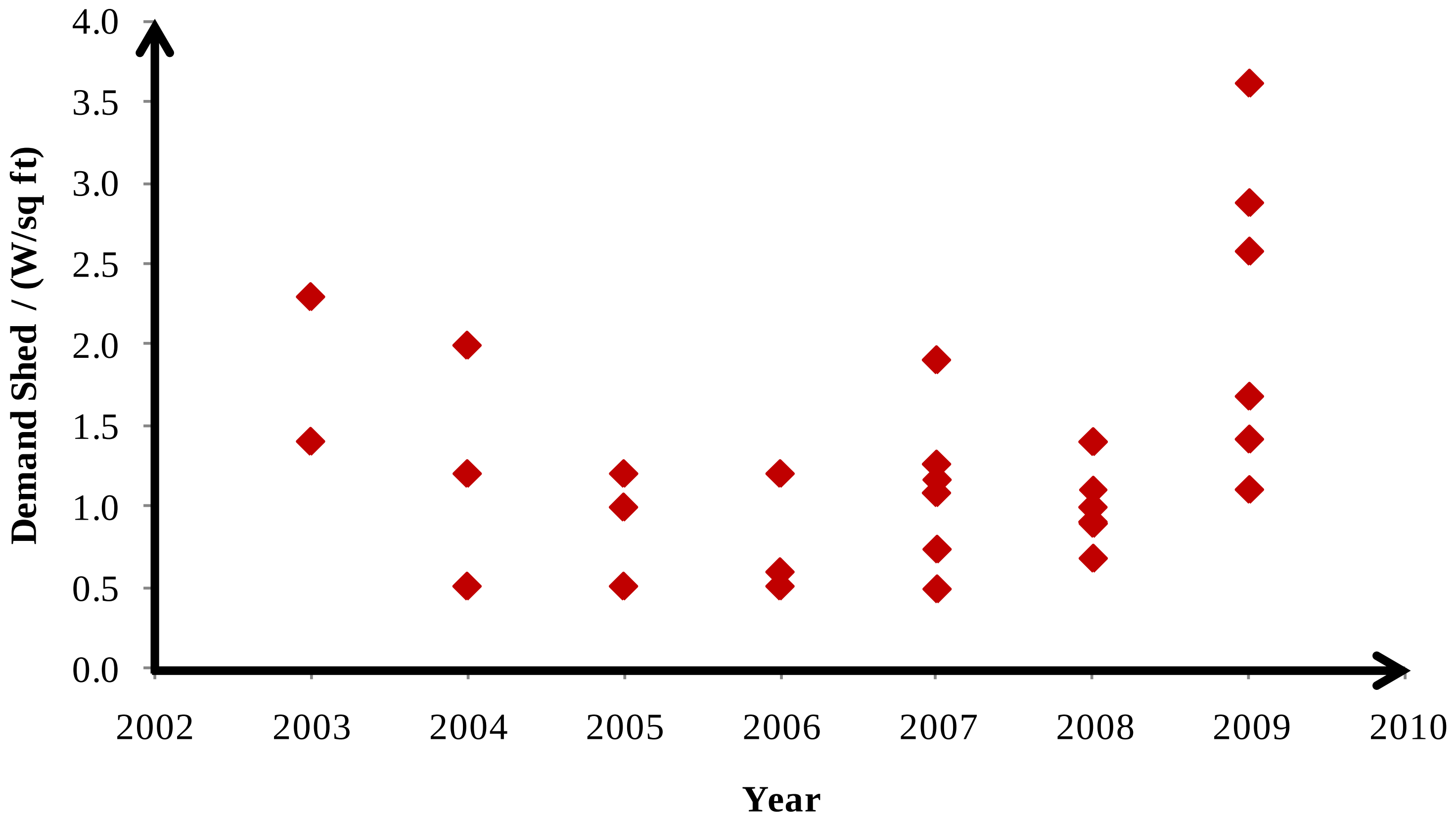
- Use real weather data – Outside air sensor or weather station installed at the building
- Use sub-metered HVAC and whole building demand data to adjust model inputs – direct measurement or short-term measurement
- Estimate more accurate internal mass level based on building constructions
- Simulation cannot simulate improper equipment and operation
- Lighting and plug load densities and schedules can be estimated from winter electric demand data when electricity is not used for heating
- Simulated zone temperatures that cannot meet or maintain the set-point value indicate that the sizing factor should be increased

Using DRQAT for Parametric Studies

- Background
  - "Pre-cooling" techniques reduce the building mass temperatures and interior temperatures in the early part of the day and reduce cooling electricity demand and electricity use in the afternoon.
  - Demand response quick assessment tool – DRQAT – was developed to evaluate DR strategies in commercial buildings based on EnergyPlus models of prototypical buildings
- Objective
  - Evaluate impact of building size, thermal mess level, weather, and DR strategies on peak demand savings in commercial buildings
  - Study the impact of three DR control strategies: *linear, step* and *exponential* temperature reset during the peak hours

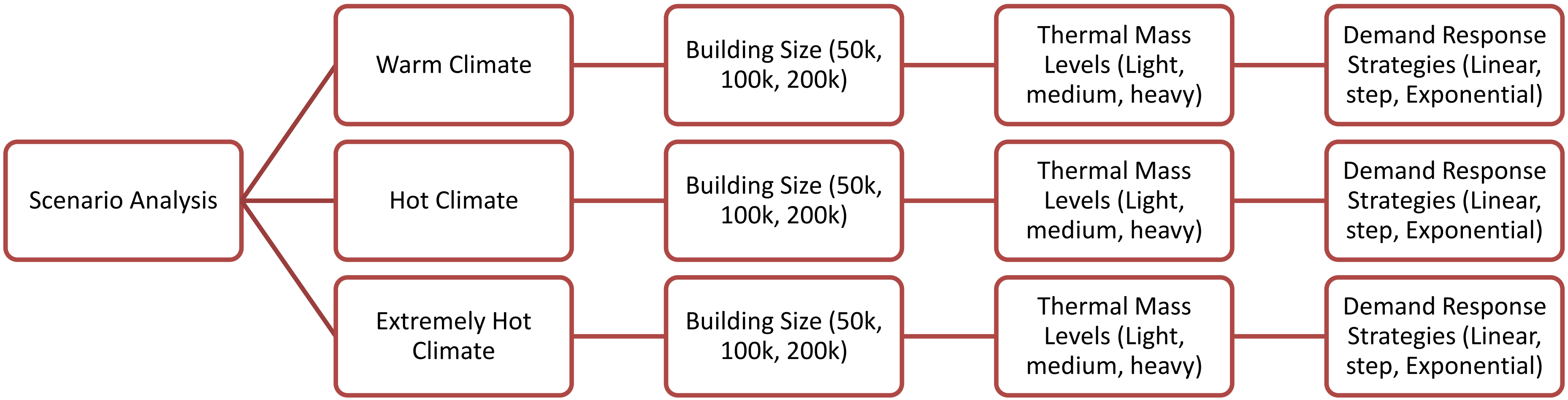
Previous Field Studies

- Demand shed in field studies: different building sizes, DR control strategies, weather conditions…



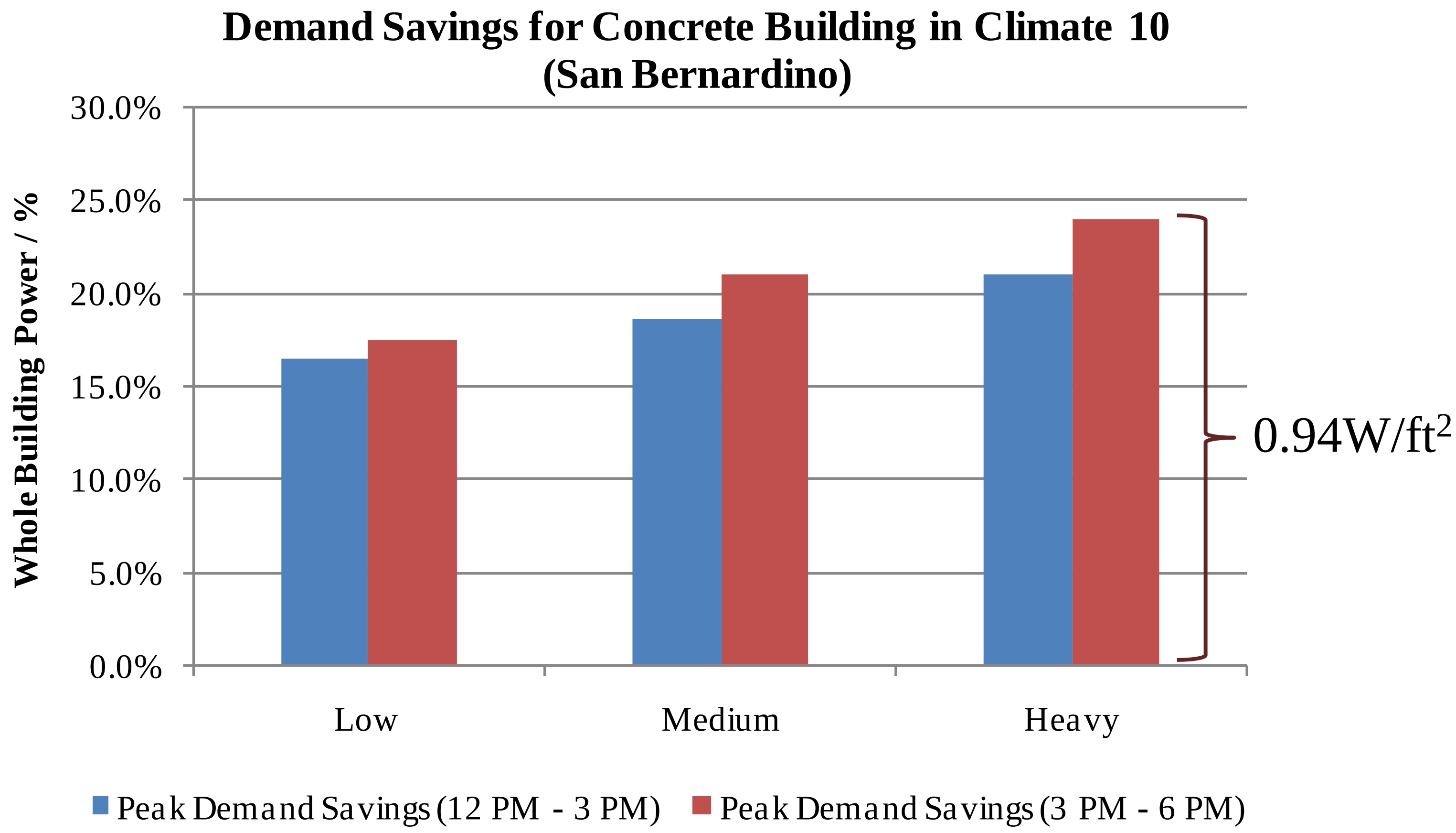
Scenario Analysis

- Weather: warm, hot, extremely hot
- Building Size: small, medium, large
- Thermal Mass: light, medium, heavy
- DR Strategy (zone temperature reset): linear, step, exponential



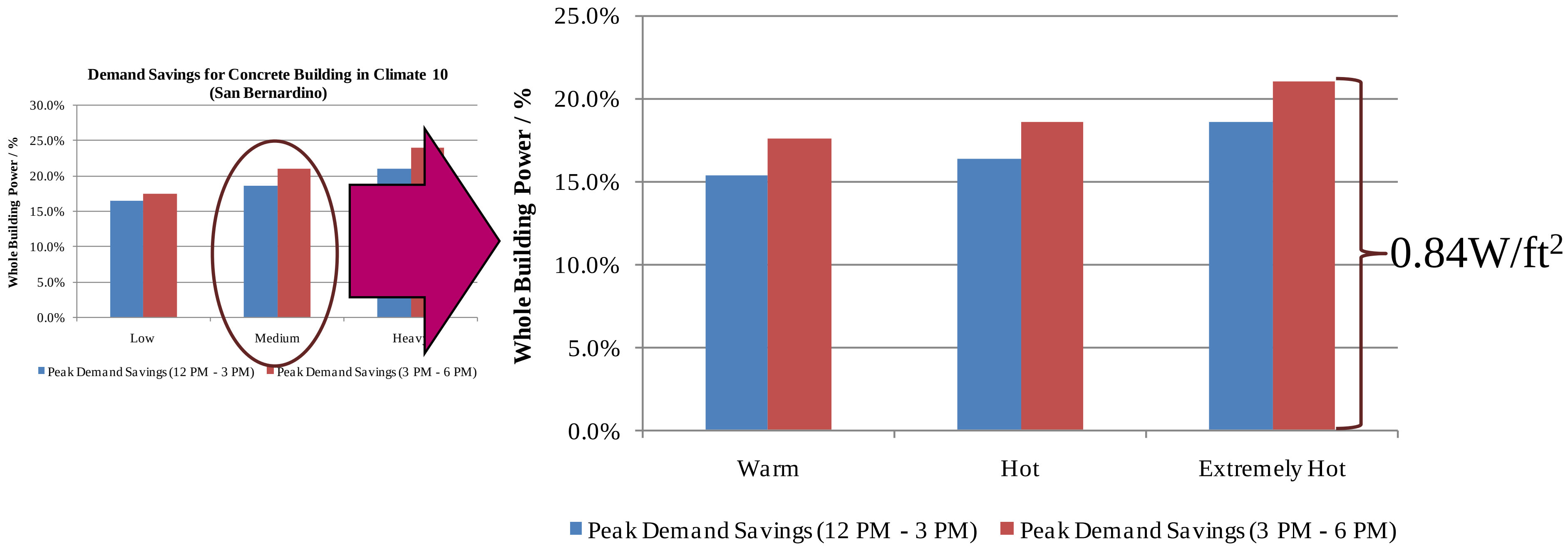
Results – Effects of Thermal Mass

- Magnitude of DR demand savings increases with building thermal mass
  - Employing the same strategy – "pre-cooling with exponential temp reset" in a medium-sized concrete building

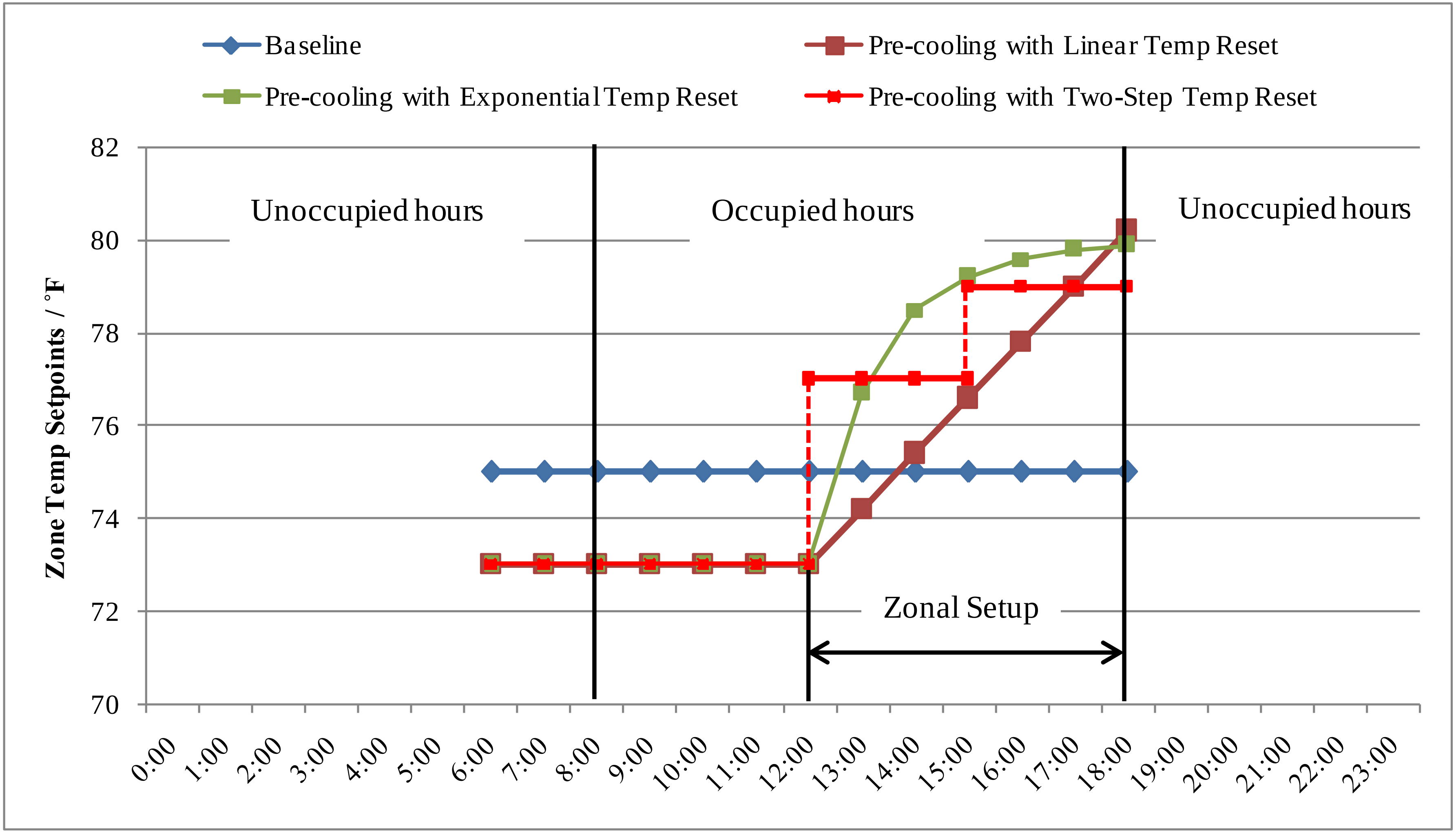


Results – Effects of Climates

- Magnitude of DR demand savings increases with outdoor temperature
  - Employing the same strategy – “pre-cooling with exponential temp reset” in a medium thermal mass building

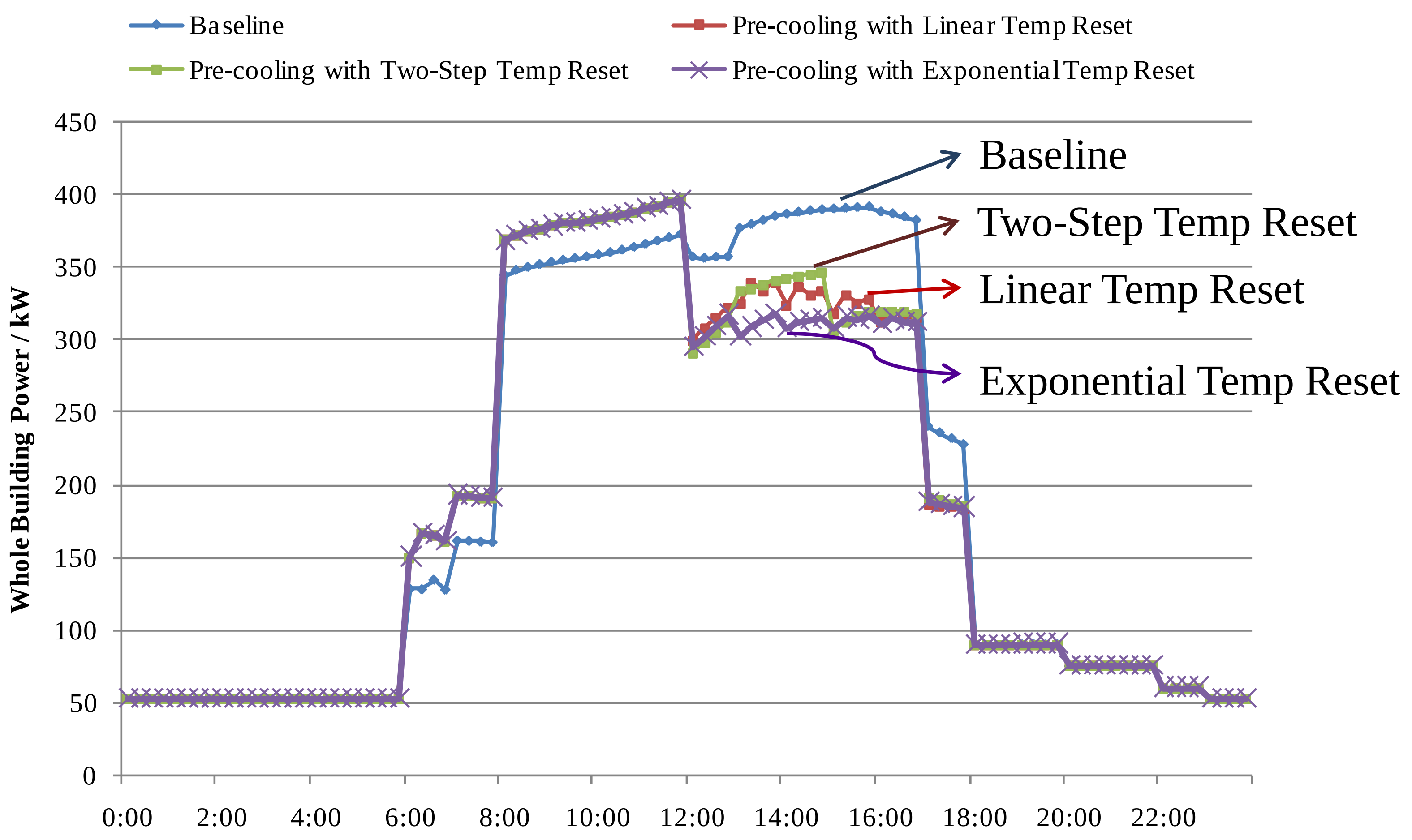


DR Pre-cooling Strategies



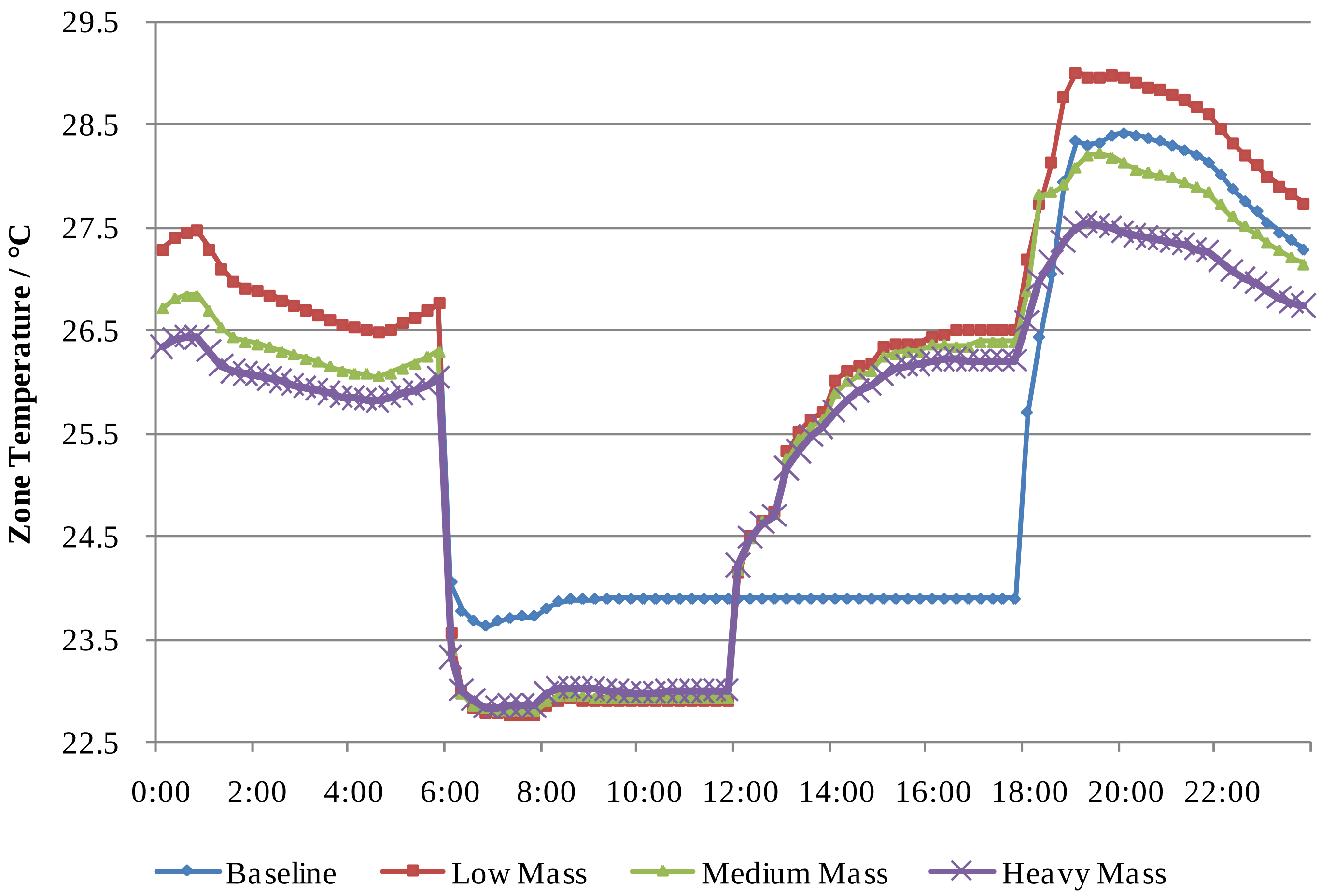
Results – Effects of DR Strategies

- The exponential temperature reset pre-cooling strategy yields the flattest demand profile during the DR event.



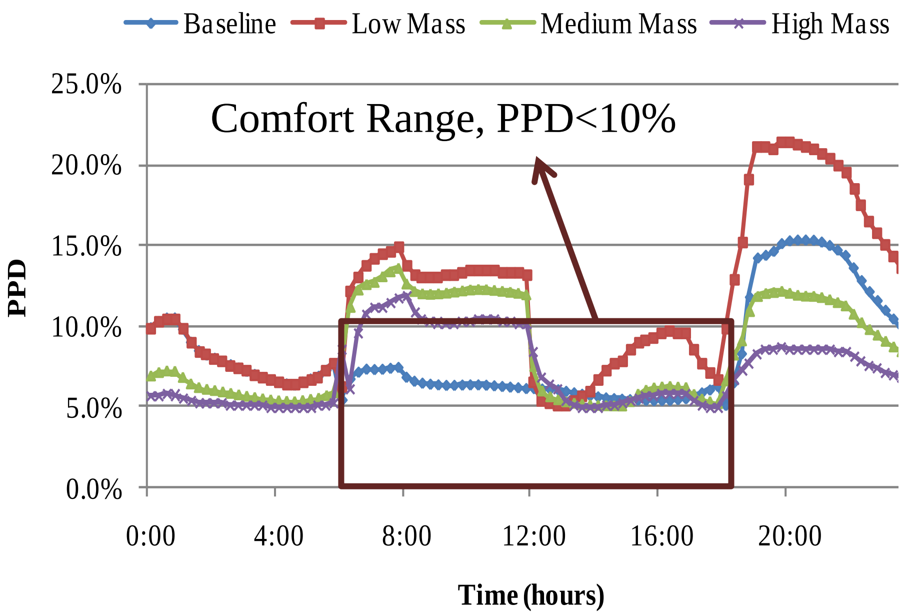
Results – Zone Temperature

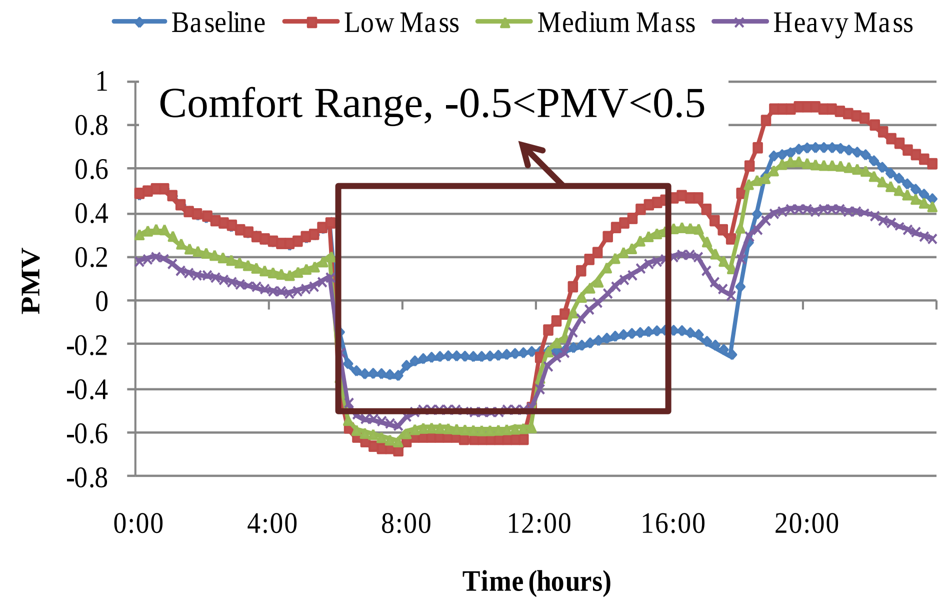
- The increase in average zone temperature during DR events with “pre-cooling with exponential temp reset” is inversely related to building thermal mass



Results – Zone Comfort

- Maintaining comfort during DR events is more difficult in buildings with low thermal mass





- **PPD:** Predicted Percentage of Dissatisfied
- **PMV:** Predicted Mean Vote

Scenario results with pre-cooling with exponential temperature reset

Climate in Summer	Thermal Mass Level	50,000 ft²		100,000 ft²		200,000 ft²	
		12 PM-3 PM	3 PM-6 PM	12 PM-3 PM	3 PM-6 PM	12 PM-3 PM	3 PM-6 PM)
Warm	Low	13.2%	15.2%	12.4%	13.4%	12.5%	13.2%
	Medium	15.3%	17.5%	15.1%	16.6%	15.1%	16.0%
	Heavy	16.2%	19.2%	17.1%	18.4%	17.2%	18.6%
Hot	Low	14.3%	15.9%	13.4%	14.9%	12.7%	14.1%
	Medium	16.3%	18.6%	15.6%	18.1%	14.9%	17.6%
	Heavy	18.0%	21.2%	17.2%	20.9%	19.2%	20.5%
Extremely Hot	Low	16.5%	17.5%	15.5%	16.6%	14.8%	15.9%
	Medium	18.6%	21.0%	18.0%	20.3%	17.5%	19.8%
	Heavy	21.0%	24.0%	20.3%	23.4%	20.0%	22.9%

Conclusions

- *Thermal mass levels*: As expected, the peak demand savings rise with increased building thermal mass levels
- *Climate Conditions*: As outside temperature increases, magnitude of DR increases
- *DR Control Strategies*: The "pre-cooling with exponential temperature set up" control strategy achieved the greatest peak demand savings and the flattest afternoon electric load shape
- *Zone Comfort*: "Exponential temperature reset" yields the flattest demand profile in a typical commercial building