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U.S. DEPARTMENT OF ENERGY

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Summary

Background

Commercial buildings in the United States consume approximately 18 quadrillion British thermal units (quads) of primary energy annually (EIA 2016). Inadequate building operations leads to preventable excess energy consumption along with failure to maintain acceptable occupant comfort. Studies have shown that as much as 30% of building energy consumption can be eliminated through more accurate sensing, more effective use of existing controls, and deployment of advanced controls (Fernandez et al. 2012; Fernandez et al. 2014; AEDG 2008). Studies also have shown that 10% to 20% of the commercial building peak load can be temporarily managed or curtailed to provide grid services (Kiliccote et al. 2016; Piette et al. 2007). Although many studies have indicated significant potential for energy savings in commercial buildings by deploying sensors and controls, very few have documented the actual measured savings (Mills 2009; Katipamula and Brambley 2008). Furthermore, previous studies only provided savings at the whole-building level (Mills 2009), making it difficult to assess the savings potential of each individual measure deployed.

Purpose

Pacific Northwest National Laboratory (PNNL) conducted this study to systematically estimate and document the potential energy savings from Re-tuning™ commercial buildings using the U.S. Department of Energy's (DOE's) EnergyPlus building energy modeling software. This study is a follow up to the previous DOE study conducted by TIAX (Roth et al. 2005). Re-tuning is a systematic process of detecting, diagnosing, and correcting operational problems with building systems and their controls in either a semi-automated or a fully-automated way. Periodic Re-tuning of building controls and heating, ventilation, and air-conditioning (HVAC) systems reduces inefficient and "faulty" operations and improves building efficiency. This low-cost process identifies and corrects building operational problems that lead to excess energy use and is implemented primarily through building automation systems (BASs)—for those buildings that have them—for immediate impact.

Models for nine EnergyPlus prototype commercial buildings were used for the simulation of each of the sensors and controls measures simulated during the study. The study also extended by analogy the savings estimates for five additional prototypes that were similar to one of the original nine. The 14 building types represented 51% of the total commercial building floor space and 57% of the U.S. commercial sector energy consumption. For each building type, the study's purpose was to quantify two impacts:

- the energy savings potential of properly deploying accurate sensors, as well as basic and advanced controls, including automated fault detection and diagnostics in the commercial building sector; and
- the potential for demand-response (DR) measures to lower commercial building electric demand during critical peak pricing (CPP) events. This load reduction potential can help facilitate the performance of grid services by buildings that may be of particular benefit under a scenario of higher penetration of distributed energy resources (DERs).

Methodology for Calculating Savings

Estimation of the potential national energy savings derived by adopting sensors and controls and DR measures involved simulation of individual and packages of energy savings and DR measures in nine

different DOE prototype building models and in the 16 climate zones defined in the International Energy Conservation Code that represent the entire United States (U.S. DOE 2017a). The simulation results were mapped by building type and climate to the expected square footage of all equivalent or substantially similar buildings in similar climates documented in the 2012 Commercial Building Energy Consumption Survey (CBECS; EIA 2012). The survey strategically selected buildings across the country to represent the national existing building stock. The buildings were assigned weights according to how many existing buildings are representative of the surveyed building within the region of choice. CBECS categorizes commercial buildings according to 17 principal building activities (PBAs), many of which have subcategories. For this study, the PBAs by the category or subcategory that could be reasonably represented by one of the nine prototype models, based on space usage, anticipated building internal loads, and anticipated types of HVAC system, were selected.

Using detailed simulations, savings from individual energy efficiency measures (EEMs) can be isolated; however, some EEMs cannot be easily modeled because of the limitation of the simulation tool. Despite the limitation, during the study 43 different EEMs and DR measures were simulated for the nine prototypical buildings in the 16 U.S. climate regions. In addition to the nine prototypical buildings, the savings were extrapolated for five additional building types because of their similarity to one of the nine prototypes simulated, resulting in a representation in total of 57% of the energy consumed and 51% of the total floor space of the commercial buildings stock. The savings were calculated for each individual EEM, each relevant building type, and each climate region, as were the national savings for each measure by building type and climate location.

Building operators and managers often deploy a package of synergistic measures because doing so is more cost effective than an individual measure. For this reason, packages of measures were developed to estimate the national savings potential. These packages represent the diversity in the status and complexity of the controls in a conceptualized set of existing buildings. This diversity helps to weight the application of specific EEMs based on the observed prevalence of opportunities to implement them in actual buildings. The three building packages are for:

- an efficient building defined as having the most common and some advanced EEMs implemented with no operational faults modeled and limited opportunities for the remaining measures;
- a typical (or average) building with a wide range of opportunities for energy savings still available despite limited easy-to-implement measures and few operational faults modeled; and
- an inefficient building defined as having no EEMs implemented and widespread operational faults in existence.

Because the national distribution of buildings classified as efficient, typical, and inefficient is unknown. Thus, three different penetration scenarios were considered:

- central/best estimate: 30% efficient, 50% typical, 20% inefficient
- low savings estimate: 50% efficient, 40% typical, 10% inefficient
- high savings estimate: 10% efficient, 40% typical, 50% inefficient.

Energy Savings for Individual Measures

Simulation results and findings for the individual EEMs and DR control measures and for the packages of measures are highlighted below. Energy savings results were derived from individual EEMs and divided into a national-level summary of savings with measures ranked by overall site energy savings and aggregated across all building types and climates. The percent savings reported are the percent of the total site energy consumption, which is further broken out into the contribution from electricity and natural gas to that total.

The total site savings, natural gas savings, and electricity savings are reported as estimates for each measure by building type and climate location. Savings were estimated for thirty-seven individual simulated measures. Many of the EEMs only apply to a few building types, so only the savings for relevant building types are reported. Refer to Appendix A for more details on individual measure results.

Table S.1 shows a summary of the range of savings modeled among the set of applicable EEMs for each building type, aggregated across all climates. For each prototype, the minimum and maximum savings for individual measures are shown for electricity, natural gas, and for both combined. The top performing EEM for electricity savings and for natural gas savings is also listed. Typically, negative savings in electricity or gas for one fuel type is offset by greater savings for the other fuel type. For example, measures that produce electricity savings through reductions in internal electric loads simultaneously reduce internal heat gains and increase the demand for natural gas. In Primary and Secondary Schools, one measure (EEM06: outdoor air damper faults/control) is modeled as leading to a significant increase on overall energy consumption even though for other building types the same measure can save significant energy. The reason for the increase is that this measure corrects a baseline fault that simulates poor damper seals by limiting the range of the outdoor air damper (both minimum and maximum flow). Because the maximum flow is limited, the baseline building is under-ventilated based on design ventilation rates when the outdoor air damper seals are poor. For all building types, the best overall measure for total savings was either EEM15: minimum VAV terminal box flow reductions, EEM16: wider deadbands and night setbacks, or EEM17: demand control ventilation. For all building types that used single-zone packaged units for space conditioning, the top performing measure for electricity savings was EEM23: advanced RTU controls.

The last row in Table S.1 includes an estimate of the range of the technical potential savings for individual measures at the national level. This involves an aggregation of savings among all building types and climate zones. For each EEM, there is an additional adjustment of the total savings to reflect the expected prevalence of opportunities to implement the measure, given that each of the measures is an opportunity in only a subset of the building stock for buildings of each type. The adjustment is a fractional multiplier that is set equal to that measure’s weighting within the set of packages. Among the set of individual measures at the national level, the total site energy savings ranged from 0% to 7.7%. The top overall measure for electricity savings was EEM23: advanced RTU controls (3.8%). For both natural gas (5.3%) and overall site energy savings (7.7%), EEM16 (wider deadbands and night setbacks) was the top performing measure.

Figure S.1 is a bubble plot showing the tradeoff between the energy cost savings and the level of effort required to implement each measure. The effort level can be considered a proxy for the cost to implement each measure. Here, the evaluation of effort is on a three-tiered scale (low, medium, and high) and is a subjective assessment, based on the authors experience. The size of each bubble is proportional to the amount of commercial floor space occupied by buildings for which the measure may be applicable. The four most promising measures, offering high cost savings at low levels of effort, and with broad applicability include EEM04: shorten HVAC schedules, EEM15: minimum VAV terminal box damper flow reductions, EEM16: widened thermostat deadbands and night setback, and EEM27:optimal start. The measures in the figure are abbreviated using their numerical code (use Table 4.1 for reference).

Table S.1. Energy Savings from Individual Measures by Building Type Aggregated across All Climate Locations and National (last row)

Prototype Model	Electricity Savings Range		Natural Gas Savings Range		Total Savings Range		Top Performing Measure	
	Min (%)	Max (%)	Min (%)	Max (%)	Min (%)	Max (%)	Electricity	Natural Gas
Small Office	0.1	7.1	-3.9	7.4	0.0	9.7	EEM23: Advanced RTU Controls	EEM16: Wider Deadbands and Night Setbacks
Medium Office	-0.2	16.0	-1.5	0.9	-0.2	16.1	EEM15: Minimum VAV Terminal Box Damper Flow Reductions	EEM17: Demand Control Ventilation
Large Office	-0.2	5.4	-2.6	12.2	-0.2	15.4	EEM26: Cooling Tower Controls	EEM15: Minimum VAV Terminal Box Damper Flow Reductions
Stripmall Retail	0.0	9.8	-6.3	11.5	0.1	12.0	EEM23: Advanced RTU Controls	EEM17: Demand Control Ventilation
StandAlone Retail	0.1	11.5	-8.4	14.2	0.2	14.8	EEM23: Advanced RTU Controls	EEM17: Demand Control Ventilation
Primary School	-0.8	5.6	-6.4	9.9	-7.2	15.6	EEM16: Wider Deadbands and Night Setbacks	EEM16: Wider Deadbands and Night Setbacks
Secondary School	-0.8	4.2	-4.0	25.5	-4.2	24.7	EEM04: Shorten HVAC Schedules	EEM17: Demand Control Ventilation
Large Hotel	-0.1	4.8	-0.7	7.7	0.0	12.4	EEM15: Minimum VAV Terminal Box Damper Flow Reductions	EEM15: Minimum VAV Terminal Box Damper Flow Reductions
Supermarket	0.0	5.4	-3.5	7.7	-0.2	9.1	EEM23: Advanced RTU Controls	EEM16: Wider Deadbands and Night Setbacks
National Total	**0.0**	**3.8**	**-2.6**	**5.3**	**0.0**	**7.7**	**EEM23: Advanced RTU Controls**	**EEM16: Wider Deadbands and Night Setbacks**

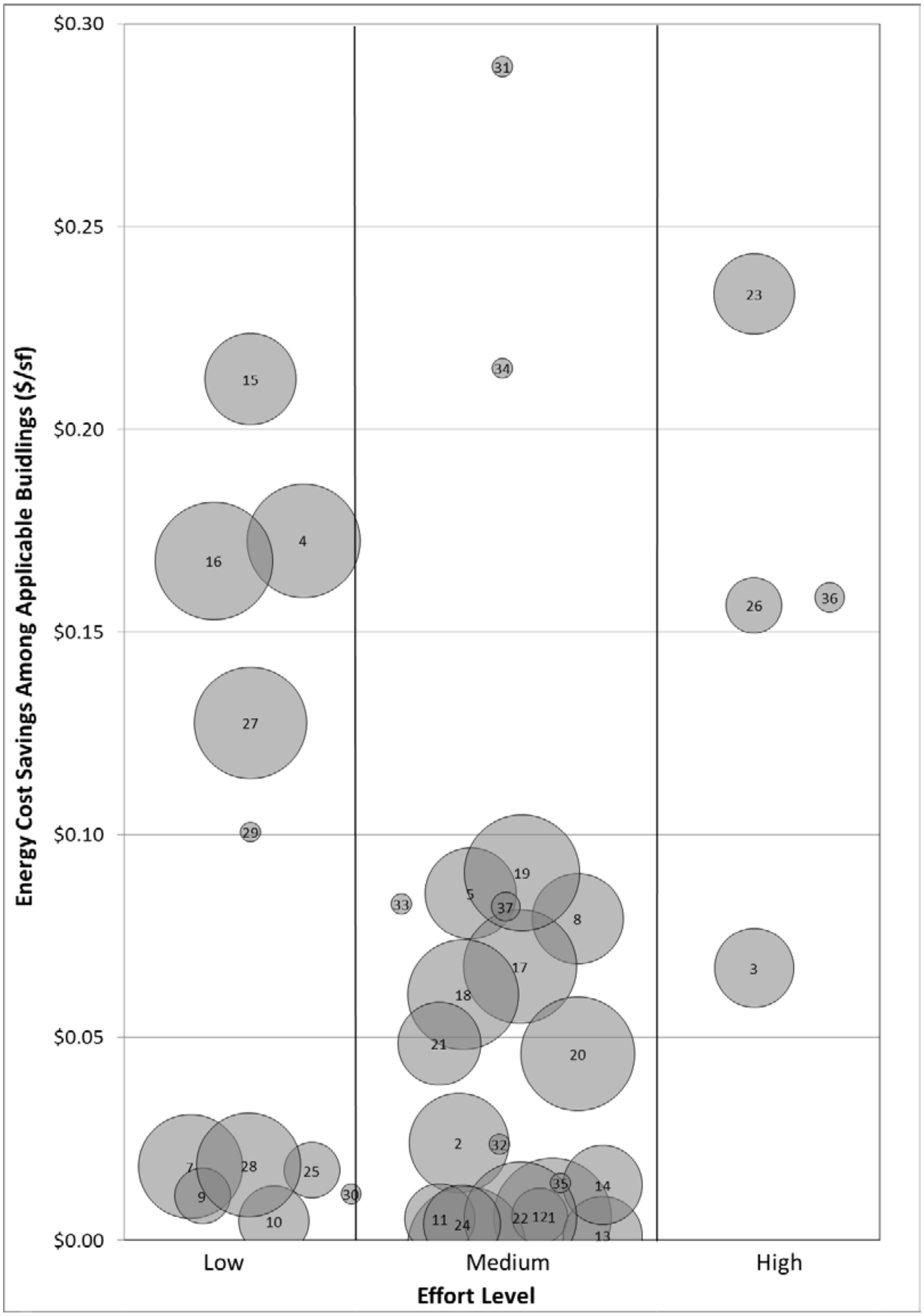

Figure S.1. Cost-Benefit Analysis for Individual Energy Efficiency Measures across All Climates and Building Types

Peak Demand Impacts of Energy Efficiency Measures

Beyond the impact of reducing energy consumption in buildings, many EEMs can also lead to reduction in the peak electricity demand. In many regions of the country, the utilities charge for both kWh (energy) and kW (demand). In some cases, the demand portion of the total electricity cost may be significant (>30%); therefore, reduction in demand can lead to an additional cost benefit for several of the EEMs. Nine of the 37 EEMs were each capable of producing at least 3% peak demand savings in at least one building type, and four of those nine were each capable of producing over 10% peak demand savings. Most of the other measures had little to no impact on peak demand, while one measure (optimal start) produced significant peak demand increases, but only for two building types.

National Energy Savings from Packages of Measures

The total site energy savings by building type for the efficient building package, the typical building package, and the inefficient building package ranged from 4% to 19%, 26% to 56%, and 30% to 59%, respectively. Based on the weighting of these three efficiency levels, the expected national savings for each set of building types were also estimated. For most building types, the potential national total site savings ranged from 23% to 30%, with the exception of Secondary School (49%) and StandAlone Retail/Dealership (41%). Figure S.2 shows the savings level for each package for each building type in green, blue, and red, as well as the weighted total savings for each building type in black.

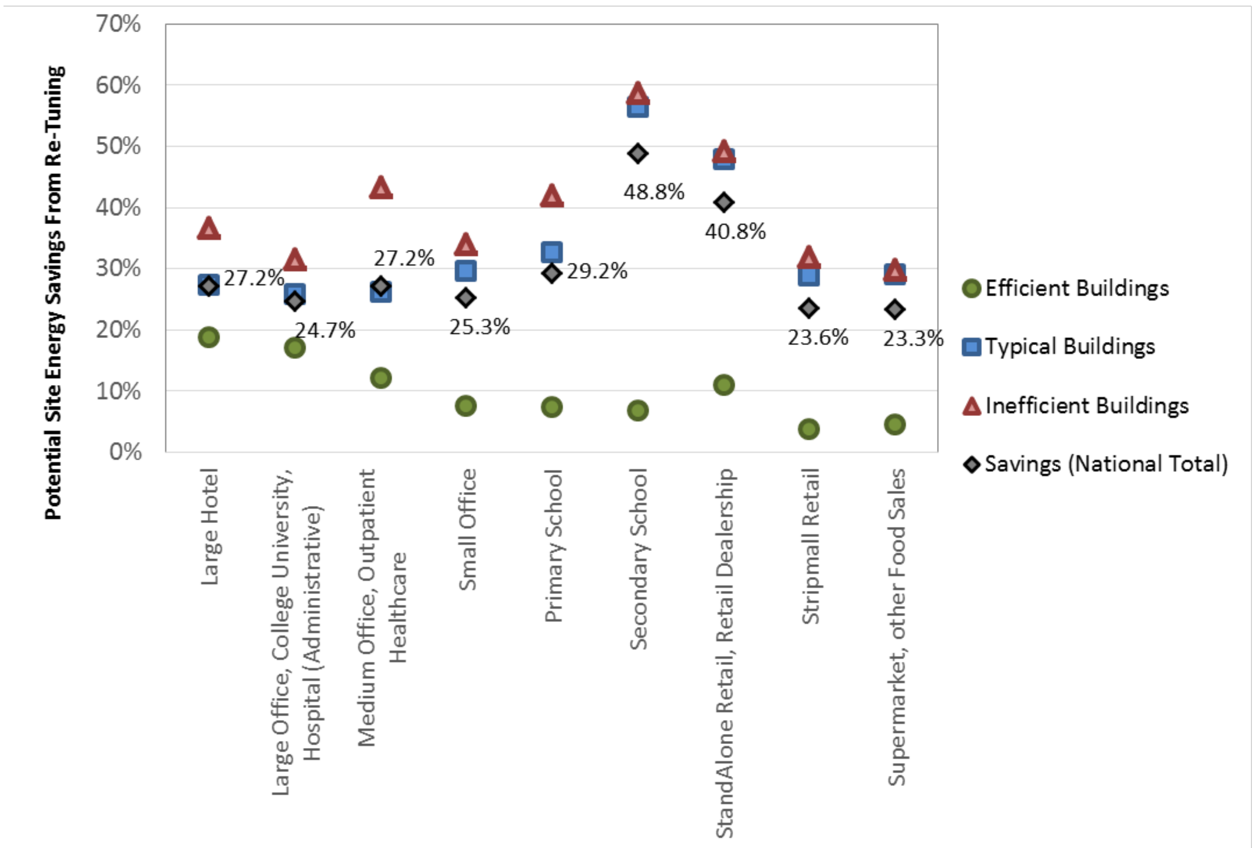

Figure S.2. Savings from Packages of Measures by Building Type

Aggregated among all building types, the annual building energy savings from EEMs is estimated to be 29%. The savings from natural gas and electricity were also estimated separately. The site natural gas savings by building type for the efficient building package, the typical building package, and the inefficient building package ranged from -6% to 13%, 0% to 45%, and 0% to 42%, respectively. A few building types have negative natural gas savings for the reasons previously discussed. The site electricity savings by building type for each of the building packages ranged from 6% to 17%, 11% to 26%, and 15% to 43%, respectively.

Figure S.2 illustrates the total national energy savings from deploying measures based on the three scenarios for the proportion of inefficient, typical, and efficient buildings selected. Considering these three illustrative scenarios is the most straightforward way to handle uncertainty about the national building stock, because the lack of data on the prevalence and magnitude of opportunities for controls improvements renders a more sophisticated uncertainty analysis impossible.

The total site energy savings ranges from 1.02 to 1.70 quads, with a best estimate of 1.32 quads of savings. Total primary energy savings ranges from 2.17 to 3.56 quads, with a best estimate of 2.74 quads of savings.

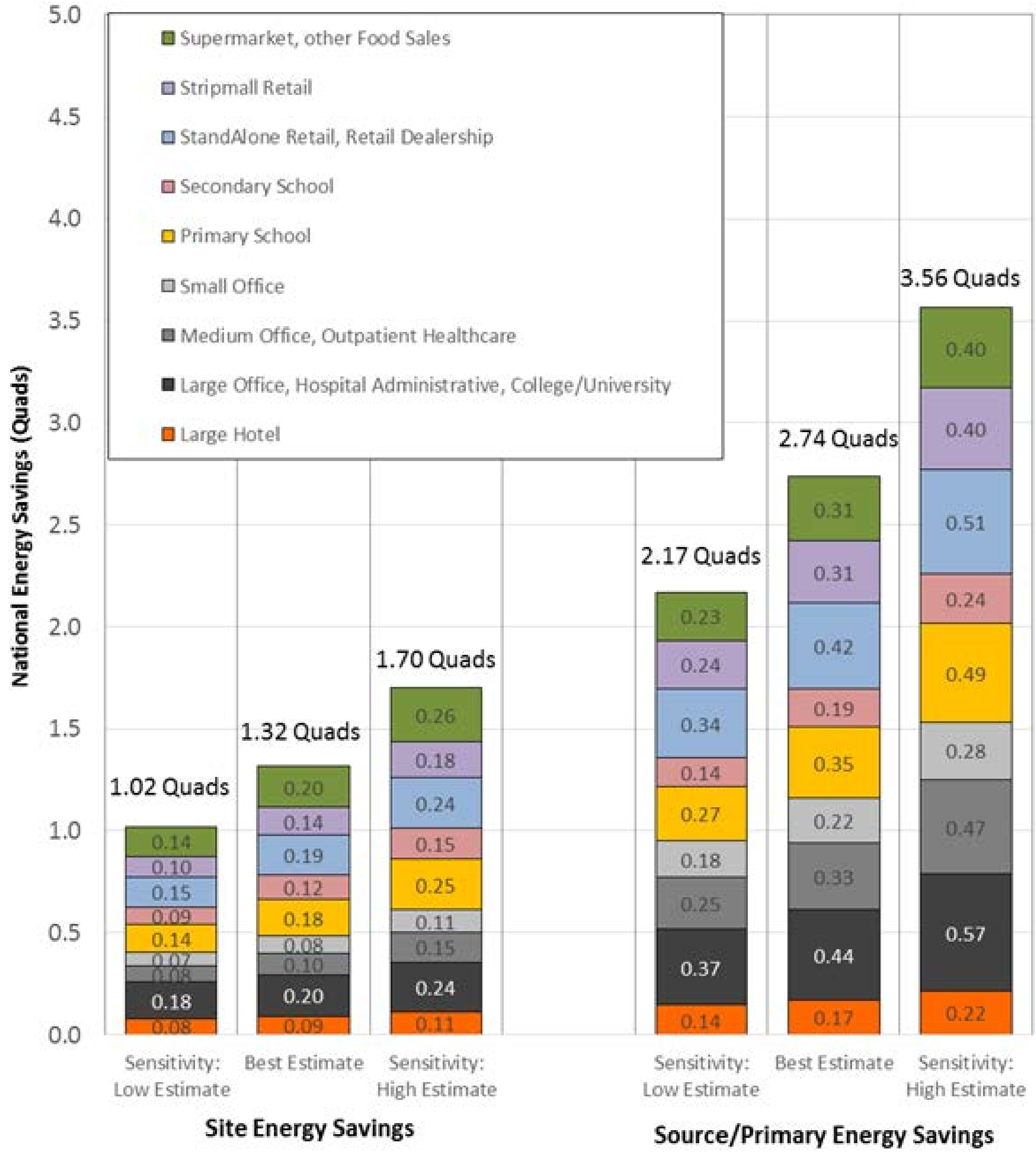

Figure S.3. National Total Site and Source Energy Savings Potential by Building Type in quadrillion Btu (quads)

Peak Reductions from Individual Demand-Response Measures

The national technical potential peak reductions from individual DR measures are shown in Figure S.3. Because the CPP (or time-of-use) utility rate is one of the commonly implemented DR mechanisms in California and other parts of the United States, a series of measures was created to estimate the possible peak reduction during critical demand periods. The national peak reductions, aggregated across all building types and climate locations, ranged from 0.2% (refrigeration) to more than 16% (pre-cooling).

Note that the refrigeration peak reduction measure only applies to Supermarket and Other Food Sales. Therefore, this measure results in only a 0.2% peak reduction across all building types. However, it results in more significant peak reductions ranging from 5% (Phoenix) to 7.7% (Los Angeles) in the buildings to which it applies.

Energy Impacts of Demand-Response Measures

Because the DR measures considered are only activated during rare CPP events, their impact on annual energy consumption is very small—in almost all cases annual energy consumption increases or decreases by less than 0.1%, which is statistically insignificant. However, the change in electricity consumption over the course of a typical CPP day can be significant, with impacts ranging between 5% and 6% increase in consumption (for pre-cooling, in three building types) to between 4% and 7% reduction for set point changes and duty cycling in some building types.

National Peak Reductions from Packages of Demand-Response Measures

Because building operators/owners often will apply synergistic DR measures as a package, two different DR packages were created—reactive and predictive. Applying these two packages to all building types and in all climate locations resulted in peak reductions of 19% (for both reactive and predictive). Figure S.4 shows the modeled electric demand savings during the CPP events for each DR measure and DR package, aggregated across all building types and climates.

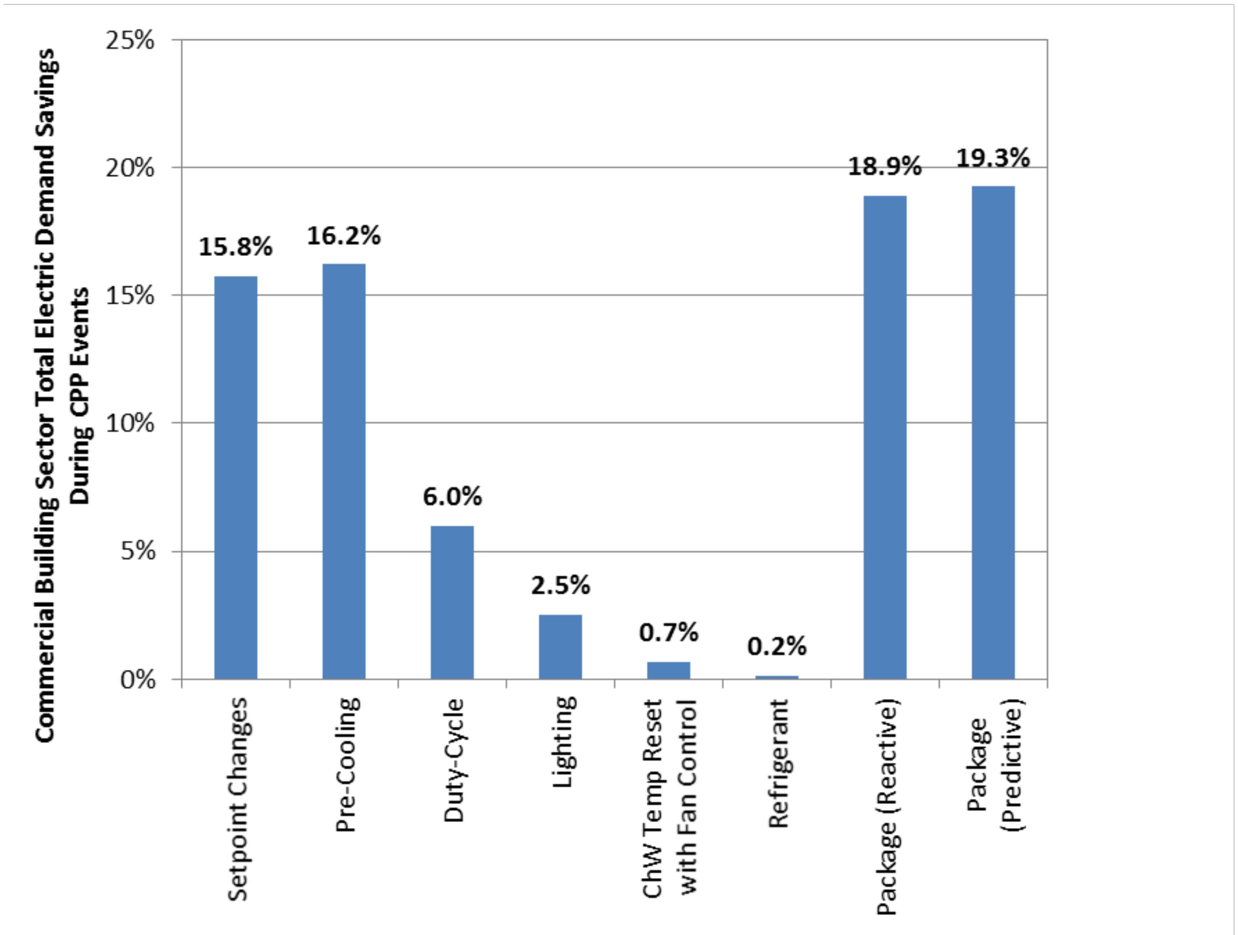

Figure S.4. Demand-Response: Aggregate National Savings by Measure and Package

Conclusions and Limitations

This study investigated the potential energy savings from implementation of basic and advanced controls measures and eliminating common faults in HVAC systems in the U.S. commercial building sector. These measures focus on equipment operation, and thus do not require major retrofits of existing equipment. For this reason, the upfront cost and payback period for these control measures tend to be more financially attractive than equipment or envelope retrofits. In many cases, however, some measures may require upgrades of building automation systems, such as enhanced communication capabilities and installation of variable-speed drives on certain fans and pumps in some buildings. This study simulated 34 energy efficiency measures (including control measures) in nine commercial building types and extended (by analogy) to another five building types that represent 57% of the U.S. commercial sector energy consumption. The measures were simulated in 16 climate locations and savings were weighted according to commercial sector square footages by climate and building type using the 2012 Commercial Building Energy Consumption Survey from the U.S. Energy Information Administration. The energy modeling also relied on packages of measures that represent a diversity of current status of building controls and equipment faults (inefficient, typical, and efficient), and compared those packages to an ideal building representing a reasonable approximation of best practice in all areas of building control. The difference between the current state of building controls and the ideal state is the assumed savings potential.

Of the 34 measures simulated, six measures showed the potential for over 2% site energy savings nationally. These measures include wider deadbands and night setback (7.8%), shortened HVAC schedules (7.1%), demand control ventilation (7.1%), reduced minimum VAV box terminal damper flow settings (6.5%), optimal start (5.9%), and supply air temperature reset (2.5%). Advanced rooftop unit fan controls achieved the highest electricity savings of all measures (4.0% of baseline energy consumption), but because of the additional natural gas consumed as a result of this measure, the overall savings was only 1.3%.

Using the three packages of measures representing the U.S. commercial building stock, the potential site energy savings across all 14 building types, representing 57% of the total energy consumed, is 29%. For individual building types at the national level, the potential savings ranged between 23% and 29% for 11 of the 14 building types, while the other three building types (Secondary Schools, StandAlone Retail, and Retail Dealership) achieved more than 40% savings nationally. Across all building types included in this study, the savings represents approximately 387,000 GWh (1.32 quadrillion Btu) of site energy savings, or 809,000 GWh (2.76 quadrillion Btu) of primary (or source) energy savings. A number of building types were not considered in this study because of lack of validated prototype building models and lack of relevance to the study. These building types can also benefit from many of the control measures identified in the report. If the savings are extrapolated to include all relevant building types that were not modeled, the savings may be in the range of 4 to 5 quadrillion Btu. This savings potential is equivalent to the per-capita energy consumption of 12 to 15 million people. For comparison, the total U.S. primary energy consumption across all sectors was 28.5 million GWh (97.4 quadrillion Btu) in 2015. This indicates that commercial building controls improvements are strategically important to meet and sustain reductions in national energy consumption.

Despite the expansiveness of the study, the following limitations exist.

1. Just over half of the commercial building sector square footage is represented with the set of modeled buildings used.

2. The first six EEMs investigated in this study represented the correction of an operational "fault" condition. Although limited information is available regarding the prevalence of faults in buildings, the prevalence of multiple faults and the severity of the fault levels for almost all faults is completely unknown. Therefore, some assumptions for which no data exists in the literature are guesses at best, and savings from their correction could use significant refinement, aided by additional research.

3. The extent to which the building models used in this study are representative of the existing building stock, whether baseline assumptions are accurate, and whether this kind of study would benefit from more diversity in baseline system types, control parameter settings, and other factors are not yet determined..

4. Additional data on controls across the buildings sector would improve the weighting of EEMs within packages and the estimates of the prevalence of opportunities for deploying various control measures, especially in office buildings.

5. Optimizing operations of individual components and optimizing whole-building operations can result in additional savings; however, the savings are generally low compared to savings resulting from improper operations. In addition, the level of effort to simulate and also deploy optimization solutions in buildings is high. Therefore, this study excluded a handful of optimization strategies that are not commonly used, but have the potential for higher energy savings.

While the results and conclusions of this study can help to ensure persistent building operations, addressing these limitations will provide further insights to the energy savings potential within the commercial building stock and the pathway to achieving these impacts.

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Acronyms and Abbreviations

°C	degree(s) Celsius
°F	degree(s) Fahrenheit
AEDG	Advanced Energy Design Guide
AERG	Advanced Energy Retrofit Guide
AHU	air-handing unit
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BAS	building automation system
Btu	British thermal unit
CBECS	Commercial Building Energy Consumption Survey
CDD	cooling-degree-day
cfm	cubic foot (feet) per minute
COP	coefficient of performance
CPP	critical peak pricing
DER	Distributed energy resources
DOAS	dedicated outdoor air system
DOE	U.S. Department of Energy
DP	differential pressure
DR	demand-response
DX	direct expansion
EEM	energy efficiency measure
EEV	electronic expansion valve
EMS	Emergency Management System
ERV	energy recovery ventilation
EUI	energy use intensity
ft	foot (feet)
ft^2 or sf	square foot (feet) ft^2
HDD	heating-degree-day
hr	hour(s)
HVAC	heating, ventilation, and air-conditioning
IECC	International Energy Conservation Code
in.	inch(es)
NOAA	National Oceanic and Atmospheric Administration
Pa	pascal(s)
PBA	principal building activity
PNNL	Pacific Northwest National Laboratory
quad	quadrillion British thermal units

RD&D	research, development, and deployment
RTU	rooftop unit
SAT	supply air temperature
VAV	variable air volume
VFD	variable-frequency drive
W	watt(s)

Contents

Figures

Tables

1.0 Introduction

In addition to consuming more energy than they should, commercial buildings also generally cannot maintain adequate comfort. As a result, inadequate sensing, monitoring, and control operations lead to significant energy waste (up to 30%). For example, over 85% of buildings representing about 43% of commercial sector building area do not have adequate control infrastructure (CBECS 2012) and still rely on time clocks, thermostats, and manual switches. Even buildings that have sophisticated building automation systems (BASs) do not typically use the full capabilities of the system, leading to many operational problems that result in significant wasted energy. It is possible to reduce energy consumption between 10% and 30% in the existing building stock by Re-tuning™, which improves and ensures persistence of proper building operations, and by fully deploying advanced controls measures (Fernandez et al. 2012; Fernandez et al. 2014). This savings is in addition to estimated savings of between 30% and 50% that can be achieved through deep energy retrofits (the combined savings is estimated to be between 40% and 60%[1]).

Re-tuning is a systematic process of detecting, diagnosing, and correcting operational problems with building systems and their controls in either semi-automated or fully-automated ways. Periodic Re-tuning of building controls and HVAC systems helps to reduce inefficient and faulty operations and improve building efficiency. The focus of this process is to identify and correct building operational problems that lead to energy waste at little cost; it might be thought of as a scaled-down retro-commissioning (RCx) process. Re-tuning is implemented primarily through BASs at little or no cost other than the labor required for making the necessary control changes. The Re-tuning approach has been shown to identify operational problems that can be corrected with low- or no-cost—and the impact is immediate (Brambley and Katipamula 2009; Mills 2009). Unlike the traditional RCx approach, which has a broader scope, Re-tuning primarily targets HVAC systems and their controls (Katipamula and Brambley 2008; Brambley and Katipamula 2009).

To achieve an advanced state of building control, several needs in the commercial buildings market must be addressed. In particular, technologies are needed to perform smart and automatic control of building systems so that these systems are scalable, reliable, and low cost. Often technologies, like BASs, that can be deployed to accommodate Re-tuning measures are very expensive to purchase and operate for smaller buildings (<50,000 sf). Furthermore, existing legacy systems solutions are lacking for the small commercial buildings market. As such, this continues to be an active area of research until controls infrastructure is a commodity product across building types that building owners and operators can purchase, easily install, and maintain on their buildings without the need for custom programming by specialized technicians.

This study was initiated to systematically estimate and document the potential savings through detailed simulation of the impact of properly deploying accurate sensors and advanced controls, including automated fault detection and diagnostics, by estimating the energy savings potential of these measures in the commercial buildings sector. Furthermore, the impact of DR measures to lower commercial building electric demand during critical peak pricing (CPP) events was investigated. This load reduction potential can help to facilitate the performance of grid services by buildings that may be of particular benefit under a scenario of higher penetration of distributed energy resources (DERs) (e.g., wind and solar photovoltaics). Both analyses rely on the simulation of individual measures and packages of measures in the U.S. Department of Energy's (DOE's) EnergyPlus building energy modeling software (U.S. DOE 2012). This study is a follow up to the previous DOE study conducted by TIAX (Roth et al. 2005).

[1] https://energy.gov/eere/buildings/advanced-energy-design-guides

1.1 Approach

Estimation of the national-level impact of controls and DR measures involves the simulation of packages of energy savings and DR measures in as many different DOE prototype building models as possible and in all 16 International Energy Conservation Code (IECC) climate zones. These simulation results are mapped by building type and by climate to the expected square footage of all equivalent or substantially similar buildings in similar climates documented in the 2012 Commercial Building Energy Consumption Survey (2012 CBECS, EIA). Packages of measures are developed based on Pacific Northwest National Laboratoy's (PNNL's) internal documentation of the prevalence of opportunities to implement individual measures on over 130 buildings that have been surveyed in the past 10 years for the Re-tuning program (Katipamula 2015). Three packages are developed that are intended to represent buildings with different energy footprints: (1) an efficient building defined as having the most common and some advanced measures installed, (2) a typical (average) building defined as having a handful of obvious and/or easy-to-implement measures installed, and (3) an inefficient building defined as having no control measures installed. Savings are evaluated by comparing the energy consumption of each of these buildings to an "ideal" building that has all of the measures implemented (excluding a few that are expected to not be economically sound or worthwhile investments based on individual measure simulation results).

Some of the measures are geared toward the correction of operational faults that have been added to the baseline models to represent inefficient buildings. Simulation of individual measures is performed first, to evaluate and understand the energy savings potential of each measure and to verify that each measure is simulated correctly in each building type. In some cases, either due to complex modeling strategies or limitations and "bugs" in EnergyPlus, a few measures are excluded for certain prototypes, both in the individual measure simulation results presented in this report as well as in the results derived from packages of measures.

A smaller set of DR measures is simulated as well. Four DR measures use different strategies to attempt to reduce the building's cooling load. This is important because the CPP events are scheduled in this study to coincide with the hottest weekdays of the year. Two additional measures are a measure to dim the lights (or to shut off a fraction of the building lights) and a measure to curtail temporarily energy-intensive processes associated with maintaining refrigeration systems (applicable to only one building type). Demand-response packages are created by selecting the top performing cooling energy reduction measure and pairing with either the lighting measure or the refrigeration measure, depending on the building type. Packaging more than one cooling energy reduction measure together is expected to cause unacceptable disruptions in occupant comfort.

1.2 Content and Organization

Including the introduction (Section 1.0), this study consists of eight sections. Section 2.0 describes the methodology used to estimate the national savings potential of the measures considered by describing the mapping of CBECS building samples and square footages to EnergyPlus prototype models for simulation. Each of the nine prototype building models used in this study and the changes that have been made to the building models to accommodate the simulation of the full set of energy efficiency measures (EEMs) are described in Section 3.0. Section 4.0 provides a description of the individual efficiency and DR measures considered for this study, including details regarding how each measure was modeled in EnergyPlus. The distribution of individual EEMs within three packages of measures used to calculate the national savings potential are discussed in Section 5.0. The results of the simulations—first describing the savings from individual EEMs by measure, by building type, and in terms of nationally-aggregated summaries; then describing the electricity demand savings derived from DR measures; and finally presenting the national savings estimates derived from simulation of the packages of measures, are presented in Section 6.0.

Section 7.0 summarizes the results and conclusions with a description of the limitations of the current study. Finally, references are listed in Section 8.0.

2.0 National Savings Calculation Methodology

The calculation of potential national energy savings from the adoption of sensors and controls measures is outlined in this section. The 2012 CBECS forms the basis of the estimation of total existing building square footage. The 2012 CBECS encompasses 5,557 buildings across the country that are strategically selected to be representative of the national existing building stock. These buildings are assigned weights according to how many existing buildings are representative of the surveyed building within the region it is located. To calculate the national energy savings potential of measures, CBECS-calculated square footage was mapped to EnergyPlus simulations, both by building type and by climate.

2.1 Mapping CBECS by Building Type

Commercial buildings are categorized by the 2012 CBECS according to principal building activity (PBA). There are 17 PBAs, many of which include subcategories. Nine prototype building models were selected for simulation as part of this study: Supermarket, Large Hotel, StandAlone Retail, Strip Mall Retail, Small Office, Medium Office, Large Office, Primary School, and Secondary School. These building types were selected because of the availability of detailed EnergyPlus reference models and the potential for savings. Furthermore, the selection was based on the PBAs by the category or subcategory that could be reasonably represented by one of the nine prototype models, based on space usage, anticipated building internal loads, and anticipated types of heating, ventilation, and air-conditioning (HVAC) system. Figure 2.1 shows the mapping process. The far left column lists each of the PBAs, in some cases broken into subcategories of PBA. The applicable PBAs that could be mapped to an EnergyPlus model are listed in black, while the PBAs that could not be mapped are listed in red. In two cases, an intermediate criterion was needed for the mapping. For office buildings, all subcategories of office buildings were combined, then the buildings were segregated according to square footage; buildings under 25,000 ft^2 were assigned to the Small Office category, buildings between 25,000 and 100,000 ft^2 were assigned to the Medium Office category, and buildings over 100,000 ft^2 were assigned to the Large Office category.

Another intermediate criterion was used for mapping the Inpatient Health Care (Hospital) PBA. For hospitals, it was determined that only the administrative portion of the building could be mapped to the Large Office prototype. To determine an estimated square footage of the administrative portion, the study investigated the space usage types and HVAC system connections for each zone in the Hospital building prototype EnergyPlus model, which was not otherwise used for this study. Offices, corridors, and nurses' lobbies were grouped as administrative zones. These zones were controlled by one of two variable air volume (VAV) units that did not control other patient rooms, laboratories, and operating areas. The total fraction of the building dedicated to these administrative spaces was 69% of the total floor area. This is the fraction of the square footage used for the CBECS mapping. Other notable mapped PBAs include Outpatient Healthcare being mapped to the Medium Office prototype, Food Sales:Convenience Store (with or without a gas station) being mapped to Supermarket, and Retail:Dealership being mapped to StandAlone Retail. In all, the PBAs that are mapped to prototype models represent 51.6% of total commercial building sector square footage and 56.8% of commercial building sector energy consumption.

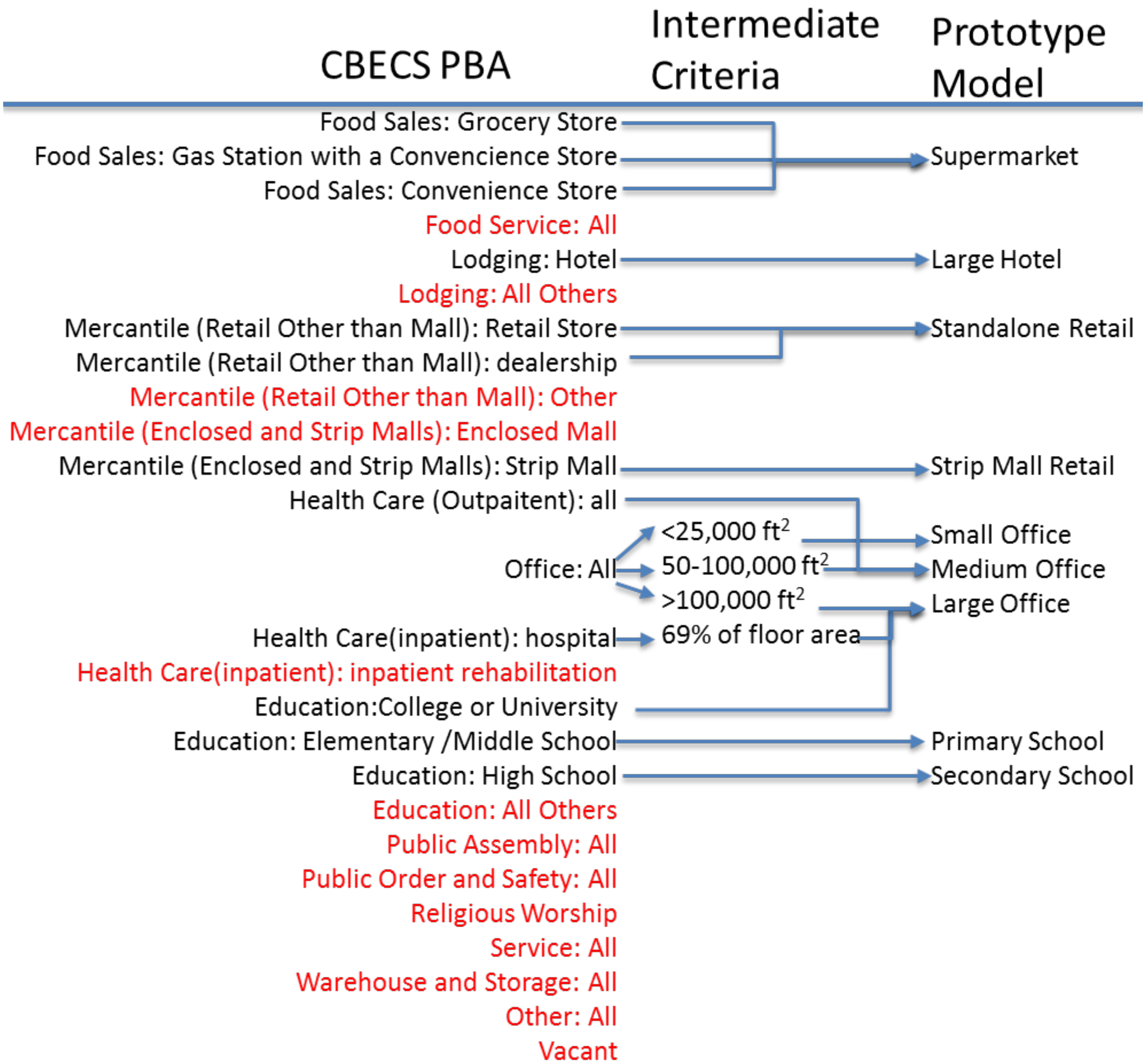

Figure 2.1. Mapping from the 2012 CBECS Principal Building Activity to the EnergyPlus Prototype

Principal building activities (PBAs) in the 2012 commercial building energy consumption survey (CBECS) do not necessarily match the available EnergyPlus prototype models. A mapping based on similar building types and in some cases, building size was undertaken to later assign floor area weights to the results generated from each prototype model. Note: black typeface indicates mapping of PBA to an EnergyPlus model while red indicates PBAs that could not be mapped and are thus not represented in this study).

2.2 Mapping CBECS by Climate

To estimate national energy savings, the impact of unique climates on the potential energy savings from each of the measures must be taken into account. This study used the IECC climate zones as delineations of unique climate regions that should be considered for building energy simulation. There are 16 IECC climate zones, which are presented in Table 2.1, along with their associated alphanumeric code; the code delineates a zone (1–8) with "1" being the hottest and "8" being the coldest on an annual basis. A letter (A, B, or C) accompanies most climate codes to indicate humidity regimes; A is humid, B is dry, and C is marine climate. One city in each climate zone is used for simulation, and these cities are specified in Table 2.1, along with the heating-degree-days, cooling-degree-days, and summer humidity conditions in those cities.

Table 2.1. Representative Cities and Climate Details

A representative U.S. city was selected in each of 16 International Energy Conservation Code (IECC) climate zones and a corresponding typical meteorological year 3 (TMY3) weather file was selected for simulation in EnergyPlus. Annual heating degree-days, cooling degree-days, and average summer dewpoints are provided based on analyses of the TMY3 files.

	IECC Climate Zone		Heating-Degree-Days (^{0}F-days)		Cooling-Degree-Days (^{0}F-days)		Dewpoint (^{0}F)
Representative City	Code	Description	HDD55	HDD65	CDD55	CDD50	June–September Average
Miami, FL	1A	Very Hot, Humid	6	130	7,585	9,404	72
Houston, TX	2A	Hot, Humid	626	1,557	5,403	6,942	70
Phoenix, AZ	2B	Hot, Dry	307	1,200	6,712	8,324	52
Atlanta, GA	3A	Warm, Humid	1,486	3,129	3,517	4,792	65
Los Angeles, CA	3B-CA	Warm, Dry, California	82	1,442	2,636	4,380	58
Las Vegas, NV	3B - other	Warm, Dry	838	2,356	5,272	6,625	38
San Francisco, CA	3C	Warm, Marine	743	3,497	947	2,208	51
Baltimore, MD	4A	Mixed, Humid	2,818	4,862	2,710	3,719	62
Albuquerque, NM	4B	Mixed, Dry	2,505	4,494	2,810	3,810	47
Seattle, WA	4C	Mixed, Marine	2,208	5,003	959	1,824	50
Chicago, IL	5A	Cool, Humid	4,099	6,405	2,111	2,978	58
Boulder, CO	5B	Cool, Dry	3,733	6,141	1,833	2,687	44
Minneapolis, MN	6A	Cold, Humid	5,503	7,898	1,907	2,717	57
Helena, MT	6B	Cold, Dry	5,063	7,880	1,159	1,841	42
Duluth, MN	7	Very Cold	7,094	10,107	796	1,351	51
Fairbanks, AK	8	Subarctic	10,903	14,096	491	918	43

The CBECS database does not have a climate characterization that is consistent with the set of 16 IECC climate zones. In fact, CBECS does not categorize by climate at all; instead, it provides only the census division (e.g., "Mountain," "East South Central"), total annual heating-degree-days (HDDs), and total annual cooling-degree-days (CDDs) as hints to the applicable IECC climate zone. The study used the following climate mapping methodology, relying only on the HDDs and CDDs provided for each CBECS entry:

1. Assembly of National Oceanic and Atmospheric Administration (NOAA) monthly weather data from 360 weather stations. The data consist of reported HDDs and CDDs at the base temperature of 65°F

for year 2012. In collecting these degree-days, the approach matches the time period used to determine the degree-days in 2012 CBECS.

2. Assigning each building to one of the 360 weather stations by calculating which weather station (within the given CBECS census region) is the closest using the best linear least squares fit of the CBECS data to the weather data. Equation (2.1) calculates the U.S. weather station closest to (or with minimum “distance” from) the CBECS building:

$$"Distance" = \sqrt{(HDD_2 - HDD_1)^2 + (CDD_2 - CDD_1)^2} \tag{2.1}$$

3. Attributing an IECC climate zone to each CBECS entry according to the climate zone designated to the assigned weather station.

Table 2.2 shows the final mapping of the 2012 CBECS square footage by the prototype model and the IECC climate zone location. The numbers were normalized by dividing by the total commercial sector square footages from 2012 CBECS. Thus, the sum of the entries in the table is equal to the fraction of 2012 CBECS square footages represented by the nine EnergyPlus prototype models (51.6%). Also note that two climate locations are modeled in IECC Climate Zone 3B (Los Angeles and Las Vegas). The weights for each building type in Climate Zone 3B are split equally between these two locations for the national savings estimates.

Table 2.2. Share of Total Commercial Building Stock Square Footage by Building Type and IECC Climate Zone Location

The 2012 Commercial Building Energy Consumption Survey (CBECS) was used to estimate the proportion of the total commercial building sector floor area represented by each building type(s) in each climate zone. Because CBECS does not provide a comparable climate zone for buildings in its database, heating and cooling degree-days provided by CBECS were used in a methodology developed to map each building to a climate zone.

Prototype Model and *additional mapped building types*	Large Office, *College/ University, Hospital (Administrative Portion)*	Medium Office, *Outpatient Healthcare*	Small Office	StandAlone Retail, *Retail Dealership*	Strip Mall Retail	Primary School	Secondary School	Large Hotel	Supermarket, *Convenience Stores*	Totals
1A (Miami)	0.10%	0.08%	0.06%	0.22%	0.14%	0.05%	0.03%	0.01%	0.01%	**0.69%**
2A (Houston)	0.89%	0.59%	0.57%	0.70%	0.82%	0.72%	0.32%	0.36%	0.10%	**5.07%**
2B (Phoenix)	0.23%	0.05%	0.04%	0.15%	0.10%	0.08%	0.06%	0.02%	0.00%	**0.74%**
3A (Atlanta)	1.23%	0.66%	0.63%	0.96%	0.65%	0.93%	0.27%	0.55%	0.15%	**6.04%**
3B (Las Vegas)	0.44%	0.46%	0.39%	0.26%	0.36%	0.41%	0.12%	0.20%	0.14%	**2.77%**
3B-CA (Los Angeles)	0.44%	0.46%	0.39%	0.26%	0.36%	0.41%	0.12%	0.20%	0.14%	**2.77%**
3C (San Francisco)	0.40%	0.14%	0.11%	0.05%	0.12%	0.06%	0.00%	0.06%	0.03%	**0.96%**
4A (Baltimore)	2.74%	1.25%	0.98%	1.03%	1.13%	1.29%	0.77%	0.68%	0.21%	**10.07%**
4B (Albuquerque)	0.44%	0.39%	0.38%	0.09%	0.10%	0.26%	0.12%	0.18%	0.06%	**2.03%**
4C (Seattle)	0.24%	0.24%	0.12%	0.27%	0.11%	0.10%	0.08%	0.00%	0.03%	**1.17%**
5A (Chicago)	2.21%	1.47%	1.27%	1.15%	1.28%	1.38%	0.88%	0.33%	0.31%	**10.28%**
5B (Denver)	1.03%	0.74%	0.45%	0.54%	0.41%	0.63%	0.27%	0.12%	0.15%	**4.34%**
6A (Minneapolis)	0.59%	0.37%	0.39%	0.31%	0.18%	0.44%	0.33%	0.09%	0.07%	**2.76%**
6B (Helena)	0.19%	0.24%	0.23%	0.12%	0.04%	0.17%	0.10%	0.08%	0.03%	**1.21%**
7 (Duluth)	0.07%	0.10%	0.10%	0.12%	0.04%	0.10%	0.05%	0.13%	0.02%	**0.73%**
8 (Fairbanks)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**0.00%**
Totals	**11.24%**	**7.25%**	**6.09%**	**6.24%**	**5.84%**	**7.03%**	**3.51%**	**3.00%**	**1.44%**	**51.63%**

To calculate national savings by building type (across all climates) for either an EEM or a package of EEMs, the building energy savings attributable to reductions in electricity was calculated according to Equation (2.2) and the building energy savings attributable to reductions in natural gas was calculated according to Equation (2.3).

$$Savings, elec_{BT} = 1 - \frac{\sum_{CZ}\left(EUI(base, elec) * weight - EUI(EEM, elc) * weight\right)}{\sum_{CZ}\left(EUI(base) * weight\right)} \quad (2.2)$$

$$Savings, gas_{BT} = 1 - \frac{\sum_{CZ}\left(EUI(base, gas) * weight - EUI(EEM, gas) * weight\right)}{\sum_{CZ}\left(EUI(base) * weight\right)} \tag{2.3}$$

where the subscript BT denotes savings for a given building type, CZ denotes the summation across all climate zones, and “base” refers to the baseline model without the EEM or package of EEMs applied.

For total national savings across all building types and climate zones, the following two equations (Equations (2.4) and (2.5)) were used, which mirror the previous two equations, but sum across building types as well. Note that for total national savings for a given EEM, the denominator sums the energy use intensities (EUIs) and weights across all building types, even if the measure was not applicable for that building type. This reduced the national savings for measures that were less globally applicable.

$$Savings, elec = 1 - \frac{\sum_{BT}\sum_{CZ}\left(EUI(base, elec) * weight - EUI(EEM, elc) * weight\right)}{\sum_{BT}\sum_{CZ}\left(EUI(base) * weight\right)} \tag{2.4}$$

$$Savings, gas = 1 - \frac{\sum_{BT}\sum_{CZ}\left(EUI(base, gas) * weight - EUI(EEM, gas) * weight\right)}{\sum_{BT}\sum_{CZ}\left(EUI(base) * weight\right)} \tag{2.5}$$

3.0 Building Prototype Models

This section describes each of the EnergyPlus building models that were used for the simulation of each of the efficiency and DR measures simulated in this report. In general, the models were either taken directly from the commercial building prototypes (U.S. DOE 2016) developed by DOE for the Building Energy Codes Program, or from further iterations of these models—for example, from the set of Advanced Energy Design Guides (AEDG 2008; AEDG 2011; AEDG2015) published by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) with support from DOE. These models formed a starting point for the development of the baseline models used in this study. Several changes were needed for each model to properly estimate the savings from the full suite of efficiency measures that were investigated. This section describes in detail each of the source models and the changes that were made for this study.

3.1 Small Office

The EnergyPlus model for Small Office was developed by modifying the prototype model used in the Advanced Energy Design Guide (AEDG 2011). The prototype is a two-story building with 20,000 ft^2 of total floor area. Figure 3.1 reveals an axonometric projection of the building shape plus a diagram of floor zoning, which is identical on the first and second floors. The diagram shows that the building has 4 ft plenum spaces above each floor (12 ft floor-to-ceiling height) and regular placement of windows for a total window-to-wall fraction of 20%. Perimeter zones are delineated by the orientation of each façade. Each perimeter zone is 12 ft deep. A core zone occupies 58% of the area of each floor. Each zone includes thermal mass that is specified as 2 ft^2 of 6 in. thick wood per square foot of floor space.[1]

The Small Office building represents buildings constructed in the 1990s. Specifically, ASHRAE Standard 90.1-1999 code was used for the wall, roof, and window construction, as shown in Table 3.1. The original intent was to use performance requirements specified in ASHRAE Standard 90.1-2004. However, because ASHRAE Standard 90.1-1999 has even more stringent requirements than Standard 90.1-2004 in some climates, ASHRAE 90.1-1999 was used instead for this analysis. Exterior walls are constructed of 8 in. concrete blocks with rigid insulation in varying thickness required to meet climate-zone–dependent code requirements and an interior ½ in.-thick gypsum board. The roof is a built-up roof with rigid insulation above a metal deck. The peak infiltration rates of outdoor air are 0.2 cfm/ft^2 of exterior surface area and coincide with the scheduled shutdown of rooftop unit (RTU) fans. When the fans are on, infiltration rates drop to one-quarter of this level.

[1] Internal mass was not included in the AEDG model, but was added for this study to be consistent with the Large Office model.

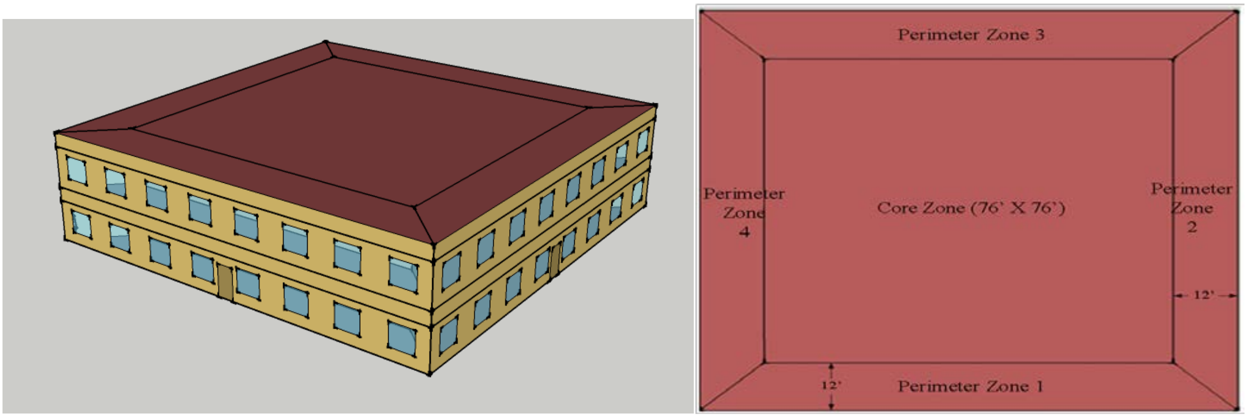

Figure 3.1. Small Office Prototype Building Shape and Zoning Diagram

Table 3.1. Envelope Characteristics for the Baseline Models

Location	Roof U-Values (Btu/hr-sf-F)	Wall U-Values (Btu/hr-sf-F)	Window U-Values (Btu/hr-sf-F)	Window Solar Heat Gain Coeff (SHGC)
Miami, FL	0.074	1.000	1.220	0.25
Houston, TX	0.066	0.340	1.220	0.25
Phoenix, AZ	0.046	0.410	1.220	0.25
Atlanta, GA	0.072	0.290	0.720	0.25
Los Angeles, CA	0.100	1.000	1.220	0.44
Las Vegas, NV	0.048	0.290	1.220	0.25
San Francisco, CA	0.088	0.490	0.720	0.39
Baltimore, MD	0.058	0.120	0.590	0.36
Albuquerque, NM	0.059	0.190	0.720	0.36
Seattle, WA	0.064	0.100	0.720	0.39
Chicago, IL	0.053	0.100	0.590	0.39
Denver, CO	0.051	0.140	0.590	0.39
Minneapolis, MN	0.045	0.071	0.520	0.39
Helena, MT	0.049	0.079	0.520	0.39
Duluth, MN	0.040	0.061	0.520	0.49
Fairbanks, AK	0.031	0.047	0.520	0.49

Internal loads include lighting at a density of 1.36 W/ft^2 and interior electric equipment at a density of 0.75 W/ft^2 in each zone. Occupant densities peak at 200 ft^2 per occupant.[3] Lighting, equipment, and occupancy schedules on weekdays, Saturdays, and Sundays are shown in Figure 3.2. Exterior lighting includes 4.89 kW of parking lot lights and 3.29 kW of other exterior building lights on photocell sensors.

[2] Lighting power densities were 1.0 W/ft^2 in the AEDG model, but were changed for this work to be consistent with the Large Office model.
[3] Occupant densities were 226 ft^2 per person in the AEDG model, but were changed for this work to be consistent with the Medium Office model.

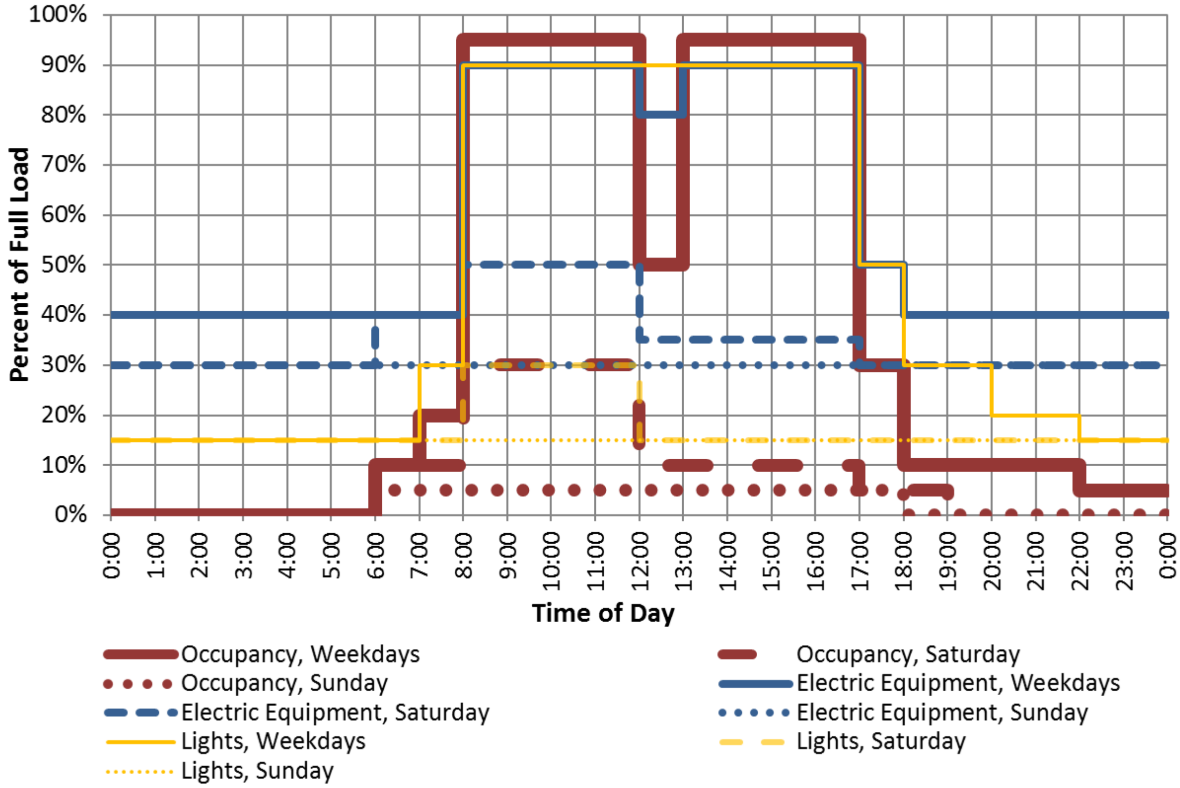

Figure 3.2. Small, Medium and Large Office – Schedules of Internal Loads

HVAC is provided for each zone via single-zone packaged RTUs. The RTUs have single-speed direct expansion (DX) cooling coils with rated coefficients of performance (COPs) of 2.73[4] and gas heating coils with rated thermal efficiency of 80%. RTU fans are constant volume fans. Zone thermostat setpoints are set at 73°F for cooling and 71°F for heating.[5] Night setback and setup temperature setpoints are 65°F and 80°F, respectively. Minimum outdoor air fractions for ventilation are set constant at 15%. Outdoor air economizers are used in all IECC climate zones, except 1a, 1b, 2a, 2b, 3a, 3b, and 4a. Operation schedules for the RTU fans, as well as hours of operation for occupied thermostat setpoints, run from 5:00 a.m. to 10:00 p.m. on weekdays and from 5:00 a.m. to 6:00 p.m. on Saturdays.[6] For domestic hot water, the building uses a 75-gallon natural-gas-fired hot water tank. Hot water use equipment has been added to the model so that cold domestic water is mixed with hot water at the point of use. Bathroom exhaust fans have been added to the two core zones of the model with constant “on” schedules for modeling control savings derived from scheduling exhaust fans.

Some additional faults are added to the Small Office baseline model to facilitate simulation of several fault correction measures. These include the addition of a low refrigerant charge fault, which lowers the COP of the RTUs’ cooling coils by 10% and their cooling capacity by 20%. Temperature bias faults of +3°C and -3°C are added to all outdoor air temperature sensors and to all return air temperature

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[4] Note that the COP for the baseline is lower than the 3.033 COP in the AEDG model because of a fault that has been added to the baseline to simulate low refrigerant charge.

[5] Thermostat setpoints were 70°F for heating and 75°F for cooling in the AEDG model, but were changed to 71°F and 73°F, respectively, for consistency with the Large Office model.

[6] Morning start-up time was 6:00 a.m. Monday through Saturday in the AEDG model, but was changed to 5:00 to provide a standardized 3 hours of morning start-up time prior to occupancy.

sensors, respectively. These temperature bias faults only affect the economizer operation. To simulate poor damper seals, the maximum outdoor air fraction was limited to 70%.

Additional advanced controls were added to better model the impact of turning on and off air systems that affect building pressurization. These include packaged air-handling units (AHUs) and exhaust fans. A common control of AHUs is to establish a differential between outdoor airflow and relief airflow, such that the AHU (and by extension the building) is always bringing in slightly more outdoor air than is being exhausted when the AHU is on, in an attempt to maintain slightly positive building pressure. This type of control is embodied in the infiltration schedule in the AEDG model, which sets infiltration to 100% when the fan is off, but decreases infiltration to 25% during the hours when the fan is scheduled to run. This schedule, however, is fixed and does not respond to the AHU fans coming on after-hours for night-cycle operation. New Energy Management System (EMS) code has been added that dynamically changes the base infiltration fraction between 25% and 100% according to the fraction of the building's AHUs that are on. For example, during night-cycle operation, if two of the Small Office's 10 AHUs come on to maintain zone temperatures, the infiltration fraction will drop from 100% to 85%. If eight of the 10 AHUs come on, the infiltration fraction will drop to 40%. A further reduction to the infiltration fraction is achieved if and when the bathroom exhaust fans shut off under the assumption that all air that is exhausted from the building must be made up through infiltration. The reduction fraction is calibrated such that the total volumetric flow rate of infiltration reduced to the entire building is equal to the total flow rate of air that the fans exhaust when they are on. This control is necessary to accurately model savings from a measure that shuts off the exhaust fans at night.

3.2 Medium Office

The EnergyPlus model for Medium Office was developed by modifying the prototype model used in the Advanced Energy Design Guide (AEDG 2011). The Medium Office prototype is a three-story building with 53,600 ft^2 of total floor area. Figure 3.3 is an axonometric projection of the building shape and Figure 3.4 is a diagram of floor zoning, which is identical on all three floors. Figure 3.3 shows that the building has 4 ft plenum spaces above each floor (13 ft floor-to-ceiling height) and a continuous band of windows for a total window-to-wall fraction of 33%. Perimeter zones are delineated by the orientation of each façade. Each perimeter zone is 15 ft deep. A core zone occupies 60% of the area of each floor. Each zone includes thermal mass that is specified as being 2 ft^2 of 6 in.-thick wood per square foot of floor space.

The Medium Office building represents buildings constructed in the 1990s. ASHRAE 90.1-1999 was the code used for wall, roof, and window construction for the same reasons as the Small Office model. Exterior walls are steel framed (stucco-exterior) with rigid insulation in varying thicknesses required to meet climate-zone–dependent code requirements and an interior 5/8 in.-thick gypsum board. The roof is a built-up roof with rigid insulation above a metal deck. Peak infiltration rates of outdoor air are 0.2 cfm/ft^2 of exterior surface area and coincide with scheduled shutdown of VAV system fans. When the fans are on, infiltration rates drop to one-quarter of this level.

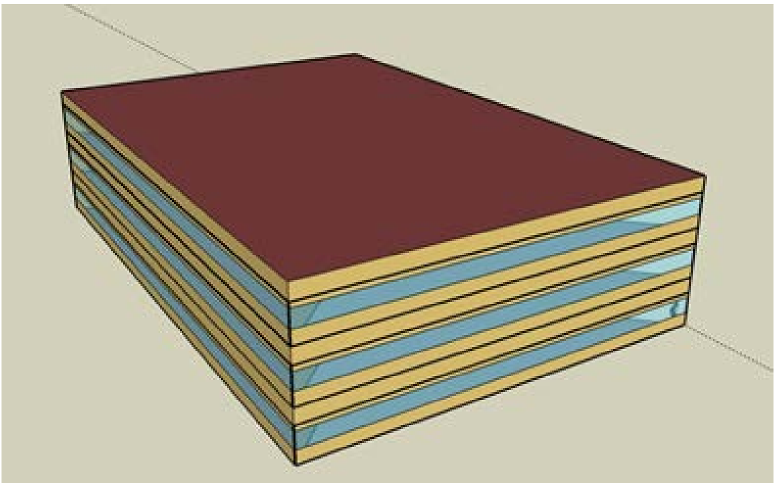

Figure 3.3. Medium Office Prototype Building Shape

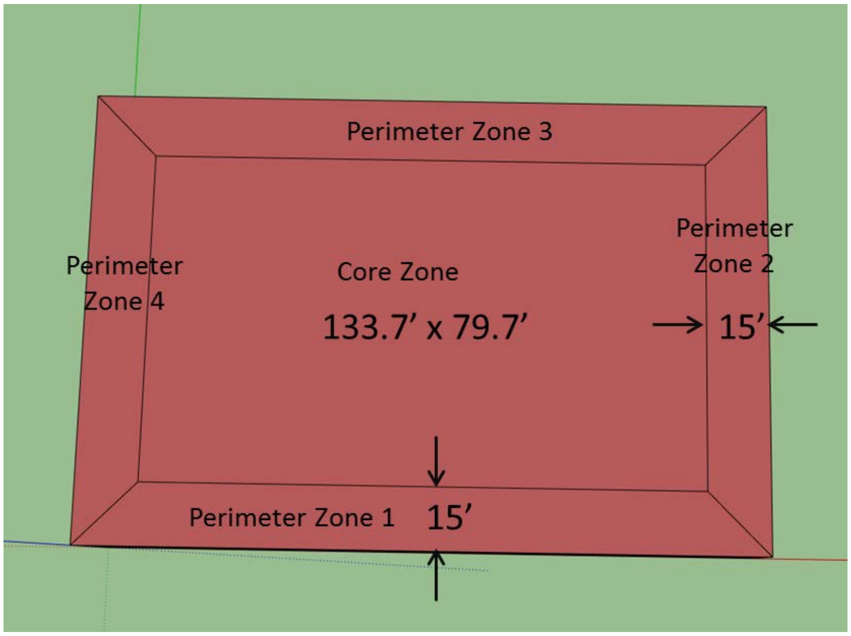

Figure 3.4. Medium Office Thermal Zoning

Internal loads include lighting at a density[7] of 1.36 W/ft^2 and interior electric equipment at a density of 0.75 W/ft^2 in each zone. Occupant densities peak at 200 ft^2 per occupant. Lighting, equipment, and occupancy schedules on weekdays, Saturdays, and Sundays are shown in Figure 3.2. Exterior lighting includes 13.12 kW of parking lot lights and 7.56 kW of other exterior building lights on photocell sensors.

HVAC is provided for each floor via a packaged VAV system. The packaged VAV air handlers have two-speed DX cooling coils with rated COPs of 2.61[8] and gas heating coils with a rated thermal efficiency

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[7] Lighting power densities were 1.0 W/ft^2 in the AEDG model, but were changed for this work to be consistent with the Large Office model.

[8] Note that the COP for the baseline is lower than the 2.9 COP in the AEDG model because of a fault that has been added to the baseline to simulate low refrigerant charge.

of 80%. VAV terminal boxes are equipped with electric reheat coils for final conditioning. Minimum VAV airflow fractions for each zone are set at 40% of the maximum flows, which are autosized in EnergyPlus. Supply air temperature setpoints for each VAV system are constant at 55°F year-round. Static pressure control is implicitly controlled to a constant setpoint via a constant fan pressure rise of 1120.5 Pa. Zone thermostat setpoints are set at 73°F for cooling and 71°F for heating.[9] Night setback and setup temperature setpoints are 65°F and 80°F, respectively. Minimum outdoor air fractions for ventilation are set constant at 15%. Outdoor air economizers are used in all IECC climate zones, except 1a, 1b, 2a, 2b, 3a, 3b, and 4a. Operation schedules for VAV supply fans, as well as hours of operation for occupied thermostat setpoints, run from 5:00 a.m. to 10:00 p.m. on weekdays and from 5:00 a.m. to 6:00 p.m. on Saturdays.[10] For domestic hot water, the building uses a 200-gallon natural-gas-fired hot water tank. Hot water use equipment has been added to the model so that cold domestic water is mixed with hot water at the point of use. Bathroom exhaust fans have been added to the three core zones of the model with constant "on" schedules for the purpose of modeling control savings from adding schedules to exhaust fans.

Some additional faults were added to the Medium Office baseline model to facilitate simulation of several fault correction measures. These include the addition of a low refrigerant charge fault, which lowers the COP of the VAV systems' DX cooling coils by 10% and their cooling capacity by 20%. Temperature bias faults of +3°C and -3°C are added to all outdoor air temperature sensors and to all return air temperature sensors, respectively. To simulate poor damper seals, the maximum outdoor air fraction is limited to 70%.

Some additional advanced control of infiltration rates has been added to better model the impact of turning on and off air systems that affect building pressurization. The strategy used for these changes is discussed in detail Section 3.1.

3.3 Large Office

The Large Office prototype is a four-story building with 200,000 ft^2 of total floor area. Figure 3.5 is an axonometric projection of the building shape and Figure 3.6 is a diagram of floor zoning, which is identical on all four floors. Figure 3.5 shows that the building has 4 ft plenum spaces above each floor (13 ft floor-to-ceiling height) and a continuous band of windows for a total window-to-wall fraction of 40%. Perimeter zones are delineated by the orientation of each façade. Each perimeter zone is 15 ft deep. A core zone occupies 60% of the area of each floor. An additional 2,860 ft^2 conference room and a 429 ft^2 computer room are also located in the interior of the top floor. The bottom three floors each have a computer room, but do not have the additional conference room. Each zone includes thermal mass that is specified as 2 ft^2 of 6 in thick wood per square foot of floor space.

The Large Office building also represents buildings constructed in the 1990s and uses ASHRAE 90.1-1999 for wall, roof, and window construction for the same reasons discussed in the Small Office and Medium Office model sections. Exterior walls are steel framed (stucco-exterior) with rigid insulation in varying thickness required to meet climate-zone–dependent code requirements and an interior 5/8 in.-thick gypsum board. The roof is a built-up roof with rigid insulation above a metal deck. Peak infiltration rates of outdoor air are 0.094 cfm/ft^2 of exterior surface area and coincide with scheduled shutdown of VAV system fans. When the fans are on, infiltration rates drop to one-quarter of this level.

[9] Thermostat setpoints were 70°F for heating and 75°F for cooling in the AEDG model, but were changed to 71°F and 73°F, respectively, for consistency with the Large Office model.
[10] Morning start-up time was 6:00 a.m. Monday through Saturday in the AEDG model, but was changed to 5:00 a.m. to provide a standardized 3 hours of morning start-up time prior to occupancy.

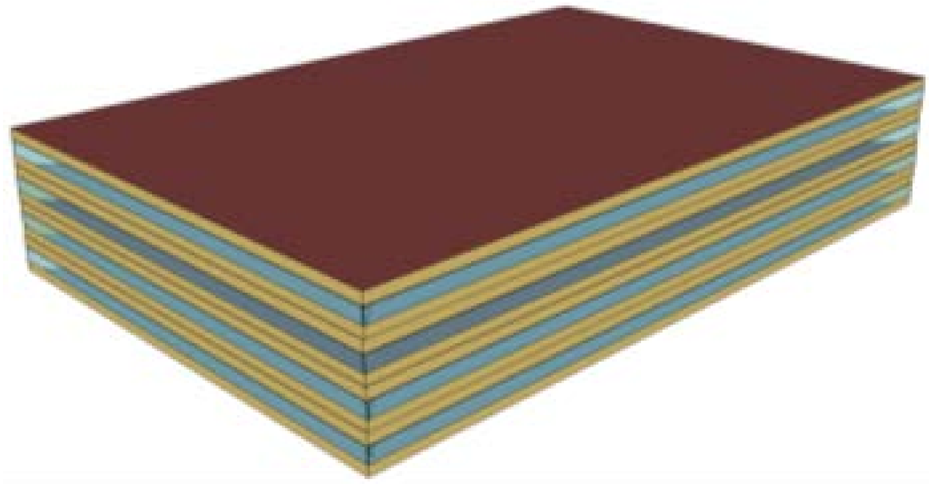

Figure 3.5. Large Office Building Shape

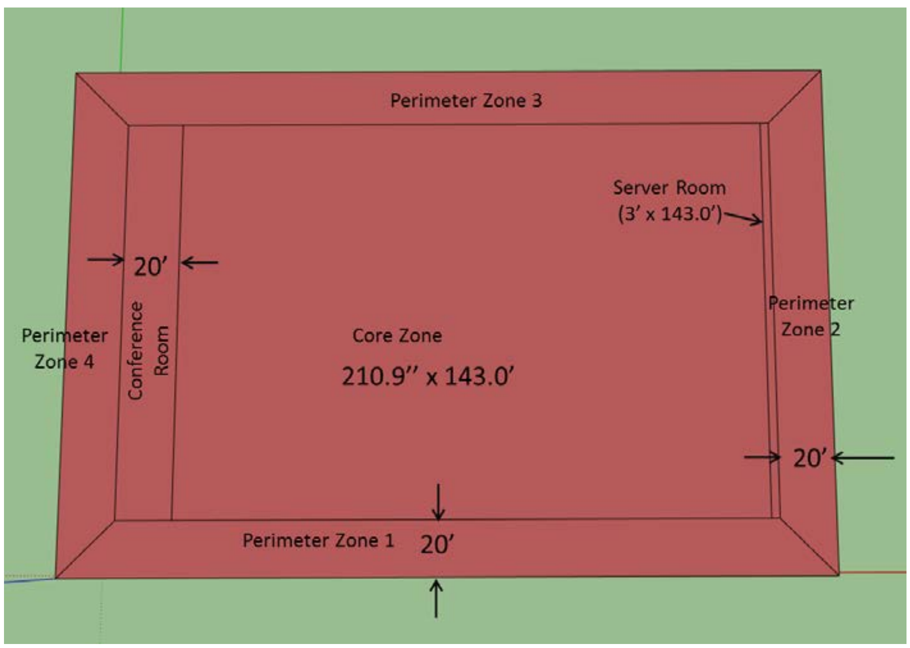

Figure 3.6. Large Office Thermal Zoning

Internal loads include lighting at a density of 1.33 W/ft^2 and interior electric equipment at a density of 0.75 W/ft^2 in each zone, except for computer rooms, which have a density of 25 W/ft^2. Occupant densities peak at 194 ft^2 per occupant in all zones except conference zones (which peak at 22 ft^2 per person) and computer rooms (which have no occupancy). Lighting, equipment, and occupancy schedules on weekdays, Saturdays, and Sundays are shown in Figure 3.2. Exterior lighting includes 23.52 kW of parking lot lights and 10.12 kW of other exterior building lights on photocell sensors.

HVAC is provided for each floor via built-up VAV air handlers. The air handlers have chilled water cooling coils and hot water heating coils. VAV terminal boxes are equipped with hot water reheat coils for final conditioning. Minimum VAV airflow fractions for each zone are set at 40% of the maximum flows, which are autosized in EnergyPlus. Supply air temperature setpoints for each VAV system are constant at 55°F year-round. Static pressure control is implicitly controlled to a constant setpoint via a constant fan pressure rise of 1,500 Pa. Zone thermostat setpoints are set at 73°F for cooling and 71°F for heating. Night setback and setup temperature setpoints are 65°F and 80°F, respectively. Minimum outdoor air fractions for ventilation are set constant at 15%. Outdoor air economizers are used in all IECC climate zones, except 1a, 1b, 2a, 2b, 3a, 3b, and 4a. Operation schedules for VAV supply fans, as well as hours of operation for occupied thermostat setpoints, run from 5:00 a.m. to 10:00 p.m. on weekdays and from 5:00 a.m. to 6:00 p.m. on Saturdays.[11]

The building has a central plant that consists of two equal-sized natural-gas-fired boilers (67% thermal efficiency) that heat a primary hot water loop fed by a constant-speed pump. A secondary loop served by a variable-speed pump delivers the hot water to VAV terminal box reheat coils. The hot water primary loop is controlled to meet a constant-supply setpoint of 180°F.

Two equal-sized chillers (5.2 rated COP) cool a primary chilled water loop fed by a constant-speed pump. A secondary loop served by a variable-speed pump delivers chilled water to the cooling coils of the building's AHUs. The chilled water primary loop is controlled to meet a constant-supply setpoint of 44°F.

A constant-speed pump delivers water from the chillers' condensers to two cooling towers, each with constant-speed fans. The boilers, chillers, and cooling towers are staged to meet their respective loads.

For domestic hot water, the building uses a 600-gallon natural-gas-fired hot water tank. Hot water use equipment has been added to the model so that cold domestic water is mixed with hot water at the point of use. There are bathroom exhaust fans located in each of the core zones of the model with constant "on" schedules.

Additional faults were added to the Large Office baseline model to facilitate simulation of several fault correction measures. These include an EMS program (discussed in the description for Measure 03) that simulates leaking AHU hot water coil valves by adding a fixed 2°C of heating across the hot water coil whenever the fan and the hot water loop are active. Temperature bias faults of +3°C and -3°C are added to all outdoor air temperature sensors and to all return air temperature sensors, respectively. To simulate poor damper seals, the maximum outdoor air fraction is limited to 70%. This model is also modified to include a run of indoor hot water piping that spans the long dimension of the building, located in the plenum space above each floor. Ninety percent of this pipe is insulated, while 10% is uninsulated. The purpose of this addition is to more accurately model the effects of hot water temperature reset.The primary loop hot water, chilled water, and condenser water pumps have been configured in this model to be interlocked with the status of the equipment they serve. For example, when a chiller shuts off, its primary pump shuts off as well. Additional EMS code has been added, however, to keep the secondary loop chilled water and hot water pumps always on whenever their respective primary equipment (chillers and boilers) are available to run (which is all the time). This is meant to simulate common control of the secondary loop pumps, wherein the pumps do not receive control feedback from hot water and chilled water valves out in the building, and by default, run continuously unless the plant systems are locked out.

Additional advanced control of infiltration rates have been added to better model the impact of turning on and off air systems that affect building pressurization. The strategy used for these changes is discussed in detail in Section 3.1

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[11] Morning start-up time was 6:00 a.m. Monday through Saturday in the AERG model, but was changed to 5:00 to provide a standardized 3 hours of morning start-up time prior to occupancy.

3.4 Large Hotel

The prototype Large Hotel building consists of six stories above ground, plus a conditioned basement floor, totaling 122,132 ft^2 of total floor area. Figure 3.7 is an axonometric projection of the building shape. The basement floor is a single conditioned zone. The first floor contains the lobby, two retail stores, a café, a storage room, a laundry room, and a mechanical room. Aside from a banquet room, dining room, and kitchen on the sixth floor, the rest of the five upper floors are devoted to guest rooms and corridors. There are 179 total guest rooms, accounting for 41% of the building's total floor area. Most of the guest rooms are accounted for in the model through duplicated zones within EnergyPlus. In the original prototype, there is one guest room zone on the north side and one guest room zone on the south side of the building's second through fifth floors that is duplicated 76 times through a zone multiplier. For this modeling work, each of these two zones was copied and each modeled as two zones, each with a multiplier of 38. The reason for this change was to accommodate a common controls measure for hotels—occupancy sensors that control guest room heating, cooling, and lights. In the original prototype, the guest room occupancy schedules use common schedules that indicate the average rate of occupancy (on a scale of 0 to 100%). To accommodate the guest room occupancy sensor measure, this average was replaced by unique zone-by-zone occupancy schedules that were either 1 for occupied or 0 for unoccupied. At all times, when weighted by square footage, the total guest room occupancy was nearly equal to the total guest room occupancy in the original prototype. Splitting the two most highly duplicated zones in two was necessary to maintain this equivalence.

The Large Hotel building is intended to represent buildings constructed in the 1990s. The code used for wall, roof, and window construction is ASHRAE 90.1-1999 for the same reasons discussed in Section 3.1. Exterior walls are 8 in. mass walls with rigid insulation in varying thicknesses required to meet climate-zone–dependent code requirements and an interior 0.5 in.-thick gypsum board. The roof is a built-up roof with rigid insulation above a metal deck. Infiltration rates vary by zone according to the values in the original prototype. The window-wall ratio for the building is 30.2%.

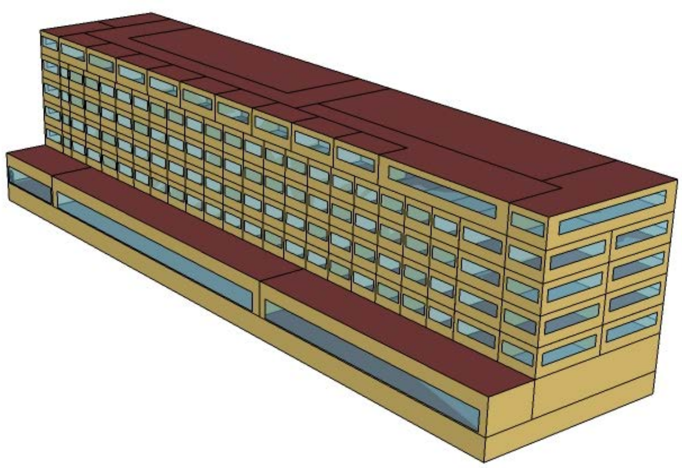

Figure 3.7. Large Hotel Building Shape

Internal loads include lighting at a density that ranges from 0.5 W/ft^2 in corridors to 1.5 W/ft^2 in the two retail stores. The area-weighted average is 1.00 W/ ft^2. Interior electric equipment densities are 0.63 W/ft^2 in guest rooms, but vary significantly in other zones; the highest densities occur in the kitchen (272 W/ft^2) and the laundry room (56 W/ft^2). The area-weighted average is 3.82 W/ ft^2. Occupant densities vary by zone and average 336 ft^2 per person. Lighting and equipment schedules on weekdays and weekends are shown in Figure 3.8 and Figure 3.9, respectively. Exterior lighting includes 23.52 kW of parking lot lights and 10.12 kW of other exterior building lights on photocell sensors.

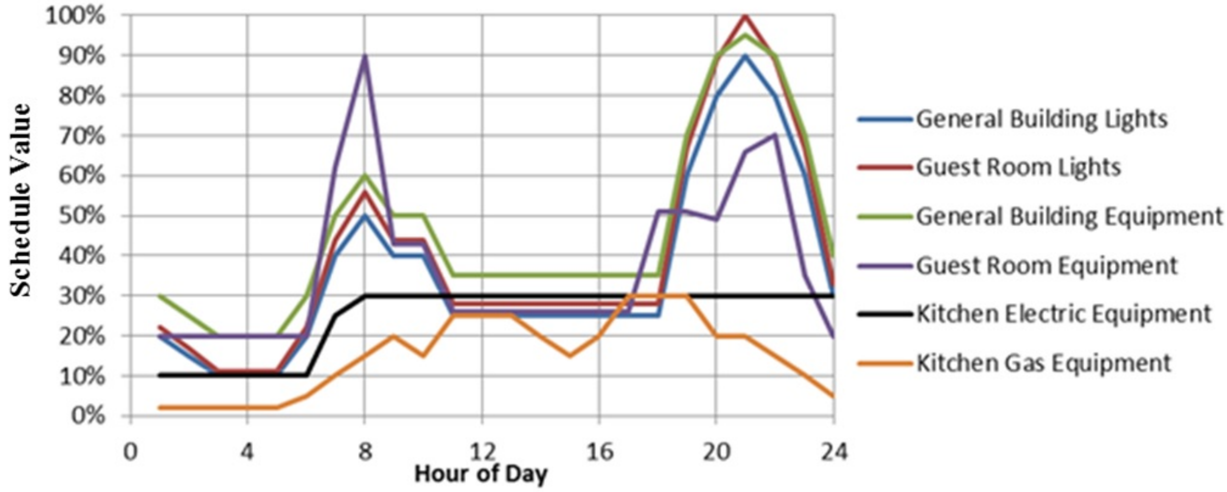

Figure 3.8. Weekday Schedules for Lighting and Equipment in Large Hotel Prototype

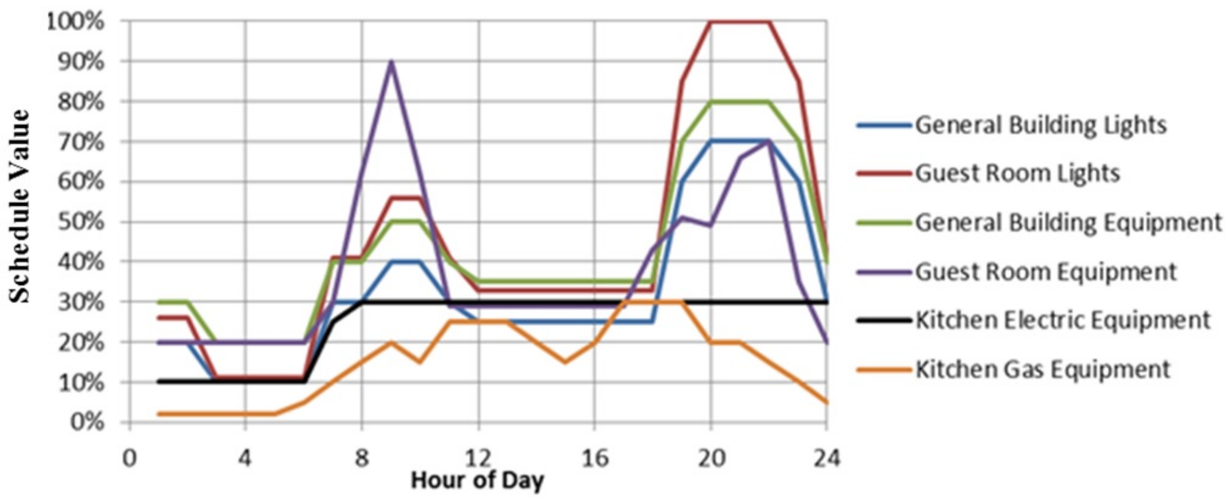

Figure 3.9. Weekend Schedules for Lighting and Equipment in the Large Hotel Prototype

HVAC systems differ between the guest rooms and the rest of the building. Guest rooms use a four-pipe fan-coil unit for heating and cooling, and receive hot water or cold water from a central plant. The fan in the unit is an on/off, constant-speed fan that cycles on to deliver heating or cooling as needed to maintain the room thermostat setpoint. For ventilation in guest rooms, a dedicated outdoor air system (DOAS) with an enthalpy wheel for heat recovery distributes conditioned ventilation air to each of the rooms. There is a heating and cooling coil downstream of the heat recovery wheel in the DOAS main air supply. The DOAS is configured with linear supply air temperature reset based on the outdoor air temperature. The setpoint is reset from 60°F at 60°F outdoor air temperature down to 55°F at 70°F outdoor air temperature. The DOAS unit is equipped with a constant-speed fan and runs continuously to provide ventilation.

The rest of the building is conditioned and ventilated using a single VAV air handler with chilled water cooling coils and hot water heating coils. VAV terminal boxes are equipped with hot water reheat coils for final conditioning. Minimum VAV airflow fractions for each zone range from 30% to 100%. The supply air temperature setpoint for the VAV system is constant at 55°F year-round. Static pressure control is implicitly controlled to a constant setpoint via a constant fan pressure rise of 1,389 Pa. Zone thermostat setpoints are set at 73°F for cooling and 71°F for heating, and these setpoints are maintained 24 hours per day, year-round. The hotel has continuous occupancy and the VAV system runs continuously without schedules.

The building has a central plant that consists of a natural-gas-fired boiler (80% thermal efficiency) that heats a building hot water loop, served by a variable-speed pump. The pump delivers the hot water to the VAV terminal box reheat coils and to the fan-coil units in each of the guest rooms. The hot water primary loop is controlled to meet a constant-supply setpoint of 180°F.

One air-cooled chiller (2.8 rated COP) cools a primary chilled water loop fed by a constant-speed pump. A secondary loop served by a variable-speed pump delivers chilled water to the cooling coils of the DOAS and the VAV air handler. The chilled water primary loop is controlled to meet a constant-supply setpoint of 44°F.

For domestic hot water, the building uses a 600-gallon natural-gas-fired hot water tank. An additional 300-gallon tank serves the laundry room.

As described in Section 3.3, a fault has been added to facilitate simulation of leaking hot water coil valves by adding a fixed 2°C of heating across the hot water coils in the DOAS and VAV AHU whenever the hot water loop is active. Also, as described for the Large Office prototype, this model is modified to include a run of indoor hot water piping that spans the long dimension of the first floor (where the boiler room is located), plus a vertical segment of pipe that travels to the top floor. Ninety percent of this pipe is insulated, while 10% is uninsulated.

3.5 StandAlone Retail

The EnergyPlus model for StandAlone Retail was developed by modifying the prototype model used in the Advanced Energy Design Guide (AEDG 2008). The StandAlone Retail prototype is a single-story building with a rectangular footprint, covering 24,695 ft^2 of total floor area, with a floor-to-ceiling height of 20 ft. Figure 3.10 is an axonometric projection of the building and Figure 3.11 is a diagram of zoning. Approximately 70% of the total floor area is contained in the core retail zone. Only the front façade of the building has any windows, and the total window-to-wall ratio is 7.1%. Exterior wall construction includes 8 in. of concrete masonry with wall insulation sufficient to meet ASHRAE 90.1-1999 new construction codes, according to each climate zone. Roof constructions include an outer roof membrane above insulation and a metal deck.

Internal loads include lighting at an average density of 1.6 W/ ft^2 and plug loads at an average density of 0.5 W/ ft^2. Plug load densities are highest at the point of sale zone at 2.0 W/ft^2 and lowest in the core retail zone at 0.3 W/ft^2. Occupant densities are 66.6 ft^2/person. Weekday, Saturday, and Sunday schedules for lighting and plug loads in all zones are shown in Figure 3.12.

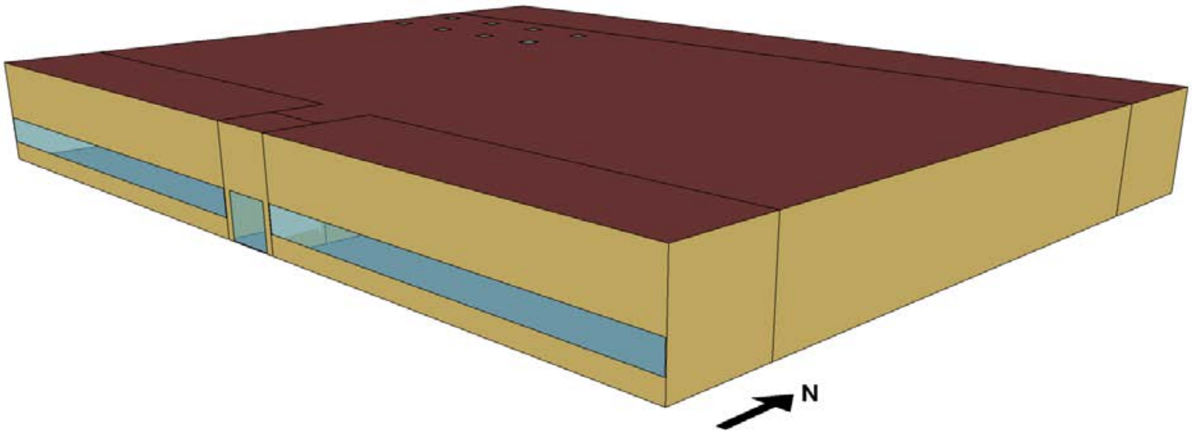

Figure 3.10. StandAlone Retail Building Shape

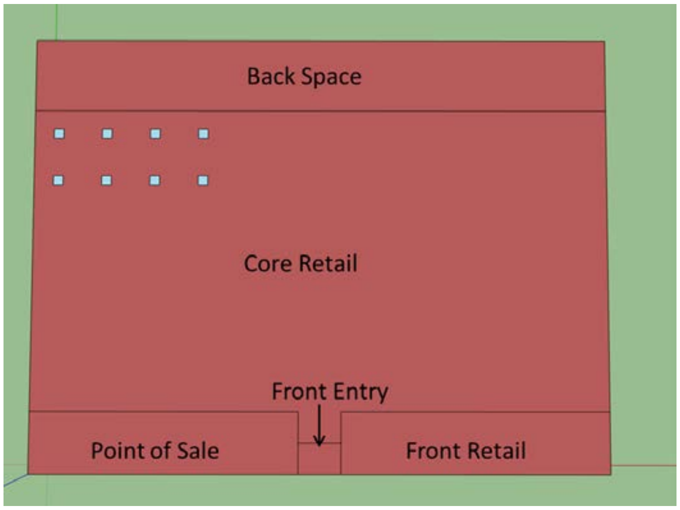

Figure 3.11. StandAlone Retail Thermal Zoning

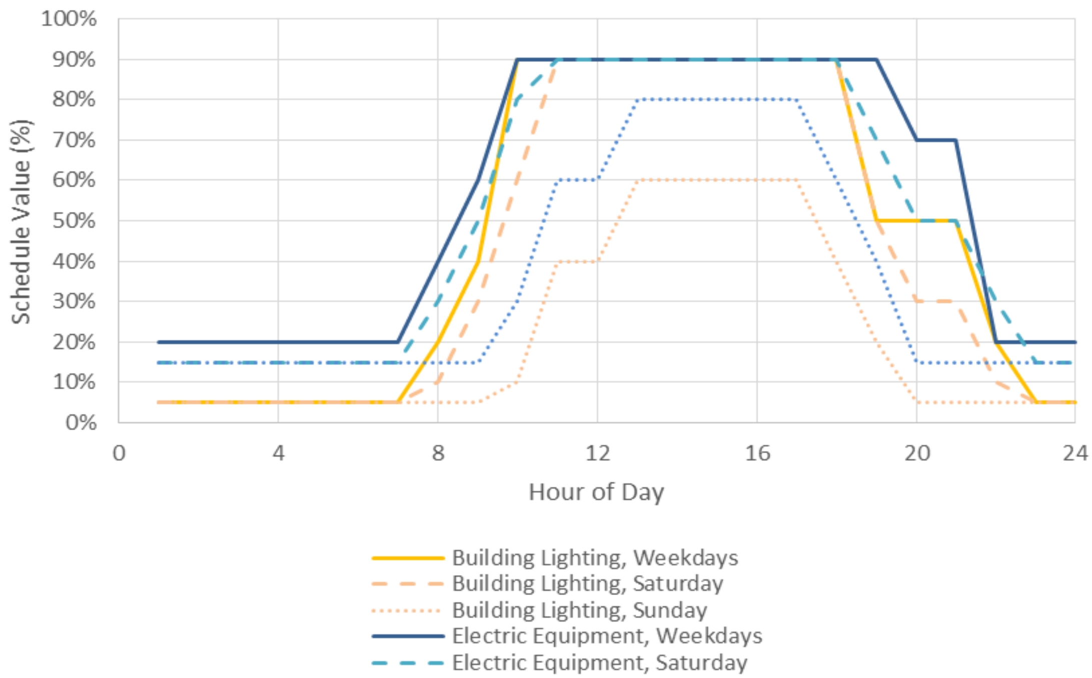

Figure 3.12. Lighting and Plug Load Schedules for Weekday and Weekends in the StandAlone Retail Model

Aside from the "Front Entry" zone, which is a very small, unconditioned zone, each of the zones in the StandAlone Retail model is conditioned and ventilated with a single-zone packaged rooftop air-conditioning unit with two-speed DX cooling and a gas heating coil. Outdoor air economizers are used in all IECC climate zones, except 1a, 1b, 2a, 2b, 3a, 3b, and 4a.

The StandAlone Retail model has been modified in several ways for this project, both to better simulate the effect of certain control measures and to introduce certain faults into the baseline model. HVAC schedules have been extended by four hours each day, relative to the prototype model used for commercial building energy codes development. The fan operation schedules now run from 5:00 a.m. to 1:00 a.m. (20 hours) Monday through Friday, from 5:00 a.m. to 2:00 a.m. on Saturday, and from 7:00 a.m. to 11:00 p.m. on Sunday. A bathroom exhaust fan has been added to the model, and is located in the "Front Retail" zone. One bathroom fixture per 50 people during peak occupancy is assumed (7 total fixtures) and 50 cfm per fixture of exhaust airflow rate is assumed for the exhaust fan (350 cfm total). A matching infiltration object, using the exhaust fan's operation schedule, has been added to simulate makeup infiltration air caused by the use of the bathroom exhaust fan. Sensor bias faults have been added to each of the return and outdoor air sensors for the packaged unit economizers as described in Section 3.1, with a 3°F outdoor air temperature bias and a -3°F return air temperature bias. Each of the four packaged RTU cooling coils has been modified to simulate a 20% undercharged refrigerant scenario, by adjusting the COP and capacity of the coils as described for the Small Office model in Section 3.1. Thermostat setpoints have been adjusted to be consistent with the other models. The occupied thermostat setpoints for heating and cooling are 71°F and 73°F, respectively, and the night setback heating and cooling setpoints are 65°F and 80°F, respectively. An EMS program has been added to automatically adjust the occupied and unoccupied hours for the thermostats, such that they are always consistent with the fan schedules.

3.6 Strip Mall Retail

The EnergyPlus model for Strip Mall Retail was developed by modifying the prototype model used in the Advanced Energy Design Guide (AEDG 2008). The Strip Mall prototype is a one-story building with 22,500 ft^2 of total floor area. Figure 3.13 is an axonometric projection of the building shape and Figure 3.14 is a diagram of floor zoning, including all 10 retail stores. The floor-to-ceiling height of the building is 17 ft and the building has a total window-to-wall fraction of 10.5%.

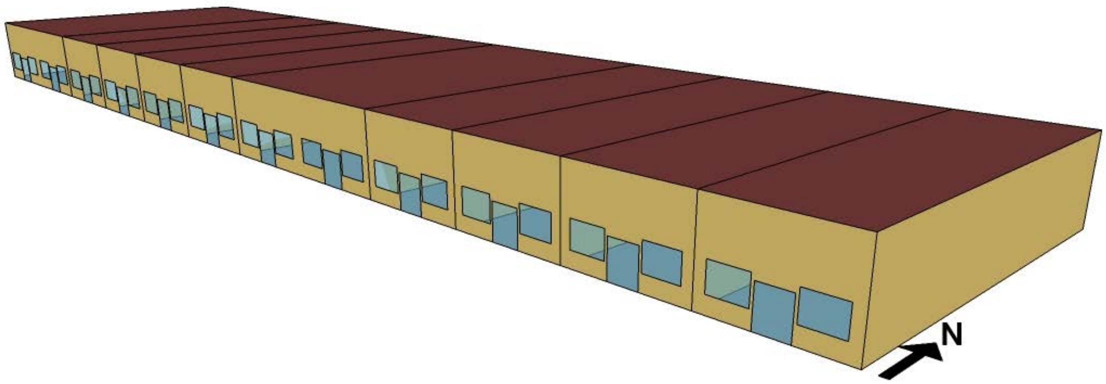

Figure 3.13. Strip Mall Building Shape

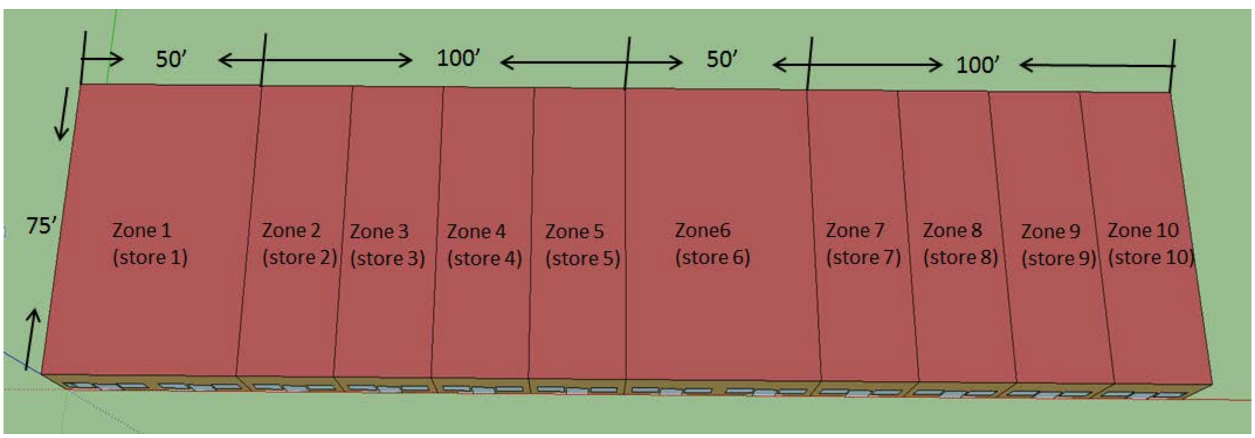

Figure 3.14. Strip Mall Thermal Zoning

This prototype building includes a total of 10 retail stores. Store 1 and Store 6 are large stores with an area of 3,750 ft^2. All the other stores are small stores with an area of 1,275 ft^2. Each zone includes thermal mass that is specified as 6 in. thick wood per square foot of floor space.

The Strip Mall building represents buildings constructed in the 1990s using the ASHRAE 90.1-1999 code for wall, roof, and window construction for the same reasons as the office models. Exterior walls are steel framed (stucco-exterior) with rigid insulation in varying thickness required to meet climate-zone-dependent code requirements and an interior 0.5 in.-thick gypsum board. The roof is a built-up roof with rigid insulation above a metal deck. Peak infiltration rates of outdoor air are 0.2016 cfm/ft^2 of exterior surface area and coincide with scheduled shutdown of RTU fans. When the fans are on, infiltration rates drop to one-quarter of this level.

Internal loads include lighting and interior electric equipment. Due to the different store types, this building includes three settings of lighting density (5.6, 3.3, and 2.7 W/ft^2) and two settings of electric equipment density (749 and 1,498 W/ft^2). Occupant densities peak at 125 ft^2 per occupant in all zones. Lighting, equipment, and occupancy schedules vary by both day of the week and by store type. Exterior lighting includes 6.356 kW of parking lot lights and 2.797 kW of other exterior building lights.

HVAC is provided for each store via a single-zone RTU with constant air volume air distribution. Zone thermostat setpoints are set at 73°F for cooling and 70°F for heating. Night setback and setup temperature setpoints are 80°F and 65°F, respectively. Minimum outdoor air fractions for ventilation are set constant at 15%. Outdoor air economizers are used in all IECC climate zones, except 1a, 1b, 2a, 2b, 3a, 3b, and 4a. Three operation schedules for fans are used, based on the occupancy schedule of each store type. The building has a packaged air-conditioning unit (3.3 rated COP) installed for each store. A gas burner (efficiency of 0.8) inside the packaged air-conditioning unit provides heating. For domestic hot water, the building uses a 40-gallon electricity hot water tank for seven of the stores.

Some additional faults are added to the Strip Mall baseline model to facilitate simulation of several fault correction measures. These include temperature bias faults of +3°C and -3°C that are added to all outdoor air temperature sensors and to all return air temperature sensors, respectively.

3.7 Primary School

The Primary School model was developed based on the DOE commercial building protoype model (U.S. DOE 2016). The Primary School prototype is a one-story building totaling 73,960 ft^2 of total floor area and having a floor-to-ceiling height of 13 ft. Figure 3.15 is an axonometric projection of the building and Figure 3.16 is a diagram of zoning. The building consists of a main body that contains a lobby, bathrooms, offices, a gym, a cafeteria, a kitchen, a library, and a mechanical room. Branching off from the main body on the west side are three classroom pods that each include a central linear corridor that runs east-west, surrounded on the north and south sides by classrooms. Windows run in a continuous band around the exterior of the building, including each of the classrooms. The overall window-wall ratio is 35%. Exterior walls are steel framed, with 2×4 steel studs spaced 16 in. on center. The exterior is stucco over an exterior 5/8 in. gypsum board with cavity insulation, and another 5/8 in. interior gypsum board. Roof construction includes an outer roof membrane above insulation and a metal deck.

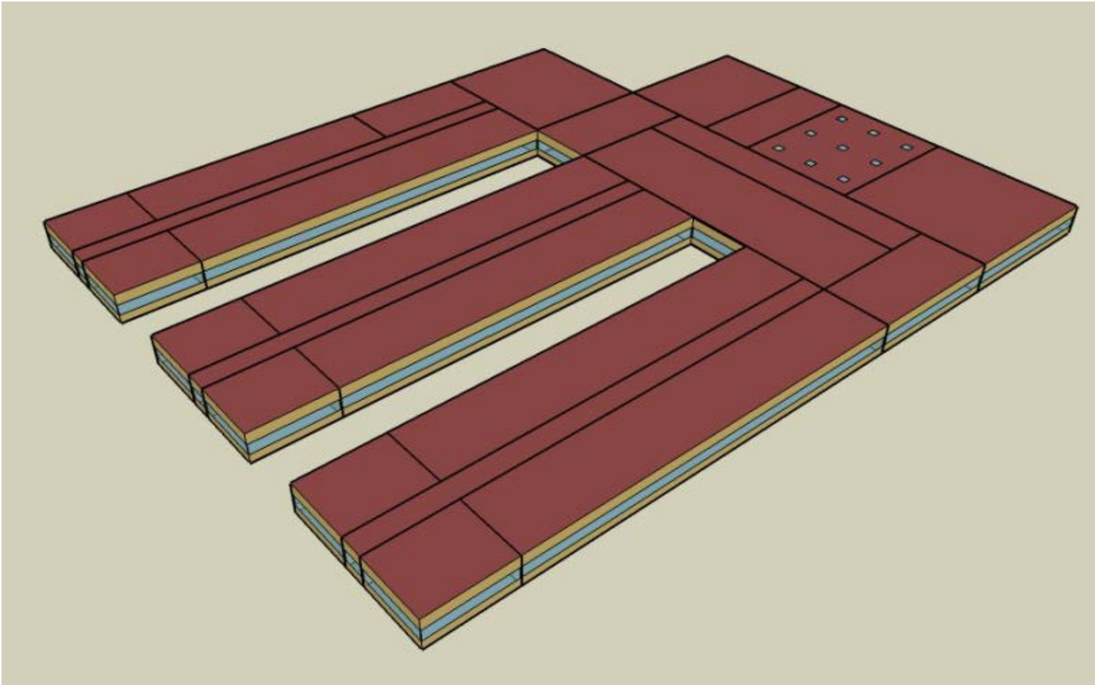

Figure 3.15. Primary School Building Shape

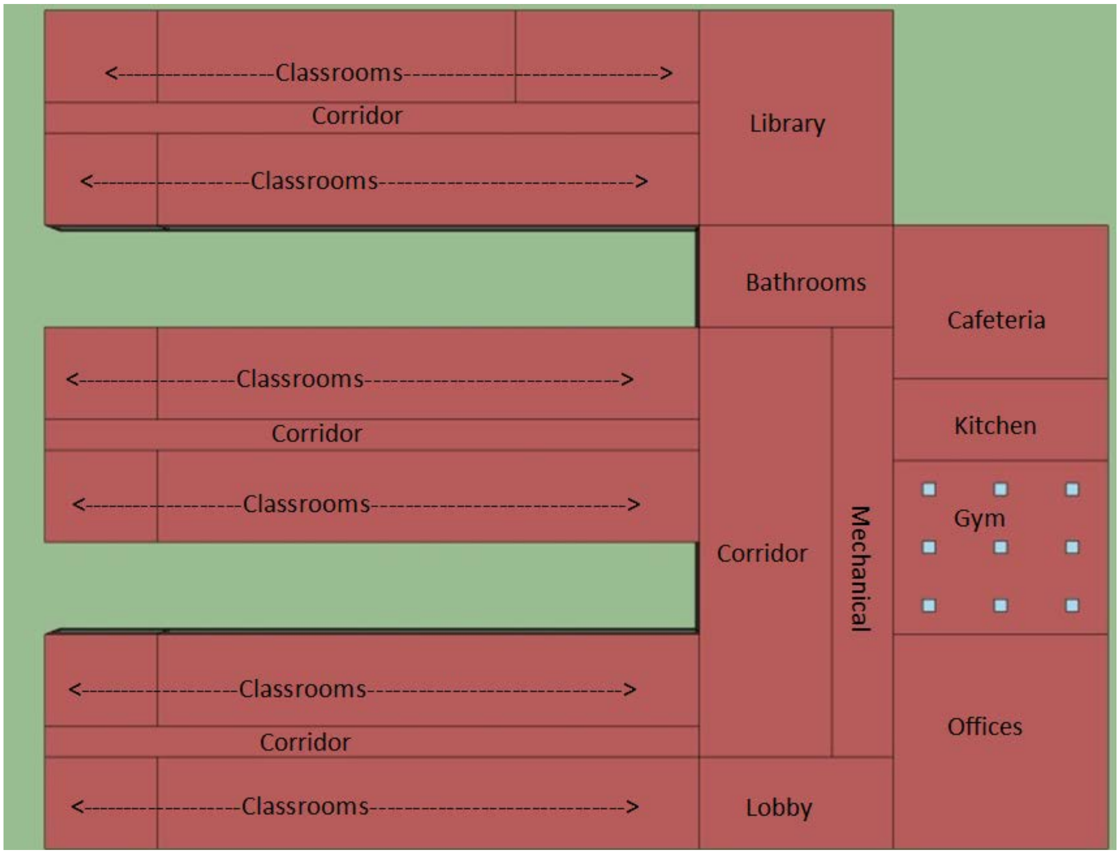

Figure 3.16. Primary School Thermal Zoning

Internal loads include lighting at an average density of 1.19 W/ft^2 and ranging from a minimum density of 0.50 W/ft^2 in corridors to 1.40 W/ ft^2 in classrooms. Plug loads average 4.80 W ft^2, but this average is skewed by the kitchen, which has a density of 151 W/ft^2. Excluding the kitchen, the average density is 1.13 W ft^2. The density in the classrooms is 1.39 W/ft^2. Occupant densities vary by zone, but average 42 ft^2/person. Schedules for internal loads vary according to the season. Schedules for study periods (January through June and September through December) are shown in Figure 3.17 and summer schedules (July and August) are shown in Figure 3.18.

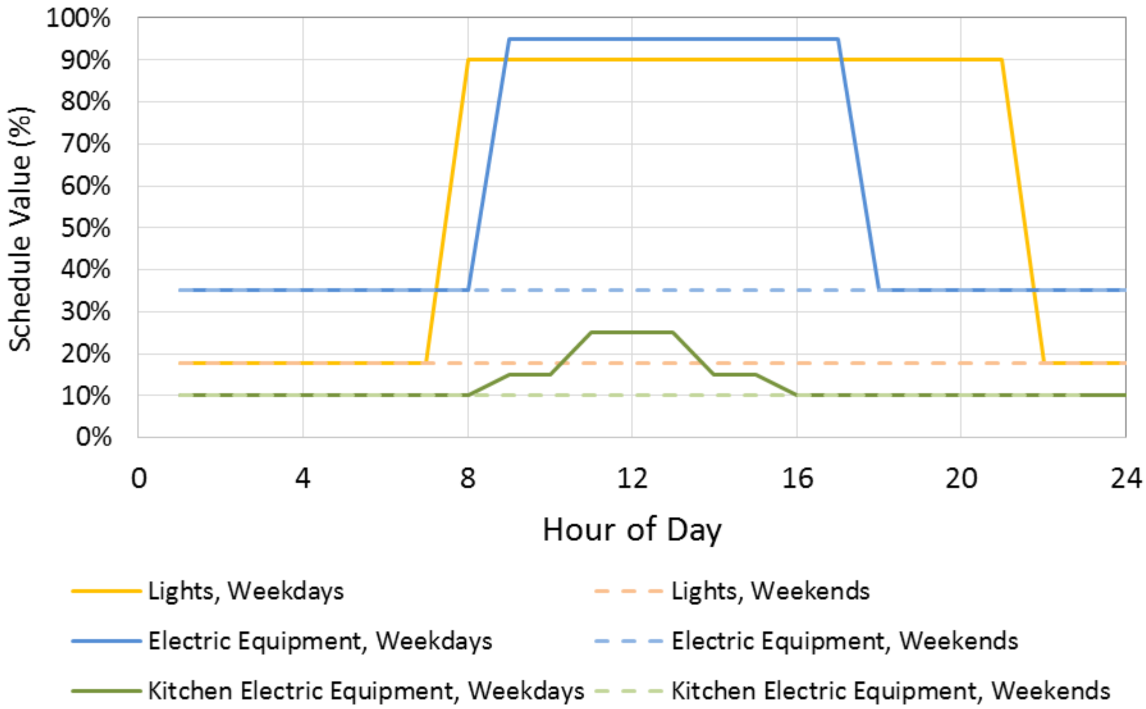

Figure 3.17. Lighting and Plug Load Schedules for Weekday and Weekends during the Study Period (January–June and September–December) in the Primary School Model

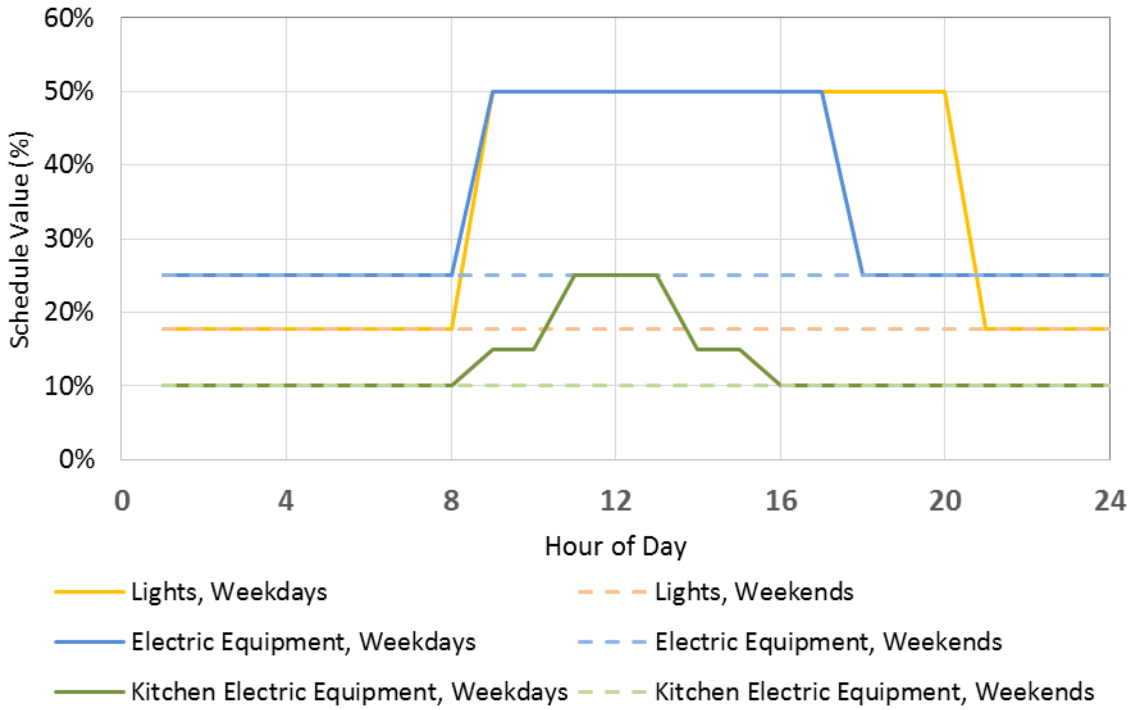

Figure 3.18. Lighting and Plug Load Schedules for Weekday and Weekends during the Study Period (July and August) in the Primary School Model

The majority of the building is ventilated and conditioned via one of four VAV systems, with the exception of the gym, kitchen, and cafeteria, which each have single-zone packaged rooftop air-conditioning units. Three of the four VAV systems each serve one of the three classroom pods. The fourth VAV system serves the remaining zones in the main body of the school. All VAV-served zones have minimum VAV airflow fractions of 40% and all VAV terminal units are equipped with reheat coils. Each of the VAV systems, as well as the single-zone packaged RTUs, are equipped with a two-speed DX cooling coil. The COP for the VAV coils is 3.23, while the COP for the RTU coils is 3.15. The COP of the RTU coils has been decreased by 10% to reflect the low refrigerant charge baseline fault discussed in Section 3.1. The RTUs are also equipped with a gas heating coil, while the VAV systems receive heating from a building hot water loop. Outdoor air economizers are used on all VAV systems and packaged RTUs in all IECC climate zones, except 1a, 1b, 2a, 2b, 3a, 3b, and 4a.

The building hot water loop is served by a natural gas boiler that has a rated efficiency of 83.71%. A variable-speed hot water pump delivers hot water to the reheat coils and to the VAV AHU heating coils. The pump operates at 60 ft of head. A 200-gallon hot water heater provides domestic hot water to the building.

For this analysis, several modifications have been made to the prototype Primary School model. Thermostat setpoints have been adjusted to be consistent with the other models. The occupied thermostat setpoints for heating and cooling are 71°F and 73°F, respectively, and the night setback heating and cooling setpoints are 65°F and 80°F, respectively. An EMS program has been added to automatically adjust the occupied and unoccupied hours for the thermostats, such that they are always consistent with the fan schedules. Several faults have been added to the model, including an HVAC scheduling fault that adds four hours to weekday fan schedules. The VAV and RTU fans are now scheduled to run from 5:00 a.m. to 1:00 a.m. (20 hours) Monday through Friday. As discussed in Section 3.1, sensor bias faults have been added to each of the return and outdoor air sensors for the VAV and RTU economizers, with a

3°F outdoor air temperature bias and a -3°F return air temperature bias. As described in Section 3.3, a fault has been added to facilitate the simulation of leaking hot water coil valves by adding a fixed 2°C of heating across the hot water coils in the VAV AHUs whenever the hot water loop is active. The bathroom exhaust fan flow rate has been increased from 600 cfm to 2,100 cfm to reflect minimum bathroom fixture requirements from the California Department of Education (2015), which requires one toilet per 50 people and one urinal per 100 people for males and one toilet per 30 people for females. The maximum occupancy on weekdays is 1,306 people, which should translate to a total of 42 fixtures. At 50 cfm per fixture of exhaust flow rate, this equates to 2,100 cfm. Matching infiltration objects have been added, using the exhaust fan's operation schedule to simulate makeup infiltration air caused by the use of the bathroom exhaust fan. As described for the Large Office prototype in Section 3.3, to better simulate the impact of hot water temperature reset, this model is also modified to include a run of indoor hot water piping that spans the length of the core of the building and also the length of each of the pods. The pipe is centrally located in corridor zones in the pods, and in the mechanical room, lobby, and library of the building core. Ninety percent of this pipe is insulated, while 10% is uninsulated.

3.8 Secondary School

The Secondary School model was developed based on the DOE commercial building prototype model (U.S. DOE 2016). The Secondary School prototype is a two-story building totaling 210,900 ft^2 of total floor area and having a floor-to-ceiling height of 13 ft for most zones, except two gyms and a cafeteria, which have a floor-to-ceiling height of 26 ft. Figure 3.19 is an axonometric projection of the building and Figure 3.20 is a diagram of zoning for the second floor, including the gyms and auditorium, which have entrances on the first floor. Compared to this zoning diagram, the only difference in zoning for the first floor is that the part of the building that covers the cafeteria and kitchen is occupied by a library on the first floor. As noted for the Primary School prototype in Section 3.7, the Secondary School model also contains three classroom pods, zoned similarly. Windows run in a continuous band around the exterior of the building, including each of the classrooms, but excluding the auxiliary gym and auditorium, which are windowless. The overall window-wall ratio is 33%. Exterior walls are steel framed, with 2×4 steel studs spaced 16 in. on center. The exterior is stucco over an exterior 5/8 in. gypsum board with cavity insulation, and another 5/8 in. interior gypsum board. Roof constructions include an outer roof membrane above insulation and a metal deck.

The prototype is a two-story building with 210,900 ft^2 of total floor area (Figure 3.19). This model contains a total of 46 conditioned zones, and most of them are classrooms. The floor-to-ceiling height of the building is 13 ft and it has a total window-to-wall fraction of 33%.

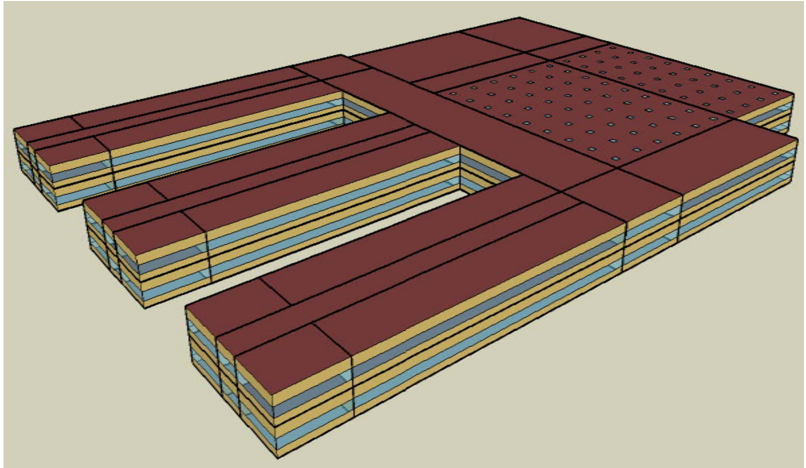

Figure 3.19. Secondary School Building Shape

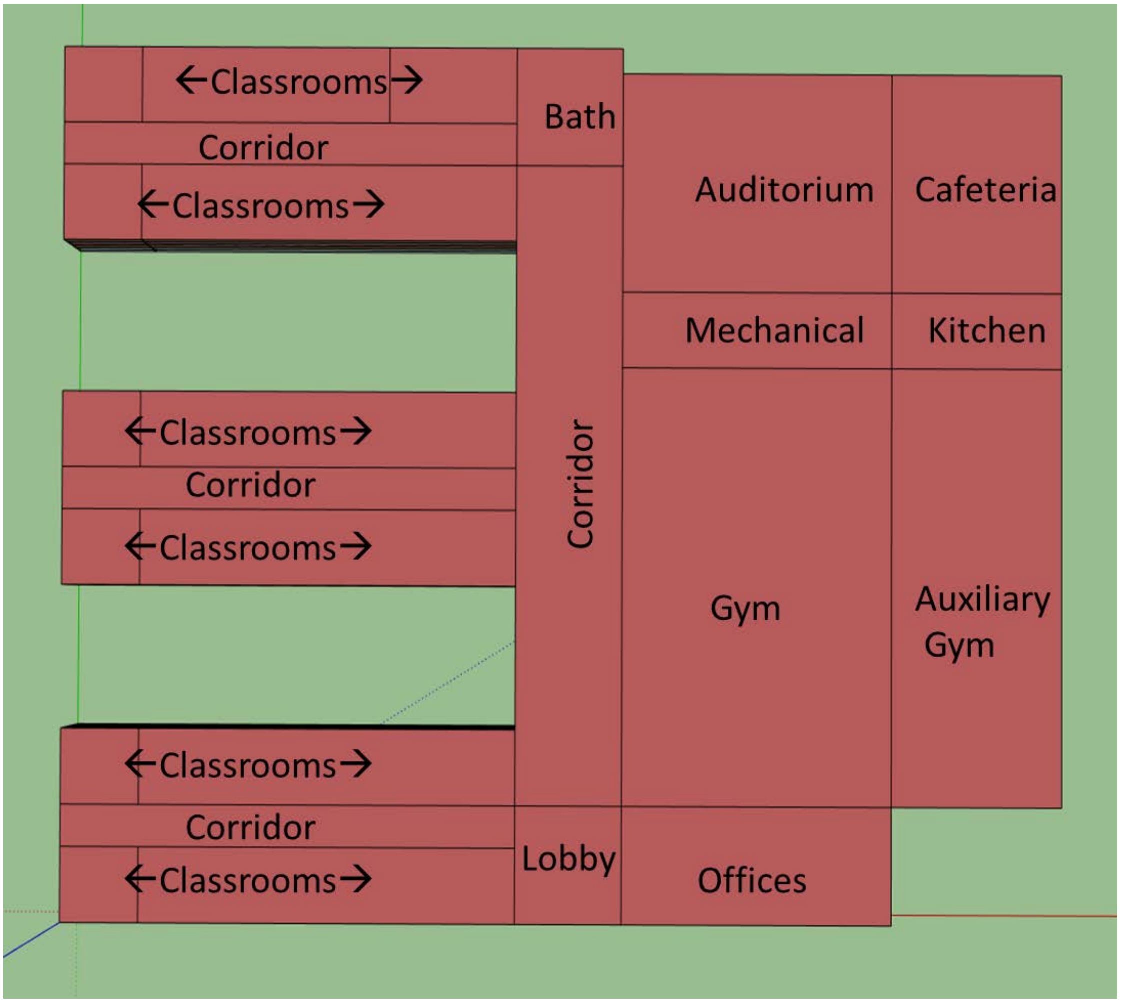

Figure 3.20. Second Floor Zoning for Secondary School

Internal loads include lighting at an average density of 1.13 W/ft^2 and ranging from a minimum density of 0.50 W/ft^2 in corridors to 1.40 W/ft^2 in classrooms. Plug loads average 3.10 W/ft^2, but this average is skewed by the kitchen, which has a density of 177 W/ft^2. Excluding the kitchen, the average density is 1.07 W/ft^2. The density in the classrooms is 0.90 W/ft^2. Occupant densities vary by zone, but average 31.7 ft^2/person. Schedules for internal loads vary according to the season. Schedules for study periods (January through June and September through December) are shown in Figure 3.17 and summer schedules (July and August) are shown in Figure 3.18 (same schedules as used for the Primary School prototype). Exterior lighting includes 8.897 kW of parking lot lights and 47.449 kW of other exterior façade lights.

A majority area of this prototype building is used as classrooms; the classrooms are divided into two categorizes based on their size. This building model also includes a gym, an auditorium, a library, two offices, a kitchen, and a café. The Secondary School building is intended to represent buildings constructed in the 1990s. Exterior walls are mass walls with 1 in. stucco, 8 in. heavyweight concrete and 0.5 in. gypsum. The roof is a built-up roof with rigid insulation above a metal deck.

Internal loads include lighting and interior electric equipment. Due to the different room types, there are various settings of lighting density. The occupancy schedule has two settings—summer schedule and semester schedule. The occupancy is limited during the summer from June 30 to September 1, and there is no occupancy assumed for the weekends. Exterior lighting includes 8.897 kW of parking lot lights and 47.449 kW of other exterior façade lights.

HVAC is provided for each zone via two system types.

- Five packaged single-zone air conditioners with constant air volume air distribution provide conditioning and ventilation to each of the gyms, the auditorium, the kitchen, and the cafeteria. Cooling is provided for each of the packaged units via DX cooling coils with COPs of 2.91. Note that this baseline COP has been reduced by 10% relative to the original prototype to simulate the baseline fault of undercharged refrigerant discussed in the description of the Small Office prototype in Section 3.1. Heating is provided by gas heating coils that have efficiencies of 80%.
- Four VAV systems with hot water reheat provide conditioned air to the rest of the building. Cooling is provided to the AHUs from an air-cooled chiller that has a rated COP of 2.8. The chilled water loop uses a variable-speed primary-only configuration. The chilled water pump is autosized, with a head of 75 ft of water. Heating is provided via a natural-gas-fired boiler that has an efficiency of 80%. The building hot water pump is autosized with a head of 60 ft of water. Minimum outdoor air fractions for ventilation are set constant at 15%.

For this project, several changes have been made to the prototype Primary School model. Thermostat setpoints have been adjusted to be consistent with the other models. The occupied thermostat setpoints for heating and cooling are 71°F and 73°F, respectively, and the night setback heating and cooling setpoints are 65°F and 80°F, respectively. An EMS program has been added to automatically adjust the occupied and unoccupied hours for the thermostats, such that they are always consistent with the fan schedules. Several faults have been added to the model, including an HVAC scheduling fault that adds four hours to weekday fan schedules. The VAV fans are now scheduled to run from 5:00 a.m. to 9:00 p.m. Monday through Friday during the study period and from 6:00 a.m. to 5:00 p.m. Monday through Friday during the summer. Packaged unit fans serving the gyms and the auditorium have schedules that run from 6:00 a.m. to 1:00 a.m. (19 hours) on weekdays during the study period and from 6:00 a.m. to 7:00 p.m. on weekdays during the summer. As discussed for the Small Office model (in Section 3.1), sensor bias faults have been added to each of the return and outdoor air sensors for the VAV and RTU economizers, with a 3°F outdoor air temperature bias and a -3°F return air temperature bias. As described in Section 3.3, a fault has been added to facilitate simulation of leaking hot water coil valves by adding a fixed 2°C of heating across the hot water coils in the VAV AHUs whenever the hot water loop is active. Matching infiltration objects have been added to account for bathroom exhaust, using the exhaust fan's operation schedule to simulate makeup infiltration air caused by the use of the bathroom exhaust fan. The infiltrations objects are applied at a uniform rate to each exterior wall as a function of its area. As described for the Large Office prototype (in Section 3.3), to better simulate the impact of hot water temperature reset, this model was also modified to include a run of indoor hot water piping that spans the length of the core of the building and also the length of each of the pods. The pipe is centrally located in corridor zones in the pods, and in the mechanical room, lobby, and library of the building core. Ninety percent of this pipe is insulated, while 10% is uninsulated. The pipe is actually assumed to be located in the ceiling cavity between the two floors, but the pipes are specified as exchanging heat with zones on the first floor.

3.9 Supermarket

The Supermarket building prototype model is based on the Grocery Store 50% Energy Savings Technical Support Document (Leach et al. 2009) with some modifications. The prototype store is a standalone one-floor building with 45,000 ft^2 of construction area. With an aspect ratio of 1.5, the store's footprint dimension is 263 ft by 173 ft. The store has a floor-to-roof height of 20 ft with no drop ceiling. The space types captured in the building model include main sales (49.8%), perimeter sales (5.1%), produce (17.0%), deli (5.4%), bakery (5.0%), active storage (10.1%), office (0.7%), meeting room (1.1%), dining room (1.1%), restroom (1.5%), mechanical room (1.3%), corridor (1.2%), and vestibule (0.7%), where the number in parentheses indicates the percentage of total building area corresponding to each space type. Figure 3.21 shows the store layout.

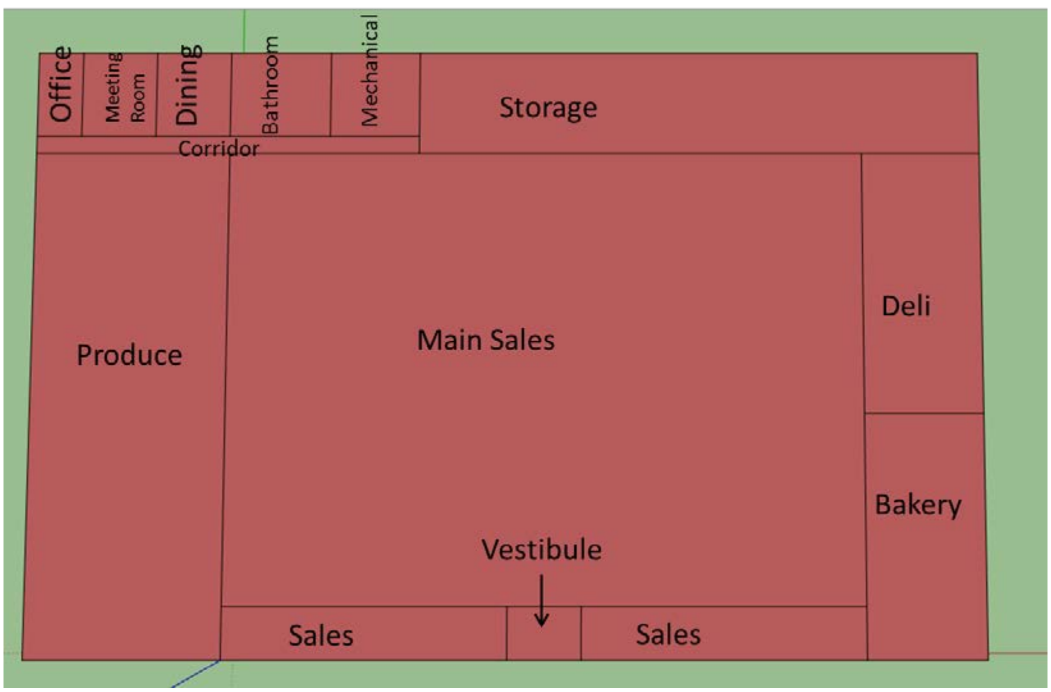

Figure 3.21. Floor Plan/Zoning for the Supermarket Building Prototype

According to the opaque envelope construction types specified in ASHRAE Standard 90.1 (ASHRAE 2004), the Supermarket prototype building has a mass wall, insulation entirely above the deck for the roof, and a slab-on-grade floor. Regarding fenestration, all glazing is assumed to be located on the main entrance wall. The vertical glazing accounts for about 8% of the total wall area. No skylight is used in the model. The building envelope performance complies with the minimum requirement by ASHRAE

Standard 90.1-1999. In each space, the internal thermal mass is modeled as 2 ft^2 of 6 in. thick wood per square foot of floor area.

Internal loads (e.g., occupants, lighting, and plug loads) and ventilation requirements were modeled the same as those in the original model (Leach et al. 2009).

Each space in Figure 3.21 is treated as an individual thermal zone served by a packaged air-conditioning unit with gas heat. Humidity control is not applied for all spaces in the store. All package units are modeled with a COP of 3.47, fan efficiency of 33%, and pressure rise of 404 Pa (381 Pa for the units without the use of economizer) (Hendron et al. 2012). All packaged units run continuously 24/7 in the baseline model.

Direct refrigeration with R404a is the system type used in the Supermarket building model. The store has four compressor racks—two low-temperature racks serving frozen food cases, ice cream cases, and walk-in freezers and two medium-temperature racks serving meat cases, dairy/deli cases, and walk-in coolers. There are a total of 7 low-temperature cases, 19 medium-temperature cases, 2 walk-in freezers, and 8 walk-in coolers.

4.0 Energy Savings and Demand-Response Control Measures

This section details the design intent and strategy for implementing each of the 43 measures that are tailored to either produce annual energy savings or used to reduce power through DR during CPP events. Table 4.1 lists each of these measures along with the building prototypes to which the measure applies. Many control measures are not applicable to all building types because of the lack of physical or control infrastructure needed to implement the measure. For example, buildings with packaged RTUs cannot take advantage of central plant measures. The descriptions of the measures provided in this section discuss the intended implementation of the measure in actual buildings. An accompanying EnergyPlus user guide is provided in Appendix B to discuss how each measure is implemented in the EnergyPlus models. Sample code and descriptions are provided there only for measures whose implementation strategy is not obvious or trivial.

Measure 01: Re-calibrate Faulty Sensors. This measure simulates the correction (recalibration) of a fault that is applied to the baseline model, in which both the outdoor air and return air sensors used to control the buildings' air handlers have constant temperature bias faults. This fault uses a new set of objects in EnergyPlus under the category FaultModel:TemperatureSensorOffset. This object only affects the outdoor air controller for each air handler, and does not affect other aspects of building control (for example, outdoor air temperature-driven supply air temperature reset or outdoor air temperature-based lockouts of heating and cooling plants). The baseline models have a 3°C positive bias applied to all outdoor air temperature sensors and a -3°C bias applied to all return air sensors. Two alternative levels (severities) of fault are also included as alternative baselines for this measure: 5°C outdoor air/-5°C return air biases and 1°C outdoor air/-1°C return air biases. The measure itself turns the implemented bias off, correcting the sensor and restoring proper control of the economizer damper. Note that sensor bias faults are random occurrences and would naturally tend to affect some, but not all buildings and would occur at varying severity levels. Because of the complexity of characterizing such a scenario, a uniform fault is applied in this measure. Note also that the baseline models all contain an additional physical fault affecting the outdoor air damper and the ability to economize (see description in Measure 06). This additional "damper leakage fault" has the consequence that even when proper sensor calibration is restored with this measure, the actual outdoor air fractions that can be achieved through economizer control remain limited (i.e., in the range of 10 to 70%).

This baseline fault is applied to all airside systems in each prototype that has economizers. This excludes the Large Hotel prototype, which does not have modulating airside economizers due to the 100% outdoor air requirements for ventilation.

Table 4.1. List of Energy Savings and Demand-Response Control Measures and Applicability to Each Prototype

Forty-three control measures are simulated among the set of nine prototype building models. Thirty-seven are energy efficiency measures, and the remaining six are DR measures. The applicability of each measure to any given building requires that the building have the necessary infrastructure in the baseline, that the measure is consistent with the mission of the building and its operating schedule, and that the measure can be simulated as intended in the EnergyPlus model.

Measure	Measure Number	Small Office	Medium Office	Large Office	Large Hotel	StandAlone Retail	Strip Mall Retail	Primary School	Secondary School	Supermarket
Re-calibrate Faulty Sensors	01	●	●	●		●	●	●	●	●
Fix Low Refrigerant Charge	02	●	●			●	●	●	●	●
Fix Leaking Heating Coil Valves	03			●	●			●	●	
Shorten HVAC Schedules	04	●	●	●		●	●	●	●	●
Supply Air Temperature Reset	05		●	●	●			●	●	
Outdoor Air Damper Faults and Control	06	●	●	●		●	●	●	●	●
Exhaust Fan Control	07	●	●	●		●		●	●	
Static Pressure Reset	08		●	●	●			●	●	
Plant shutdown when there is no load	09			●				●		
Chilled Water Differential Pressure Reset	10			●	●				●	
Chilled Water Temperature Reset	11			●	●				●	
Condenser Water Temperature Reset	12			●						
Hot Water Differential Pressure Reset	13			●	●			●	●	
Hot Water Temperature Reset	14			●	●			●	●	
Minimum VAV Terminal Box Damper Flow Reductions	15		●	●	●			●	●	
Wider Deadbands and Night Setback	16	●	●	●	●	●	●	●	●	●
Demand Control Ventilation	17	●	●	●		●	●	●	●	●
Lighting Occupancy Presence Sensors	18	●	●	●	●	●		●	●	●
Daylighting Controls	19	●	●	●		●	●	●	●	
Exterior Lighting	20	●	●	●		●	●	●	●	●
Advanced Plug Load Controls	21	●	●	●						

Table 4.1. (contd)

Measure	Measure Number	Small Office	Medium Office	Large Office	Large Hotel	StandAlone Retail	Strip Mall retail	Primary School	Secondary School	Supermarket
Night Purge	22	●	●	●		●	●	●	●	
Advanced RTU Controls	23	●				●	●		●	●
Elevator Lighting	24		●	●	●					
Waterside Economizer	25			●						
Cooling Tower Controls	26			●						
Optimal Start	27	●	●	●		●	●	●	●	
Optimal Stop	28		●	●		●	●	●	●	
Refrigerated Case Lighting Controls	29									●
Walk-In Refrigerator/Freezer Lighting Controls	30									●
Refrigeration Floating Head Pressure	31									●
Refrigeration Floating Suction Pressure	32									●
Optimize Defrost Strategy	33									●
Anti-Sweat Heater Control	34									●
Evaporator Fan Speed Control	35									●
Occupancy Sensors for Thermostats and Room Lighting	36				●					
Optimized Use of Heat Recovery Wheel	37				●					
Demand-Response: Setpoint Changes	38	●	●	●	●	●	●	●	●	●
Demand-Response: Pre-Cool	39	●	●	●	●	●	●	●	●	●
Demand-Response: Duty Cycle	40	●	●	●		●	●	●	●	●
Demand-Response: Lighting	41	●	●	●	●	●	●	●	●	
Demand-Response: Chilled Water Temperature Reset	42			●	●				●	
Demand-Response: Refrigeration	43									●

Measure 02: Fix Low Refrigerant Charge. This measure simulates the correction (recalibration) of a fault that is applied to packaged air-conditioning systems in the baseline models. The fault is a low refrigerant charge either caused by initial undercharging of refrigerant or refrigerant leakage. In the baseline models, the refrigerant is assumed to be 20% undercharged (in other words, only 80% of the ideal refrigerant charge is in place). Two alternative levels (severities) of fault are also included as alternative baselines for this measure: 30% undercharged and 10% undercharged. The undercharging is conceptual, and as modeled, affects the COP and cooling capacity of the air-conditioning unit. Kim and Braun (2010) assembled test data from manufacturers of four RTU air conditioners using R-22 refrigerant (typical of older existing RTUs) and plotted the effect of refrigerant charge on COP and capacity. The

data presented by Kim and Braun were used here to modify the COP and capacity of the air-conditioning system as indicated in Table 4.2.

Table 4.2. COP and Capacity Multipliers Used to Simulate Refrigerant Undercharging

	10% Undercharge	20% Undercharge	30% Undercharge
COP Multiplier	96%	90%	80%
Capacity Multiplier	92%	80%	65%

To accurately simulate the capacity reductions in EnergyPlus, the models were first run using autosizing for system capacity (autosized capacities varied by climate), then they were re-sized via hard-coded numbers for the final simulation.

This measure is applied to all packaged AHUs and RTUs, which are present in all prototype models except the Large Hotel and Large Office models.

Measure 03: Fix Leaking Heating Coil Valves. This measure simulates the correction of a fault that is applied to the hot water coil valves in each of the AHUs (but not to any hot water VAV reheat valves). The fault simulates continuous leakage of hot water through the valve when the building's hot water pump is running. This fault is applied to the baseline models for buildings that have a central heating plant with a hot water loop. This set of models includes Large Office and Primary School prototypes. EnergyPlus does not have an object or set of objects to simulate leaking coil faults, so this measure uses the EMS to customize programming to simulate this condition. The custom code works by forcing the coil to heat any air moving through the AHU by a constant 2°C whenever the hot water pump is verified to be on. While the actual temperature rise across the heating coil may vary in a leakage scenario based on the hot water temperature, the entering air temperature, and the airflow rate across the coil, this constant approach is used for simplicity. Two alternative levels (severities) of fault are also included as alternative baselines for this measure: 5°C temperature rise and 1°C temperature rise. The measure fixes the fault by eliminating any temperature rise across the coil when it is not in use.

Measure 04: Shorten HVAC Operation Schedules. This measure simulates the correction of HVAC schedules that are applied more widely than necessary. Although this pertains to the management of the scheduling of HVAC equipment, it is classified as a fault in this context to the extent that the schedules are applied inappropriately or have been neglected. The application of the correction of this measure (restoring tighter HVAC schedules) is also similar to the other faults described in Measures 01 through 03. For each of the baseline models, the fault is applied by extending the existing HVAC schedules in the evenings by 4 hours for each day of the week during which there are existing scheduled hours of fan operation. In addition to the 4-hour extended schedule baseline fault, an alternative baseline with 2-hour extended schedules was also created.

An exception to this modeling strategy is the Supermarket prototype, for which the baseline operation calls for 24 hour per day operation year-round, and EEM04 adjusts the HVAC schedules to be OFF for 6 hours, from midnight to 6:00 a.m. There is no alternative baseline for this prototype.

Table 4.3 details the extended schedules that are applied to the baseline with 4-hour extended schedules, the alternative baseline with 2-hour extended schedules, and the restored schedules as part of Measure 04, for each building prototype.

All changes in schedules are applied to fan schedules, heating and cooling thermostat setpoint schedules, and infiltration schedules. Note that schedules that specify end times after midnight are handled in

EnergyPlus by adjusting morning schedules for the following day. For example, if weekday schedules extend to 1:00 a.m., this would entail creating a schedule for Saturday that was ON until 1:00 a.m. because of Friday's operations.

This measure applies to all prototypes, except Large Hotel, which has 24-hour per day operation, year-round.

Table 4.3. Weekday, Saturday, and Sunday Schedules in the Baseline Models and Restored HVAC Schedule (Measure 04) Models

Prototype Model	Weekday Schedule	Saturday Schedule	Sunday Schedule
Large Office Baseline (4 hr)	5:00 a.m.–10:00 p.m.	5:00 a.m.–6:00 p.m.	Off
Large Office Alt Baseline (2 hr)	5:00 a.m.–8:00 p.m.	5:00 a.m.–4:00 p.m.	Off
Large Office Measure 04	5:00 a.m.–6:00 p.m.	5:00 a.m.–2:00 p.m.	Off
Medium Office Baseline (4 hr)	5:00 a.m.–10:00 p.m.	5:00 a.m.–6:00 p.m.	Off
Medium Office Alt Baseline (2 hr)	5:00 a.m.–8:00 p.m.	5:00 a.m.–4:00 p.m.	Off
Medium Office Measure 04	5:00 a.m.–6:00 p.m.	5:00 a.m.–2:00 p.m.	Off
Small Office Baseline	5:00 a.m.–10:00 p.m.	5:00 a.m.–6:00 p.m.	Off
Small Office Alt Baseline (2 hr)	5:00 a.m.–8:00 p.m.	5:00 a.m.–4:00 p.m.	Off
Small Office Measure 04	5:00 a.m.–6:00 p.m.	5:00 a.m.–2:00 p.m.	Off
Strip Mall Store Type 1 Baseline (4 hr)	7:00 a.m.–3:00 a.m.	7:00 a.m.–4:00 a.m.	7:00 a.m.–3:00 a.m.
Strip Mall Store Type 1 Alt Baseline (2 hr)	7:00 a.m.–1:00 a.m.	7:00 a.m.–2:00 a.m.	7:00 a.m.–1:00 a.m.
Strip Mall Store Type 1 Measure 04	7:00 a.m.–11:00 p.m.	7:00 a.m.–midnight	7:00 a.m.–11:00 p.m.
Strip Mall Store Type 2 Baseline (4 hr)	6:00 a.m.–midnight	6:00 a.m.–10:00 p.m.	7:00 a.m.–9:00 p.m.
Strip Mall Store Type 2 Alt Baseline (2 hr)	6:00 a.m.–10:00 p.m.	6:00 a.m.–8:00 p.m.	7:00 a.m.–7:00 p.m.
Strip Mall Store Type 2 Measure 04	6:00 a.m.–8:00 p.m.	6:00 a.m.–6:00 p.m.	7:00 a.m.–5:00 p.m.
Strip Mall Store Type 3 Baseline (4 hr)	7:00 a.m.–1:00am	7:00 a.m.–11:00 p.m.	8:00 a.m.–10:00 p.m.
Strip Mall Store Type 3 Alt Baseline (2 hr)	7:00 a.m.–11:00 p.m.	7:00 a.m.–9:00 p.m.	8:00 a.m.–8:00 p.m.
Strip Mall Store Type 3 Measure 04	7:00 a.m.–9:00 p.m.	7:00 a.m.–7:00 p.m.	8:00 a.m.–6:00 p.m.
StandAlone Retail Baseline	5:00 a.m.–1:00 a.m.	5:00 a.m.–2:00 a.m.	7:00 a.m.–11:00 p.m.
StandAlone Retail Alt Baseline (2 hr)	5:00 a.m.–11:00 p.m.	5:00 a.m.–midnight	7:00 a.m.–9:00 p.m.
StandAlone Retail Measure 04	5:00 a.m.–9:00 p.m.	5:00 a.m.–10:00 p.m.	7:00 a.m.–7:00 p.m.
Primary School Baseline	5:00 a.m.–1:00am	Off	Off
Primary School Alt Baseline (2 hr)	5:00 a.m.–11:00 p.m.	Off	Off
Primary School Measure 04	5:00 a.m.–9:00 p.m.	Off	Off
Secondary School Gym and Auditorium; Study Period Baseline	6:00 a.m.–1:00am	Off	Off
Secondary School Gym and	6:00 a.m.–11:00 p.m.	Off	Off

Prototype Model	Weekday Schedule	Saturday Schedule	Sunday Schedule
Auditorium; Study Period Alt Baseline (2 hr)			
Secondary School Gym and Auditorium; Study Period Measure 04	6:00 a.m.–9:00 p.m.	Off	Off
Secondary School Gym and Auditorium; Summer Baseline	6:00 a.m.–7:00 p.m.	Off	Off
Secondary School Gym and Auditorium; Summer Alt Baseline (2 hr)	6:00 a.m.–5:00 p.m.	Off	Off
Secondary School Gym and Auditorium; Summer Measure 04	6:00 a.m.–3:00 p.m.	Off	Off
Secondary School Other Zones; Study Period Baseline	5:00 a.m.–9:00 p.m.	Off	Off
Secondary School Other Zones; Study Period Alt Baseline (2 hr)	5:00 a.m.–7:00 p.m.	Off	Off
Secondary School Other Zones; Study Period Measure 04	5:00 a.m.–5:00 p.m.	Off	Off
Secondary School Other Zones; Summer Baseline	6:00 a.m.–5:00 p.m.	Off	Off
Secondary School Other Zones; Summer Alt Baseline (2 hr)	6:00 a.m.–3:00 p.m.	Off	Off
Secondary School Other Zones; Summer Measure 04	6:00 a.m.–1:00 p.m.	Off	Off
Supermarket Baseline	24/7 operation	24/7 operation	24/7 operation
Supermarket Measure 04	6:00 a.m.–midnight	6:00 a.m.–midnight	6:00 a.m.–midnight

Measure 05: Supply Air Temperature (SAT) Reset. For all buildings with VAV systems for air distribution (Medium Office, Large Office, Large Hotel, Primary School, and Secondary School), the baseline prototype uses constant-SAT setpoints of 55°F at all times. Warmer SAT setpoints, when applied appropriately, can help to reduce simultaneous heating (at the VAV box reheat coils) and cooling (at the AHU's cooling coil). This measure includes three alternative strategies for SAT control:

- *Outdoor Air Temperature-Based Reset:* This is a simple method for automatic control of SAT. While more complex methods of SAT reset exist and can be useful in guaranteeing comfort conditions in building zones more holistically, Fernandez et al. (2012) demonstrated through modeling that there is very little difference in overall energy savings between the simple SAT reset method and a complex reset taking into account both outdoor air temperature and zone-level cooling demands. For this measure, when the outside air temperature is greater than 75°F, the SAT is set at 55°F. When the outside air temperature is less than 45°F, the SAT is set at 60°F. When the outside air temperature is in between 45°F and 75°F, the SAT varies linearly between 60°F and 55°F.
- *Seasonal Control*: This is a method of SAT control that is often applied in buildings without access to BAS programing to reset automatically the SAT. As an alternative, many building operators resort instead to applying a seasonal change of SAT setpoints that can be implemented via operator override. In this measure, the SAT is set to 55°F in the summer and 60°F in the winter. Based on the specific climate, the spring and fall setpoint switch dates change to anticipate appropriate times to switch back and forth. These dates are listed in Table 4.4. The dates roughly correspond to when

average outdoor air high temperatures rise above or fall below 65°F. In hot and humid climates, temperatures are considered too warm throughout the winter for any seasonal switch to be feasible.

- *Night-Cycle Mode SAT Reset*: Many buildings maintain the same sequences of operation for VAV system control in occupied mode as well as in night-cycle mode (to maintain setback and setup temperatures). In the winter, this can lead to recirculated air being cooled to 55°F in the AHU before being sent to the zones for maintaining heating setback temperatures. An alternative strategy is to raise the setpoint such that air is only being recirculated in the building, and only heated where there is a heating load. This measure uses EMS to switch the SAT setpoint to 70°F when the HVAC schedule is off (unoccupied) and the outdoor air temperature is below 60°F.

Table 4.4. Seasonal Switch Dates for Supply Air Temperature Reset

Location	Spring Switch to 55°F	Fall Switch to 60°F
Albuquerque, NM	4/30	10/15
Atlanta, GA	3/31	10/31
Baltimore, MD	4/30	10/31
Chicago, IL	4/30	10/15
Denver, CO	4/30	9/30
Duluth, MN	5/31	8/31
Fairbanks, AK	6/15	7/31
Helena, MT	5/31	9/30
Houston, TX	55°F Year-round	
Las Vegas, NV	3/31	10/31
Los Angeles, CA	4/15	10/31
Miami, FL	55°F Year-round	
Minneapolis, MN	4/30	9/30
Phoenix, AZ	2/28	11/30
San Francisco, CA	6/30	9/30
Seattle, WA	5/31	9/30

Measure 06: Outdoor Air Damper Faults and Control. This measure restores proper outdoor air damper operation and control in two ways:

- It corrects the operational fault in the baseline model that limits the outdoor air fraction to a minimum of 10% and a maximum of 70% by allowing the dampers to control fully between 0% and 100% and implicitly fixes any problems with damper sealing. These changes are accomplished through simple schedule changes in the controller: outdoor air objects for each air handler.
- It controls to zero minimum outdoor air during unoccupied periods. In the baseline, the minimum fraction of outdoor air is constant at all times at 15% for all prototypes, except for Medium Office, for which the minimum is 30% in order to maintain ventilation requirements. This measure adjusts the minimum fractions of outdoor air to be 0% during unoccupied periods. Unoccupied periods are determined for this measure according to times when the fan systems are scheduled off. Baseline fan schedules are listed in Table 4.3. This measure pertains to all prototypes except for Large Hotel, which is continuously occupied, and cannot therefore adjust minimum outdoor air schedules according to an unoccupied period. For the Supermarket prototype, this measure is applicable, but

only in conjunction with the schedule reduction measure (Measure 04) because the baseline operation of Supermarket fan systems is 24/7.

Measure 07: Exhaust Fan Control. This measure synchronizes exhaust fan schedules (for bathroom exhausts) with the HVAC operation schedule used for AHUs such that bathroom exhaust fans shut off at night and when the building is otherwise unoccupied. In the baseline, the exhaust fans run all the time. This measure is implemented in EnergyPlus by specifying the HVAC operation schedule as the new "availability schedule" for the exhaust fans (Fan:ZoneExhaust). When the exhaust fan is shut off, the overall volumetric flow rate of infiltration air to the building (which is spread uniformly over the building exterior) is reduced in equal proportion to the volumetric flow rate of air that the fan exhausts when it is on. To accommodate this modeling strategy, additional zoneinfiltration:designflowrate objects are added in the baseline for each zone and given the same schedule as the exhaust fan.

Measure 08: Static Pressure Reset. This measure simulates the reset of fan static pressure setpoints for VAV systems. The static pressure downstream of the supply fan is typically controlled to a fixed setpoint in VAV systems. This ensures that there is always adequate air pressure to every VAV box, even if all VAV boxes are calling for maximum airflow rates. During most operating conditions, however, reduced overall airflow demands mean that the static pressure setpoint can be reduced without compromising airflow for any of the VAV boxes.

Accurate modeling of airflow dynamics in a VAV system requires a complex characterization of the pressure drop characteristics of the ductwork between the supply fan and each VAV box. EnergyPlus does not support this level of detailed specification, and thus the airflow rates at each terminal box are not affected by the specified "fan pressure rise" (i.e., static pressure), nor are they affected by the airflow demands elsewhere in the VAV network. Although EnergyPlus does track VAV terminal unit damper positions, these positions are calculated as the ratio of current airflow rates to design airflow rates at each VAV box, which is an approximation and not reflective of what those damper positions actually mean.

The lack of feedback of fan static pressure to VAV box damper positions means that modeling static pressure reset in EnergyPlus is at best a first-order approximation of the actual process and thus the achievable savings. Nevertheless, two methods of static pressure reset are modeled:

- *Maximum Damper Position.* This method simulates control of static pressure setpoints in response to the most open damper position in the VAV network. Ordinarily, a trim-and-respond feedback control would be used to maintain the most open damper at between 90 and 100%; however, because this cannot be done in EnergyPlus, a simple ratio is used to adjust the fan pressure rise. If the maximum damper command is 50% or lower, the fan pressure rise is set to half of its default value. If the maximum damper command is 95% or greater, the fan pressure rise is set to the full value. In between, the fan pressure rise is linearly reset.
- *Time of Day Reset.* This is an alternative strategy that is often implemented in buildings that have pneumatically controlled VAV boxes. These boxes do not communicate damper position to the BAS, and the typical control based on VAV box damper feedback cannot be applied. As an alternative, static pressure setpoints can be reset based on time of day to anticipate periods of low airflow demand that are driven by reduced occupancy. For Large and Medium Office prototypes, the time-of-day schedule for reduced static pressure setpoints is from 5:00 p.m. to 5:00 a.m., Monday through Friday and from 1:00 p.m. Saturday to 5:00 a.m. Monday morning. During these times, the static pressure is reduced to half of its default value.

Measure 9: Plant Shutdown When There is No Load. In the baseline models with central plant systems with secondary loops (building loops), the secondary loop pump is on at all times that the plant is available to run. This is meant to simulate common control of the secondary loop pumps, wherein the pumps do not receive control feedback from hot water and chilled water valves in the building, and by default, run continuously unless the plant systems are locked out. When there is no load in the building, the pumps drop to their minimum speeds, and recirculate water through a bypass valve. This measure simulates shutting off the secondary loop pumps when there is no load from any of the hot water or chilled water coils in the building. This measure relies on the use of custom EMS code to ensure that the secondary loop pumps are turned off whenever the lead equipment in the primary loop shuts off (this equipment in turn automatically shuts off when there is no load).

Although Large Office, Large Hotel, and Primary School prototypes all include secondary pumps for chilled and/or hot water loops, this measure could only be simulated as intended for the Large Office prototype. The custom EMS code did not work as intended in the other two prototypes.

Measure 10: Chilled Water Differential Pressure (DP) Reset. This measure simulates the reset of the chilled water secondary loop pump's differential pressure setpoint in response to chilled water valve coil positons. As was the case for static pressure setpoints for the VAV systems, the chilled water differential pressure is typically set to a fixed value that guarantees that all coils will have enough water flow during design cooling conditions. During part load conditions, there is the potential to reduce the differential pressure setpoint, while still providing chilled water coil valves with sufficient flow to meet their setpoints. This lowers the pressure head across the pump, thereby reducing pumping power. Differential pressure reset for chilled water loops is a possibility for buildings that have variable-speed chilled water pumps, including the Large Office, Large Hotel, and Secondary School prototypes.

The same modeling problems that limit the accurate modeling of static pressure reset affect differential pressure resets as well. There is no feedback of pump head to cooling coil valve positions. In the case of differential pressure resets, there is less potential for development of EMS programming to simulate demand-based reductions in pump head. Instead, aggregate chilled water flow rates are used as a proxy for the fraction of total cooling demand, and thus the potential for reductions in differential pressure. By adjusting the pump power curve that is a function of part load ratio, the pumping power can be customized to reflect assumed reductions in chilled water differential pressures at lower aggregate flow rates (pump part load ratios). The specific curves used in the baseline Large Office model and the chilled water DP Reset model can be found in the provided EnergyPlus code for Measure 10 in Appendix B. Figure 4.1 shows the two curves graphically along with the relative savings from the baseline to the DP Reset measure.

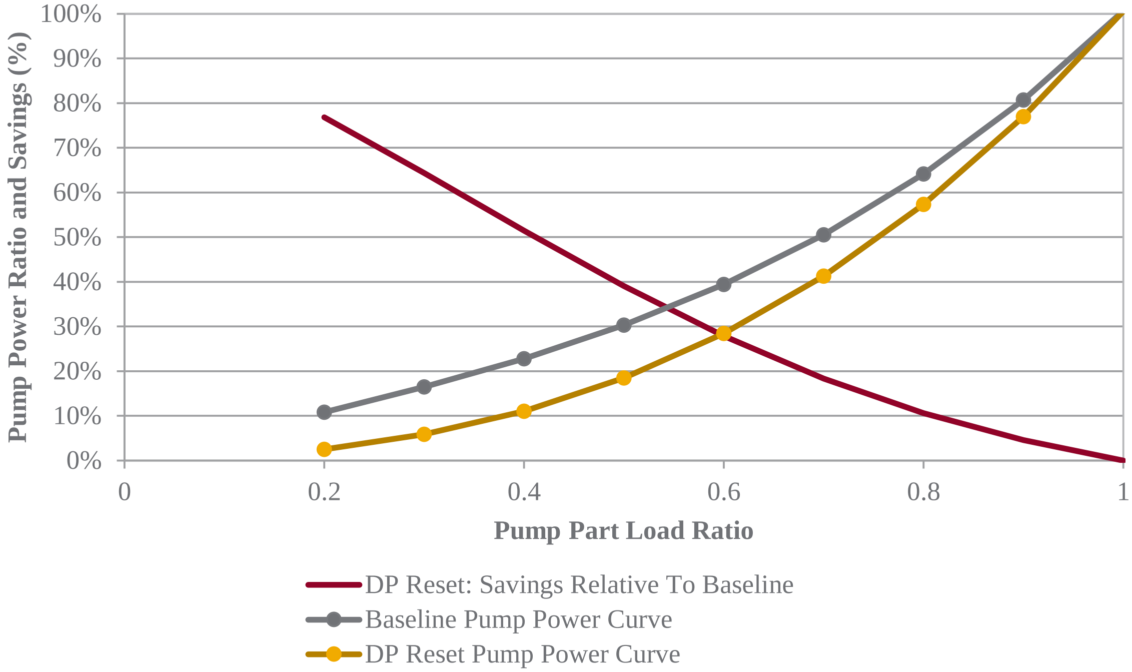

Figure 4.1. Comparison of Baseline and DP Reset Pump Power Curves and Energy Savings for Measure 10

Measure 11: Chilled Water Temperature Reset. As chilled water temperature increases, the suction pressure of the chiller increases, lowering the pressure "lift" between the high and low pressure sides of the refrigeration loop. This decreases the amount of electric power used by the compressor. As chilled water temperatures increase, however, larger volumes of chilled water are needed to meet the same cooling loads, making the chilled water pumps work harder. Optimizing chilled water temperatures requires balancing of these two competing end uses. Although a truly optimal strategy is not feasible in practice, strategies that increase chilled water temperatures at times of low chilled water demand are typically successful at reducing overall system electric power. Chilled water temperature reset is modeled for the Large Hotel and Secondary School prototypes. The Large Office prototype has a chilled water plant, but this measure caused unexpected chiller staging problems that could not be resolved, and the measure is therefore not simulated for the Large Office model.

Two strategies are modeled for this measure:

- *Seasonal Reset:* Many buildings have limited capabilities for adjusting the chilled water temperature setpoint dynamically. Many large buildings cannot control the chilled water temperature via the building automation system because control resides at the field level controller for each of the chillers. In cases like this, chilled water temperature reset can usually only be achieved through manual reset of the chilled water temperatures at the chilled water control panel. A seasonal reset limits the amount of time operators need to devote to managing chilled water temperatures. This measure simulates the use of a summer chilled water temperature setpoint of 44°F and a winter setpoint of 48°F. The spring and fall dates used to switch from the summer to the winter setpoints mirror the dates used for seasonal SAT reset for Measure 05 in Table 4.4.
- *Outdoor Air Temperature-Based Reset:* An outdoor air temperature-based reset of chilled water temperature is a simple method for dynamically changing the chilled water temperature in response to the anticipated demand for cooling. This measure resets the chilled water temperature from 44°F for

outdoor air temperatures above 80°F up to 50°F for outdoor air temperatures below 60°F with a linear reset of the chilled water temperature setpoint in between this range.

Measure 12: Condenser Water Temperature Reset: Similar to chilled water temperature reset, finding the best condenser water temperature setpoint is an optimization problem. Lowering the condenser water temperature lowers the condensing pressure of the chillers' vapor compression cycle, thereby lowering the compressor lift and reducing chiller electric power. However, lowering this setpoint can also mean that the tower fans run harder (if they are variable-speed fans) or that more tower fans are staged on, which tends to increase fan power. A common condenser water temperature reset algorithm is to reset the condenser water temperature, based on a constant approach temperature, to the outdoor air wet-bulb temperature (which is the theoretical lower limit of the condenser water temperature in a "perfect" cooling tower). This measure maintains a 4°C approach temperature to the outdoor air wet-bulb temperature. A lower limit for the setpoint of 65°F is used, which is a common lower limit requirement for many chillers. An upper limit for the setpoint of 80°F acts to drive the tower to minimize the outlet temperature of the condenser water from the towers during hot and humid conditions to mitigate excessive chiller power consumption. Condenser water temperature reset is modeled only for the Large Office prototype because it is the only building with water-cooled chillers and cooling towers.

Measure 13: Hot Water Differential Pressure Reset. The modeling approach for hot water differential pressure reset is handled the same way as for chilled water differential pressure reset—by adjusting pump curves for hot water loop secondary loop pumps using the same changes to pump power curve coefficients. Hot water temperature reset is modeled in the Large Hotel, Large Office, Primary and Secondary School prototypes. This measure produces some small electricity savings, but because pump electricity is mostly dissipated as heat in the hot water loop, the pump electricity savings is offset by similar increases in natural gas for heating. In terms of energy cost and primary energy consumption, however, this measure still produces a net savings.

Measure 14: Hot Water Temperature Reset. Reducing hot water temperatures during periods of low heating demand can save energy through a variety of mechanisms. For condensing hot water boilers, there is typically a large increase in boiler efficiency (by as much as 12%) as hot water supply temperatures are decreased from high-demand setpoints (above 140°) to low-demand setpoints (as low as 90–100°F). Prototype models currently do not include condensing boilers, therefore, the generation efficiency of hot water is constant with respect to hot water supply temperature.

Lowering the hot water temperature can also save energy by means of reduced thermal losses from uninsulated or poorly insulated piping (especially in mechanical rooms and plumbing chases). In some buildings, these problems are pervasive enough that interior temperatures in most zones actually drift higher than their occupied setpoints overnight in cold weather

Measure 15: Minimum VAV Terminal Box Damper Flow Reductions. VAV terminal boxes typically have minimum airflow requirements that are set during commissioning as a conservative measure to guarantee zone ventilation requirements are met at all times based on design occupancy. For many zones, this design occupancy is rarely, if ever achieved and when it is achieved, internal loads tend to drive the zone into cooling mode, which increases airflow to the zone anyway. Consequently, high minimum airflow setpoints tend to be unnecessary and are counterproductive to energy performance. High minimum airflow rates force the zone to accept too much relatively cool supply air from the AHU, forcing the zone into heating mode. Lowering the minimum airflow rates reduces the aggregate airflow demands of the VAV system, saving fan and cooling energy, and saving significantly on zone-level reheat.

This measure is applicable to all prototypes with multi-zone VAV systems (Medium and Large Office, Large Hotel, Primary and Secondary School). In this measure for all VAV-served zones, constant minimum airflow fractions are reduced to 25% of the maximum airflow rate. The baseline minimum VAV airflow rates are 40% of the maximum airflow rates for all zones in all prototypes, with the exception of the Large Hotel prototype, where baseline minimum airflow fractions vary from 30% to 100% by zone for the VAV system in that building.

Measure 16: Widened Thermostat Deadbands and Night Setback. This measure encompasses two strategies to modify thermostat setpoints. The first strategy is to widen the deadbands between the effective heating and effective cooling setpoints. Many buildings use a thermostat control that uses a central zone setpoint with a deadband or a range of temperatures where no heating or cooling is required. This range helps to keep from switching from heating to cooling mode too frequently, and it also saves energy by lowering the effective heating and raising the effective cooling setpoint. Each of the prototype baseline models has been modified to include effective heating setpoints of 71°F and effective cooling setpoints of 73°F during occupied hours (equivalent to a central setpoint of 72°F with a +/-1°F deadband). This measure widens the deadband to +/-3°F, for an effective heating setpoint of 69°F and an effective cooling setpoint of 75°F.

In addition, the heating night setback limits for individual zones have been expanded. In the baseline for each of the prototypes, the night setback temperature has been set to 65°F and this measure reduces that setpoint to 60°F.

This measure is simulated for all building prototypes, but there is a variation on the implementation strategy for the Large Hotel prototype. Because the Large Hotel prototype does not have any unoccupied periods, night setback is not modeled as part of this measure. The Large Hotel prototype does, however, include more aggressively widened deadbands for corridor spaces. Corridors in the Large Hotel prototype are modeled with an effective heating setpoint of 65°F and an effective cooling setpoint of 85°F as part of this measure, while the rest of the public spaces have widened deadbands of +/-3°F as discussed above. Because guest rooms typically have user-adjustable thermostats, which can be adjusted up and down at will to achieve the optimal desired temperature by guests, the deadband is largely irrelevant to effective heating and cooling setpoints for these rooms. For this reason, guest rooms are excluded from this measure. However, Measure 36 simulated for this study includes the use of occupancy sensors for control of thermostat setpoints (and lighting) in guest rooms.

Measure 17: Demand Control Ventilation. Minimum outdoor air requirements for buildings are typically set based on design occupancy. Two different strategies are modeled depending on building type:

- *Zone Sum Procedure.* This procedure is used for buildings with multi-zone VAV systems (Large Office, Medium Office, Primary School, Secondary School, and Supermarket) with the exception of Large Hotel, where this measure is excluded because it creates unresolved errors.

  This measure simulates a building that dynamically complies with ASHRAE Standard 62.1 ventilation requirements. For each AHU using this demand control ventilation measure, the ventilation requirement is the sum of the ventilation requirements in each zone (5 cfm per person plus 0.06 cfm/ft^2 of floor area for office spaces). As the occupancy changes, so does the minimum ventilation. In reality, this kind of control would be very difficult to implement, but this measure is intended to simulate a perfect demand control ventilation scenario.

  Note that this measure's effectiveness is limited by leaking economizer dampers, which limit the outdoor air fraction to a minimum of 10%. When these two measures are both included simultaneously, the demand control ventilation can drive the minimum outdoor air as low as it needs to go.

- *Indoor Air Quality Procedure*. This procedure is used for buildings with single-zone packaged equipment (Small Office, Strip Mall Retail, StandAlone Retail, Auditorium and Gyms of Secondary School). This demand control ventilation strategy uses an estimation of zone carbon dioxide (CO_2) concentration to drive the minimum outdoor air requirements, maintaining the levels of indoor air CO^2 at or below 1000 ppm.

Measure 18: Occupancy Presence Sensors for Lighting. This measure simulates the use of occupancy presence sensors in applicable spaces by adjusting lighting schedules according to the anticipated fraction of lighting that will shut off. This measure is implemented as indicated in Table 4.5 by zone type. Table 4.5 lists the fraction of lighting that shuts off during the day (occupied hours) and at night (unoccupied hours), and the sources and assumptions for the values used.

Table 4.6 shows for each prototype, which types of zones exist that are subject to occupancy sensor control for Measure 18, and the overall fraction of building floor area that is affected by occupancy sensors. The highest fractions (85–90%) are for primary and secondary schools. Occupancy sensors are not applicable in the Strip Mall Retail prototype because the entire building is devoted to sales areas, which are inappropriate for occupancy control. The Supermarket prototype has several zones with applicability, but they only constitute 5.7% of the total floor area. For the Large Hotel prototype, this measure only simulates the use of conventional lighting occupancy sensors for public areas of the hotel. In addition, a separate measure (Measure 36) simulates the use of another technology that employs guest room occupancy detection to shut off lights and set back thermostats.

Table 4.5. Lighting Savings Assumptions in Applicable Zones for Lighting Occupancy Presence Sensors for Measure 18

Type of Zone	Day Savings (Occupied)	Night Savings	Source	Assumption
Private Office	28%	69%	VonNeida et al. (2000)	10-minute delay
Office Conference	38%	69%	VonNeida et al. (2000)	10-minute delay
Bathroom	34%	79%	VonNeida et al. (2000)	10-minute delay
Classroom	20%	20%	VonNeida et al. (2000); Floyd et al. (1996)	Intermediate between two cited sources
Corridor	55%	55%	AHLA (2016)	Central value of savings range reported
Storage, Mechanical	62.5%	62.%	AHLA (2016)	Central value of savings range reported for storage in source cited
Meeting, Banquet and Dining areas	43.5%	43.5%	AHLA (2016)	Central value of range for hotel “conference rooms” given in source cited
Library, Gym, Auditorium	28%	69%	VonNeida et al. (2000)	Assumed same savings patterns as private office

Table 4.6. Occupancy Presence Sensor Application by Prototype Model for Measure 18

Prototype Model	Types of Zones	Fraction of Building Floor Area
Small Office	Private Office (Perimeter)	34.7%
Medium Office	Private Office (Perimeter)	40.8%
Large Office	Private Office (Perimeter), Conference Room	42.2%
Primary School	Classroom, Corridor, Library, Gym, Bathroom, Office	86.8%
Secondary School	Classroom, Corridor, Library, Gym, Auditorium, Bathroom, Office	90.0%
Large Hotel	Office, Storage, Dining, Banquet, Laundry, Mechanical	43.6%
Strip Mall Retail	None	0.0%
StandAlone Retail	Back Room (Storage)	16.5%
Supermarket	Office, Bathroom, Storage, Mechanical, Meeting, Dining	5.7%

Measure 19: Daylighting Control. This measure simulates the use of daylighting controls for perimeter zone lighting. The measure dims lights in a 15 ft zone closest to the windows in perimeter zones using a light sensor that maintains an illuminance setpoint of 300 lux. In some prototypes, such as Small and Medium Office, perimeter zones are less than or equal to 15 ft wide and the entire perimeter zone is affected by the control. For other prototypes and zones, a fraction of perimeter zones is specified as being controlled by daylighting sensors according to the calculated fraction of the zone that is within 15 ft of the exterior wall.

For the office prototypes, implementation of this measure makes use of daylighting control objects that are already included in each of the baseline models (but are switched off in the baseline). This measure switches daylighting control on. A sample daylighting control object from the Large Office prototype is included below. For other prototypes, daylighting control objects were created for perimeter zones. Daylighting control was modeled for all prototypes except Large Hotel (for which greatly reduced lighting schedules during the day make daylighting sensors an unattractive investment), and Supermarket (which has very limited windows and insufficient natural daylighting to make this measure feasible). The StandAlone Retail prototype only has windows along one of the four facades, and this measure was not as impactful in that model.

Measure 20: Exterior Lighting Control. In the baseline for each prototype model, parking lot lights are controlled on and off according to an astronomical clock that simulates the use of a photocell. This keeps the lights strictly on at night and strictly off during the day. This measure still uses a simulated photocell to shut parking lot lights off during the day, but only keeps all of the parking lot lights on at night during building occupied hours (plus an additional hour before and after occupancy). This allows the parking lot lights to shut off when no one is reasonably expected to be using the parking lot. When parking lot lights shut off at night, 25% remain on for safety.

This measure is simulated for all prototypes except for Large Hotel, which may require parking lot lights to be on at full power all night to accommodate guests. Scheduled off times and parking lot total installed lighting power is shown for all applicable prototypes in Table 4.7.

Table 4.7. Parking Lot Installed Lighting and Scheduled OFF Hours for Measure 20

Prototype	Parking Lot Installed Lighting (W)	Scheduled Off Hours (Weekdays)	Scheduled Off Hours (Saturday)	Scheduled Off Hours (Sunday)
Small Office	4,896	7:00 p.m. to 5:00 a.m.	7:00 p.m. to 5:00 a.m.	All day
Medium Office	13,122	7:00 p.m. to 5:00 a.m.	7:00 p.m. to 5:00 a.m.	All day
Large Office	23,516	7:00 p.m. to 5:00 a.m.	7:00 p.m. to 5:00 a.m.	All day
StandAlone Retail	5,251	10:00 p.m. to 7:00 a.m.	11:00 p.m. to 7:00 a.m.	8:00 p.m. to 9:00 a.m.
Strip Mall Retail	6,356	Midnight to 7:00 a.m.	1:00 a.m. to 7:00 a.m.	Midnight to 8:00 a.m.
Supermarket	10,940	1:00 a.m. to 5:00 a.m.	1:00 a.m. to 5:00 a.m.	1:00 a.m. to 5:00 a.m.
Primary School	2,202	10:00 p.m. to 6:00 a.m.	All day	All day
Secondary School (Study Period)	8,897	10:00 p.m. to 6:00 a.m.	All day	All day
Secondary School (Summer)	8,897	4:00 p.m. to 7:00 a.m.	All day	All day

Measure 21: Advanced Plug Load Control. This measure simulates adopting advanced control devices that can turn off plug loads when they are not in use, such as smart power strips for task lighting and office equipment, special occupancy-based sensors for vending machines, and time switches for water coolers. This strategy is implemented by adjusting the fraction of plug loads that are on at all hours. The adjustments vary according to occupancy status and the biggest reductions occur overnight. Figure 4.2 shows these changes graphically for weekdays, Saturdays, and Sundays.

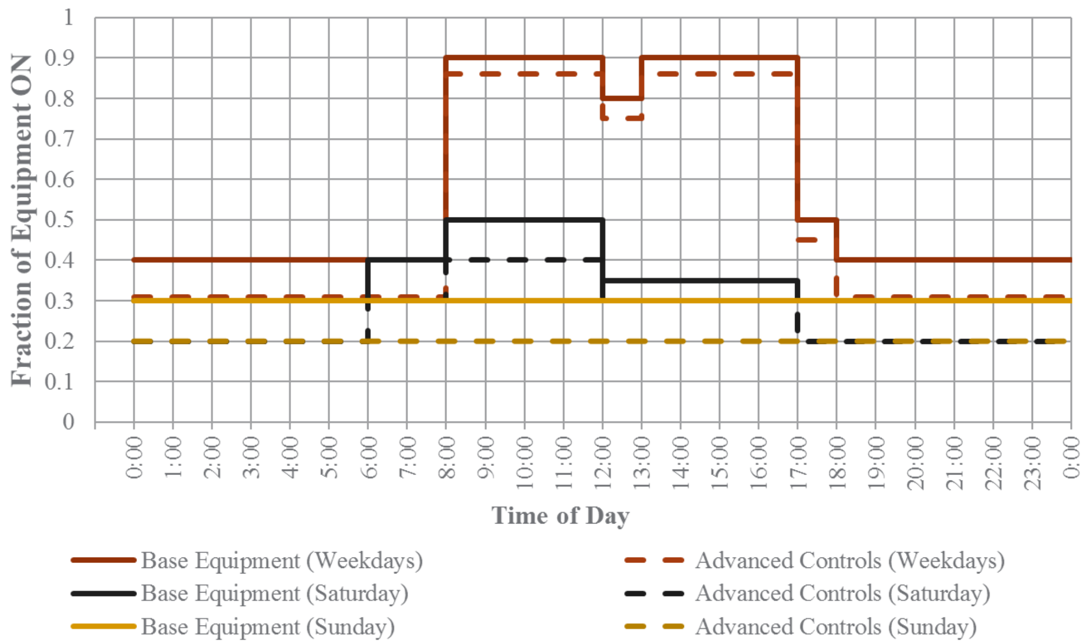

Figure 4.2. Schedule Changes to Plug Load Fraction with Measure 21

Measure 22: Night Purge. This measure simulates the use of a special early morning cycle of the AHUs that make use of full airside economizing to pre-cool the building in advance of occupancy. This form of control can potentially be effective for buildings that have a high thermal mass in (especially) dry climates with low nighttime temperatures during at least part of the cooling season. Control of night purge cycles can be challenging because the algorithm used to initiate a night purge cycle has to be well attuned to whether the cooling provided will be a net benefit to the building or will be counterproductive. The following parameters are specified for the initiation of night purge cycles:

- At least one zone in the AHU network must have a temperature above 71°F.
- The outdoor air temperature must be at least 2°C (3.6°F) colder than the specified control zone.
- The night purge cycle will be terminated if any zone falls below 60°F.
- The supply fan will run at 35% of its design flow during the night purge cycles.
- Static pressure setpoints will be half of default occupied levels.
- An additional EMS control code is added to control the availability of the night purge cycle. This code only allows the purge cycle to proceed if the average outdoor air temperature over the previous 48 hours was warmer than 60°F. This is meant to prevent night-cycle operation during the heating season, which would occur otherwise based only on one zone (including computer server zones) being too warm.

Night Purge is simulated in all prototypes that include scheduled night shutdown of fan systems. This excludes Supermarket and Large Hotel prototypes.

Measure 23: Advanced RTU Control. This measure simulates the installation of a controller on a packaged RTU that reduces the speed of the supply fan based on the mode of operation. Several modes of operation, the fraction of time spent in each mode (for each timestep), and the specified fan speed fractions are defined in Table 4.8. Fan speeds at all times are limited to 90%, which on its own reduces fan power by 21%. Further fan power reductions are achieved when the RTU is in economizer mode (75% fan speed, 47% power reduction) and in ventilation mode (40% fan speed, 87% fan power reduction).

This measure is simulated for all packaged single-zone RTUs, which appear in the Small Office, Strip Mall, StandAlone Retail, Supermarket, and Secondary School prototypes.

Table 4.8. Advanced RTU Control Definitions for Measure 23

Mode of Operation	Fraction of time Definition	Fan Speed Fraction	Fan Power Reduction
Economizer	If outdoor airflow is greater than minimum outdoor airflow, fraction of time not in cooling mode	0.75	47%
Ventilation	If actual outdoor airflow equals minimum outdoor airflow, fraction of time not in heating mode or cooling mode	0.4	87%
Heating	EMS sensor determines heating coil runtime fraction	0.9	21%
Cooling Stage 1 (Single-Stage Cooling Coils Only)	EMS sensor determines cooling coil runtime fraction	0.9	21%

Mode of Operation	Fraction of time Definition	Fan Speed Fraction	Fan Power Reduction
Cooling Stage 1 (Two-Stage Cooling Coils)	EMS sensor finds the difference between the cooling coil runtime fraction and the compressor speed ratio (which is the fraction of time the unit spends in *full* cooling)	0.75	47%
Cooling Stage 2 (Two-Stage Cooling Coils)	EMS sensor determines compressor speed ratio	0.9	21%

Measure 24: Elevator Cab Lighting and Ventilation Control. This measure simulates the use of motion sensors in elevator cabs to turn off lights and ventilation when the cabs are unoccupied. Elevators are present in the Medium Office, Large Office, and Large Hotel prototypes. As implemented, this measure affects both the design level and schedule for elevators. For all prototypes, the design power for elevator lights and fans are reduced by 34.6%. In the baseline for each model, the fans and lights are on all of the time. This measure reduces the runtime fraction for the elevator lights and fans according to the schedule shown in Figure 4.3.

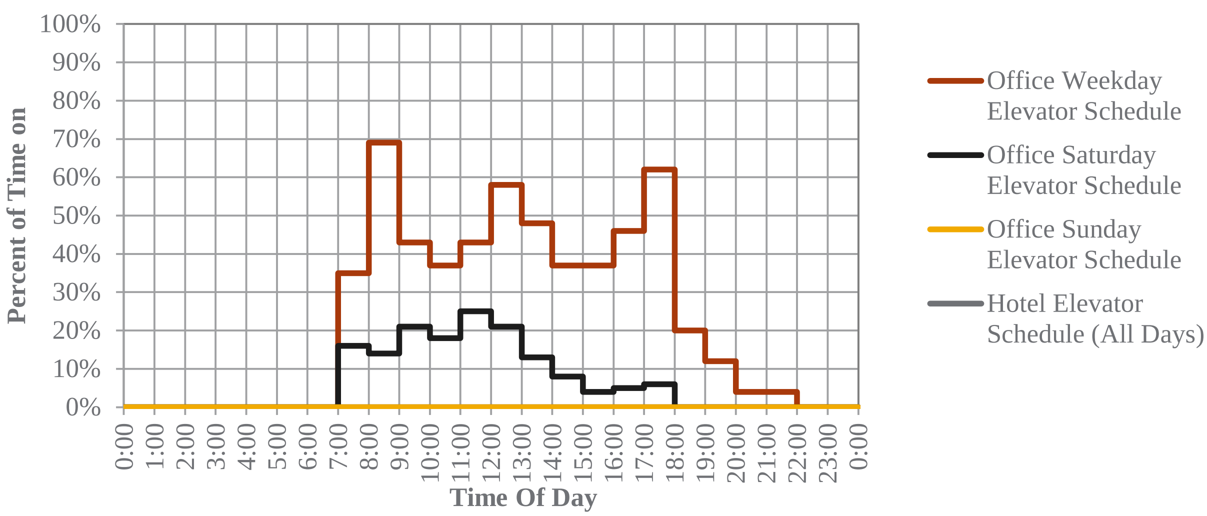

Figure 4.3. Schedule for Elevator Cab Fan and Lights Using Occupancy Presence Sensor (Measure 24)

Measure 25: Waterside Economizer. This measure simulates the impact of using a waterside economizer for free cooling. A waterside economizer works by running the cooling tower loop in the winter and parts of the shoulder seasons as a source of cooling, and transferring cooling energy to the building (secondary) cooling loop. This requires a dedicated plate-and-frame heat exchanger that is used only during waterside economizer operations, during which time the chillers are locked out. To be clear, the intent of this measure is to capture the energy savings from a building operating its waterside economizer when it was previously unused. To add a waterside economizer to an existing building is a very expensive process that involves the purchase of the plate-and-frame heat exchanger and the re-configuration of the building's chilled and condenser water piping. This measure is expected to capture savings most effectively from buildings that do not already have airside economizers. In this study, airside economizers were not used in several of the warmer climate zones. For buildings that already have airside economizers, free cooling is generally already available at all of the same times, and can be accomplished using less energy. The control scheme used to enable the waterside economizer requires the outdoor air wet-bulb temperature to be colder than 6°C (42.8°F). If this is the case, the waterside economizer will be enabled, and the chilled water temperature setpoint will be allowed to rise as high as 51°F, but will generally target maintenance of 44°F chilled water, given that the outdoor conditions are favorable for producing cold enough chilled water. This control scheme is developed using an EMS program.

Measure 26: Cooling Tower Controls (Variable-Speed Fan). This measure simulates the addition of variable-frequency-drives (VFDs) to cooling towers. For the Large Office prototype (the only one with cooling towers), this entails replacement of two single-speed cooling tower objects with variable-speed cooling tower objects for the main cooling plant, and replacement of a smaller cooling tower object for the data centers with a variable-speed tower object. The variable-speed tower is specified to have the same design fan power as the single-speed tower in the new EnergyPlus objects. This measure does not include any further control strategies specific to the variable-speed towers, but this measure and Measure 12 (condenser water temperature reset) should act synergistically to produce savings.

Measure 27: Optimal Start. This measure simulates the use of predictive controls that are often used to control the scheduled morning start-up of AHUs. Optimal start is commonly available as a configurable module within BASs supplied by most vendors. These pre-programmed routines take in information about interior (zone) and exterior temperatures using an algorithm that “learns” how long it takes to heat up or cool down the building to a desired temperature in the morning.

Optimal start is implemented in EnergyPlus using the AvailabilityManager:OptimumStart object. This object must have an availability schedule that is the inverse of the AvailabilityManager:NightCycle object, which controls the availability of fans to come on to meet night setback conditions. These two availability managers are configured to give optimal start a 3-hour window during which to schedule the fan systems on. In the case of the office prototypes, this window is from 5:00 a.m. to 8:00 a.m. The 5:00 a.m. earliest start time coincides with the default morning start time for AHUs in the baseline models. The Optimal Start control uses a recommended calculation methodology from ASHRAE (called Adaptive ASHRAE) and selects the maximum calculated time among all zones served by each AHU. Optimal start is simulated for all prototypes except Large Hotel and Supermarket, which have continuous occupancy and fan system operation in the baseline.

Measure 28: Optimal Stop. Optimal stop is a control strategy that seeks to shut down the AHU early to let the building “coast” just prior to the end of occupancy. This is most feasible when outdoor air temperatures are close to the building’s balance point temperature (assumed to be around 60°F). There is no object or set of objects for modeling Optimal Stop in EnergyPlus, so a custom EMS code was developed to implement a form of Optimal Stop that is controlled based on outdoor air temperatures alone. Figure 4.4 shows graphically how many hours are subtracted from the HVAC schedules at the end of operation in the evenings based on the outdoor air temperature. In addition to adjusting the fan schedule, the EMS code also adjusts heating and cooling setpoints, minimum airflow fractions, and infiltration rates to unoccupied levels after the new calculated stop time.

Optimal Stop is simulated for all prototypes except Large Hotel and Supermarket, which have continuous occupancy and fan system operation in the baseline. Small Office was additionally excluded because of simulation errors that resulted from the custom programming required to simulate this measure.

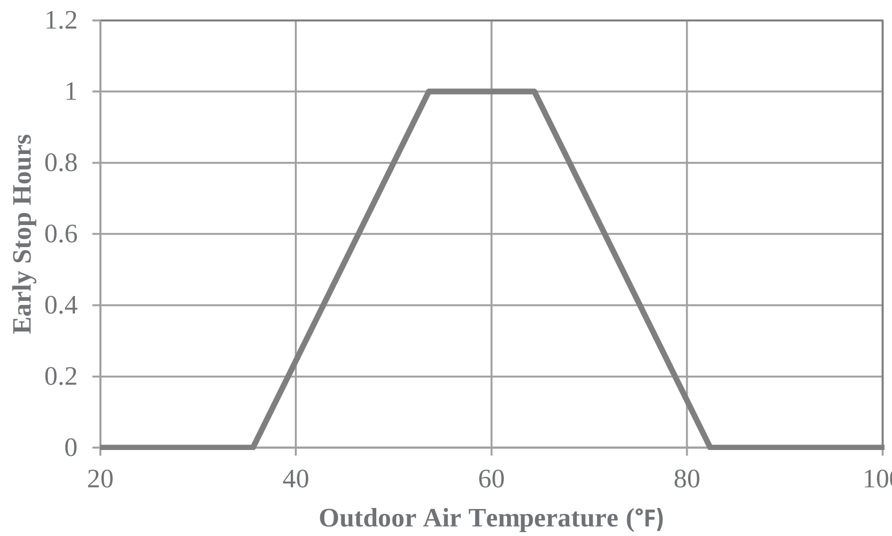

Figure 4.4. Optimal Stop: Early Stop Hours Subtracted from Evening HVAC Schedules for Measure 28

Measure 29: Refrigerated Case Lighting Controls. This measure, which pertains only to the Supermarket prototype, shuts off all lighting in each of the 26 refrigerated display cases that contain lights (17,608 W total installed lighting) during the period from 1 hour after the store close until 1 hour prior to store opening. The two 1-hour time windows are intended to be used for stocking and possible display case checkup. The store business hours are from 6:00 a.m. to 10:00 p.m. Hence, the refrigerated case lighting is turned off from 11:00 p.m. to 5:00 a.m. seven days per week.

Measure 30: Walk-in Refrigerator/Freezer Lighting Controls. This measure, which pertains only to the Supermarket prototype, shuts off lights in each of the 10 walk-in refrigerators and freezers (1,723 W total installed lighting) from the hours of 11:00 p.m. to 5:00 a.m.(after store business hours), seven days per week.

Measure 31: Refrigeration Floating Head Pressure. This measure pertains only to the Supermarket prototype and is geared toward saving energy on the main refrigeration system that serves refrigerated cases and displays throughout the sales area. Most refrigeration systems are set up with constant head pressure setpoints that are geared toward rejecting the maximum amount of heat from the condensers during design conditions (hot summer days). Floating head pressure control optimizes the high pressure setpoint for the refrigeration loop by dynamically setting the “head pressure” setpoint according to ambient conditions. In practice, reduced head pressures during less challenging outdoor air conditions are achieved by increasing the speed of the condenser fans, which rejects more heat from the high pressure side of the system, causing the pressure to drop, and hence the pressure lift across the compressor to drop. This reduces compressor power requirements. This strategy is directly analogous to condenser water temperature reset for chiller systems, and care must be taken to not waste energy at the condenser fans. A typical strategy is to target a condensing temperature setpoint as a fixed offset, typically 10°F above the outdoor dry-bulb (for air-cooled condensers) or wet-bulb (for water-cooled condensers) temperature. Further optimization can be achieved by using an offset that changes according to the refrigeration demand in the building.

This measure is simulated in EnergyPlus by reducing the minimum condenser temperature in each Refrigerator:System object from 26.7 to 15.6°C, and by switching from constant speed control of the air-cooled refrigeration condensers to variable-speed control

Measure 32: Refrigeration Floating Suction Pressure. This measure pertains only to the Supermarket prototype and is geared toward saving energy on the main refrigeration system that serves refrigerated cases and displays throughout the sales area. Similar to conventional fixed head pressure control discussed in Measure 31, conventional control of refrigeration systems for supermarkets involves fixed suction (evaporator) pressure control. For any refrigerant, a given suction pressure is associated with a corresponding temperature in the evaporator coils. Maintaining a fixed suction pressure roughly maintains the same temperature in the refrigerator or freezer where the coil is located. This statement would be true if the ambient conditions inside the store were fixed, but a somewhat lower evaporator temperature is needed when the temperatures inside the store are warmer (as they can be on summer days) in order to maintain constant temperatures in the refrigerator or freezer.

Floating suction pressure control allows the suction pressure to rise (usually by up to 5%), in order to maintain fixed refrigerator and freezer temperatures, typically achieving savings during winter and shoulder seasons.

Measure 33: Optimize Defrost Strategy: This measure pertains only to the Supermarket prototype and is geared toward saving energy on the main refrigeration system that serves refrigerated cases and displays throughout the sales area. As relatively humid air from the indoor environment infiltrates into refrigerator and freezer cases due to the door opening or due to the design of open display cases, the moisture condenses as frost on the evaporator coil, which is the coldest surface in the case and is usually below freezing during compressor operation. To combat this, refrigeration systems are designed to have a defrost cycle, in most cases using a defrost heater to melt accumulated ice off of the evaporator coils. In other cases, a technique called hot gas defrost may be used by routing hot refrigeration gas from the compressor discharge through the evaporator. The baseline model has the conventional control of defrost cycling, which uses a fixed time interval between defrost cycles and a fixed time period for the defrost cycle itself. A variety of strategies have been developed to use a demand-based approach to only initiate a defrost cycle when there is sufficient ice accumulation and to terminate a defrost cycle at the earliest possible time. The optimal defrost strategy modeled is a “time-temperature control” strategy that uses a temperature sensor on the evaporator to determine when the frost has melted and the defrost cycle can be terminated. Figure 4.5 shows the fraction of the baseline defrost time needed in the demand-based strategy, as a function of indoor dewpoint temperature.

This optimized defrost cycle approach is applied to seven low-temperature refrigerated display cases and five walk-ins that use electric resistance for evaporator defrost. Non-low-temperature display cases and walk-ins usually use “off-cycle” for defrost control. In those cases, there is no energy benefit to shortening the defrost cycle.

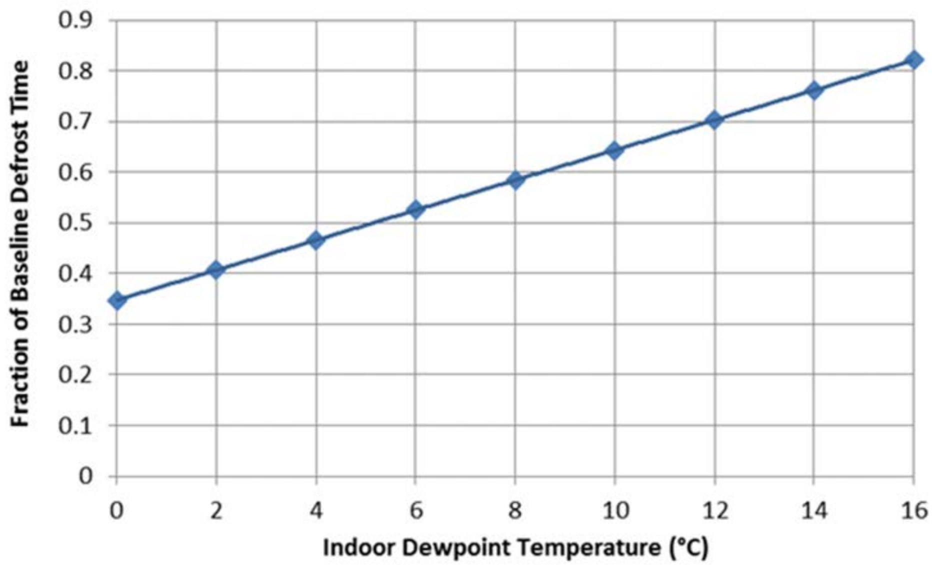

Figure 4.5. Defrost Time Fraction for Optimal Defrost Control for Measure 33

Measure 34: Anti-Sweat Heater Control. This measure, which pertains only to the Supermarket prototype, simulates an advanced control strategy for anti-sweat heaters, which are heating strips that prevent moisture from condensing and accumulating on the glass doors and frames of low-temperature refrigerated display cases. Conventional anti-sweat heaters run continuously at the design power, regardless of the ambient conditions in the store. Advanced anti-sweat heater controllers adjust the heat needed according to the store temperature and relative humidity.

Measure 35: Evaporator Fan Speed Control: This measure, which pertains only to the Supermarket prototype, saves energy by reducing fan power in walk-in coolers and walk-in freezers. In conventional control of walk-ins, fans located in evaporator boxes run continuously at full speed, even if the thermostat is not calling for a cooling cycle or if the evaporator is only cooling at part load. Under this measure, the evaporator fan speed should be based on the position of the evaporator's electronic expansion valve (EEV). When the valve is in a greater than 50% open position, the fan motors run at 100%, and when the EEV is operating at 50% or less, the fan motor reduces to the 80% speed mode (AEDG 2015). This control reduces the speed of the evaporator fan by 20% when the cooling rate from the evaporator is less than 50% of the design cooling rate.

Measure 36: Occupancy Sensors for Thermostats and Room Lighting: This measure, which pertains only to the Large Hotel prototype, simulates the use of occupancy sensor technologies for individual guest rooms that shuts off lighting and sets back the thermostats in the room when the guests leave. This is typically done using special room key card docking ports. The state of California made this technology mandatory for hotels and motels as of July 2014. An EMS program was developed to shut off all lights, and set back the thermostat to "standby" setpoints of 67°F for heating and 76°F for cooling. These setpoints are wide enough to achieve savings, but narrow enough to not risk making guest rooms too hot or cold (long recovery times) upon re-entry. A portion of the EMS code covering three guest rooms is shown below.

Measure 37: Optimized Use of Heat Recovery Wheel: This measure is unique to the Large Hotel prototype, because it is the only prototype with energy recovery ventilation (ERV) using a heat recovery wheel. The baseline operation of the ERV system already called for efficient operation of the ERV by using variable-speed wheel operation to target the desired SAT and by locking out the wheel during economizing conditions. This measure goes one-step further by disabling the wheel (and diverting supply air around the wheel) during times when the additional energy caused by the pressure drop penalty from the wheel outweighs the energy savings from using the wheel. The pressure drop through typical enthalpy wheels is around 1.0 in. of water column or 250 Pa, which can add significant fan power.

This measure would require the use of return air, outdoor air, and conditioned air temperature and humidity sensors plus supply airflow sensors in the DOAS (to make use of the kind of programming demonstrated here), or could be roughly implemented by locking out the heat recovery wheel when the absolute difference between the return and outdoor air temperatures is less than 5°F or 3°C.

Measure 38: Demand-Response-SetpointChanges: This DR measure automatically adjusts the cooling setpoint temperatures throughout the building during a DR event. DR events have been defined as CPP periods in four hour windows from 3:00 p.m. to 7:00 p.m. during the eight hottest weekdays of the year in each climate location. The setpoint changes entail raising the cooling thermostat setpoint to 78.4°F immediately coincident with the start of the CPP event, then releasing the thermostat setpoint to its normal value at the end of the event

Measure 39: Demand-Response-Pre-Cooling: This DR measure is a variation of Measure 28 that anticipates the near-term future occurrence of a CPP event (see description of CPP events in the description of Measure 38) and responds proactively by pre-cooling the building in the three hours in advance of the CPP event to cooler-than-normal setpoints. Doing this is intended to help the building coast for as much of the CPP event as possible. Starting from three hours before the CPP event, the cooling thermostat setpoint is dropped from 73.0°F to 71.2°F. Starting from two hours prior to the CPP event, the cooling setpoint is dropped to 69.4°F, and in the last hour prior to the event, the setpoint is dropped to 67.6°F.

Measure 40: Demand-Response-Duty Cycle: This DR measure is a second variation of Measure 38 that attempts to mitigate long periods of discomfort resulting from DR by cycling between airside systems that are affected by DR. In this particular scheme, every hour, one out of every three-air systems in the building has its cooling coil disabled. The next hour, a second third of the air systems are affected similarly, while the first set returns to normal operation, and so on.

Measure 41: Demand-Response-Lighting: This DR measure requires the installation of dimmable lighting that can be controlled by an automation system that will respond to a DR signal. The measure reduces the power input to the building lights by 10% starting at the beginning of a CPP event (see definition of CPP event in description for Measure 38) and returns lighting to normal levels at the end of the event.

Measure 42 Demand-Response-Chilled Water Temperature Reset: This DR measure responds to a CPP event (see definition of CPP event in description for Measure 38) by raising the chilled water temperature to 50°F and locking the secondary loop chilled water pump's VFD at the value it was at immediately before the CPP event. This prevents the building from responding to higher chilled water temperatures by increasing water flow and pump power. The increase in chilled water temperature and lockout of the pump VFD last only during the CPP event itself.

Measure 43 Demand-Response- Refrigeration: This DR measure responds to a CPP event (see definition of CPP event in description for Measure 38) by

- preventing any of the refrigeration units in the Supermarket prototype from undergoing an evaporator coil defrost cycle during the CPP event;
- shutting off refrigerated case lighting during the CPP event; and

- shutting off the anti-sweat heaters during the event. EnergyPlus does not allow for anti-sweat heaters to be shut off via a schedule, so the demand savings by shutting off the heaters is estimated by subtracting anti-sweat heater power consumption from the final electric demand of the building. This calculated savings does not capture additional savings in refrigeration derived from the reduction in heat gain inside the refrigerated cases that accompanies the shut off of anti-sweat heaters.

5.0 Packages of Controls and Demand-Response Measures

Building operators or managers often deploy a package of synergistic measures rather than individual measures. Deploying a package of measures will in most cases be more cost effective than deploying individual measure. Therefore, packages of controls measures have been created to estimate the national savings potential. These packages create some diversity in the status and complexity of the controls in a conceptualized set of existing buildings. This diversity helps to weight the application of specific EEMs based on the observed prevalence of opportunities to implement those EEMs in actual buildings. Conceptually, the three buildings are

- an efficient building with most common and some advanced EEMs already in place, no operational faults modeled, and limited opportunities remaining;
- a typical building with a few obvious or easy-to-implement control measures and a handful of operational faults, but with a wide range of opportunities for energy savings still available; and
- an inefficient building with no EEMs already in place and widespread operational faults.

Table 5.1 shows the full set of measures in each package. Measures that are not applicable to certain building types do not appear in the packages for those building types. The observed prevalence of opportunity (shown in column 2 of Table 5.1) indicates the fraction of buildings for which each measure has been recommended for implementation among a set of 130 buildings surveyed over the past 10 years for the Re-tuning program (Katipamula, 2015). Other building types did not have a large enough sample size to include in this analysis.

EEMs with over 50% observed prevalence of opportunity are nearly universally applicable, and are not already present in any of the three building packages. EEMs with between 25% and 50% prevalence of opportunity are considered to be implemented already in efficient buildings, but not in typical or inefficient buildings. EEMs with less than 25% prevalence of opportunity are nearly universally implemented with the only remaining opportunity for implementation in the inefficient buildings. Measures not applicable to office-type buildings were placed into one of the three packages based on commercial building analysis expertise. To make the overall prevalence of each measure in the national savings estimates similar to the observed prevalence from Re-tuning experience, the packages are weighted as follows:

- efficient building (30%)
- typical building (50%)
- inefficient building (20%).

This weighting is a slight increase in the prevalence of each measure relative to its observed prevalence. This helps to account for the following.

- Many buildings that were re-tuned may not have had an opportunity for a given EEM due to limitations on infrastructure and the need for capital investment to implement (e.g., lack of BAS connections to devices, lack of variable-speed drives as pre-requisites for speed resets). These measures are still considered as possibilities in the designated buildings.
- There may have been some missed opportunities in a few buildings.

Energy consumption from each of the three packages is compared to the energy consumption from a modeled "ideal" building (column 3 of Table 5.1) that has all EEMs implemented, except for those determined through this study to be poor candidates because of lackluster savings in relation to expected monetary investment in their implementation.

There are many uncertainties that exist in the overall savings estimates based on this methodology. These uncertainties, among other factors, include the prevalence of opportunities to implement each measure, the magnitude of the opportunity for measure deployment based on the baseline building conditions, the representation of a diverse set of buildings with a single model (for each type of building), and uncertainty related to the strategy for modeling each measure. A sensitivity analysis is presented in Section 6.4 as an attempt to understand the impact of the building efficiency level weights (presented in this section) on the overall savings. A broader understanding of uncertainty associated with the modeled savings is not possible because of the complexity of the sources of uncertainty and the lack of reliable data on factors such as the prevalence and magnitude of opportunities for controls improvements.
Two DR packages were developed to estimate whole-building and national-level electric demand savings from implementing a set of DR measures simultaneously during the CPP events. The first package (A) is a “reactive” package, meaning that this package can be implemented immediately upon the initiation of a CPP event, without any prior knowledge or planning for the timing of the event. The second package (B) is a predictive package, meaning that this package can be implemented when there is advanced warning (at least four hours ahead of time) of an impending CPP event, and that the building has the ability to prepare for the event by pre-cooling interior spaces and the building’s thermal mass in advance. Four of the six DR measures proposed for commercial buildings are designed to perform actions that limit the amount of cooling provided to the building. Performing several of these measures together is not advisable because it could lead to major disruptions in thermal comfort. Therefore, the packages were designed to select the highest performing DR measure for cooling reductions for reactive measure (which in all cases, happened to be raising the cooling thermostat setpoints–Measure 38) or predictive measure (Measure 39). This top cooling measure was paired with any remaining DR measures affecting other building electric loads. In the case of Supermarket, this included a set of measures for reducing refrigeration demand (Measure 43), and for all other building types, it included a measure to dim or shut off targeted lighting systems (Measure 41). The inclusion of the DR measures into the two packages is summarized in Table 5.2.

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Table 5.1. Packages of EEMs used to Estimate National Savings

Three packages of EEMs are developed to represent efficient buildings, typical buildings, and inefficient buildings based on a survey of 130 buildings (Katipamula 2015). Each package is compared to an ideal building with all measures included to estimate the potential for additional savings.

Energy Efficiency Measure	Prevalence Of Opportunity for Savings	Reference Case (Ideal Building)	Efficient Building (30%)	Typical Building (50%)	Inefficient Building (20%)
EEM01: Re-calibrate Faulty Sensors	30%	✓	✓		
EEM02: Fix Low Refrigerant Charge		✓	✓	✓	
EEM03: Fix Leaking Heating Coil Valves	25%	✓	✓	✓	
EEM04: Shorten HVAC Schedules	48%	✓	✓		
EEM05: Supply Air Temperature Reset	79%	✓			
EEM06: Outdoor Air Damper Faults and Control	44%	✓	✓		
EEM07: Exhaust Fan Control	44%	✓	✓		
EEM08: Static Pressure Reset	76%	✓			
EEM09: Plant Shutdown When There is no Load	5%	✓	✓	✓	
EEM10: Chilled Water Differential Pressure Reset	32%	✓	✓		
EEM11: Chilled Water Temperature Reset	52%	✓			
EEM12: Condenser Water Temperature Reset	33%	✓	✓		
EEM13: Hot Water Differential Pressure Reset	23%	✓	✓	✓	
EEM14: Hot Water Temperature Reset	47%	✓	✓		
EEM15: Minimum VAV Terminal Box Damper Flow Reductions	15%	✓	✓	✓	
EEM16: Wider Deadbands and Night Setbacks	46%	✓	✓		
EEM17: Demand Control Ventilation	30%	✓	✓		
EEM18: Lighting Occupancy Sensors	23%	✓	✓	✓	
EEM19: Daylighting Controls	13%	✓	✓	✓	
EEM20: Exterior Lighting		✓	✓		
EEM21: Advanced Plug Load Controls		✓			
EEM22: Night Purge	3%				
EEM23: Advanced RTU Controls		✓			
EEM24: Elevator Lighting					
EEM25: Waterside Economizer					
EEM26: Cooling Tower Controls		✓	✓		
EEM27: Optimal Start	48%	✓	✓		
EEM28: Optimal Stop	48%	✓	✓		
EEM29: Refrigerated Case Lighting Controls		✓	✓	✓	
EEM30: Walk-In Refrigerator/Freezer Lighting Controls		✓	✓	✓	
EEM31: Refrigeration Floating Head Pressure		✓	✓		
EEM32: Refrigeration Floating Suction Pressure		✓			
EEM33: Optimize Defrost Strategy		✓			
EEM34: Anti-Sweat Heater Control		✓	✓		
EEM35: Evaporator Fan Speed Control		✓			
EEM36: Occupancy Sensors for Thermostats and Room Lighting		✓	✓		
EEM37: Optimized Use of Heat Recovery Wheel		✓			

Table 5.2. Packages of DR Measures used to Estimate National Savings

Two packages of DR packages are created, in each case combining one of the highest performing DR measures affecting cooling with another impacting either refrigeration (Supermarket) or lighting (all other building types). The two packages represent a reactive package, where the response is initiated only at the beginning of a critical peak pricing event, and one that represents a predictive package, initiated several hours prior to the event to maximize the demand savings.

Demand-Response Measure	DR Package A: Reactive	DR Package B: Predictive
DR Measure 38: Setpoint Changes	✓	
DR Measure 39: Pre-cooling		✓
DR Measure 40: Duty Cycle	Not included	Not included
DR Measure 41: Lighting	All Prototypes except Supermarket	All Prototypes except Supermarket
DR Measure 42: Chilled Water Temperature Control	Not included	Not included
DR Measure 43: Refrigeration	Supermarket Only	Supermarket Only

6.0 Results and Discussion

This section begins with individual energy efficiency control measure results for each building prototype, ranked by impact, and aggregated across all climates. Next, the results are broken down into a national-level summary of savings with measures ranked by overall site energy savings and aggregated across all building types and climates. Detailed simulation results for each individual measure, showing the specific savings by climate zone and building type, are provided graphically in Appendix A.

The national-level energy savings potential of EEMs are also presented in this section. This national summary shows the modeled aggregate energy savings across all climates for each of the three packages of efficiency scenarios (inefficient, typical, and efficient buildings) as well as the weighted total national savings for each building type. This section also shows the savings for each package broken out by climate and building prototype.

The discussion of energy efficiency measures is followed by a summary of DR results. A national summary of DR measures and packages of measures is presented in the following section, including an aggregation of the total commercial buildings sector potential electricity demand reductions during CPP events for each DR measure and package. Finally, electric demand savings are broken out by climate and building prototype for each DR measure.

6.1 Individual Measure Results by Building Type

Figure 6.1 through Figure 6.9 show the individual EEMs, ranked by energy savings for each of the nine simulated prototype buildings and their associated (mapped) building types from CBECS. These summaries show the impact of implementing any given EEM on each of the building prototypes with the savings aggregated across all climates. Detailed simulation results by climate for individual measures are located in Appendix A. In summary, the energy savings potential of the energy efficiency measures is impacted by climate zones as follows.

- For measures that attempt to reduce excess ventilation and infiltration (EEM17: demand control ventilation, EEM07: exhaust fan control, EEM06: outdoor air damper faults and control), there is often a modest electricity savings in cool climates and a high natural gas savings in cold climates. For very mild/marine climates, represented by cities like Seattle and San Francisco, simulation results often show little to no (even negative) savings from these types of measures. This might be due to some free cooling from the outdoor air that airside economizers are not taking advantage of.
- For measures that reduce internal electric loads, either through reduction of lighting (EEM18: occupancy sensors, EEM19: daylighting controls), plug loads (EEM24: advanced plug load control), or fans (EEM23: advanced RTU control), when the building is in heating mode, the heating system must compensate for the lost heat gains by providing additional mechanical heating. In warm/hot climates with short heating seasons, there is minimal additional heating; however, in cold climates; the increase in heating can be substantial, in some cases equal in magnitude to the electricity saved. Even in these cases, however, it is still worthwhile to pursue these measures because electricity is worth much more, in both cost and primary energy impact than natural gas.
- Chilled water system measures (EEM11: chilled water differential pressure reset, EEM12: chilled water temperature reset and EEM13: condenser water temperature reset) have peak savings in warm but not in hot climates. These measures produce savings by providing less aggressive operations during part load conditions. Warm climates have a long cooling season with plenty of opportunities for part load resets, while hot climates (Miami, Houston, and Phoenix) tend to be too hot most of the

year to benefit from these measures. Cold climates have lower savings because of a short cooling season.

- Supply air temperature reset (EEM05) and minimum VAV terminal box flow reductions (EEM15) both work to eliminate simultaneous heating and cooling in VAV systems. This pattern occurs most frequently during cool or cold weather, so the savings increases for these two measures, as the climate gets colder.

For small office buildings (Figure 6.1), the total site savings ranged from 0% (EEM22: night purge) to approximately 10% (EEM16: wider deadbands and night setbacks). The natural gas savings ranged from negative 4% (EEM23: advanced RTU controls) to almost 8% (EEM16: wider deadbands and night setbacks) and the electricity savings ranged between 0% (EEM22: night purge) and 7% (EEM23: advanced RTU controls).

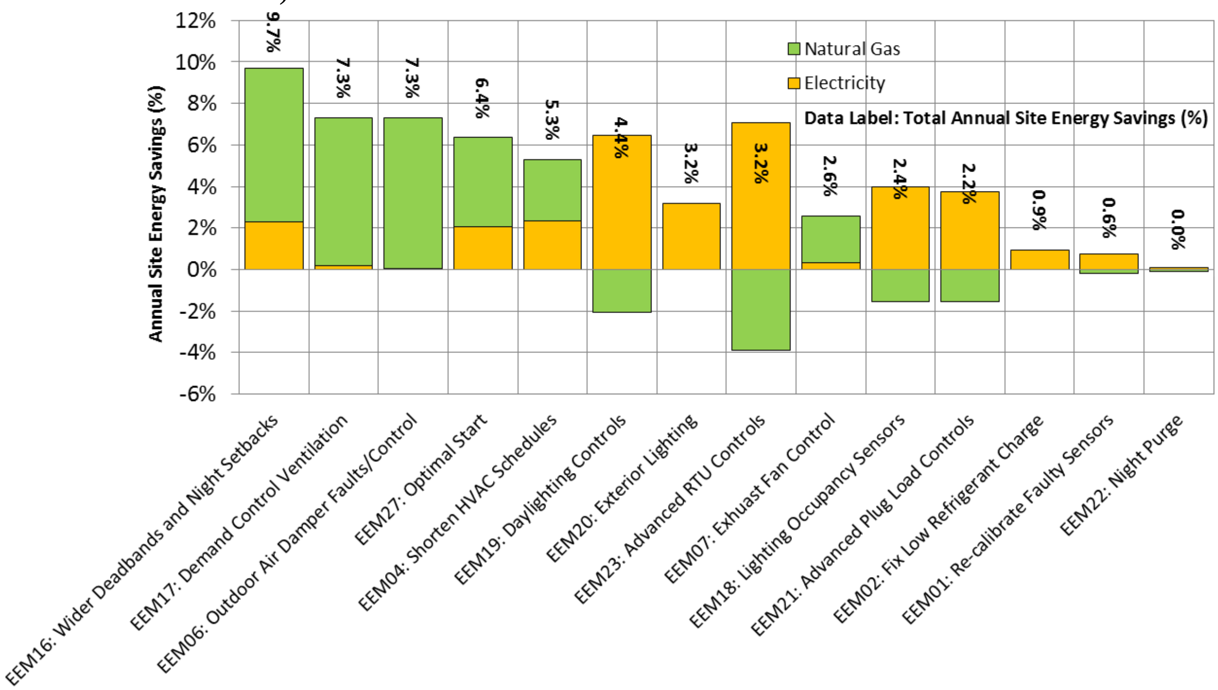

Figure 6.1. Individual EEMs Ranked by Impact for Small Office Buildings

For medium office and outpatient healthcare buildings (Figure 6.2), the total site savings ranged from -0.2% (EEM28: optimal stop) to more than 16% (EEM15: minimum variable-air-volume [VAV] terminal box damper flow reductions). The natural gas savings ranged from -1.5% (EEM05: supply air temperature reset) to about 1% (EEM17: demand control ventilation) and the electricity savings ranged between 0% (EEM28: optimal stop) and 16% (EEM15: minimum VAV terminal box damper flow reductions). Because this building type uses electricity, most forms of space heating, natural gas savings are small.

For large office, college/university, and hospital (administrative portion) buildings (Figure 6.3), the total site savings ranged from -0.2% (EEEM18: lighting occupancy sensors) to more than 15% (EEM15: minimum VAV terminal box damper flow reductions). The natural gas savings ranged from -2.5% (EEM19: daylighting controls) to 12% (EEM15: minimum VAV terminal box damper flow reductions). Although a number of EEMs result in positive natural gas savings, a few EEMs result in negative savings. Again, the negative natural gas savings are due to controls that result in electricity savings while increasing the heating load (e.g., daylighting controls). The electricity savings ranged from near zero (EEM06: outdoor air damper faults/controls) to 5% (EEM26: cooling tower controls).

For primary school buildings (Figure 6.4), the total site savings ranged from -7% (EEM06: outdoor air damper faults/controls) to 16% (EEM16: wider deadbands and night setbacks). Note that correcting the outdoor air damper fault (EEM06: outdoor air damper faults/controls) results in meeting proper ventilation rates, which increases energy consumption. The natural gas savings ranged from -6% (EEM06: outdoor air damper faults/controls) to 10% (EEM16: wider deadbands and night setbacks) and the electricity savings ranged between -1% (EEM06: outdoor air damper faults/controls) and 6% (EEM16: wider deadbands and night setbacks).

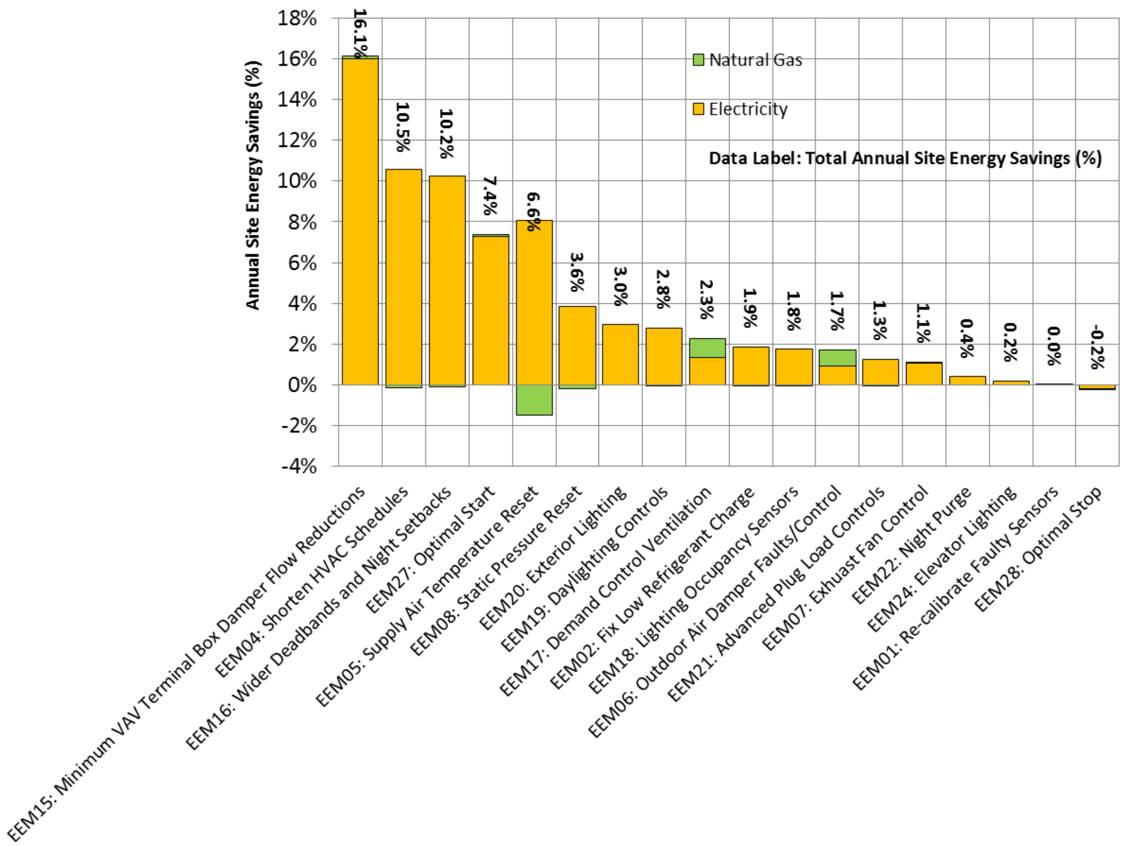

Figure 6.2. Individual EEMs Ranked by Impact for Medium Office and Outpatient Healthcare Buildings

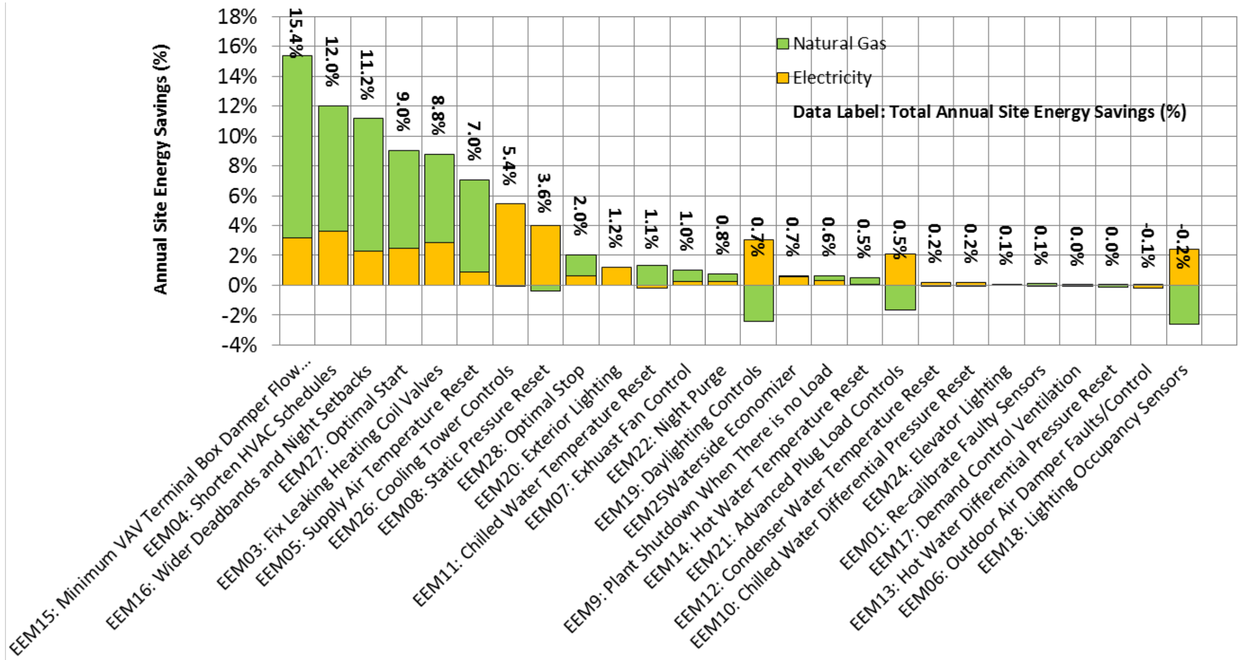

Figure 6.3. Individual EEMs Ranked by Impact for Large Office, College/University, and Hospital (Administrative)

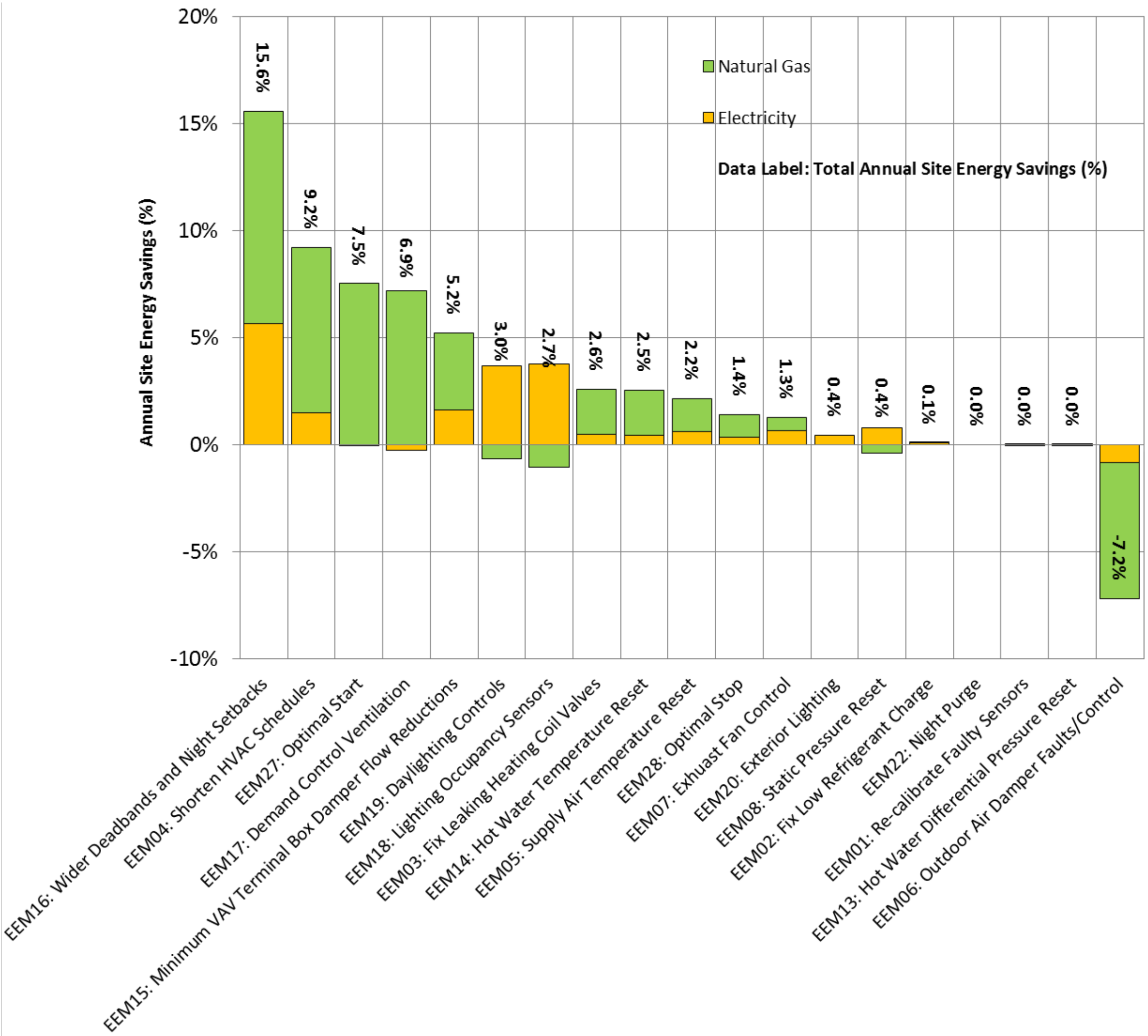

Figure 6.4. Individual EEMs Ranked by Impact for Primary School

For Secondary School buildings (Figure 6.5), the total site savings ranged from -4% (EEEM06: outdoor air damper faulty/controls) to 25% (EEM17: demand control ventilation). The natural gas savings ranged from -4% (EEM06: outdoor air damper faulty/controls) to more than 25% (EEM17: demand control ventilation) and electricity savings from 0% (EEM06: outdoor air damper faulty/controls) to 4% (EEM04: shorten HVAC schedules).

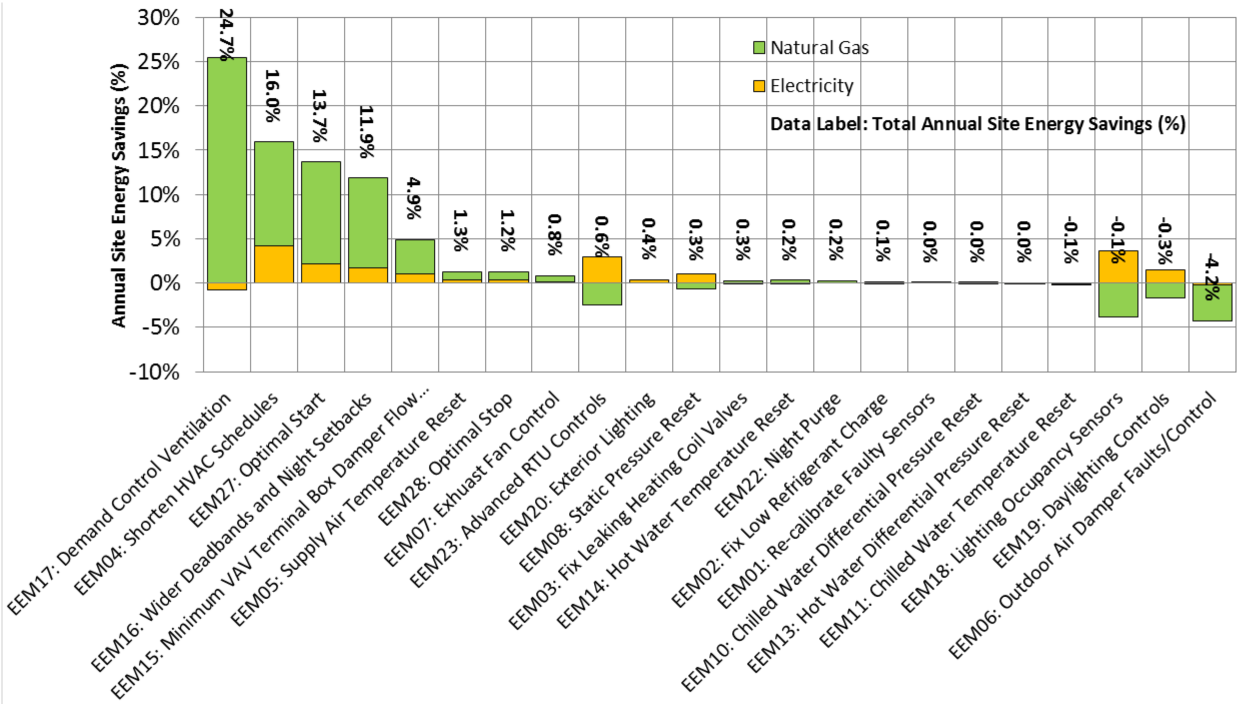

Figure 6.5. Individual EEMs ranked by impact for Secondary School

For large hotel buildings (Figure 6.6), the total site savings ranged from 0% (EEM13: hot water differential pressure reset) to 12% (EEM15: minimum VAV terminal box flow reductions). The natural gas savings ranged from -1% (EEM18: lighting occupancy sensors) to 8% (EEM15: minimum VAV terminal box flow reductions) and electricity savings ranged from 0% (EEM13: hot water differential pressure reset) to 5% (EEM15: minimum VAV terminal box flow reductions).

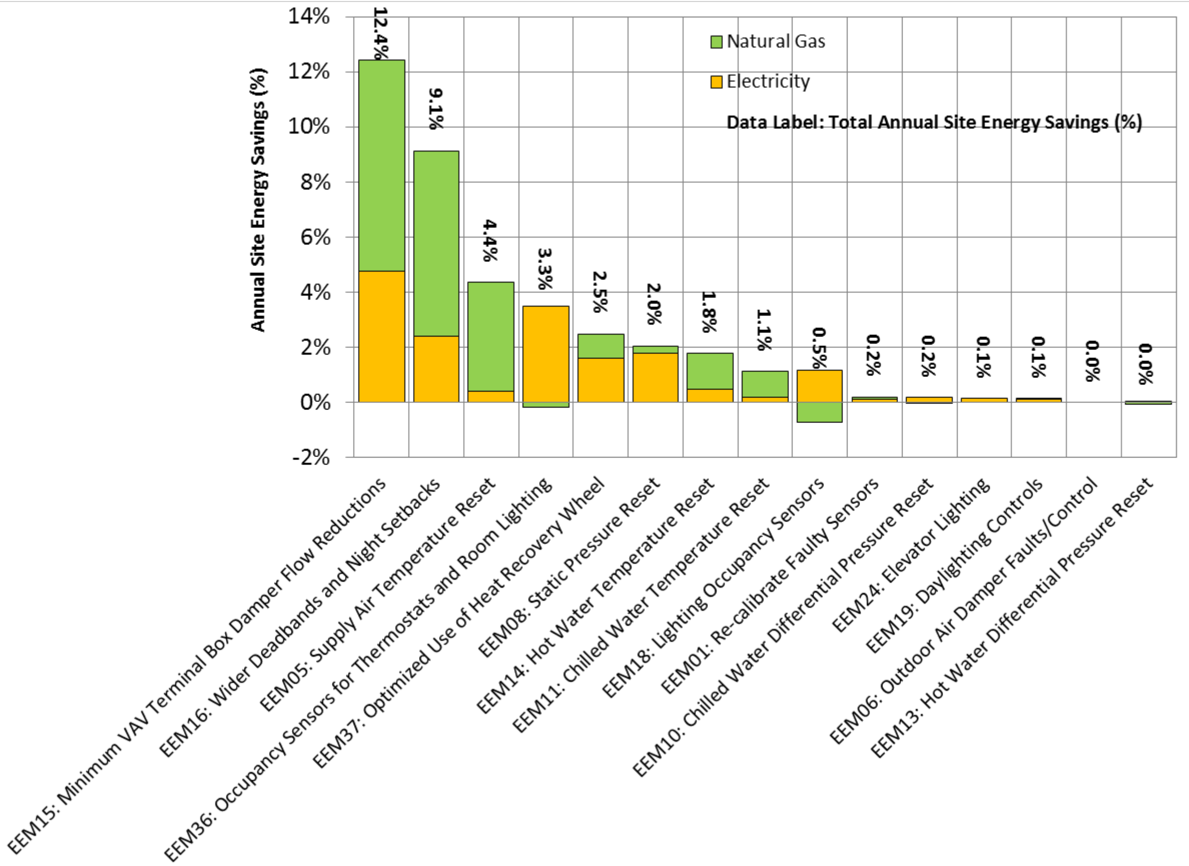

Figure 6.6. Individual EEMs Ranked by Impact for Large Hotel

For standalone retail and retail dealership buildings (Figure 6.7), the total site savings ranged from 0.2% (EEM01: re-calibrate faulty sensors) to almost 15% (EEM17: demand control ventilation). The natural gas savings ranged from -8% (EEM23: advanced RTU controls) to more than 14% (EEM17: demand control ventilation) and electricity savings ranged from zero (EEM01: re-calibrate faulty sensors) to 11% (EEM23: advanced RTU controls).

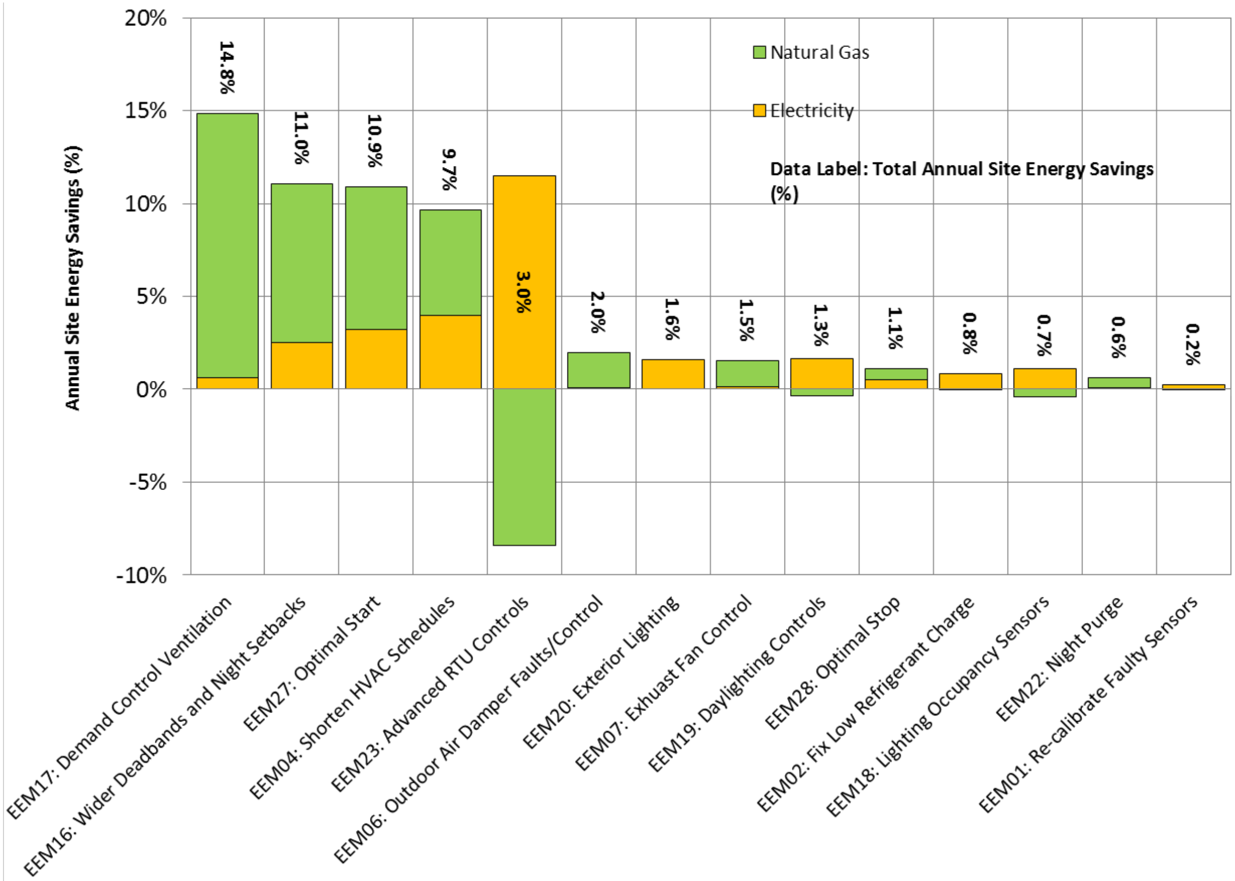

Figure 6.7. Individual EEMs Ranked by Impact for StandAlone Retail and Retail Dealership

For strip malls (Figure 6.8), the total site savings ranged from 0.1% (EEM22: night purge) to more than 12% (EEM17: demand control ventilation). The natural gas savings ranged from -6% (EEM23: advanced RTU controls) to almost 12% (EEM17: demand control ventilation) and electricity savings ranged from 0% (EEM22: night purge) to almost 10% (EEM23: advanced RTU controls).

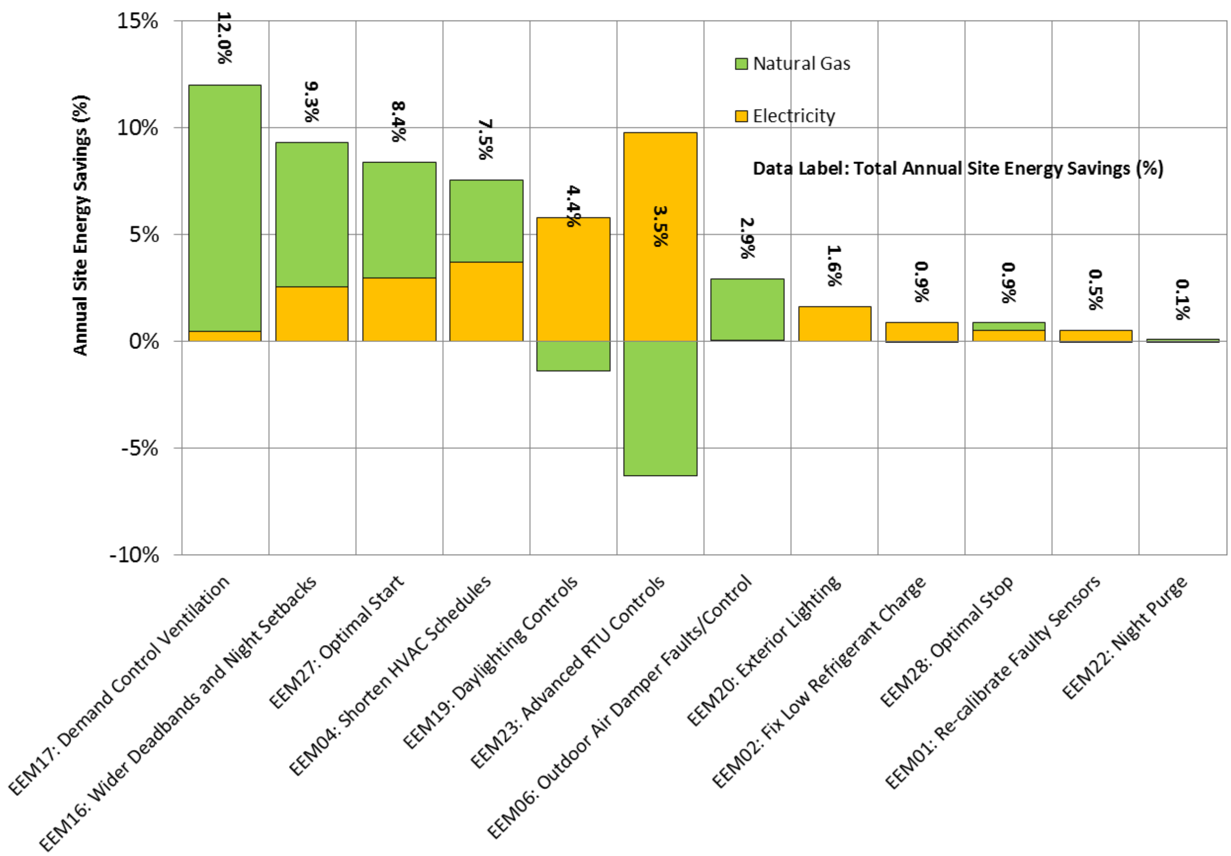

Figure 6.8. Individual EEMs Ranked by Impact for Strip Mall Retail

For supermarket and other food sales buildings (Figure 6.9), the total site savings ranged from almost zero (EEM01: re-calibrate faulty sensors) to more than 9% (EEM04: shorten HVAC schedules). The natural gas savings ranged from zero (EEM01: re-calibrate faulty sensors) to 7% (EEM04: shorten HVAC schedules) and electricity savings ranged from zero (EEM01: re-calibrate faulty sensors) to more than 5% (EEM23: advanced RTU controls).

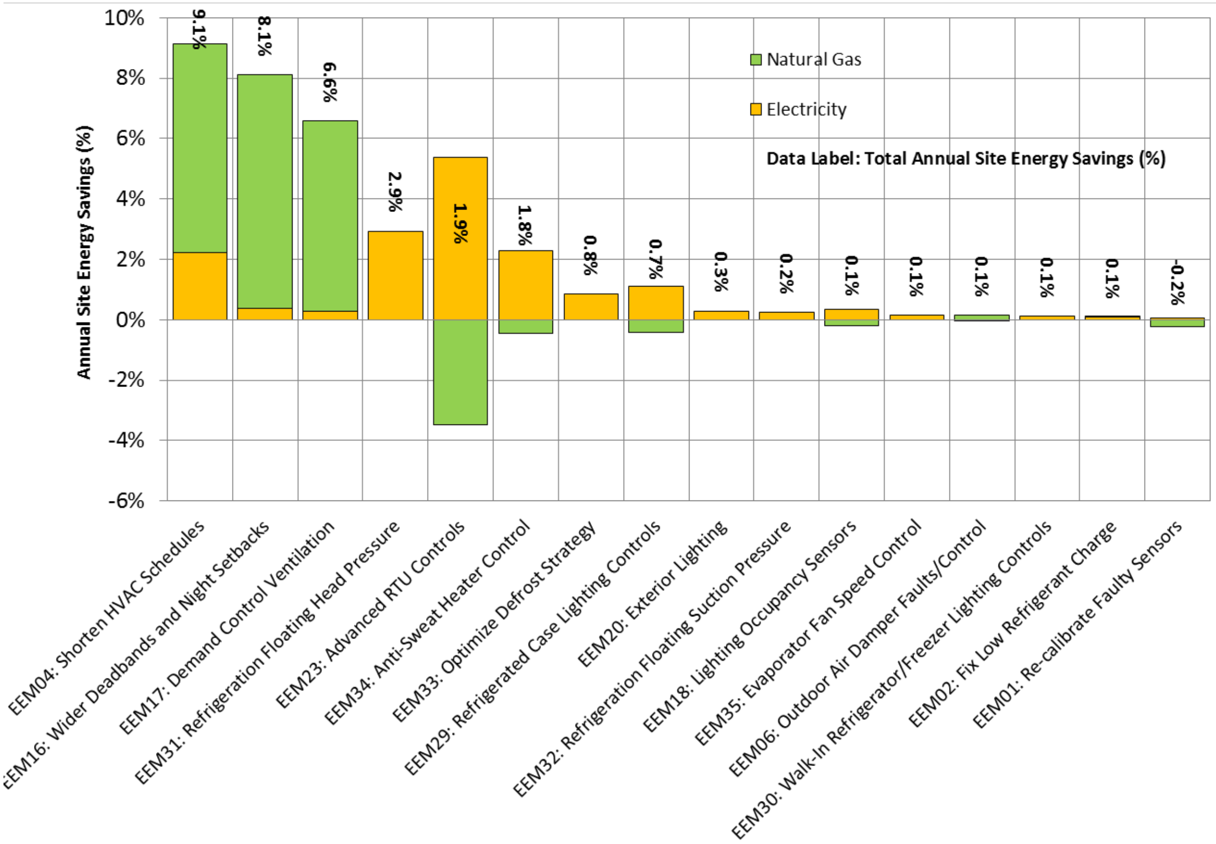

Figure 6.9. Individual EEMs Ranked by Impact for Supermarket and Other Food Sales

6.2 National Summary of Individual Measure Results

Figure 6.10 and Figure 6.11 show the national-level energy savings for each measure ranked by energy savings impact—or in other words, the estimated national technical potential savings, in percentage terms. Two figures are used instead of one because of the large number of measures. The national savings is calculated by aggregating savings for each measure across all building types that were included in the study, multiplied by the prevalence of each measure as applied in the national-level packages (see Table 5.1 for details on the inclusion of each measure in each of the packages and the associated weights of the packages) For example, measure EEM16 (widened deadbands and night setbacks) is applied to the inefficient building with a 20% weight and the typical building with a 50% weight (but not the efficient building with 30% weight), so overall, the impact of the measure is multiplied by a factor of 70%. This summary of measure impact best estimates the potential savings to the existing building stock from full implementation of a given measure in every building where the opportunity exists.

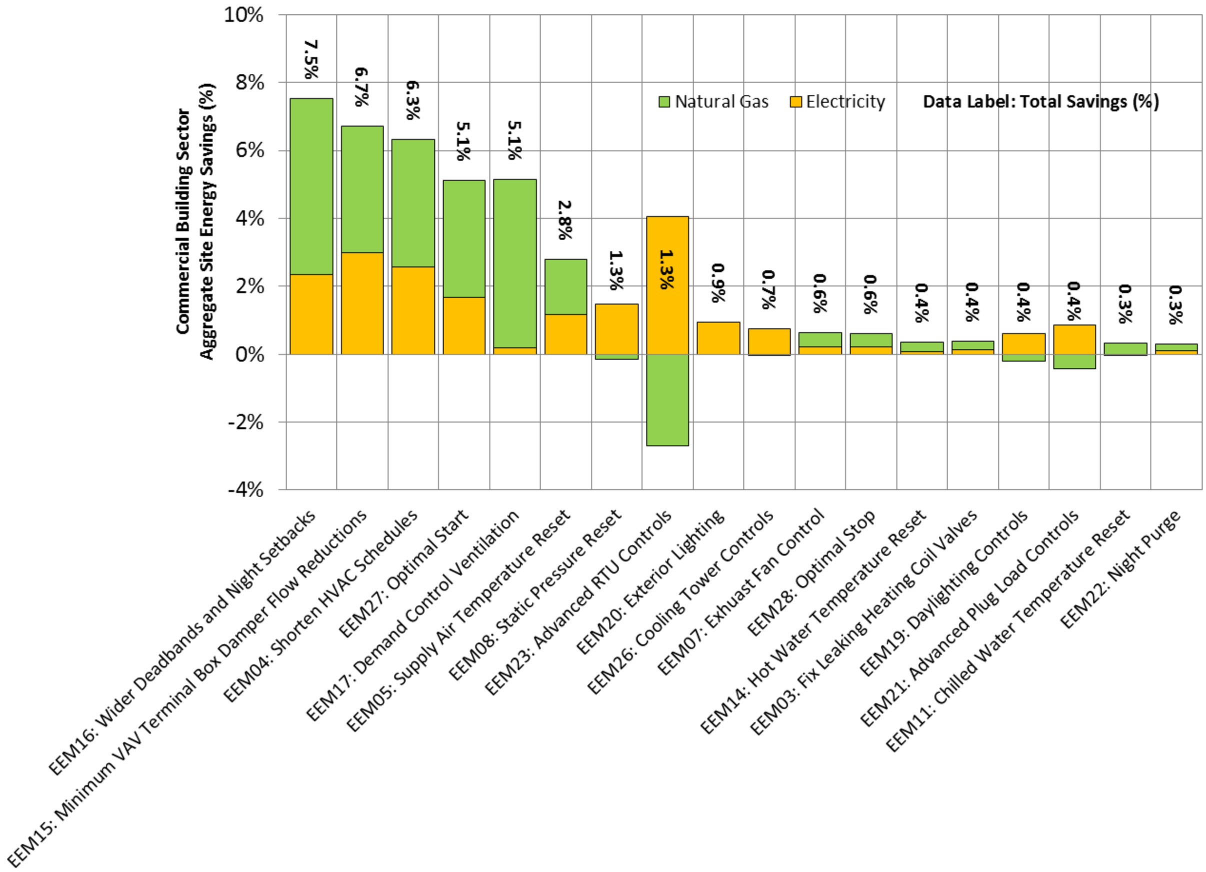

Figure 6.10. Commercial Building Sector Energy Savings Summary: Individual Measures Ranked by EEM and Weighted by Prevalence (>0.25% Savings)

A national technical potential for each measure among the share of the commercial building stock represented by the nine prototype models is estimated by multiplying the aggregate savings among all building types by the prevalence of opportunity for the measure as applied in the national-level packages. Technical potential is limited by the share of applicable building types and by the assumed fraction of buildings where the measure can still be implemented.

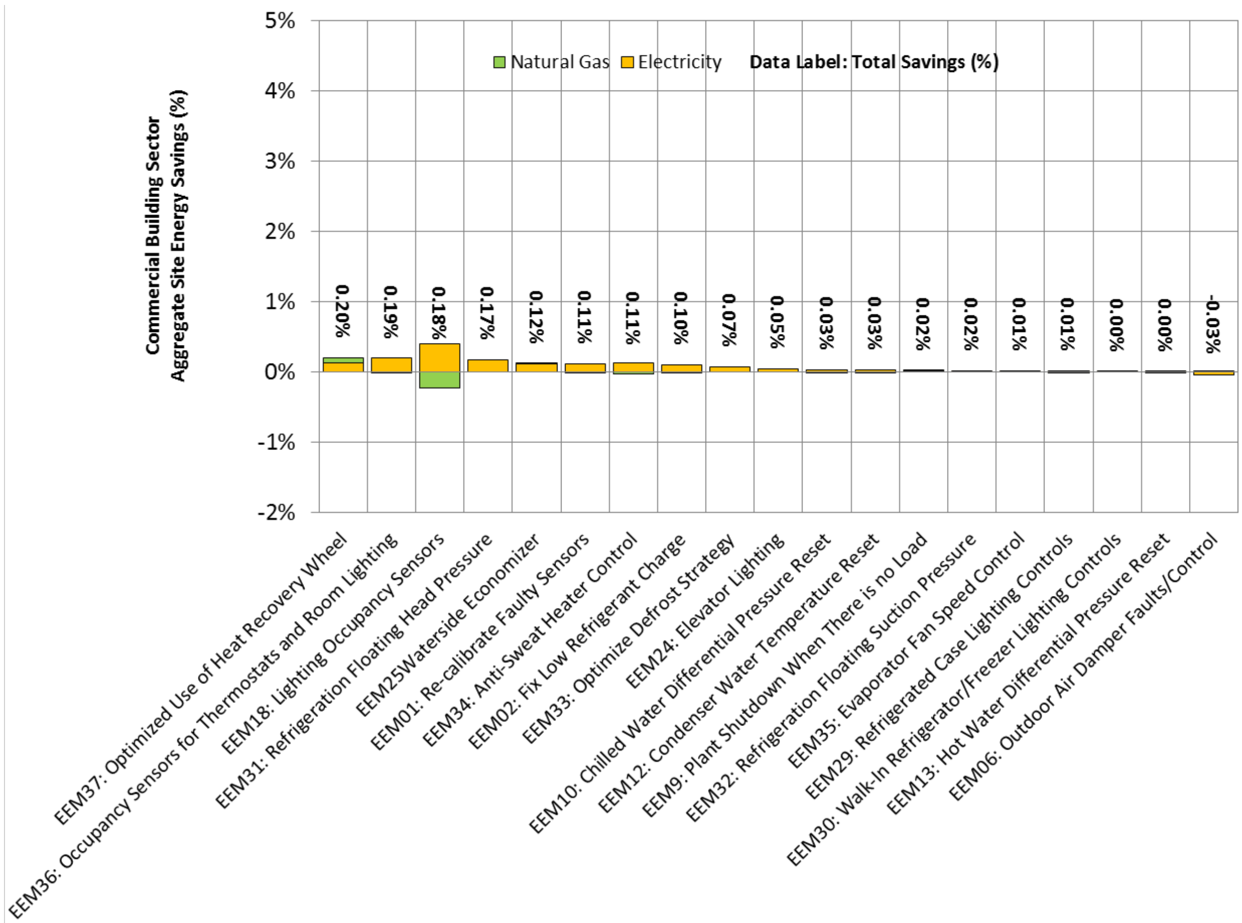

Figure 6.11. Commercial Building Sector Energy Savings Summary: Individual Measures Ranked by EEM and Weighted by Prevalence (<0.25% Savings)

A national technical potential for each measure among the share of the commercial building stock represented by the nine prototype models is estimated by multiplying the aggregate savings among all building types by the prevalence of opportunity for the measure as applied in the national-level packages. Technical potential is limited by the share of applicable building types and by the assumed fraction of buildings where the measure can still be implemented.

6.3 Cost-Benefit Analysis of Individual Measures

In addition to the energy savings, an aggregate cost savings estimate is also generated for each measure, normalized by the total square footage of the applicable buildings (excluding buildings that do not have an opportunity to implement the measure), in order to provide a cost-benefit analysis assessment of each energy efficiency measure. These estimates rely on national estimates of commercial electricity and natural gas prices. In the year ending October 2016, the average monthly natural gas price was $7.48 per thousand cubic feet (EIA 2017a) and the average electricity price was 10.47 cents per kilowatt-hour (EIA 2017b).

Estimating the implementation cost of each measure is more challenging, due in part to wide range of costs for many measures based on the specific building automation system, other building infrastructure, and local labor costs. The measures are grouped into three levels of anticipated implementation or labor effort (low, medium, and high) rather than estimating these costs explicitly.

Figure 6.12 illustrates the cost savings as a function of labor of each of the energy efficiency measures investigated in this study using a bubble plot. The vertical height is the calculated aggregate annual energy cost savings per square foot among all applicable building types in all climates. The size of each bubble is proportional to the fraction of commercial sector square footage that the measure is applicable. Bubbles that appear in the top left of the plot are the most desirable from a cost-benefit standpoint, while measures near the bottom right are the least desirable. Low-effort measures with high cost savings include EEM04: shorten HVAC schedules, EEM15: minimum VAV terminal box damper flow reductions, EEM16: wider deadbands and night setback, and EEM27: optimal start. Several of the supermarket measures score well on a cost/square foot basis because of the high-energy consumption of the refrigeration system in supermarkets and thus the high energy use intensity of those buildings. One of the highest cost saving measures is EEM23: advanced RTU controls; however, this measure is expected to be accompanied by a high level of effort. There are a cluster of 11 measures toward the bottom of the medium effort bin that may or may not be cost effective depending on the specific costs and benefits at particular buildings. These include measures like EEM13: hot water differential pressure reset, EEM22: night purge, and EEM01: sensor calibration.

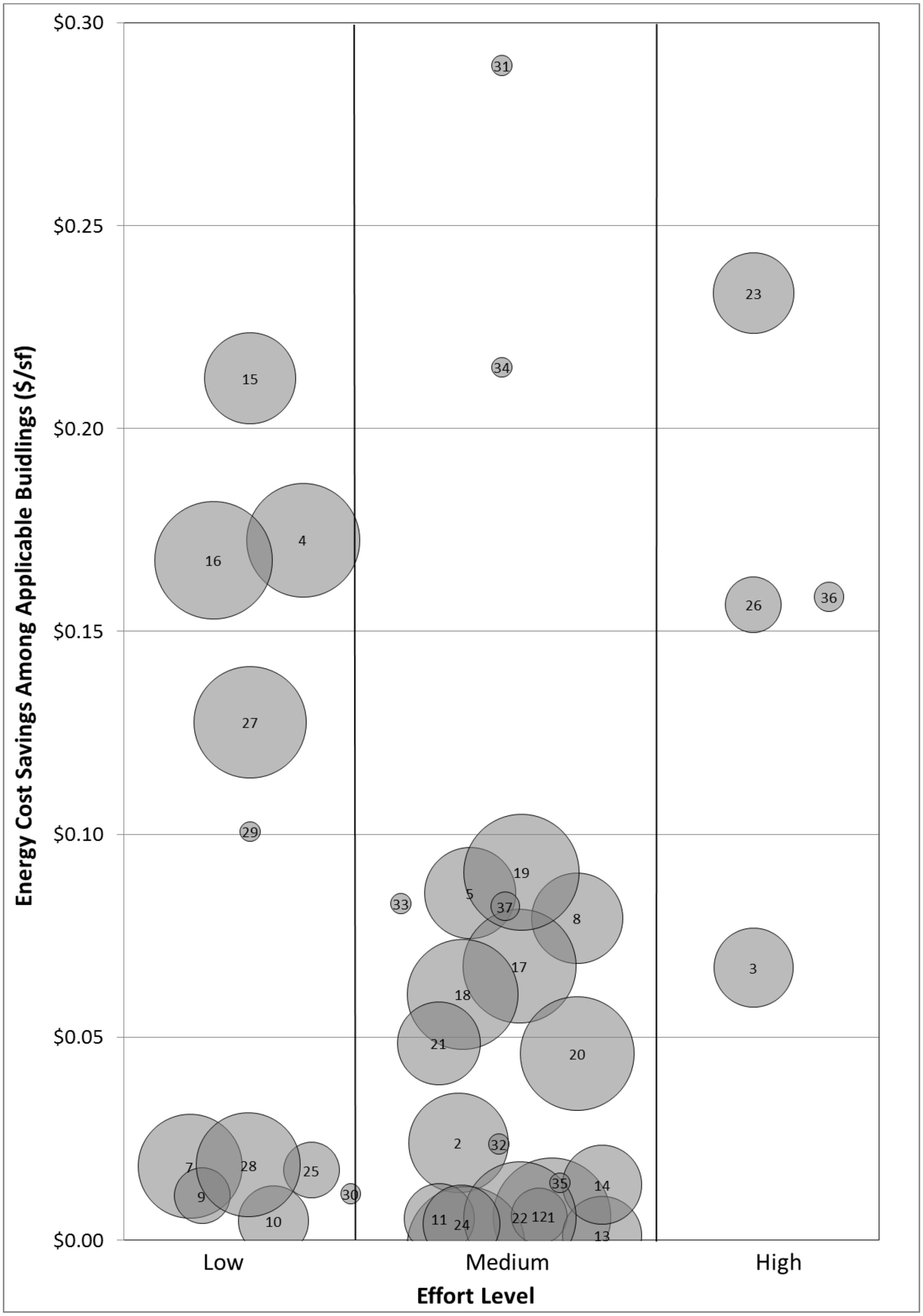

Figure 6.12. Cost-Benefit Analysis for Individual Energy Efficiency Measures across All Climates and Building Types (the number in the bubble the EEM number)

Costs for each measure are normalized per square foot of building area and calculated only for buildings where the given measure is applicable, using average U.S. commercial prices for electricity and natural gas (EIA 2017a, EIA 2017b). An effort level is assigned to each building based on expected capital and labor requirements to implement. Bubble sizes reflect the estimated applicable commercial sector floor area for each measure. Note that although there are only three discrete levels of effort assumed, the bubbles for each measure are spread out horizontally as needed within the bin for each category for legibility purposes.

6.4 Peak Demand Savings from Individual Energy Efficiency Measures

Beyond the impact on reducing energy consumption in buildings, many EEMs can also lead to reduction in the peak electricity demand. In many regions of the country, the utilities charge for both kWh (energy) and kW (demand). In some cases, the demand portion of the total electricity cost may be significant (>30%); therefore, reduction in demand can lead to an additional cost benefit for several of the EEMs. From the perspective of the grid, these measures can provide the same function as permanent DR measures in their ability to curtail electricity consumption during times of peak demand. Note that many utilities base their peak demand charges on a monthly peak, although a few utilities have a ratchet clause that could include a peak on an annual or seasonal basis (winter or summer). For this analysis, the peak reductions reported are on an annual basis.

Figure 6.13 shows a summary of annual peak demand impacts for each of the 37 EEMs in the form of a box-and-whisker plot. The height of the boxes represents the range of national peak demand reduction (aggregated by climate) among all applicable building types. The whiskers indicate the range of peak demand reductions among all building types and climate zones.

Four measures each produced in excess of 10% peak annaul electricity demand for at least one building type. These measures include EEM17: demand control ventilation, EEM19: daylighting control, EEM15: minimum VAV terminal box damper position, and EEM16: wider deadbands and night setback. Another five measures can, in certain building types, produce peak demand reductions of between 3% and 8%. The measures capable of producing meaningful demand savings are those that make changes to default operations during occupied hours in design-day type summer conditions. Daylighting controls are particularly beneficial because they maximize lighting savings during periods where it is very bright outside, which is likely to be the case during periods of maximum grid demand. Many other measures, including reset of temperatures and pressures for air and water systems, achieve savings only during part load operations and are not effective at lowering peak demand. The only measure to produce meaningful increase in peak demand for any building type was optimal start, perhaps by shifting cooling to later in the day in buildings with significant thermal mass. Although the peak demand increased for optimal start by 28% for the Medium Office prototype and by 5% for the Large Office prototype, increases in demand were below 2% for all other building types—and smaller buildings did not appear to have any peak demand impact from optimal start. In addition, implementation of the measure can be modified if the goal is also to avoid peak demand. The modified implemenation may reduce the energy savings but may avoid additional demand charges.

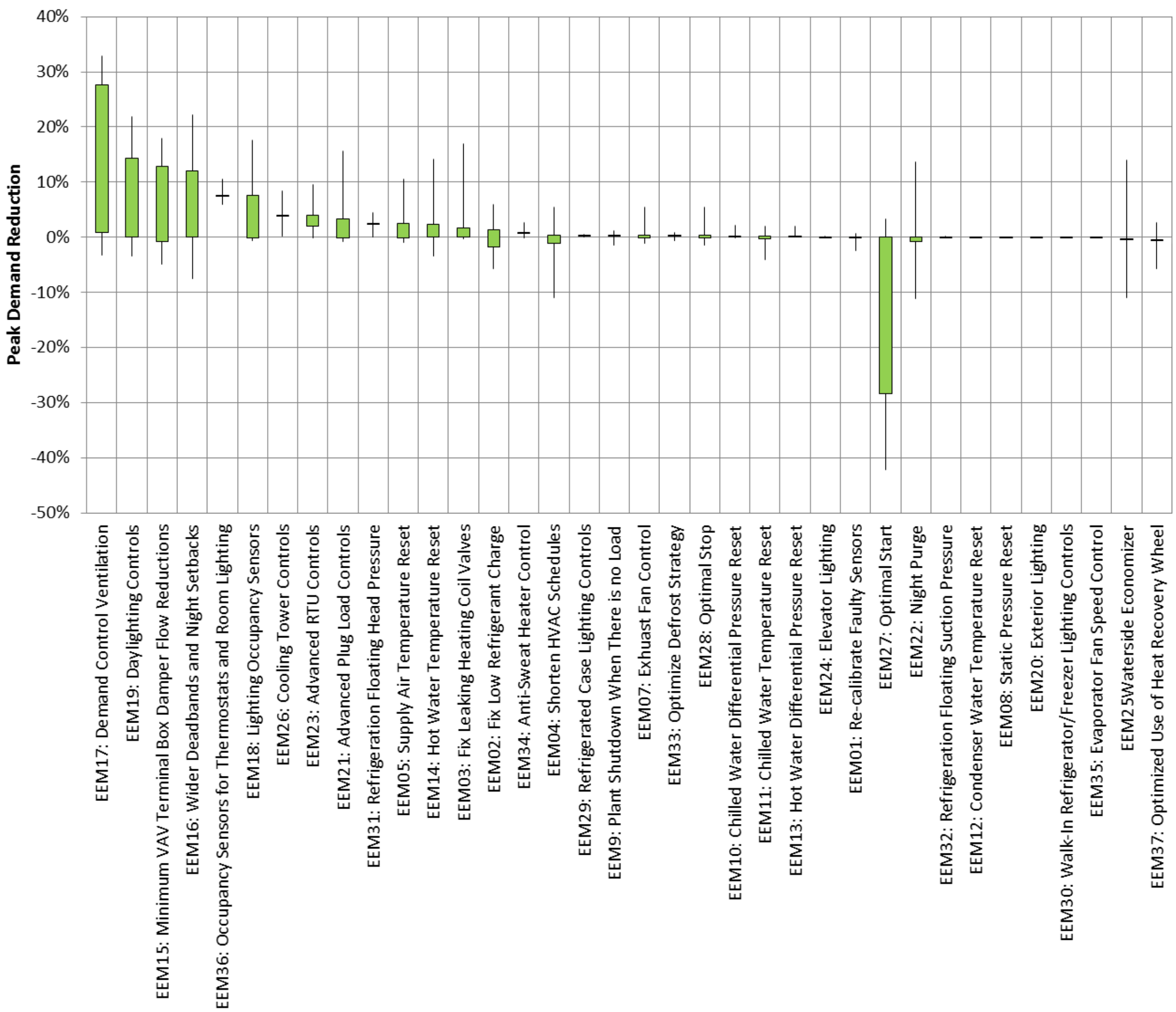

Figure 6.13. Peak Demand impacts from Energy Efficiency Measures

All of the energy efficiency measures are analyzed for their independent impact on lowering the annual peak electricity demand. Green boxes represent the range of peak savings (aggregated by climate) among the applicable building types. The whiskers above and below the boxes indicate the maximum and minimum ranges of peak demand savings, respectively, among all simulations.

6.5 Demand-Response Results by Measure

Individual DR measure results, organized by measure, are included in this section, in addition to the results for each prototype simulated.

6.5.1 Measure 38: Demand-Response: Setpoint Changes

Figure 6.14, Figure 6.15, and Figure 6.16 show the performance impact of cooling thermostat setpoint reductions during CPP events for all applicable prototypes. This measure showed strong demand reductions, often above 15% for most prototypes. The exception was the Supermarket building, for which demand savings were very modest. Modeled demand savings did not in general show clear patterns in terms of climate, except that cities with extreme design-day conditions (e.g., Phoenix) seemed to show somewhat lower demand savings. This measure was not particularly effective in supermarkets, where higher zone temperatures can increase refrigeration electricity loads.

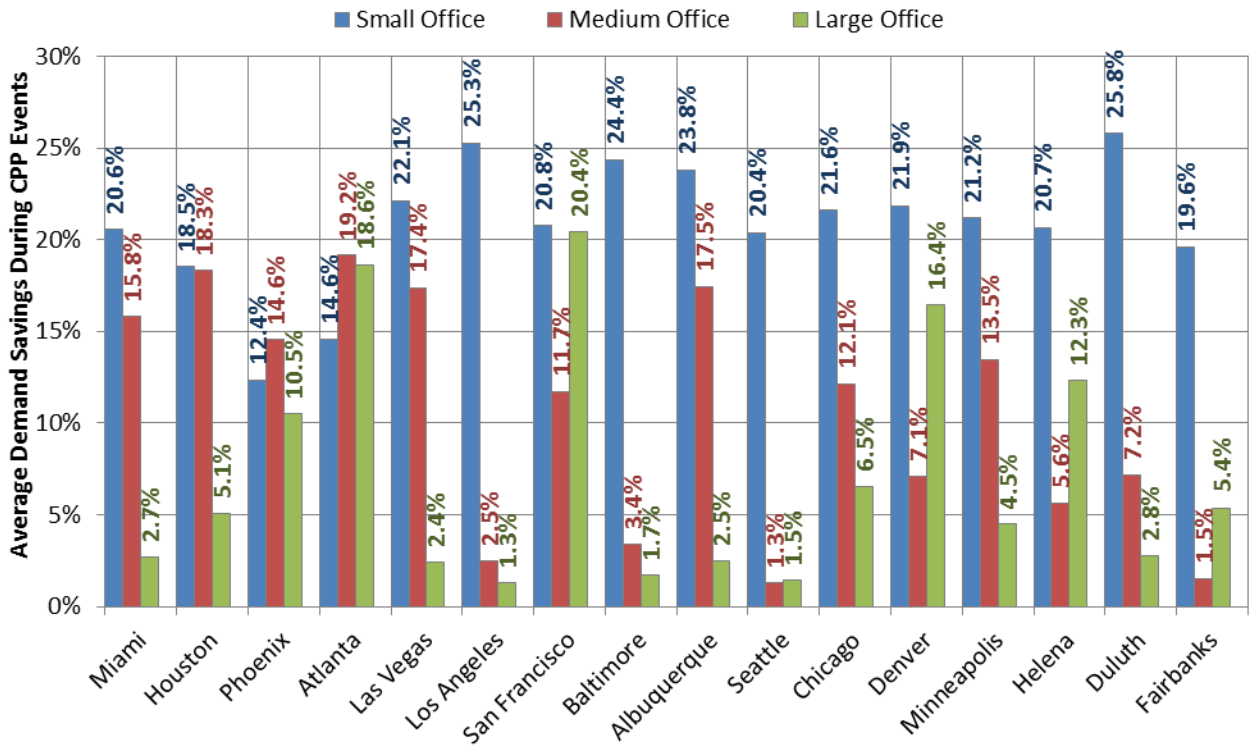

Figure 6.14. Demand-Response: Electric Demand Savings: Measure 38 (Setpoint Changes): Office Prototypes

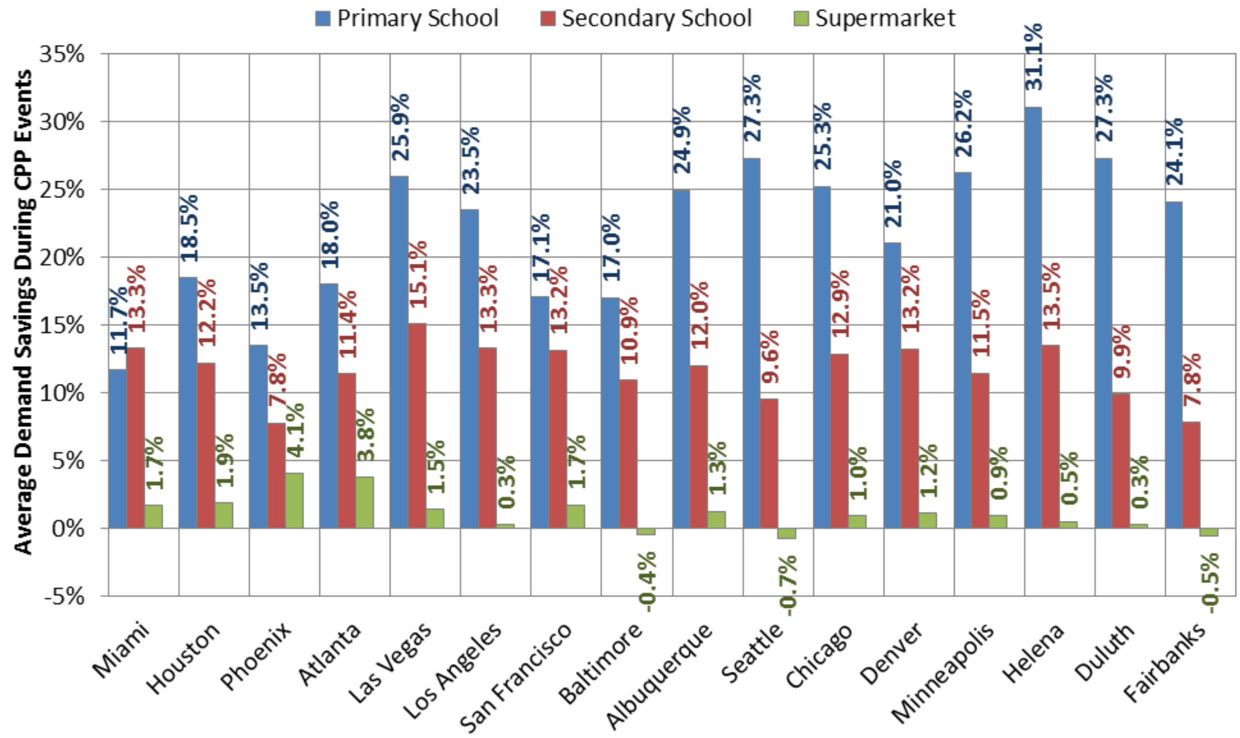

Figure 6.15. Demand-Response: Electric Demand Savings: Measure 38 (Setpoint Changes): Primary School, Secondary School, and Supermarket Prototypes

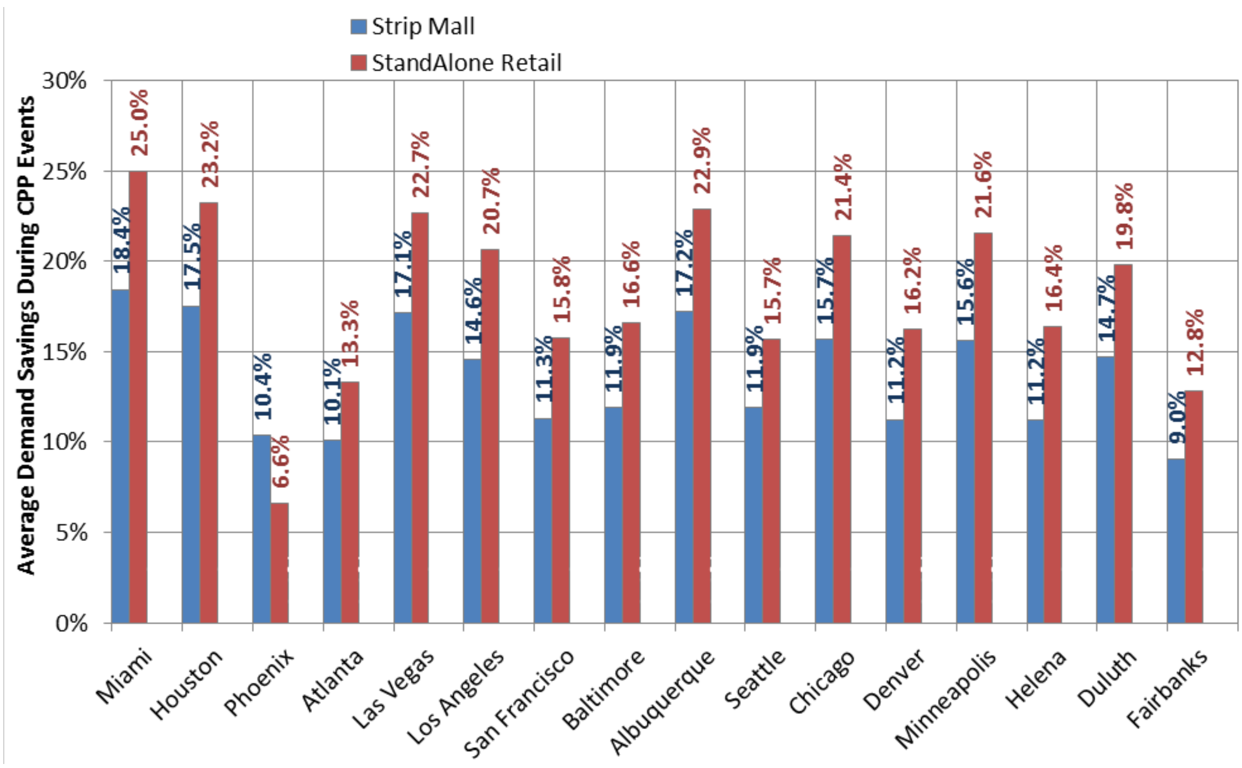

Figure 6.16. Demand-Response: Electric Demand Savings: Measure 38 (Setpoint Changes): Strip Mall and StandAlone Retail Prototypes

6.5.2 Measure 39: Demand-Response: Pre-cooling

Figure 6.17, Figure 6.18, and Figure 6.19 illustrate modeled savings from the pre-cooling DR measure. The results were very similar to Measure 38 (Setpoint Changes), except generally for slightly stronger demand savings. As mentioned previously, the results of this measure are in question because of suspected problems with the simulation of building thermal mass in EnergyPlus. Some specific simulation results are difficult to explain (for example the increase in demand for San Francisco in Small Office, despite strong savings in Los Angeles).

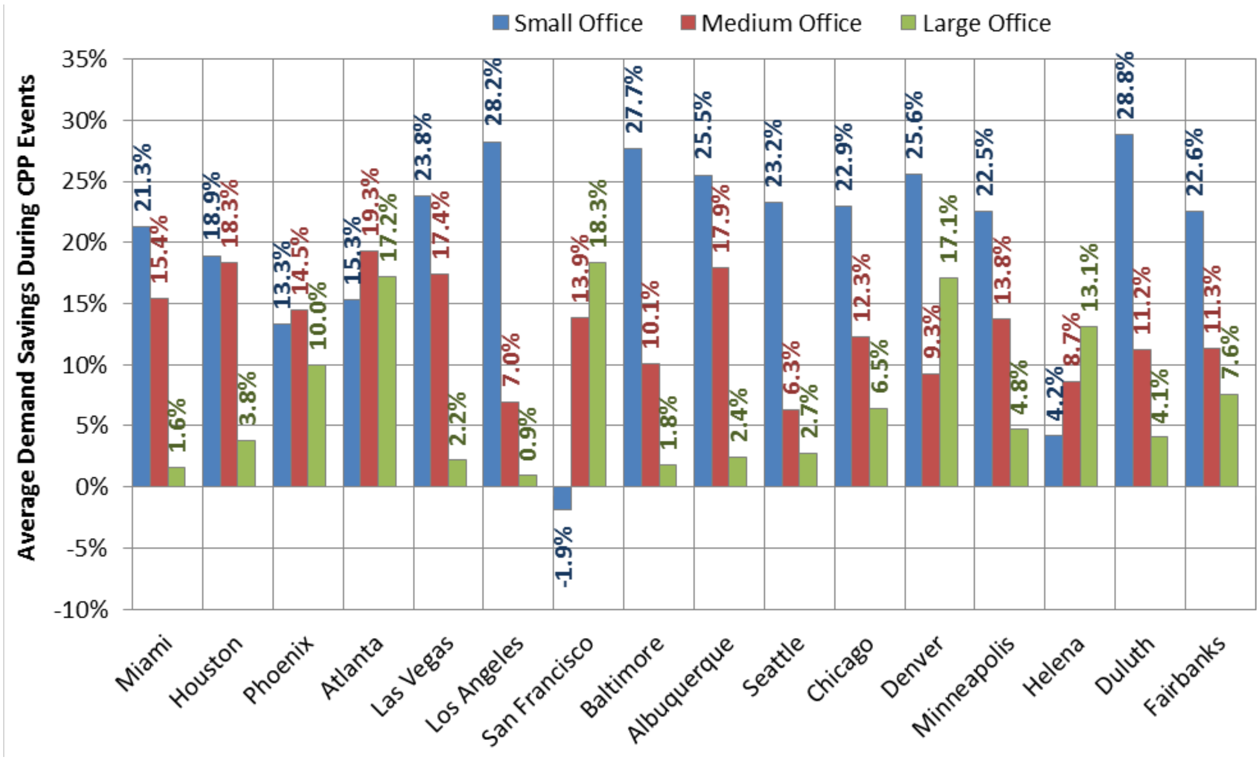

Figure 6.17. Demand-Response: Electric Demand Savings: Measure 39 (Pre-Cooling): Office Prototypes

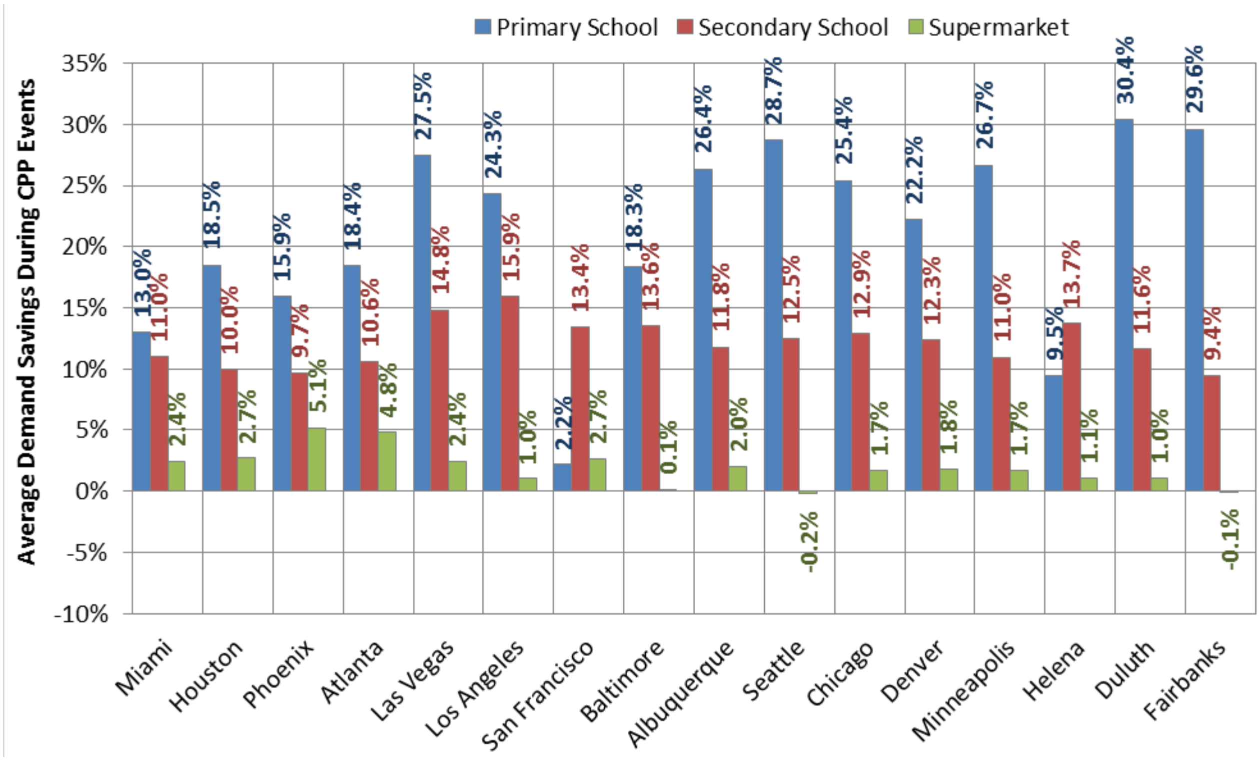

Figure 6.18. Large Office Demand-Response Performance: Measure 39 (Pre-Cooling): Primary School, Secondary School, and Supermarket Prototypes

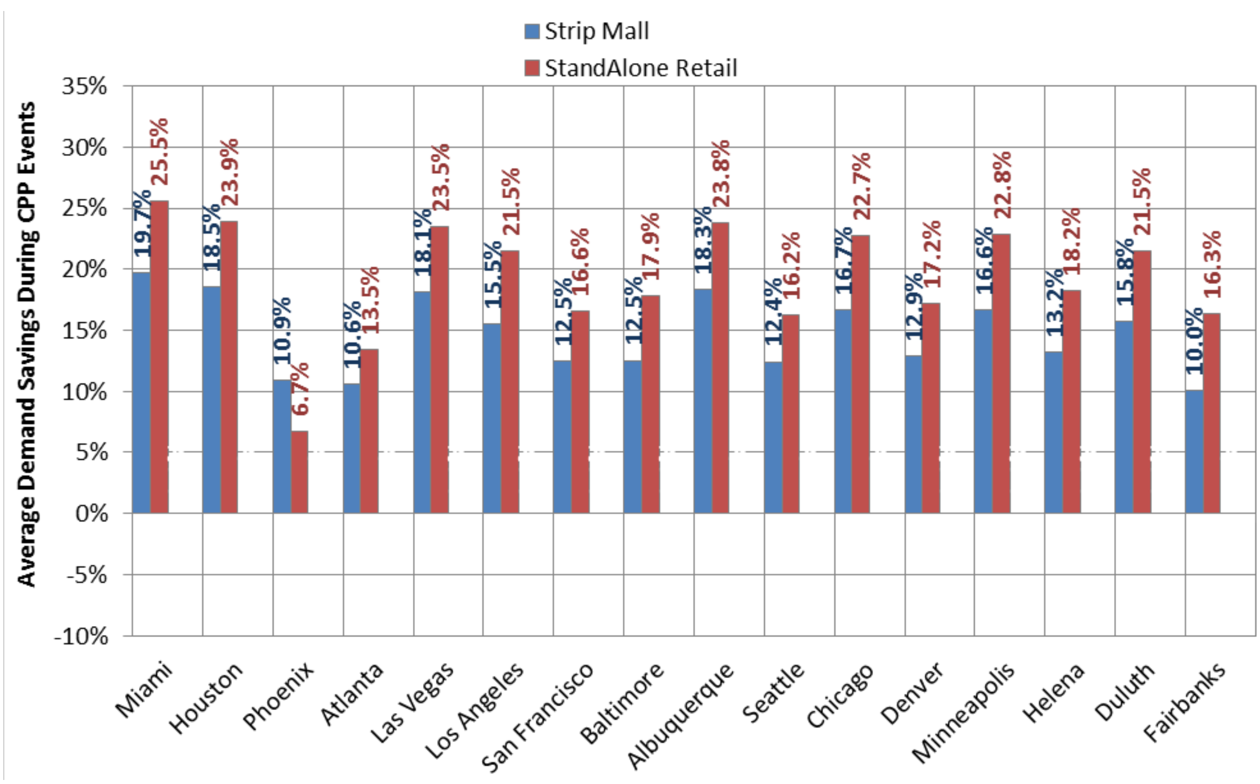

Figure 6.19. Demand-Response: Electric Demand Savings: Measure 39 (Pre-Cooling): Strip Mall and StandAlone Retail Prototypes

6.5.3 Measure 40: Demand-Response: Duty Cycle

Figure 6.20, Figure 6.21, and Figure 6.22 show the performance impact of cycling cooling equipment on and off in hourly increments. This measure seems best suited for buildings served by single-zone packaged HVAC equipment, and although the demand savings were lower than for Measures 38 or 39, it may still be considered a better option to achieve cooling savings in those building types, to the extent that it causes less disruption in thermal comfort. Cycling equipment on and off, however, is also known to be detrimental to the lifetime of motor-driven loads, including compressors.

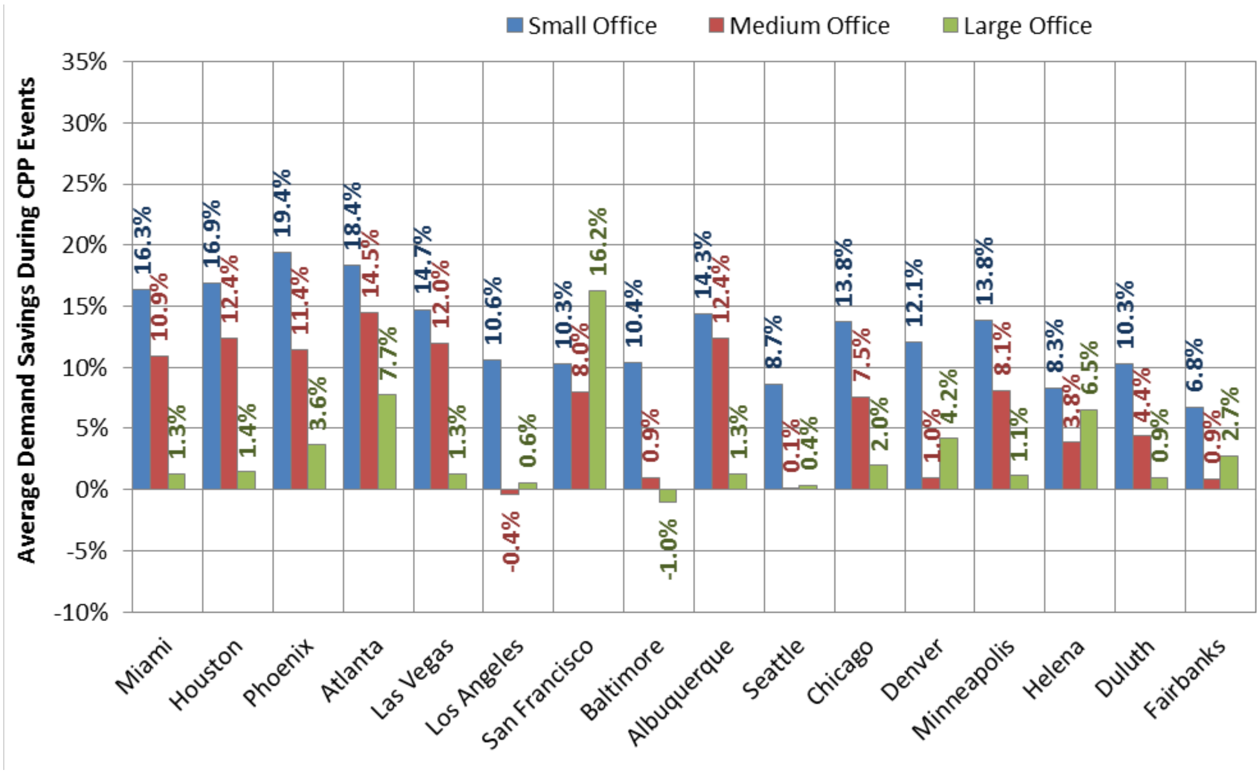

Figure 6.20. Demand-Response: Electric Demand Savings: Measure 40 (Duty Cycle): Office Prototypes

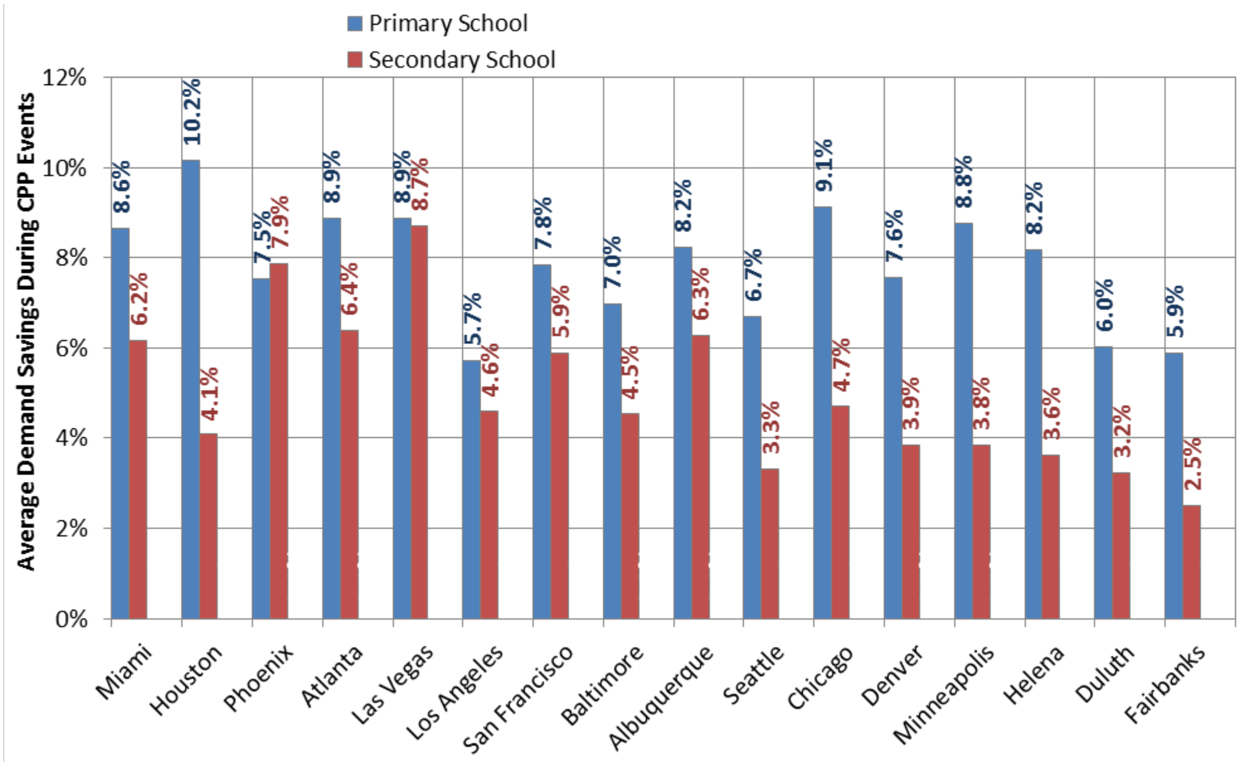

Figure 6.21. Demand-Response: Electric Demand Savings: Measure 40 (Duty Cycle): Primary and Secondary School Prototypes

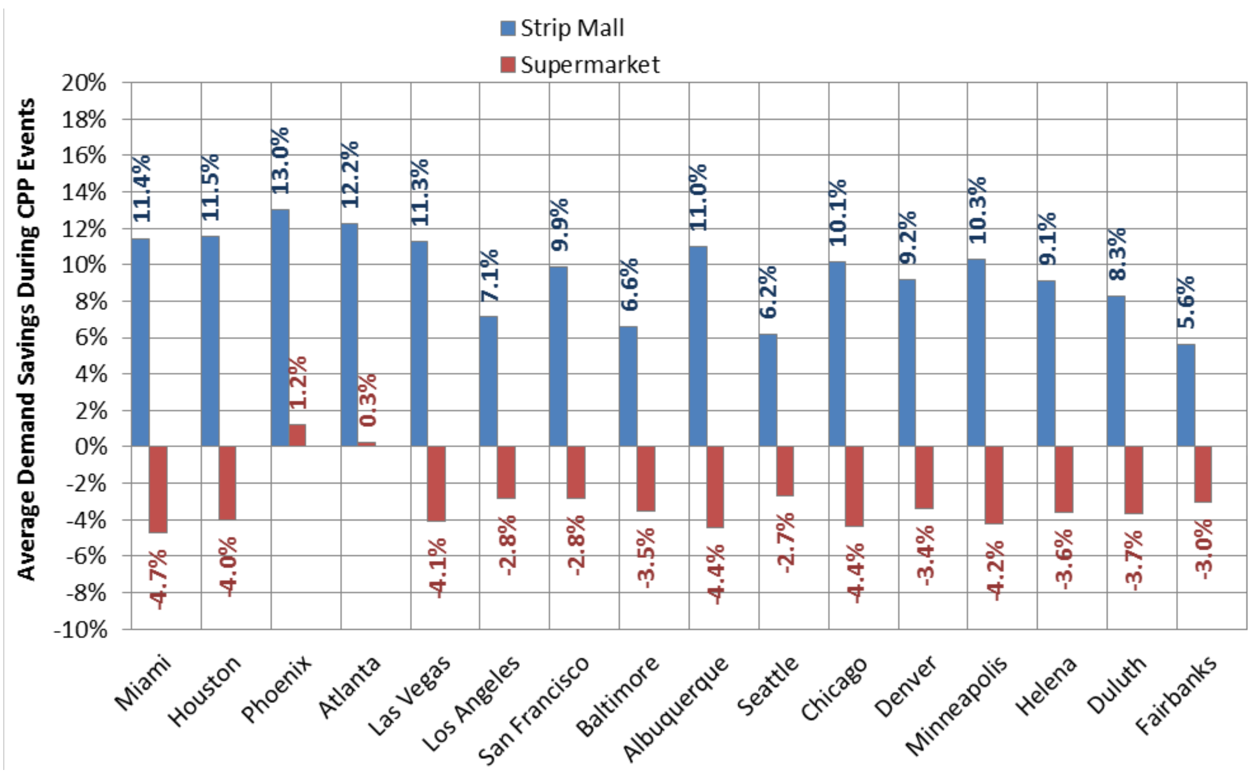

Figure 6.22. Demand-Response: Electric Demand Savings: Measure 40 (Duty Cycle): Strip Mall and Supermarket Prototypes

6.5.4 Measure 41: Demand-Response: Lighting Control

Figure 6.23, Figure 6.24, and Figure 6.25 show the performance impact of dimming lights by 10% during CPP events. Demand savings were much more consistent and predictable from this measure; they were typically between 1.5% and 4.0%.

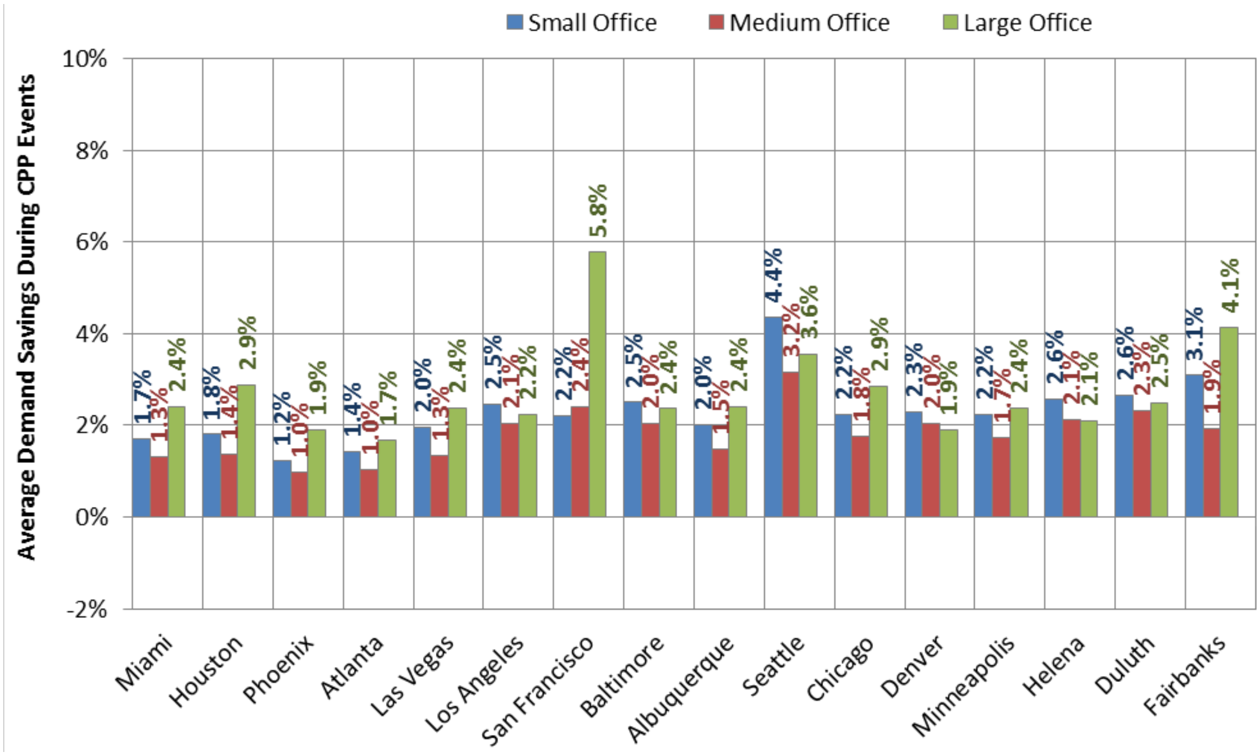

Figure 6.23. Demand-Response: Electric Demand Savings: Measure 41 (Lighting): Office Prototypes

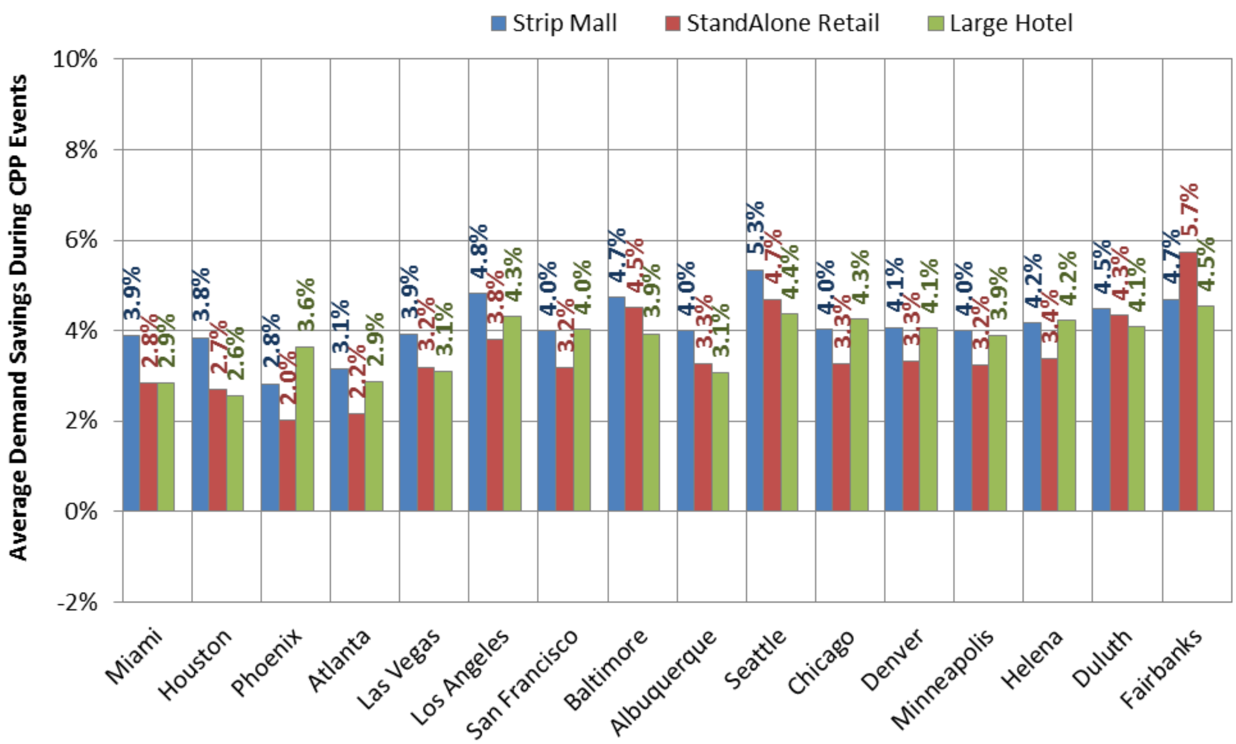

Figure 6.24. Demand-Response: Electric Demand Savings: Measure 41 (Lighting): Strip Mall, StandAlone Retail, and Large Hotel Prototypes

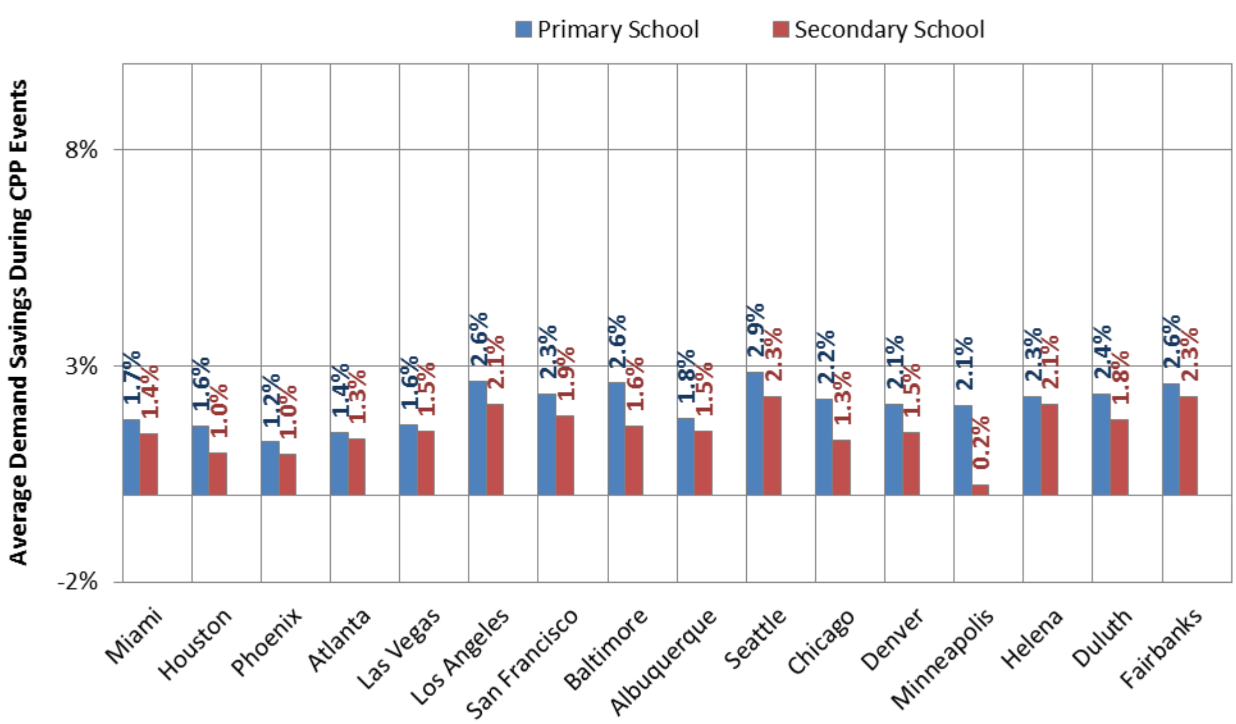

Figure 6.25. Demand-Response: Electric Demand Savings: Measure 41 (Lighting): Primary School and Secondary School Prototypes

6.5.5 Measure 42: Demand-Response: Chilled Water Temperature Control

Figure 6.26 shows DR savings from raising the chilled water temperature while holding fan speeds constant. Demand savings for the Large Office and Large Hotel prototypes were typically in the range of 2–5%, but some unusual increases in demand were modeled in some climates. Savings for the Secondary School prototype were much higher, at around 10–15%.

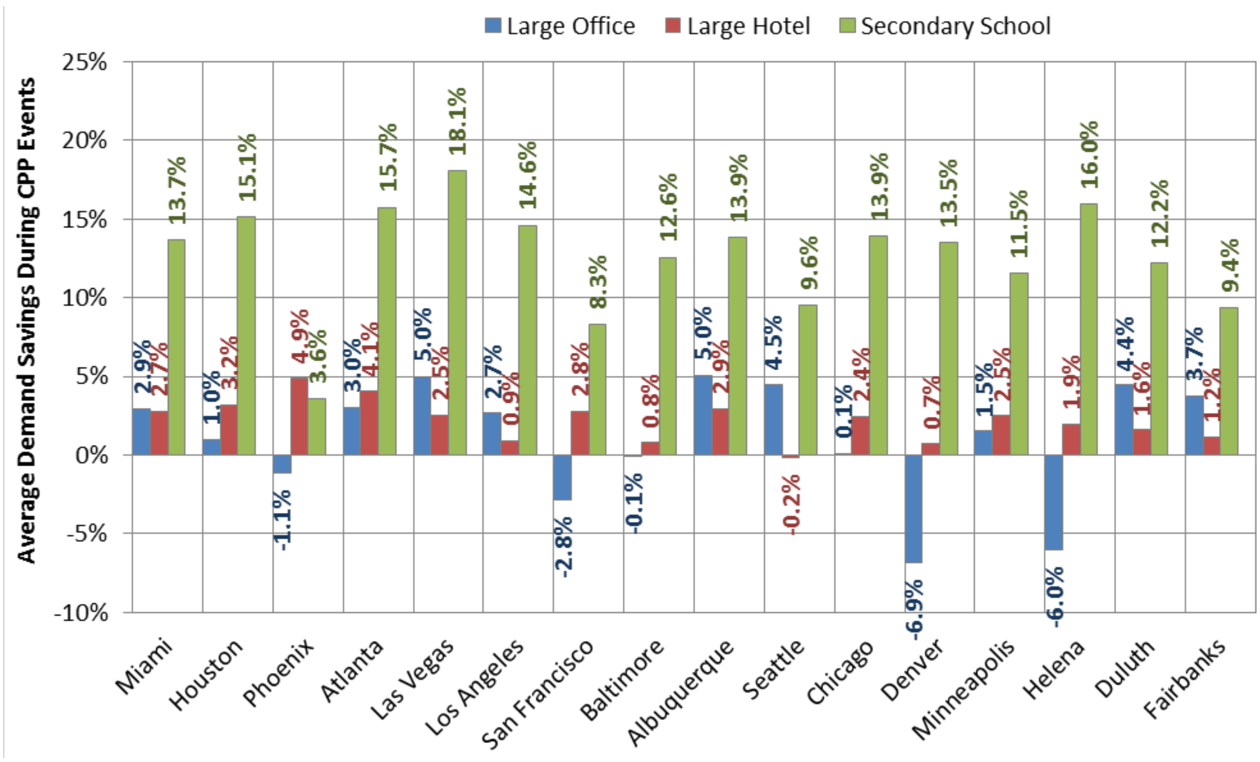

Figure 6.26. Demand-Response: Electric Demand Savings: Measure 42 (Chilled Water Temperature Control): Large Office, Large Hotel, and Secondary School Prototypes

6.5.6 Measure 43: Demand-Response: Refrigeration

Figure 6.27 shows demand savings for refrigeration DR strategies in supermarkets. Modeled savings were relatively consistent between climates at 5–8% of baseline electric demand during CPP events.

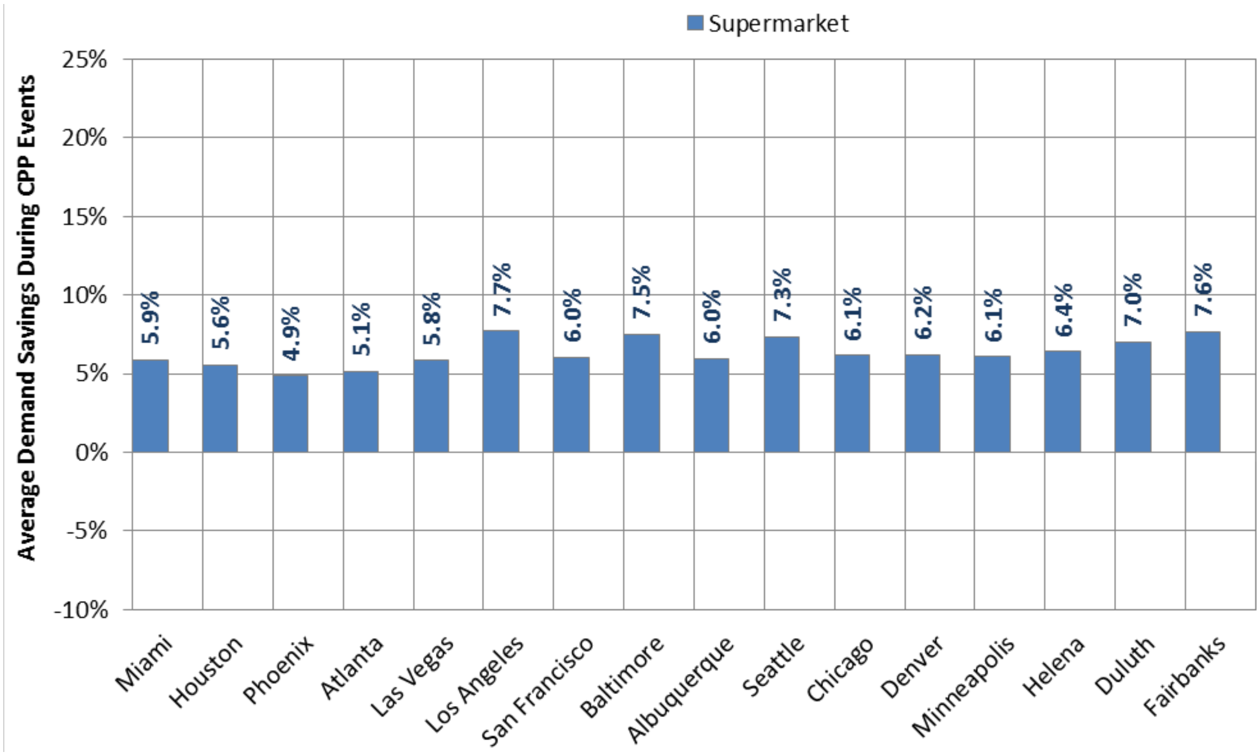

Figure 6.27. Demand-Response: Electric Demand Savings: Measure 43 (Refrigeration): Supermarket Prototypes

6.6 National Summary of Demand-Response Measures

Figure 6.28 provides an estimate of the aggregate electric demand savings in the commercial building sector during CPP events that can be achieved using the suite of DR measures modeled in this study. Setpoint changes and pre-cooling are by far the most impactful DR measures. The pre-cooling measure is intuitively expected to be a significant improvement upon the setpoint changes measure. The pre-cooling measure brings the building to a significantly lower temperature and stores cooling in its thermal mass, then resets the thermostat setpoints to the same temperature during the CPP event as the setpoint changes measure. EnergyPlus, however, on the whole shows only a 0.4% electric demand savings for pre-cooling, relative to setpoint changes. This modest gain may be a reflection of inaccuracies in the way EnergyPlus handles building thermal mass. Other researchers have observed this kind of issue in the past in other applications of EnergyPlus. As a cooling-oriented measure, duty cycling and chilled water temperature control are less effective and less universally applicable as setpoint changes and pre-cooling measures. Duty cycling suffers from rebound spikes in demand when units that were temporarily turned off are brought back on. Lighting control can be performed independently from cooling-oriented DR measures. The two work together synergistically to produce more demand savings than the sum of both measures independently (around 19%, nationally).

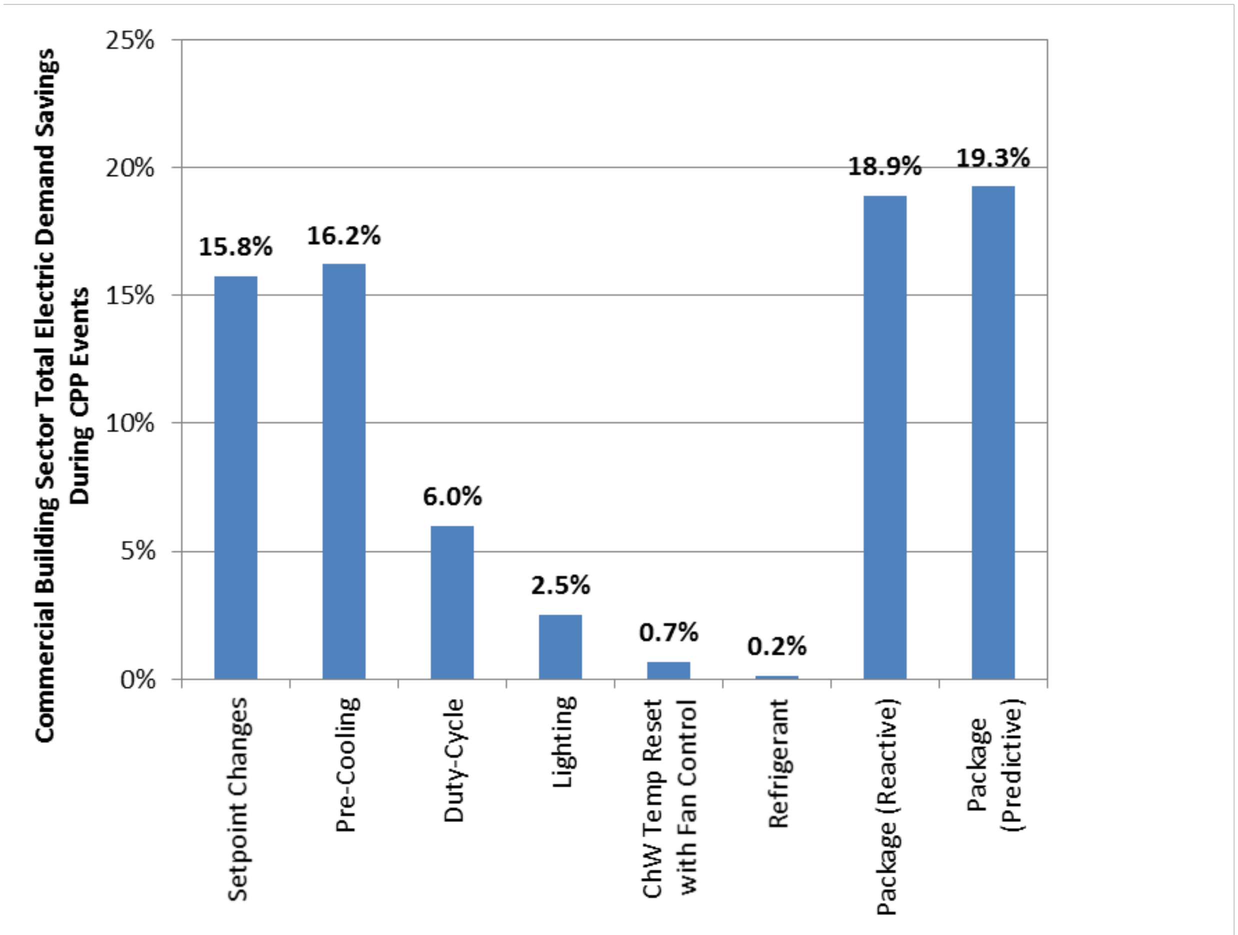

Figure 6.28. Demand-Response: Aggregate National Savings by Measure and Package

A national technical potential was estimated for electric demand reduction during CPP events among the share of the commercial building stock represented by the nine prototype models. Technical potential is limited by the share of applicable building types (e.g., while the refrigerant measure produces about 6% demand savings in Supermarkets, it is only applicable to that building type, so the aggregate demand savings is just 0.2%).

6.7 Energy Impacts of Demand-Response Measures

Some DR measures (e.g., pre-cooling) have the potential to increase energy consumption while others may reduce energy consumption. After an analysis of the simulation results, it was found that the DR measures included in this study had a negligible impact on annual energy consumption. This is an expected consequence of the conceptual utilization of the DR measures during only eight days per year (CPP events) and the fact that most DR measures are only utilized for four hours during each of those events. CPP events are unlikely to occur significantly more often than eight days per year, so participation should not be based on energy impact. In general, the impact is less than 0.1% of annual energy consumption (in most cases energy savings, but in some cases increased consumption). *Note that savings of this magnitude are statistically insignificant because the uncertainties associated with modeling are much higher*.

Another way of analyzing the energy impact of CPP events is to focus on the change in electricity consumption over individual CPP days. Figure 6.29 shows that the DR events typically led to between 0% and 5% reduction in total electricity consumption over the course of the day. In some cases, DR events may increase electricity between 3% and 6% over the course of the day. Pre-cooling in some building types can lead to increased consumption due to the more aggressive cooling set points prior to the DR event. Set point changes and duty cycling were modeled as leading to slight increases in annual electricity demand for Supermarkets. This may be because higher temperatures indoors lead to higher loads on refrigeration systems.

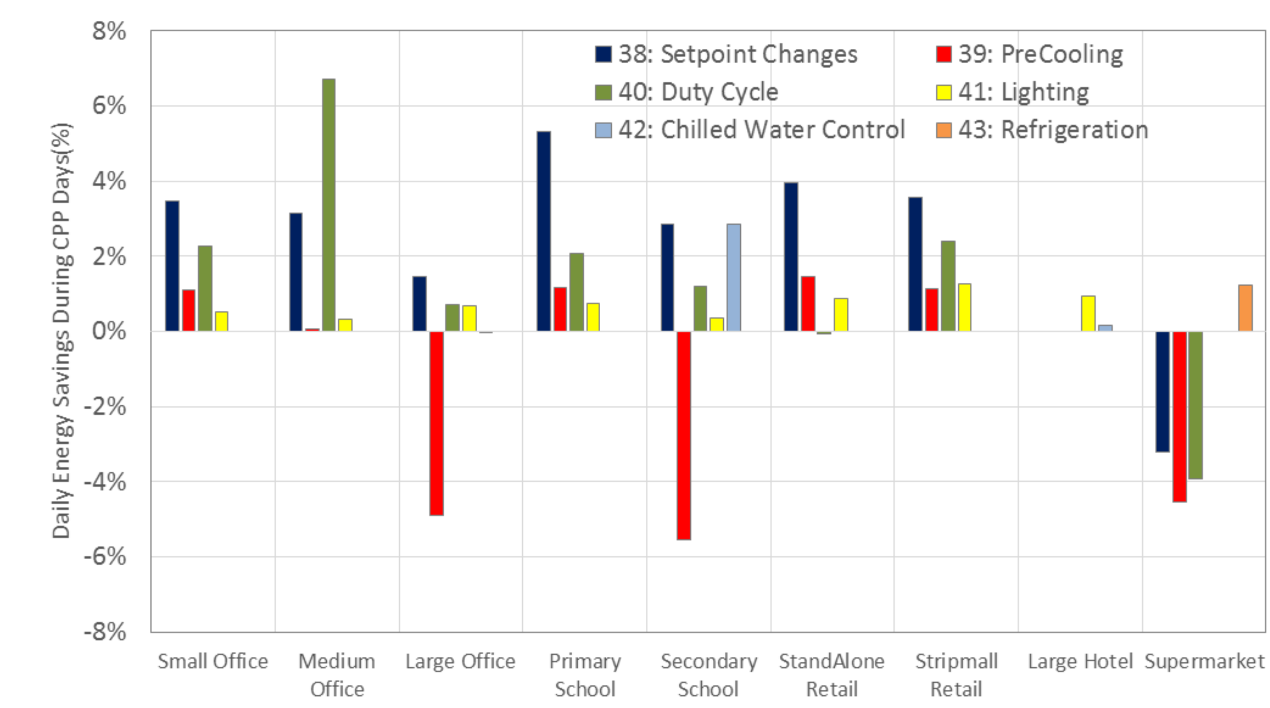

Figure 6.29. Average Daily Energy Impact from Demand-Response Measures on CPP days

6.8 Results for Packages of Measures

Three packages of measures have been created to estimate the national savings potential: 1) efficient building, 2) typical building, and 3) inefficient building. The efficient building package only includes a few EEMs because the buildings that this package applies to (about 30% of the building stock) are considered to be efficient with little possibility of improvement. On the other hand, the inefficient building package is assumed to exhibit significant savings potential (all EEMs) because of the lack of controls measures implemented (applies to 50% of the building stock). The typical building package consists of a balance between opportunity for additional savings and prevalence of controls measures already implemented (30% of building stock).

The savings from each of the three packages—inefficient (Package A), typical (Package B), and efficient buildings (Package C)—by prototype and by climate, as well as a national summary are discussed in the following sections.

6.8.1 Package A: Inefficient Buildings

Figure 6.30, Figure 6.31, and Figure 6.32 show savings by climate and by prototype for each of the inefficient building packages, broken out into site electricity savings and site natural gas savings.

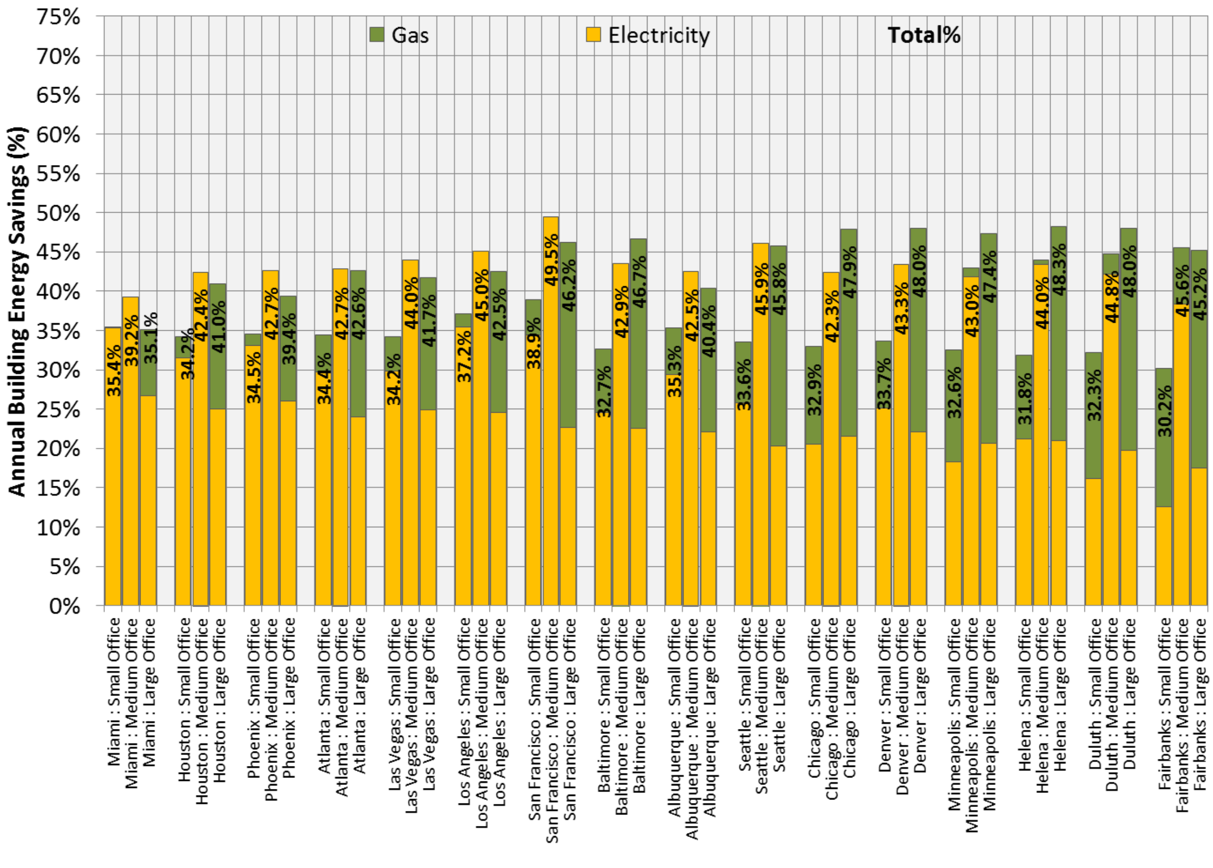

Figure 6.30. Energy Savings for Packages of Controls Measures by Climate Type for “Inefficient” Buildings: Office Prototypes

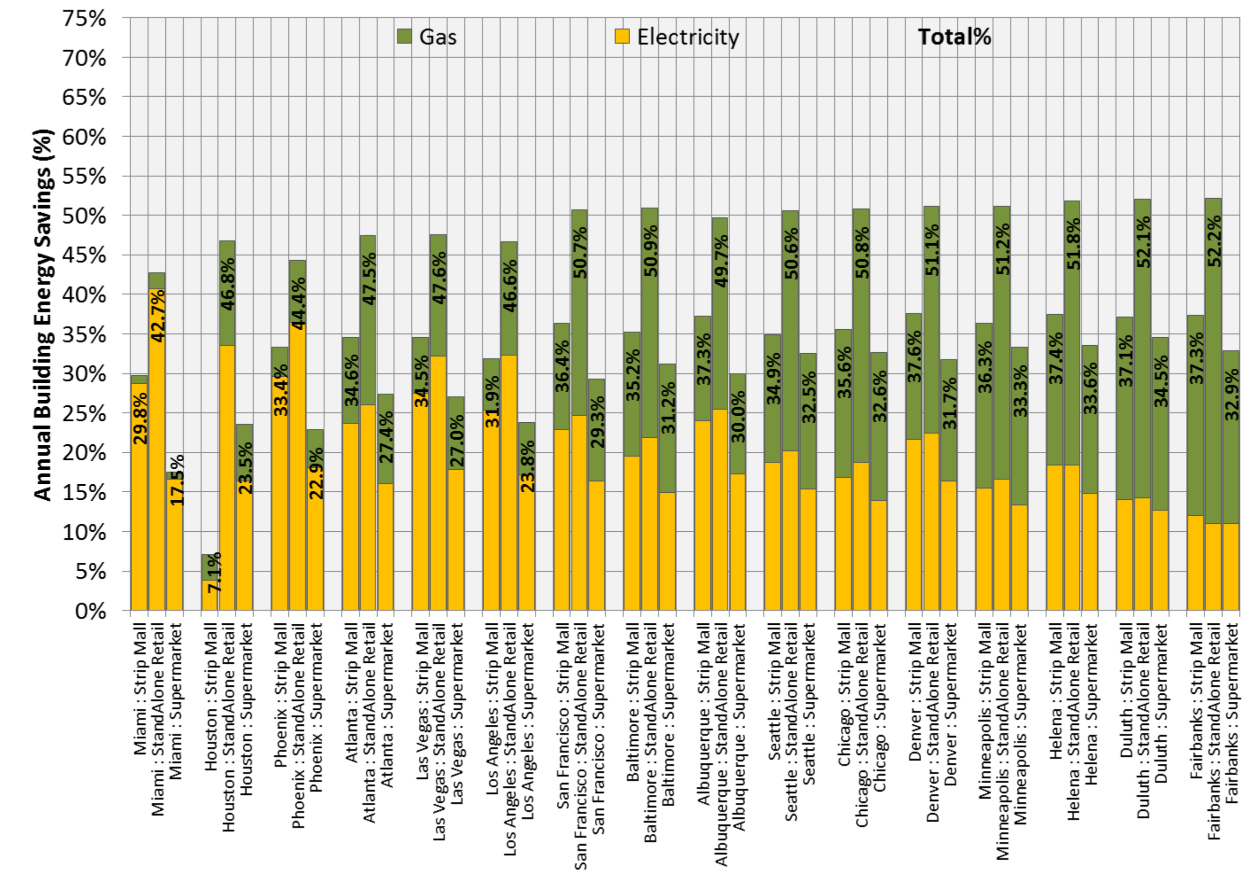

Figure 6.31. Energy Savings for Packages of Controls Measures by Climate Type for "Inefficient" Buildings: Strip Mall, StandAlone Retail, and Supermarket Prototypes

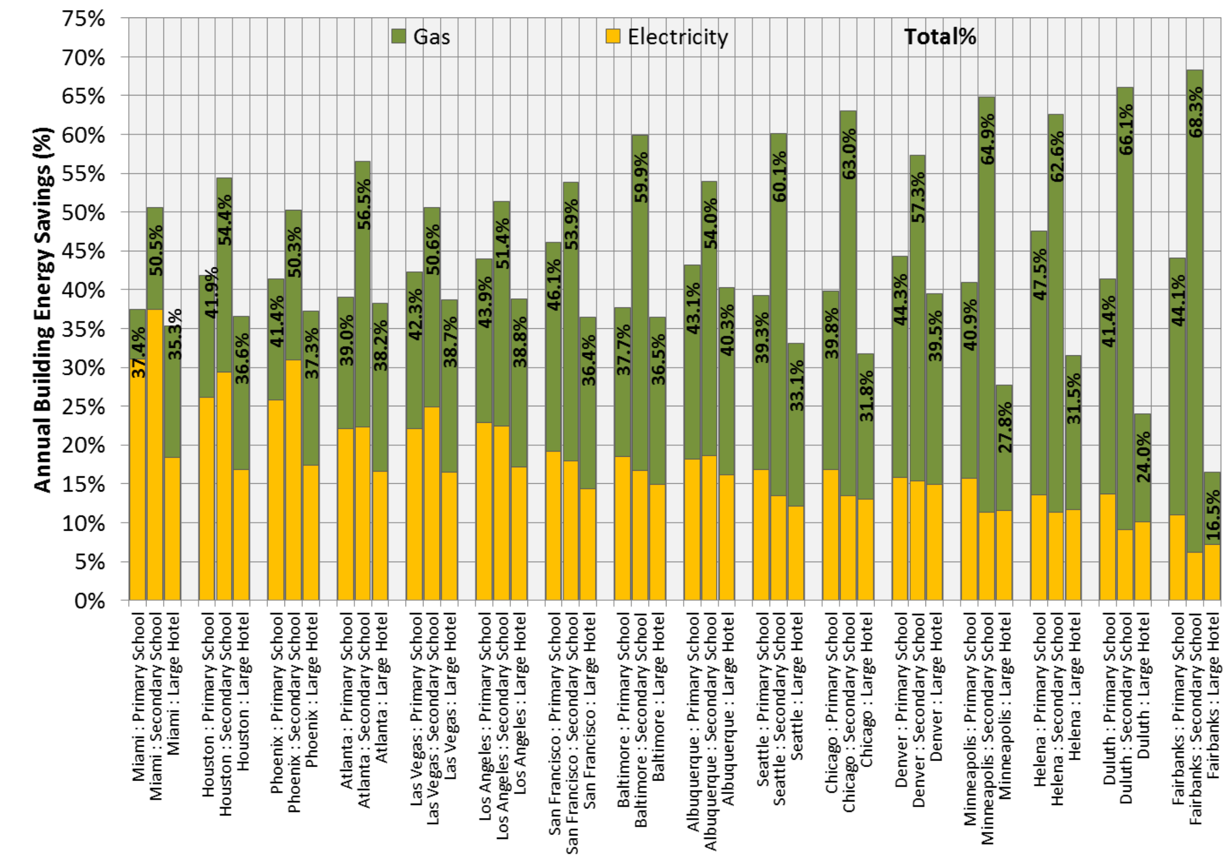

Figure 6.32. Energy Savings for Packages of Controls Measures by Climate Type for "Inefficient" Buildings: Primary School, Secondary School, and Large Hotel Prototypes

6.8.2 Package B: Typical Buildings

Figure 6.33, Figure 6.34, and Figure 6.35 show savings by climate and by prototype for each of the typical building packages, broken out into site electricity savings and site natural gas savings.

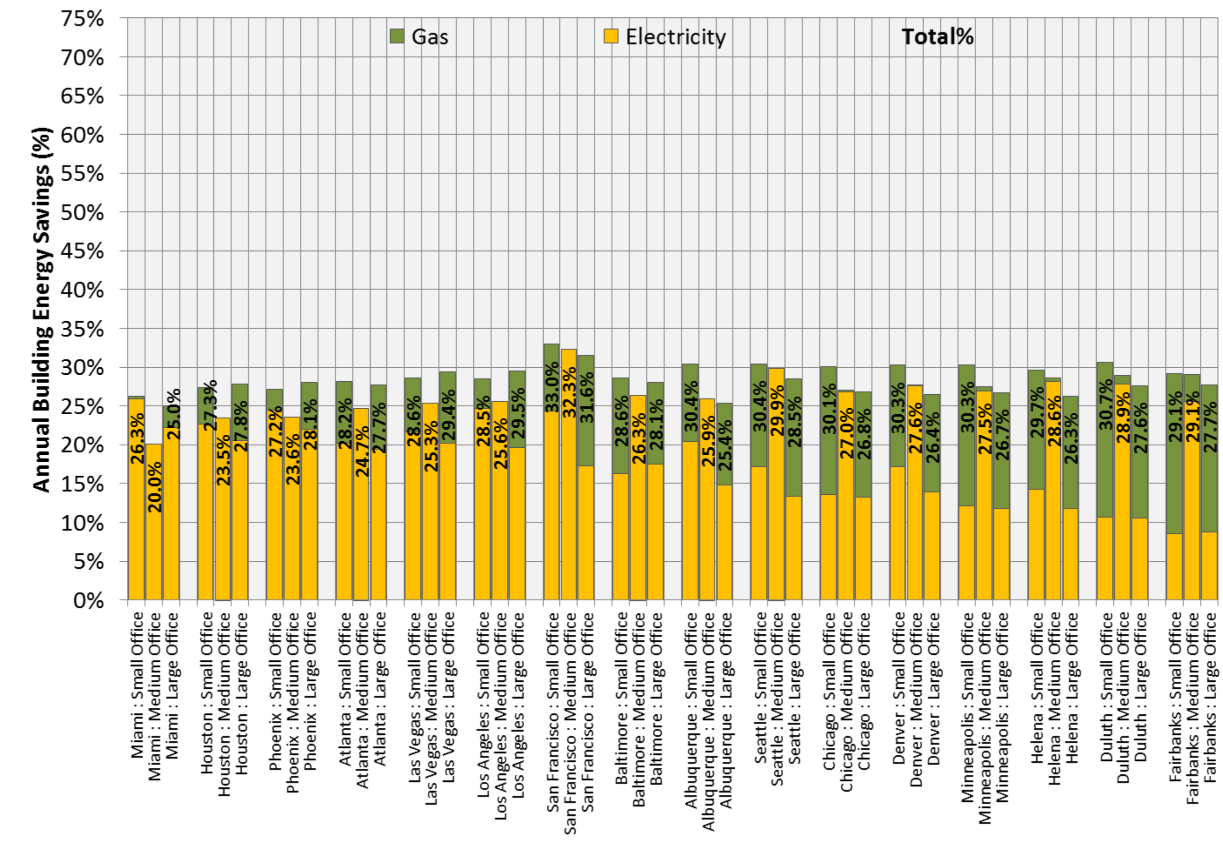

Figure 6.33. Energy Savings for Packages of Controls Measures by Climate Type for "Typical" Buildings: Office Prototypes

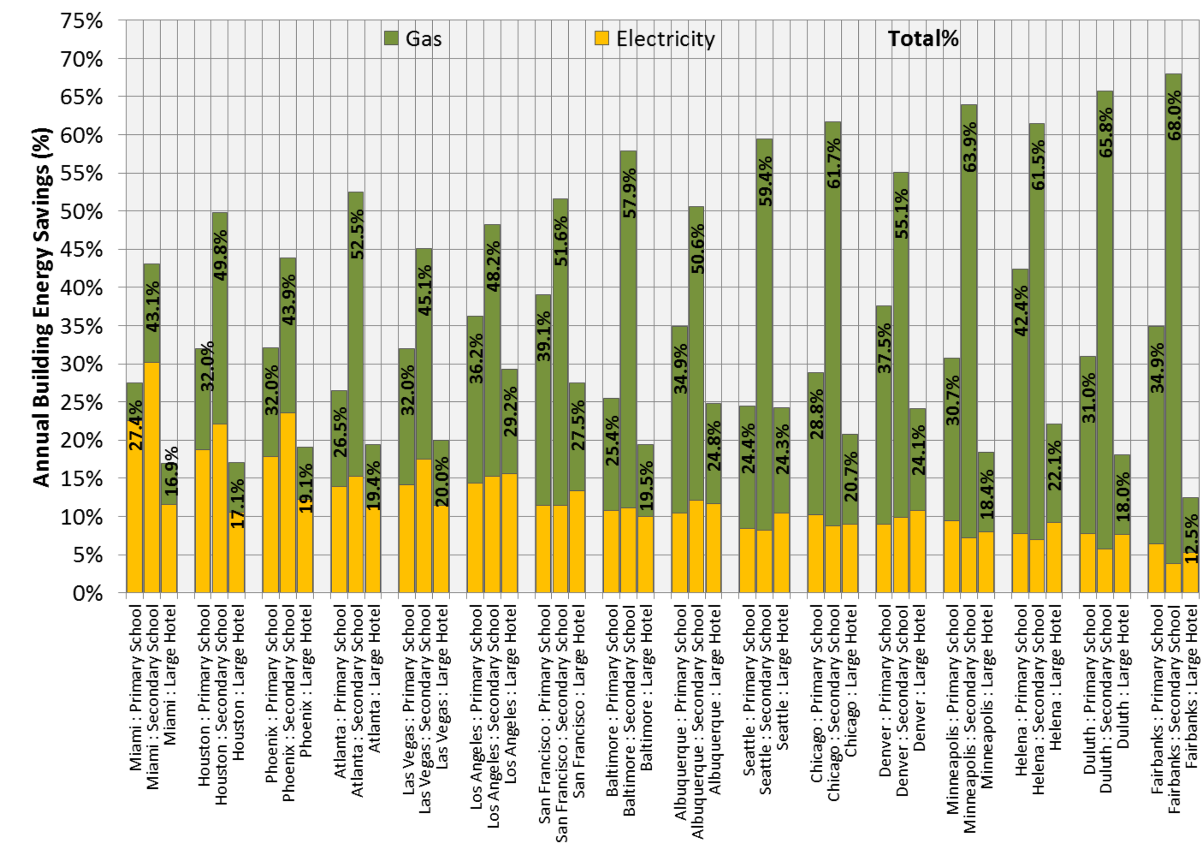

Figure 6.34. Energy Savings for Packages of Controls Measures by Climate Type for "Typical" Buildings: Primary School, Secondary School, and Large Hotel Prototypes

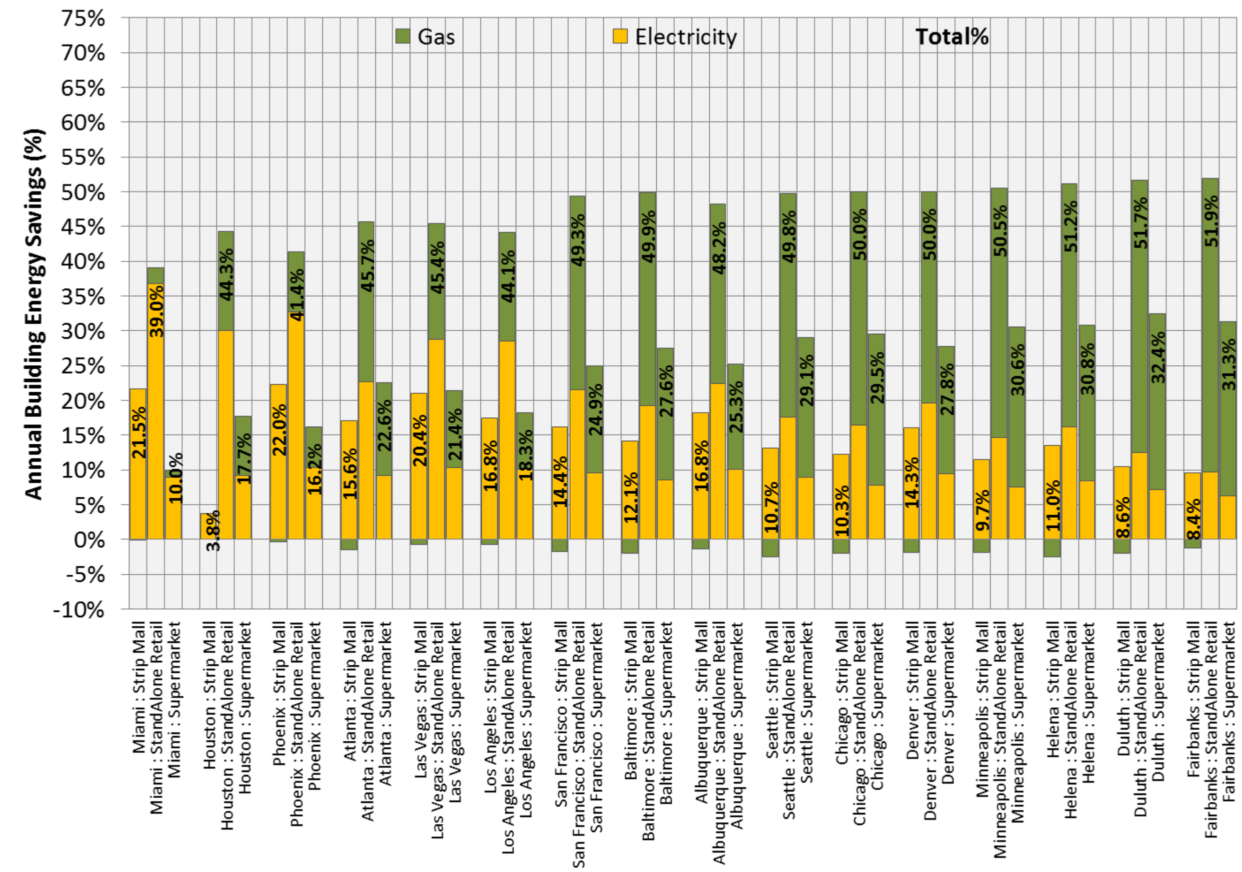

Figure 6.35. Energy Savings for Packages of Controls Measures by Climate Type for "Typical" Buildings: Strip Mall, StandAlone Retail, and Supermarket Prototypes

6.8.3 Package C: Efficient Buildings

Figure 6.36, Figure 6.37, and Figure 6.38 show savings by climate and by prototype for each of the efficient building packages, broken out into site electricity savings and site natural gas savings.

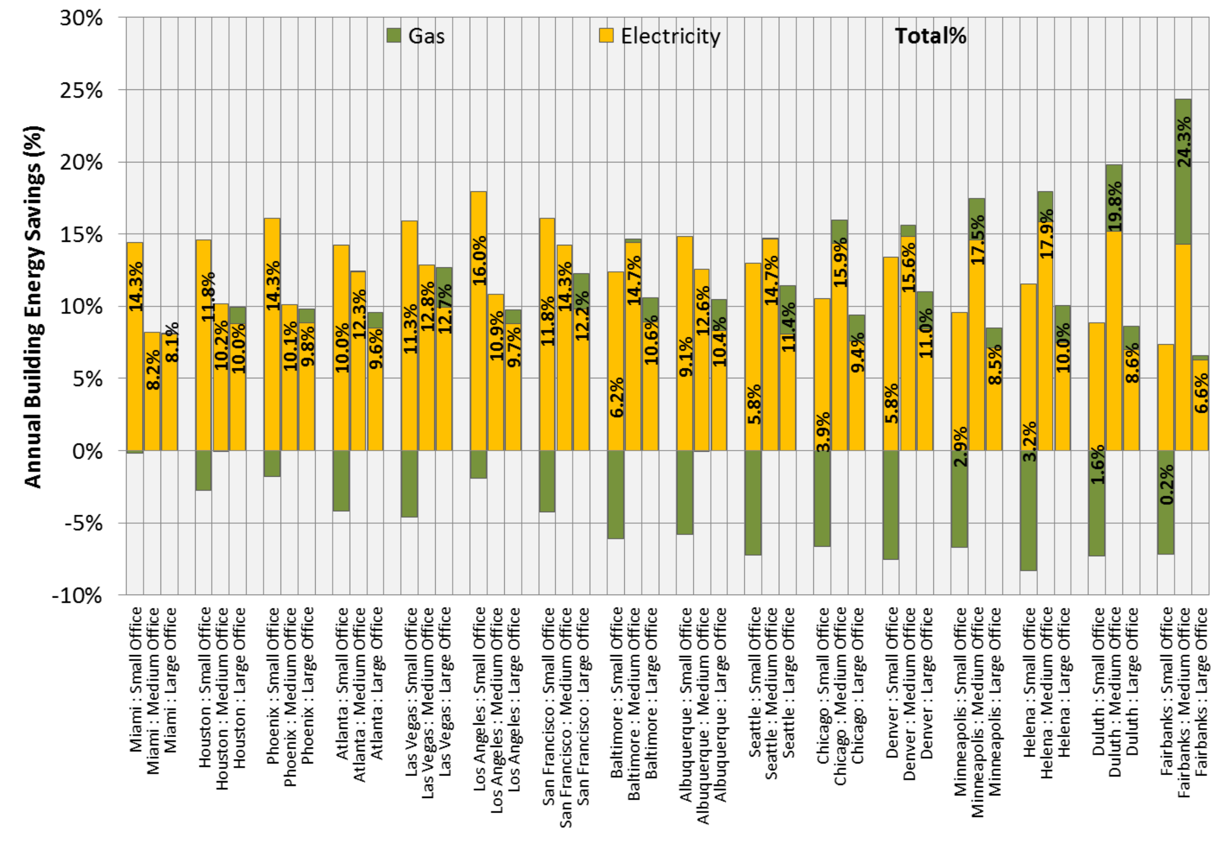

Figure 6.36. Energy Savings for Packages of Controls Measures by Climate Type for “Efficient” Buildings: Office Prototypes

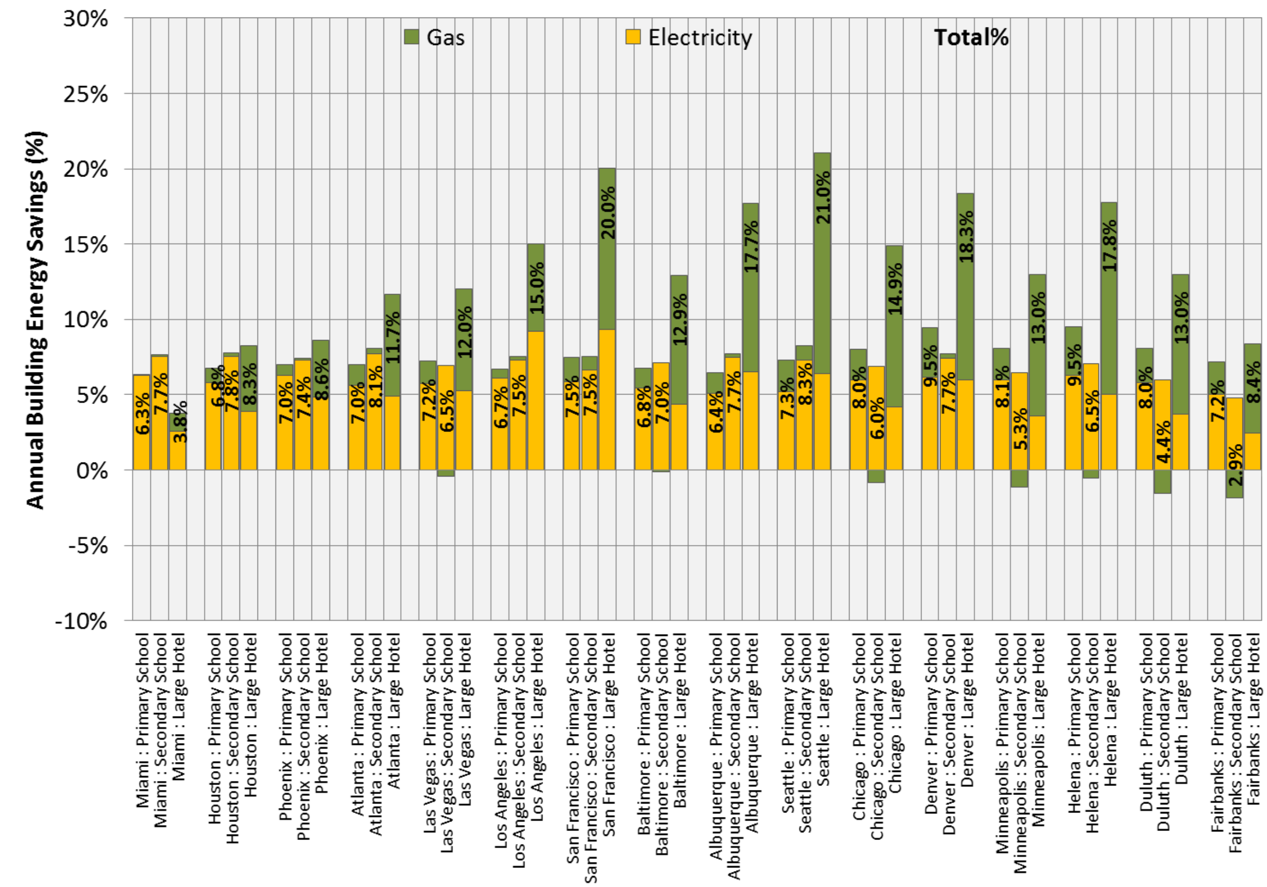

Figure 6.37. Energy Savings for Packages of Controls Measures by Climate Type for "Efficient" Buildings: Primary School, Secondary School, and Large Hotel Prototypes

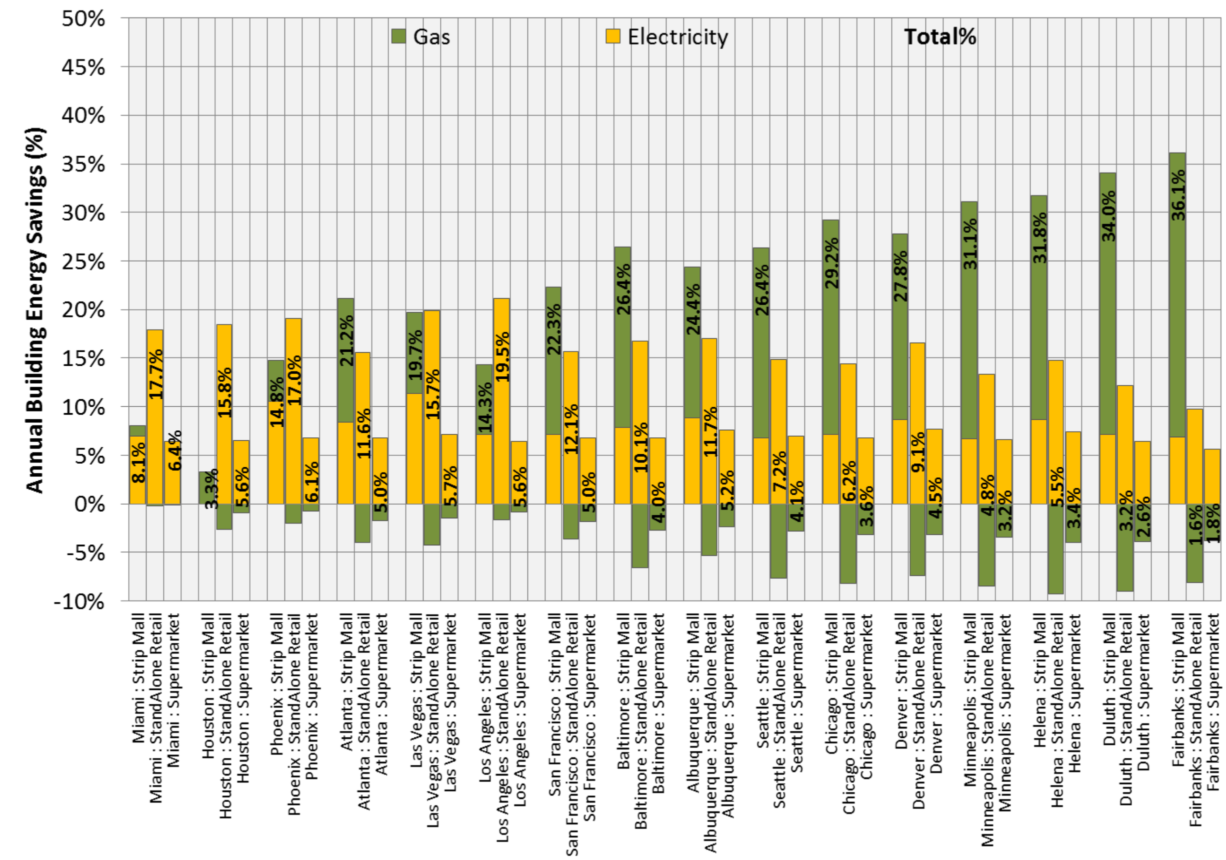

Figure 6.38. Energy Savings for Packages of Controls Measures by Climate Type for "Efficient" Buildings: Strip Mall, StandAlone Retail, and Supermarket Prototypes

6.8.4 National Savings Summary

The national savings potential from EEMs was determined through a national aggregation of the modeled savings from each of the packages by building prototype, weighted by the prevalence of each building efficiency level used to define the packages. Figure 6.39 shows the savings (in percentage terms) from each building efficiency level for each set of building types. Savings was lower for the efficient buildings (in green), intermediate for the typical buildings (blue), and highest for inefficient buildings (red). Based on the weighting of these three efficiency levels, the expected national savings for each set of building types is represented by a black diamond. For most building types, the potential national savings ranges from 23 to 30%, with the exception of Secondary School (49%) and StandAlone Retail/Dealership (41%). Aggregated among all building types, the annual building energy savings from efficiency measures was estimated to be 29%.

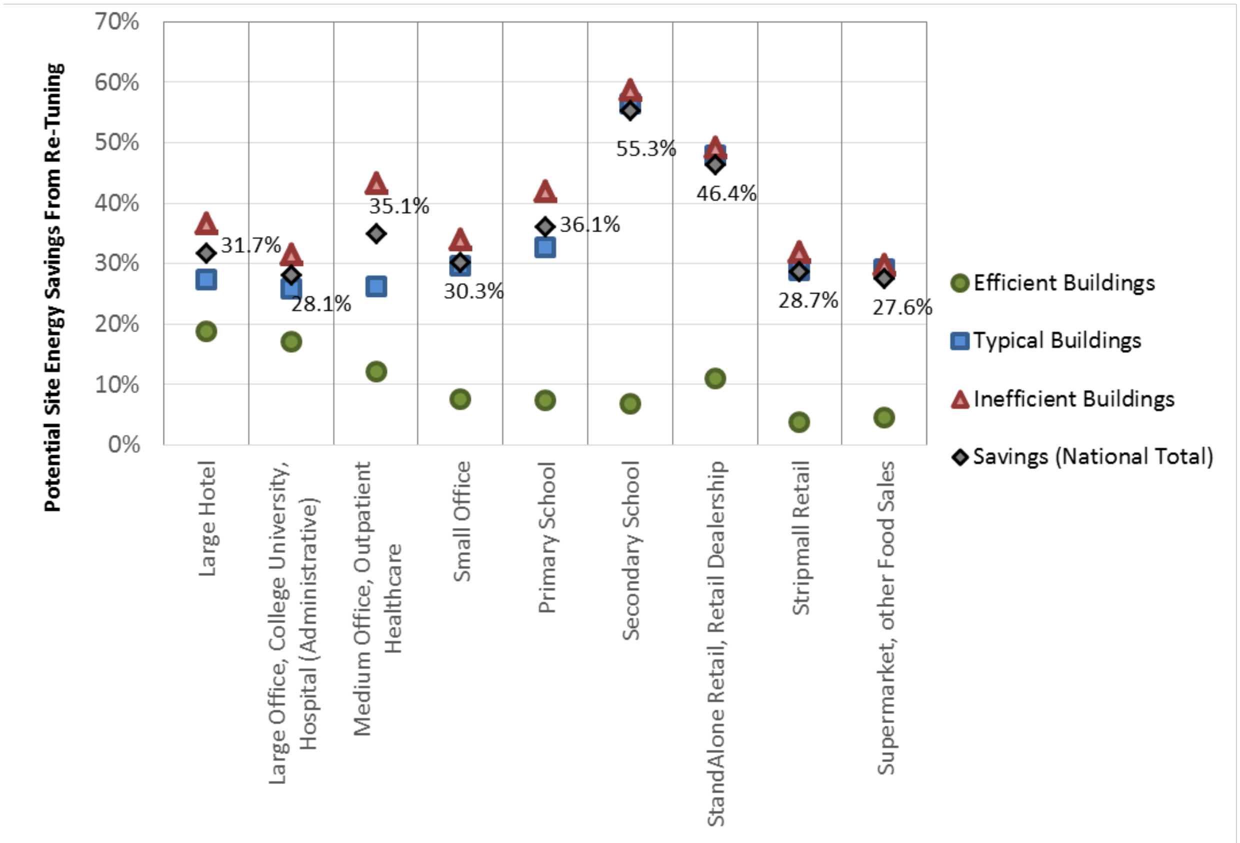

Figure 6.39. Summary of Total Energy Savings for Packages of Control Measures by Building Type

Energy savings from the three packages of measures is estimated for each building type by aggregating the savings across all climate zones. The total technical potential savings is estimated by weighting each building type package (efficient, typical and inefficient) according to its expected prevalence in the national commercial building stock.

Figure 6.40 divides the savings for each package in each prototype model into electricity and gas savings to show the relative contribution of each. Figure 6.41 shows the total national site and source energy savings in quadrillion British thermal units (quads) for each building type. This study did not analyze primary energy savings at the local level and aggregate to national savings. Instead, national scale primary energy conversion factors of 1.05 for natural gas and 3.14 for electricity were used to approximate primary energy savings. A sensitivity analysis on the national proportion of building efficiency levels (efficient, typical, and inefficient) was included to address potential concerns around the uncertainty of the savings estimate. Due to the lack of data on the prevalence and magnitude of opportunities for controls improvements for most measures in most building types, this is the most straightforward way to handle uncertainty in this study. The sensitivity analysis perturbs the weighting of efficiency levels in the central/best estimate (which uses previously discussed weighting) as shown in Table 6.1.

Table 6.1. Weights used for the Sensitivity Analysis

Sensitivity	Efficient	Typical	Inefficient
Central/Best Estimate	30%	50%	20%
Low Savings Estimate	50%	40%	10%
High Savings Estimate	10%	40%	50%

The total site energy savings ranges from 1.02 to 1.70 quads, with a best estimate of 1.32 quads of savings. Total primary energy savings ranges from 2.17 to 3.56 quads, with a best estimate of 2.74 quads of savings. The total savings is 1.32 quads of energy (site) and 2.76 quads of energy (source).

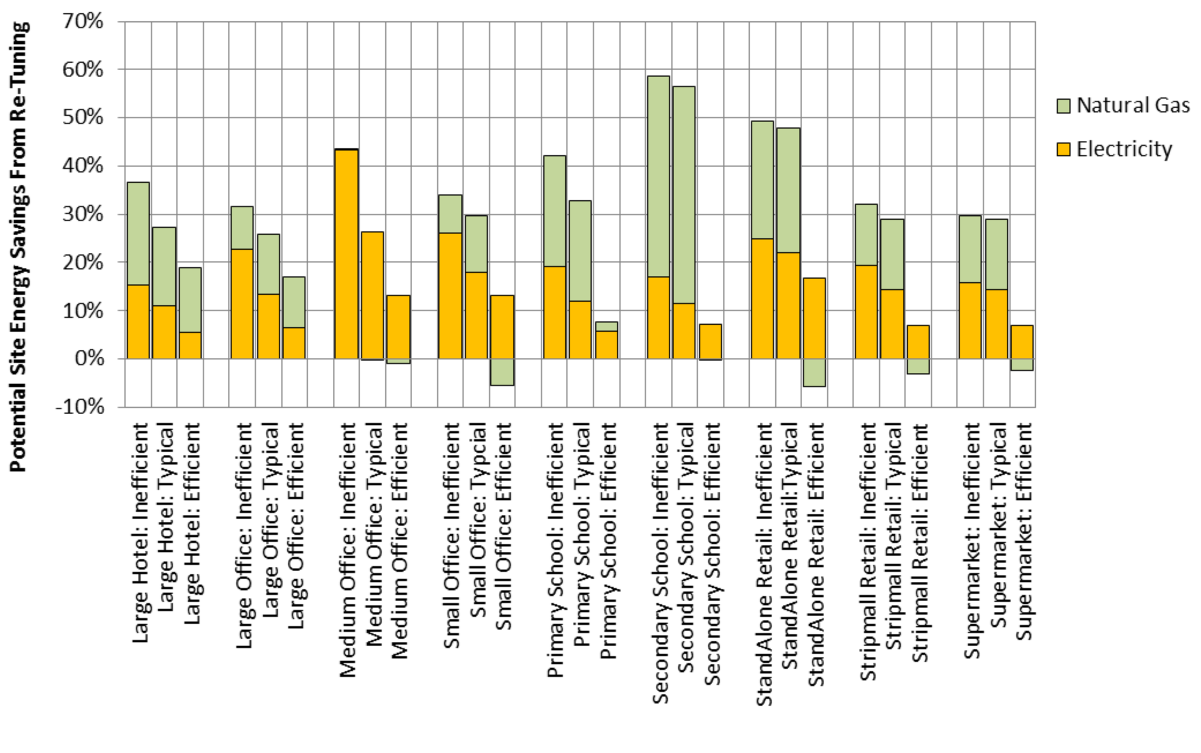

Figure 6.40. Natural Gas and Electricity Savings by Package of Measures

Energy savings from the three packages of measures is estimated for each building type by aggregating the savings across all climate zones. A breakdown of the savings between gas and electricity for each building type package (efficient, typical and inefficient) is provided.

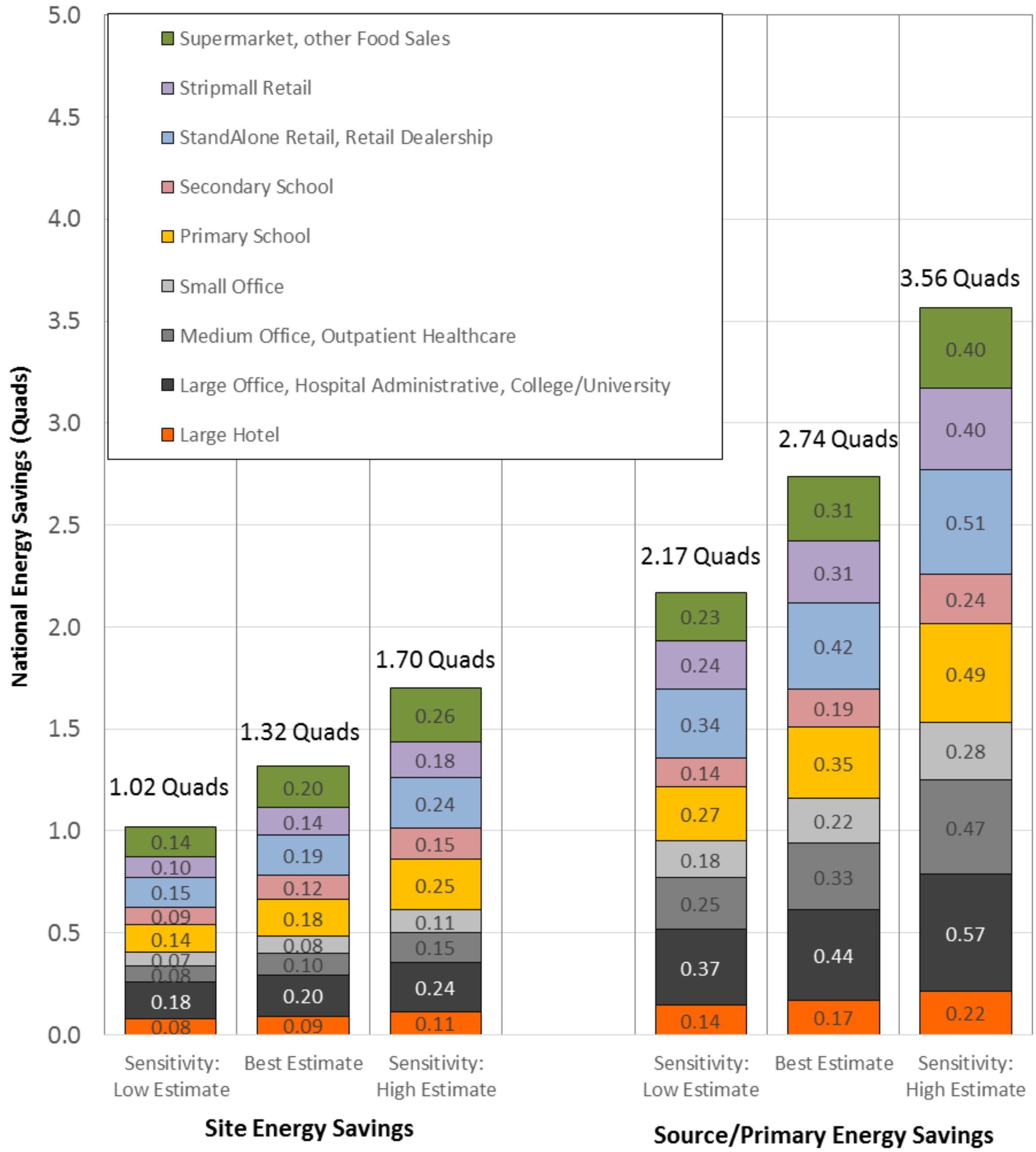

Figure 6.41. National Total Site and Source Energy Savings Potential by Building Type in quadrillion Btu (quads)

Aggregate technical potential savings for the packages among all climate zones and building types is estimated based on the weighted savings from the packages of measures combined with the total energy consumption by building type from CBECS 2012. Source energy savings is estimated by applying national average primary energy conversion factors for electricity (3.14) and natural gas (1.05). Three scenarios are presented, based on application of a sensitivity analysis on the national proportions of the three building efficiency levels (inefficient, typical, and efficient).

7.0 Summary of Results and Conclusions

Commercial buildings in the United States consume about 18 quads of primary energy (EIA 2016). Small- and medium-sized commercial buildings (<100,000 sf), in particular, represent over 95% of the commercial building stock and consume over 60% of total site energy. Large commercial buildings (>100,000 sf) represent only 5% of the commercial building stock, on the other hand, but account for over 40% of the total building energy consumption. Although many studies have indicated significant potential (as much as 30%) for reducing the energy consumption in commercial buildings, very few have documented the savings. Even the studies that documented the savings provide data at the whole-building level, which makes it difficult to assess the potential from each individual measure deployed. In addition, many studies have shown that between 10% and 20% of the commercial building peak load can be temporarily managed/curtailed to provide grid services (Mills 2009; Katipamula and Brambley 2008). Therefore, the main motivation for this study was to quantify the potential energy and cost savings derived from the use of more accurate sensing, better utilization of existing controls, deployment of more advanced controls, and deployment of grid services.

The measures in this study focused on equipment operation and control, and thus did not include major retrofits of existing equipment. For this reason, the upfront cost and payback period for these control measures tend to be more financially attractive than implementing equipment or building envelope retrofits. In many cases, however, some measures may require upgrades of building automation systems, such as enhanced communication capabilities and installation of variable-speed drives on certain fans and pumps in some buildings. This study simulated 34 control measures in 9 commercial building types—extended (by analogy) to another 5 building types—that collectively represent 57% of the U.S. commercial building sector energy consumption. The measures were simulated in 16 climate locations and savings were weighted according to commercial building sector square footages by climate and building types using the 2012 CBECS conducted by the U.S. Energy Information Administration. The energy modeling also relied on packages of measures that represent the diversity of the current status of building controls (inefficient, typical, and efficient), and compared those packages to an ideal building representing a reasonable approximation of best practices in all areas of building control. The difference between the current state of building controls and the ideal state is the assumed savings potential.

A detailed simulation-based approach was used to quantify these savings in this study. While savings from individual EEMs can be isolated using detailed simulations, the types of EEMs that can be simulated are limited. Despite this limitation, 43 different EEMs were simulated for nine prototypical buildings in 16 U.S. climate regions. In addition to the nine prototypical buildings, the savings were extrapolated for five additional building types because of their similarity with one of the nine prototypes simulated. Note that a number of EEMs are not applicable to all building types because they lack the physical or control infrastructure needed to implement the measure. For example, buildings with RTUs cannot take advantage of central plant measures. The set of 14 buildings that were selected as part of this study does not represent the full potential for energy savings from controls improvements, but instead represented practical limitations such as available baseline energy models. These 14 buildings represented 51% of floor space and 57% of the total U.S. commercial building stock.

The savings were calculated for each individual EEM, for each relevant building type, and for each climate region; as were the national savings for each measure by building type and the savings for each measure by building type and climate location. Furthermore, because building owners may choose to apply a package of synergistic measures rather than an individual measure, a set of packages were also created: 1) efficient building package, 2) typical building package and 3) inefficient building package. The savings calculated for the individual measures were also calculated for the packaged measures.

The results from this study indicate significant energy savings are possible in small- and medium-sized buildings, in particular, by managing schedules and set points, daylighting controls, and other factors. The savings range between 3% and 15% for each EEM considered. The package savings for these buildings range between 25% and 40%. Just controlling schedules and enforcing set points will result in savings of over 20%. Only 12% of these buildings have BASs, so the vast majority of these buildings lack proper controls infrastructure. The results of this study further indicate that for large commercial buildings, significant savings can be derived by “optimizing” minimum VAV terminal box flow; managing HVAC schedules; and ensuring the use of wider deadband and night setbacks, optimal start, and demand-controlled ventilation. The savings range between 10% and 15% for each EEM considered. The package savings for these buildings range between 25% and 50%.

7.1 Energy Savings from Individual Measures

The total site savings, natural gas savings, and electricity savings are estimated for each measure by building type and climate location (Figure A.1 through Figure A.58). A total of 37 individual measures were simulated and the savings estimated. Many of the EEMs only apply to a few building types, so, if a measure is not applicable to a given building type, the savings are either not reported or the measure is not included in the graph that reports the results. Refer to Appendix A for more details on individual measure results.

Table 7.1 shows a summary of the range of savings modeled among the set of applicable EEMs for each building type, aggregated across all climates. For each prototype, the minimum and maximum savings for individual measures are shown for electricity, natural gas, and both combined. The top performing EEM for electricity savings and for natural gas savings is also listed. Typically, negative savings in electricity or gas for one fuel type is offset by greater savings in the other fuel type. For example, measures that produce electricity savings through reductions in internal electric loads simultaneously reduce internal heat gains and increase the demand for natural gas. For Primary and Secondary School, one measure (EEM06: outdoor air damper faults/control), which for other building types can save significant energy, is modeled as leading to a significant increase on overall energy consumption. The reason for the increase is that this measure corrects a baseline fault that simulates poor damper seals by limiting the range of the outdoor air damper (both minimum and maximum flow). Because the maximum flow is limited, the baseline building is under-ventilated based on design ventilation rates when the outdoor air damper seals are poor. For all building types, the best overall measure for total savings was either EEM15: minimum VAV terminal box flow reductions, EEM16: wider deadbands and night setbacks, or EEM17: demand control ventilation. For all building types that used single-zone packaged units for space conditioning, the top performing measure for electricity savings was EEM23: advanced RTU controls.

The last row of Table 7.1 includes an estimate of the range of the technical potential savings for individual measures at the national level. This involves an aggregation of savings among all building types and climate zones. For each EEM, there is an additional adjustment of the total savings to reflect the expected prevalence of opportunities to implement the measure, given that that each of the measures is an opportunity in only a subset of the building stock for buildings of each type. The adjustment is a fractional multiplier that is set equal to that measure’s weighting within the set of packages. Among the set of individual measures at the national level, the total site energy savings ranged from 0% to 7.7%. The top overall measure for electricity savings was EEM23: advanced RTU controls (3.8%). For both natural gas (5.3%) and overall site energy savings (7.7%), EEM16 (wider deadbands and night setbacks) was the top performing measure.

Table 7.1. Energy Savings from Individual Measures by Building Type Aggregated across All Climate Locations and National (last row)

Prototype Model	Electricity Savings Range Min (%)	Electricity Savings Range Max (%)	Natural Gas Savings Range Min (%)	Natural Gas Savings Range Max (%)	Total Savings Range Min (%)	Total Savings Range Max (%)	Top Performing Measure: Electricity	Top Performing Measure: Natural Gas
Small Office	0.1	7.1	-3.9	7.4	0.0	9.7	EEM23: Advanced RTU Controls	EEM16: Wider Deadbands and Night Setbacks
Medium Office	-0.2	16.0	-1.5	0.9	-0.2	16.1	EEM15: Minimum VAV Terminal Box Damper Flow Reductions	EEM17: Demand Control Ventilation
Large Office	-0.2	5.4	-2.6	12.2	-0.2	15.4	EEM26: Cooling Tower Controls	EEM15: Minimum VAV Terminal Box Damper Flow Reductions
Stripmall Retail	0.0	9.8	-6.3	11.5	0.1	12.0	EEM23: Advanced RTU Controls	EEM17: Demand Control Ventilation
StandAlone Retail	0.1	11.5	-8.4	14.2	0.2	14.8	EEM23: Advanced RTU Controls	EEM17: Demand Control Ventilation
Primary School	-0.8	5.6	-6.4	9.9	-7.2	15.6	EEM16: Wider Deadbands and Night Setbacks	EEM16: Wider Deadbands and Night Setbacks
Secondary School	-0.8	4.2	-4.0	25.5	-4.2	24.7	EEM04: Shorten HVAC Schedules	EEM17: Demand Control Ventilation
Large Hotel	-0.1	4.8	-0.7	7.7	0.0	12.4	EEM15: Minimum VAV Terminal Box Damper Flow Reductions	EEM15: Minimum VAV Terminal Box Damper Flow Reductions
Supermarket	0.0	5.4	-3.5	7.7	-0.2	9.1	EEM23: Advanced RTU Controls	EEM16: Wider Deadbands and Night Setbacks
National Total	**0.0**	**3.8**	**-2.6**	**5.3**	**0.0**	**7.7**	**EEM23: Advanced RTU Controls**	**EEM16: Wider Deadbands and Night Setbacks**

7.2 Energy Savings from Individual Measures by Building Type Aggregated across All Climate Locations

A set of simulations was run to estimate the impact of implementing any given EEM on each of the building prototypes, with the savings averaged across all climates (using the CBECS building weights). The total savings as well as savings for individual fuel types (electricity and natural gas) are reported as the fraction of the total building site energy consumption that was saved. These savings metrics are used for all of the analyses.

For small office buildings (Figure 6.1), the total site savings ranged from 0% (EEM22: night purge) to approximately 10% (EEM16: wider deadbands and night setbacks). The natural gas savings ranged from -4% (EEM23: advanced RTU controls) to almost 8% (EEM16: wider deadbands and night setbacks) and the electricity savings ranged between 0% (EEM22: night purge) and 7% (EEM23: advanced RTU controls). Note that for some EEMs, although there was always a net positive savings, there was an increase in natural gas consumption (e.g., EEM23: advanced RTU controls). The reason for this increase is that the reduction in electricity consumption resulted in a decrease in heat gain, which needed to be compensated for by additional heat energy. Approximately half of the EEMs relevant to small office buildings lead to natural gas savings and half lead to electricity savings.

For medium office and outpatient healthcare buildings (Figure 6.2), the total site savings ranged between -0.2% (EEM28: optimal stop) and more than 16% (EEM15: minimum variable-air-volume [VAV] terminal box damper flow reductions). The natural gas savings ranged from -1% (EEM05: supply air temperature reset) to approximately 1% (EEM17: demand control ventilation) and the electricity savings ranged between 0% (EEM28: optimal stop) and 16% (EEM15: minimum VAV terminal box damper flow reductions). Because this building type uses electricity for most forms of space heating, natural gas savings are small.

For large office, college/university, and hospital (administrative portion) buildings (Figure 6.3), the total site savings ranged between -0.2% (EEEM18: lighting occupancy sensors) and more than 15% (EEM15: minimum VAV terminal box damper flow reductions). The natural gas savings ranged from -2.5% (EEM19: daylighting controls) to 12% (EEM15: minimum VAV terminal box damper flow reductions). Although a number of EEMs result in positive natural gas savings, a few EEMs result in negative savings. Again, the negative natural gas savings are a result of controls that result in electricity savings, but increase in the heating load (e.g., daylighting controls). The electricity savings ranged from near 0% (EEM06: outdoor air damper faults/controls) to 6% (EEM26: cooling tower controls).

For primary school buildings (Figure 6.4), the total site savings ranged from -7% (EEM06: outdoor air damper faults/controls) to 16% (EEM16: wider deadbands and night setbacks). Note that correcting the outdoor air damper fault (EEM06: outdoor air damper faults/controls) results in meeting proper ventilation rates, which increases energy consumption. The natural gas savings ranged from -6% (EEM06: outdoor air damper faults/controls) to 10% (EEM16: wider deadbands and night setbacks) and the electricity savings ranged from -1% (EEM06: outdoor air damper faults/controls) to 6% (EEM16: wider deadbands and night setbacks).

For secondary school buildings (Figure 6.5), the total site savings ranged from -4% (EEEM06: outdoor air damper faulty/controls) to 25% (EEM17: demand control ventilation). The natural gas savings ranged from -4% (EEM06: outdoor air damper faulty/controls) to more than 25% (EEM17: demand control ventilation) and electricity savings from 0% (EEM06: outdoor air damper faulty/controls) to 4% (EEM04: shorten HVAC schedules).

For large hotel buildings (Figure 6.6), the total site savings ranged from 0% (EEM13: hot water differential pressure reset) to 12% (EEM15: minimum VAV terminal box damper flow reductions). The natural gas savings ranged from 0% (EEM13: hot water differential pressure reset) to 7% (EEM16: wider deadbands and night setbacks) and electricity savings ranged from 0% (EEM13: hot water differential pressure reset) to 3.5% (EEM16: wider deadbands and night setbacks).

For standalone retail and retail dealership buildings (Figure 6.7), the total site savings ranged from 0.2% (EEM01: re-calibrate faulty sensors) to almost 15% (EEM17: demand control ventilation). The natural gas savings ranged from -8% (EEM23: advanced RTU controls) to more than 14% (EEM17: demand control ventilation) and electricity savings ranged from 0% (EEM01: re-calibrate faulty sensors) to 12% (EEM23: advanced RTU controls).

For strip malls (Figure 6.8), the total site savings ranged from 0.1% (EEM22: night purge) to more than 12% (EEM17: demand control ventilation). The natural gas savings ranged from -6% (EEM23: advanced RTU controls) to almost 12% (EEM17: demand control ventilation) and electricity savings ranged from 0% (EEM22: night purge) to almost 10% (EEM23: advanced RTU controls).

For supermarket and other food sales buildings (Figure 6.9), the total site savings ranged from almost 0.2% (EEM01: re-calibrate faulty sensors) to more than 9% (EEM04: shorten HVAC schedules). The natural gas savings ranged from 0% (EEM01: re-calibrate faulty sensors) to 7% (EEM04: shorten HVAC schedules) and electricity savings ranged from 0% (EEM01: re-calibrate faulty sensors) to more than 5% (EEM23: advanced RTU controls).

7.3 Energy Savings from Individual Measures Aggregated Across All Building Types and All Climate Locations

Of the 34 measures simulated, 6 measures, when simulated individually and weighted according to the expected prevalence of opportunity for their implementation, showed the potential for over 2% of the total site energy savings, nationally. These measures are the first six, ranked by impact, in Figure 7.1.

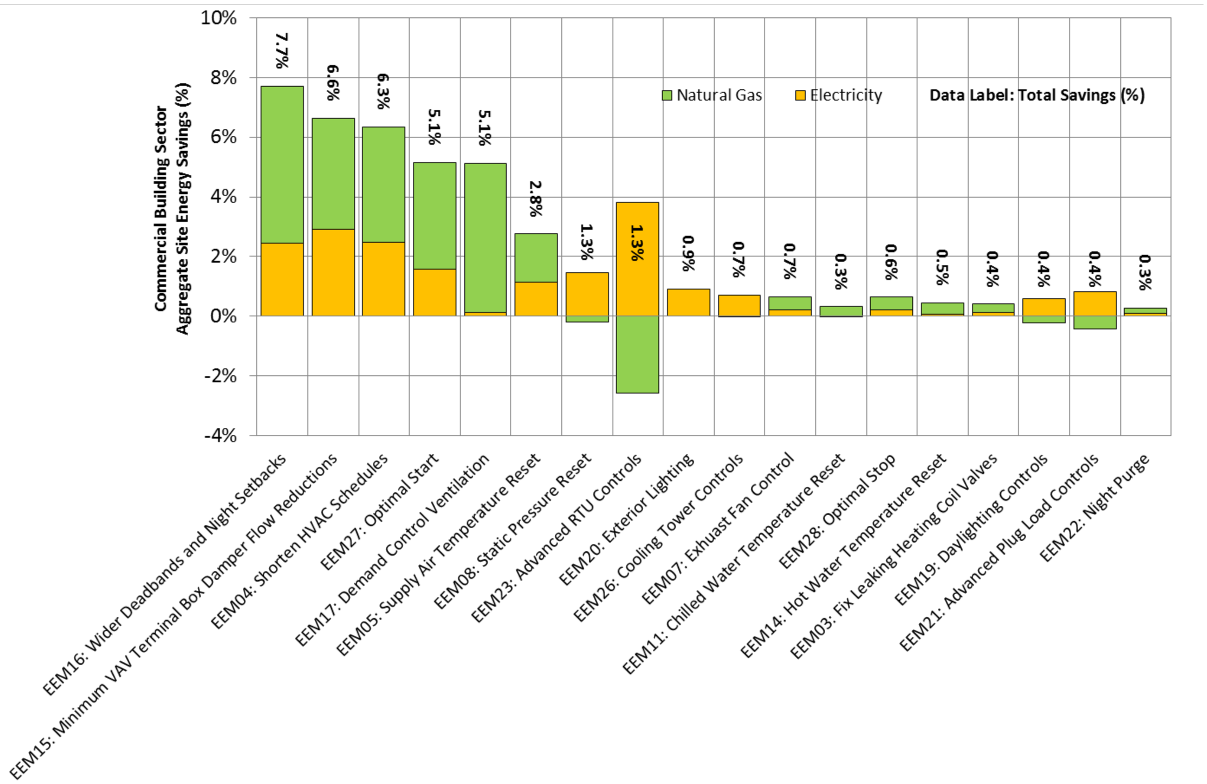

Figure 7.1. National Potential Savings for Individual Measures among all Building Types and Climates (Top 18 Measures)

A national technical potential for each measure among the share of the commercial building stock represented by the nine prototype models is estimated by multiplying the aggregate savings among all building types by the prevalence of opportunity for the measure as applied in the national-level packages. Technical potential is limited by the share of applicable building types and by the assumed fraction of buildings for which the measure can still be implemented.

All of the other measures had national-level savings less than or equal to 1.3%. One important measure in this latter set is advanced RTU fan controls. For this measure, electricity savings amounted to 3.8% of baseline energy consumption (the highest among all measures), but increases in natural gas usage of 2.5% for this measure offset the site energy savings. Nevertheless, electricity consumption in buildings is more strategically important to target for reduction than natural gas because each unit of electricity consumption in buildings is responsible for 3.14 units of primary energy consumption (as a national average), whereas for natural gas, the conversion factor is close to 1. Additionally, electricity historically costs 4–5 times as much as natural gas (national average), per unit of site energy consumed, so the value proposition to the building owner is much stronger for electricity savings.

Using the 3 packages of measures representing the U.S. commercial building stock, the potential site energy savings across all 14 building types is 29%. For individual building types at the national level, the potential savings ranged between 23% and 29% for 11 of the 14 building types, while the other 3 building types (Secondary Schools, StandAlone Retail, and Retail Dealership) achieved more than 40% savings nationally. Across all building types included in this study, the savings represents approximately 387,000 GWh (1.32 quadrillion Btu) of site energy savings, or 803,000 GWh (2.74 quadrillion Btu) of primary (or source) energy savings. A number of building types were not considered in this study; these building types can also benefit from many of the control measures identified in this report. If the savings are extrapolated to include all building types, the savings may be in the range of 4 to 5 quadrillion Btu. If this savings potential were realized, it would represent the equivalent of 200 to 250 million short tons of coal, or the per-capita consumption of 12 to 15 million people. For comparison, the total U.S. primary energy consumption across all sectors was 28.5 million GWh (97.4 quadrillion Btu) in 2015. This makes commercial building controls improvements strategically important to meeting and sustaining reductions in national energy consumption.

7.4 Peak Demand Impacts of Energy Efficiency Measures

The impact on annual peak electricity demand from each of the EEMs was also analyzed for this study. Peak demand reductions are a side benefit both to the building owner in the form of reduced electricity costs and to the grid. Of the 37 EEMs, nine were capable of producing at least 3% peak demand savings in at least one building type, and four of those nine were each capable of producing over 10% peak demand savings. Most of the other measures had little to no impact on peak demand, although one measure (optimal start) produced significant peak demand increases, but only for two building types.

7.5 National Energy Savings from a Package of Measures

In many cases, the building operator/managers will deploy a package of synergistic measures rather than an individual measure. Deploying a package of measures will in most cases be more cost effective than deploying individual measures. The three packages of measures created to estimate the national savings potential were described in Section 5.0.

The total site energy savings by building type for the efficient building package, the typical building package, and the inefficient building package ranged from 4% to 19%, 26% to 56%, and 30% to 59%, respectively. Based on the weighting of these three efficiency levels, the expected national savings for each set of building types were also estimated. For most building types, the potential national total site savings ranged from 23 to 30%, with the exception of Secondary School (49%) and StandAlone Retail/Dealership (41%).

Aggregated among all building types, the annual building energy savings from efficiency measures is estimated to be 29%. The savings from natural gas and electricity were also estimated. The site natural gas savings by building type for the efficient building package, the typical building package, and the inefficient building package ranged from -6% to 13%, 0% to 45%, and 0% to 42%, respectively. A few building types have negative natural gas savings for the reasons previously discussed. The site electricity savings by building type for each of the respective building packages ranged from 6% to 17%, 11% to 26%, and 15% to 43%.

The total site energy savings ranged from 1.02 to 1.70 quads, with a best estimate of 1.32 quads of savings. Total primary energy savings ranges from 2.17 to 3.56 quads, with a best estimate of 2.74 quads of savings. For comparison, note that commercial buildings consumed 2.6 quads for lighting, the largest single end use.[1] It should be noted that the 14 building types that were represented in this study account for 52% of commercial building floor space and 57% of the commercial buildings sector energy consumption. Significant additional savings would be expected in the remaining set of commercial buildings that were outside the scope of this study.

7.6 Peak Reductions from Individual Demand-Response Measures

The peak reductions for each of 6six DR measures were estimated for each of the 9 primary building types for each of the 16 climate locations (Figure 6.14 through Figure 6.27). The reductions varied across the building types and climate locations. The duty cycle measure, when applied to Supermarkets, resulted in an increase in demand rather than a decrease (this phenomena is still being investigated).

Because critical peak pricing is one of the common DR rates that is widely used in California and other parts of the United States, a series of measures was created to estimate the possible peak reduction (Figure 6.28). The national peak reductions, aggregated across all building types and climate locations, ranged from 0.2% (refrigerant) to more than 16% (pre-cooling). Nationally, the peak reduction is almost 16% for setpoint changes, 6% for duty cycling, 2.5% for lighting, and 0.7% for chilled water temperature reset control.

The refrigeration peak reduction measure only applies to Supermarket and Other Food Sales; therefore, this measure results in only a 0.2% peak reduction across all building types. However, when it is applied to just Supermarket and Food Sales, it results in peak reductions from 5% (Phoenix) to 7.7% (Los Angeles).

7.7 Energy Impacts of Demand-Response Measures

The impact on annual energy consumption from peak demand measures is very small—in almost all cases annual energy consumption increases or decreases by less than 0.1%, which is statistically insignificant. In terms of the change in electricity consumption over the course of a typical CPP day, impacts range between 5% and 6% increase in consumption (for pre-cooling, in three building types) to between 4% and 7% reduction for set point changes and duty cycling in some building types.

7.8 National Peak Reductions from Packages of Demand-Response Measures

Because building operators/owners often will apply synergistic DR measures as a package, two different DR packages were created—reactive and predictive. Applying these two packages to all building types

[1] DOE EIA. May 2016. Annual Energy Outlook 2016. See Table 5, Commercial Sector Key Indicators and Consumption, Reference Case.

and in all climate locations resulted in peak reductions of approximately 18.9% (reactive) and 19.3% (predictive).

7.9 Limitations of the Study

Although this study was expansive, the set of modeled buildings analyzed only represents just over half of the commercial building sector in square footage. This limitation is due in part to the fact that many of the CBECS Principal Building Activities do not have associated EnergyPlus prototype models. New prototype models are needed to represent the entire U.S. building stock—in particular, enclosed malls, public assembly buildings (theaters, convention centers), public order and safety buildings, and religious worship buildings.

Additional limitations exist in the EEMs themselves. For example, the first six EEMs investigated represented the correction of an operational "fault" condition. Although limited information is available regarding the prevalence of faults in buildings, the prevalence of many faults and the severity of the fault levels for almost all faults is completely unknown. For example, EEM3 investigated the savings from fixing/replacing leaking hot water coil valves. It is well known that a significant number of these valves are not operating properly and are leaking (flowing through) hot water when they are supposed to be closed. In the study, this fault was modeled to occur in all AHU hot water coil valves (but no VAV hot water reheat coil valves) at an average impact of 2°C of heating. This assumption and other fault assumptions are guesses at best, and savings from their correction could use significant refinement, aided by additional research.

Occupancy-based controls have shown to provide significant energy savings in office buildings (Zhang et al. 2013). The current study included some EEMs that relate to occupancy-based lighting and HVAC controls that applied to specific building types (e.g., large hotels). The study also included some EEMs that raised/lowered set point during unoccupied periods; however, these were not occupancy driven, they were schedule driven. To model the occupancy-based control measures, a good individual occupancy pattern for all building types is required. In addition, this study did not take into account the fact that even though commercial buildings are supposed to be positively pressurized when the HVAC systems are running during occupied periods, many buildings are in fact negatively pressurized due to reasons such as an imbalance between outdoor air intake and exhaust, resulting in significant infiltration.

Several questions also need to be further investigated regarding benchmarking. For example, the extent to which building models used in this study are representative of the existing building stock; whether baseline assumptions are all accurate; and whether this kind of study would benefit from more diversity in baseline system types and control parameter settings. Some available data were used to estimate the prevalence of opportunities for deploying various control measures, especially in office buildings. However, more extensive research into the state of controls across the commercial building sector would greatly improve this picture and aid in the weighting of EEMs within packages.

Further enhancements to EnergyPlus could also improve estimates of energy savings. For example, improvements could be made in the modeling of variable-speed pumps and fans that often rely on pressure-feedback–based controls. Modeling the static pressure reset for VAV systems accurately requires a complex characterization of the pressure drop characteristics of the ductwork between the supply fan and each VAV box. EnergyPlus does not support this level of detailed specification, and thus the airflow rates at each terminal box are not affected by the specified "fan pressure rise" (i.e., static pressure), nor are they affected by the airflow demands elsewhere in the VAV network. Although EnergyPlus does track VAV terminal unit damper positions, these positions are calculated as the ratio of current airflow rates to design airflow rates at each VAV box, which is an approximation and not reflective of what those damper positions actually mean. A similar simplification exists in the simulation methodology for pumps.

This study investigated the vast majority of potential control measures that could be deployed in buildings, and the savings estimated are likely close to the technical potential for controls-based energy savings. Optimizing operations of individual components and optimizing whole-building operations can result in additional savings; however, the savings are generally low compared to savings resulting from improper or faulty operations. In addition, the level of effort to simulate and also deploy optimization solutions in buildings is high. Therefore, this study excluded a handful of optimization strategies that are not commonly used, but have the potential to further "push the envelope" of energy savings. These include, but are not limited to the following options.

- ***Chiller Plant Sequencing and Optimization***: Minimize energy use for the entire chiller plant through optimized chiller and pump staging, leaving chilled water temperature, tower outlet temperature, and chilled water pump differential pressure.
- ***VAV System Optimization***: Minimize the air system energy through the control of discharge air temperature and supply fan static pressure based on zone load conditions.
- ***Predictive Controls***: Change HVAC system control strategies based on the predicted load and weather conditions.

These strategies are difficult to model in the current EnergyPlus software and could be better enabled by a controller in EnergyPlus that investigates the expected energy consumption from a range of scenarios and dynamically selects the best operating conditions for multiple pieces of equipment.

7.10 Next Steps

Achieving the savings potential estimated in this study relies on the proper implementation of the controls measures described. For buildings that employ BASs to manage HVAC operations, this requires programming of control sequences by local distributors or consultants that are aware of best practices, replacement of legacy pneumatic systems, interoperability between control vendors, and scalability to the meet the varied needs of these large buildings. Because most small- and medium-sized commercial buildings do not install BASs, proper commissioning after the completion of construction and retro-commissioning (post-occupancy) in an automated and low-cost manner is necessary to ensure persistent building operations. Both technological advancements and education of controls installers and operators is necessary to overcome these challenges.

Furthermore, management of "flexible" building loads, or loads that can be temporarily curtailed, offer an opportunity to mitigate some of the imbalances resulting from the variability of distributed energy resources that are forming an increasing fraction of the grid capacity. However, curtailment often leads to decreases in the service levels that the assets provide to the building (e.g., exercising the loads may affect comfort). This study showed that up to 20% of the building electricity consumption can be reduced for short periods (less than four hours) with little impact on the occupants and the services levels. Development and deployment of transaction-based controls (or transactive controls)—controls that use external signals (e.g., price, imbalance, frequency, voltage) in addition to traditional control parameters—can enhance building-grid integration as they allow for the buildings loads to react to external signals while balancing the agreed upon impact to the occupants and the service levels. To exercise the flexible loads in the building—through transaction-based controls—requires software applications and low-cost platforms to enable deployment in buildings.

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Appendix A

Detailed Individual Measure Results by Building Type and Climate

Appendix A

Detailed Individual Measure Results by Building Type and Climate

Individual measure results are included in this appendix, organized by measure. Results for each prototype simulated are included in the section about each measure. One or more graphs is provided for each measure to demonstrate the impact of climate and building type on energy savings. The labeled percentage for each climate is the total site energy savings. This is disaggregated into bars that show the contribution to that total savings from electricity and natural gas.

A.1 Measure 01: Re-calibrate Faulty Sensors

Figure A.1 shows climate-specific savings for three selected prototypes. There is some variation in the savings by prototype according to the baseline need for outdoor air for ventilation. For example, the Small Office prototype has a lot of flexibility to increase or decrease the amount of air that is brought in for economizing because the actual outdoor airflow fractions for ventilation are low (below the minimum damper setting of 15%). However, with high occupant densities in the Primary and Secondary School prototypes, required ventilation air forces the need for high outdoor air fractions at all times and therefore allows for very little flexibility in economizing. This reduces possible gains from correcting economizer temperature sensor faults. Savings nationally are further limited by buildings that do not have economizers enabled in the first place. For this study, it was assumed that in all warm climates where economizers were not mandatory according to commercial building codes (Climate Zones 1–3), no economizers are used. The savings in those climates are therefore modeled as zero.

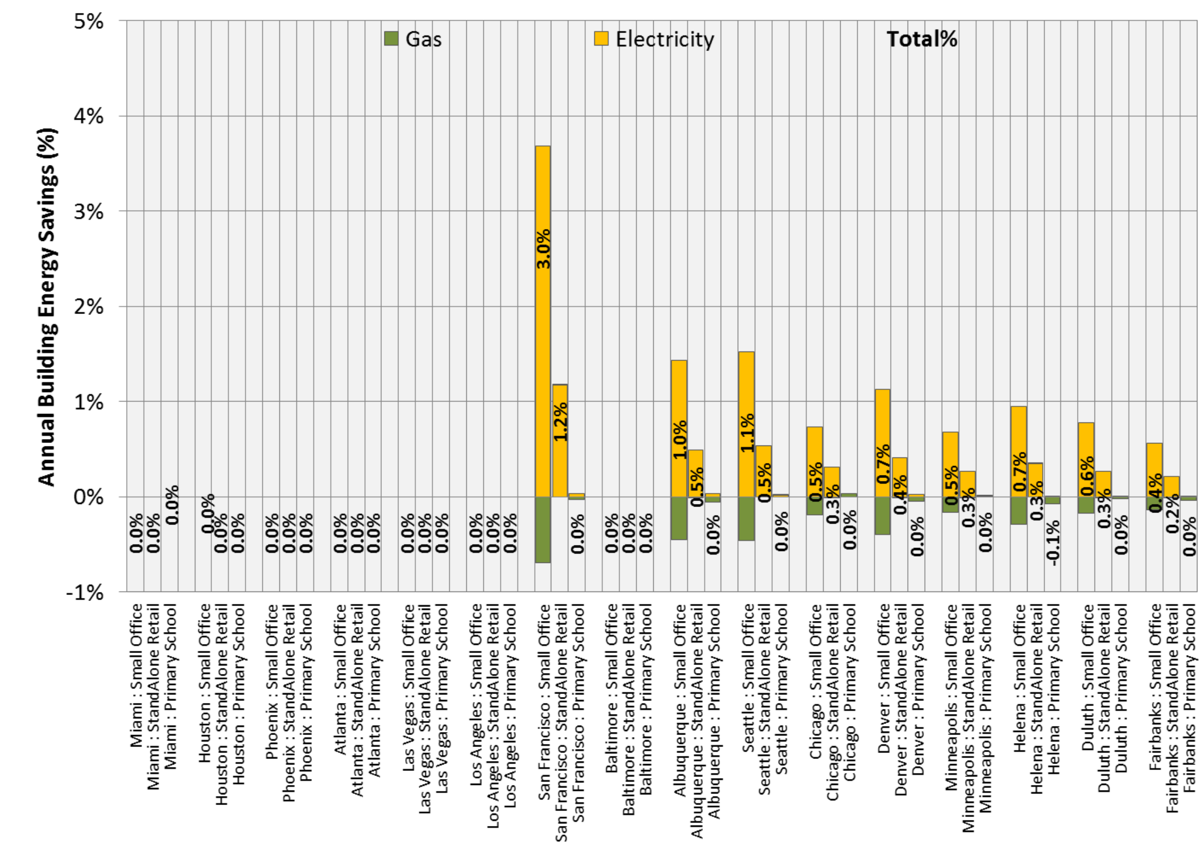

Figure A.1. Energy Savings: Measure 01 (Re-calibrate Faulty Sensors) for Small Office, StandAlone Retail, Primary School Prototypes

A.2 Measure 02: Fix Low Refrigerant Charge

Figure A.2 and Figure A.3 show the impact of correcting RTUs that are 20% undercharged with refrigerant. The impact is directly proportional to climate-driven cooling demands and benefits the hotter sites the most. The savings are also dependent on how much of the building is served by packaged systems subject to the application of this undercharge fault. Building types in Figure A.2 are fully served by these units and show savings of 1–5% in warm climates, whereas building types in Figure A.3 have only select zones served by packaged units, and the savings are a fraction of a percent at best.

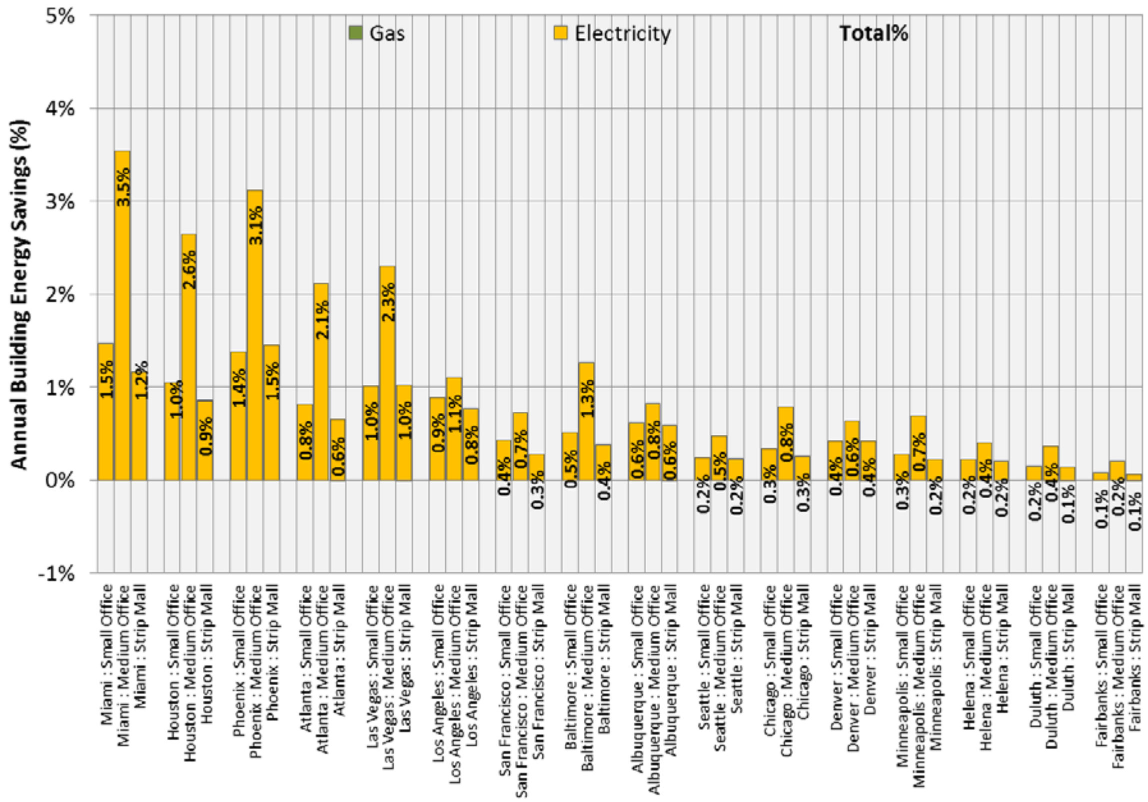

Figure A.2. Energy Savings: Measure 02 (Fix Low Refrigerant Charge) for Small Office, Medium Office, and Strip Mall Prototypes

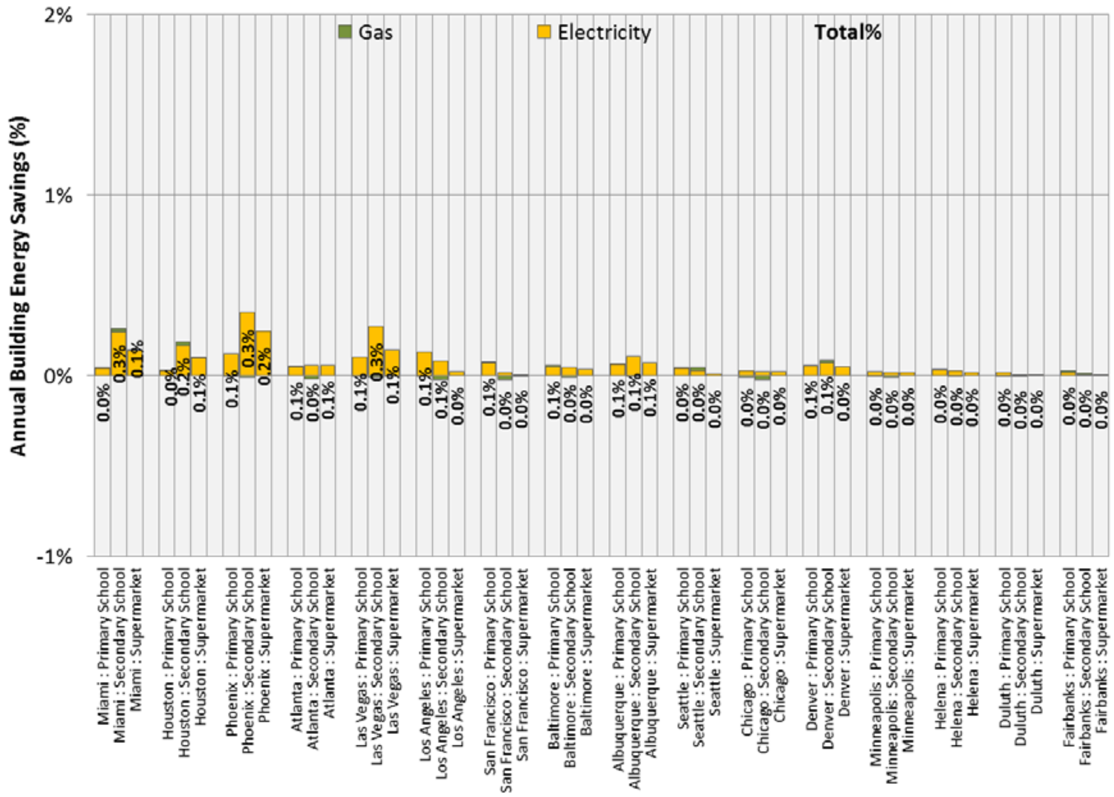

Figure A.3. Energy Savings: Measure 02 (Fix Low Refrigerant Charge) for Primary School, Secondary School, Supermarket

A.3 Measure 03: Fix Leaking Heating Coil Valves

This measure was simulated for the four prototypes with hot water coils in VAV systems. The savings varied considerably with both climate (better savings in cool or cold climates) and building type, with by far the strongest savings simulated for the Large Office prototype. This has to do with how often the heating coils in the VAV system are used. For building types with high occupancy and high outdoor airflow rates (the two school prototypes and the hotel), the heating coil in each VAV system is used very frequently to maintain the supply air temperature (SAT), and, as a result, a leaking coil has a much lower impact on energy consumption. However, for the Large Office with much lower effective minimum outdoor air fractions, the VAV heating coil stays off except for during extremely cold weather, and the impact of a continuously leaking heating coil is substantial. Figure A.4 shows savings for three of the four building prototypes for which this measure was applicable. Savings estimates are very sensitive to the actual prevalence and severity (positive or negative) of leaking heating coil valve faults. Although this fault was applied to all VAV AHU-section heating coils, which is not realistic, it was not applied to any VAV reheat coils (where many faults of this type also exist), so the savings estimate may actually be realistic.

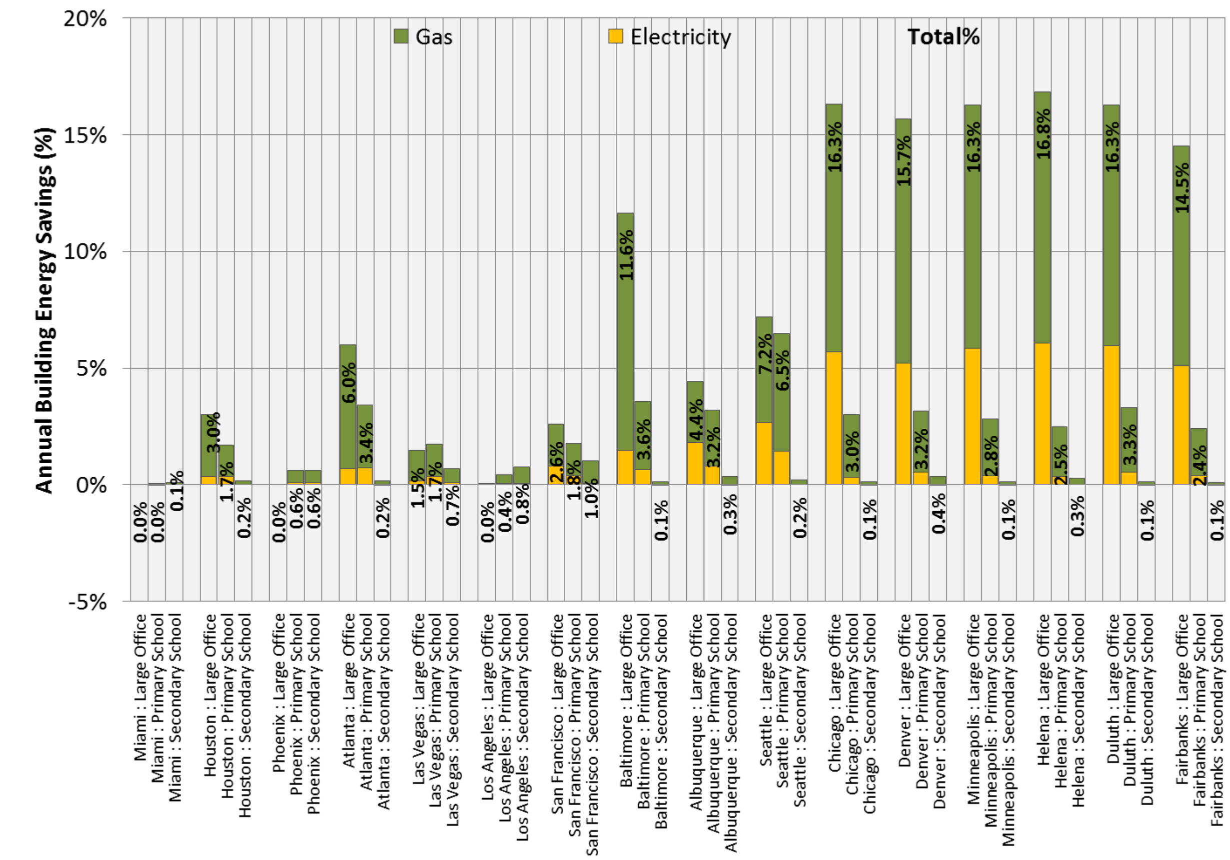

Figure A.4. Energy Savings: Measure 03 (Fix Leaking Heating Coil Valves) for Large Office, Primary School, and Large Hotel Prototypes

A.4 Measure 04: Shorten HVAC Schedules

Figure A.5, Figure A.6, and Figure A.7 show the impact of shortening HVAC schedules by four hours in the evening for all applicable prototypes. This reduces fan energy savings across the board, and has major impacts on cooling energy savings in warm climates and heating energy savings in cold climates. Savings generally range from 5–15%, and is not strongly dependent on climate. The weighted national site energy savings estimate among all building types and climates for this measure is 10.9% (4.28% from electricity and 6.57% from natural gas).

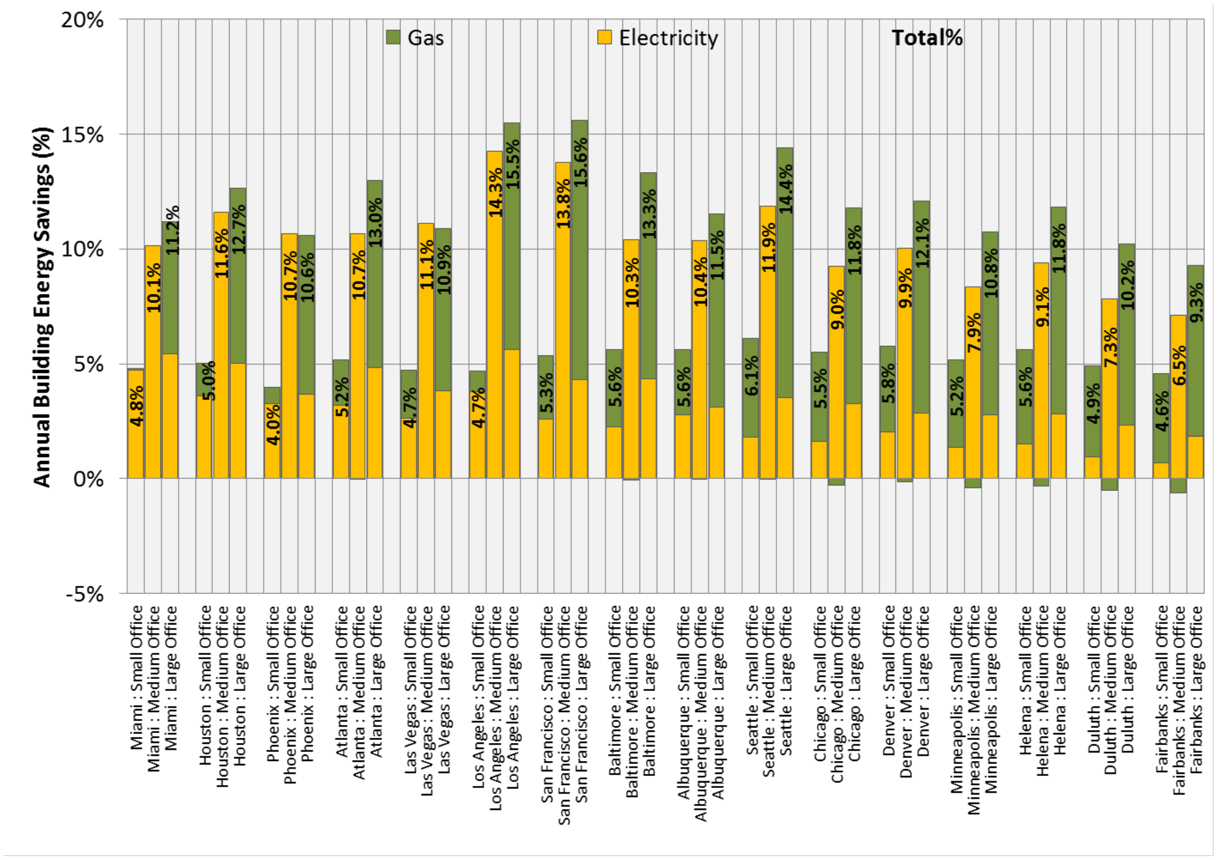

Figure A.5. Energy Savings: Measure 04 (A: Shorten HVAC Schedules)

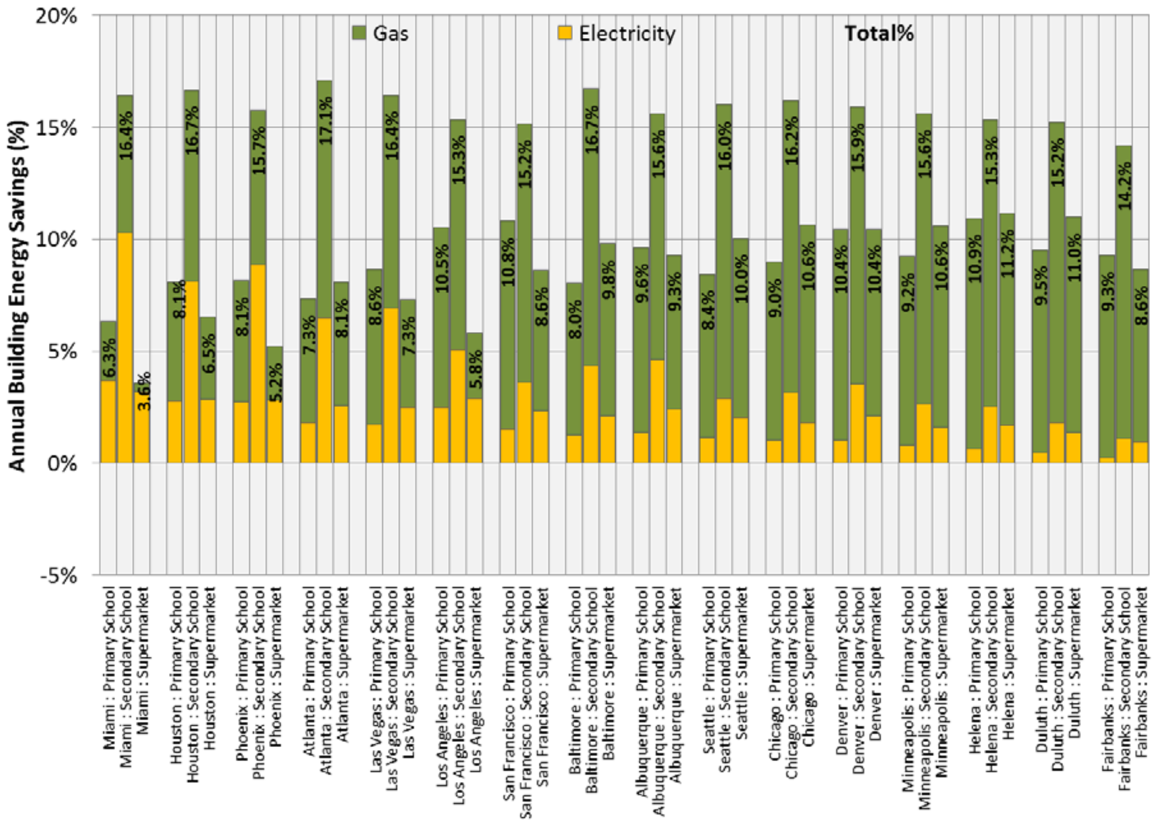

Figure A.6. Energy Savings: Measure 04 (B: Shorten HVAC Schedules)

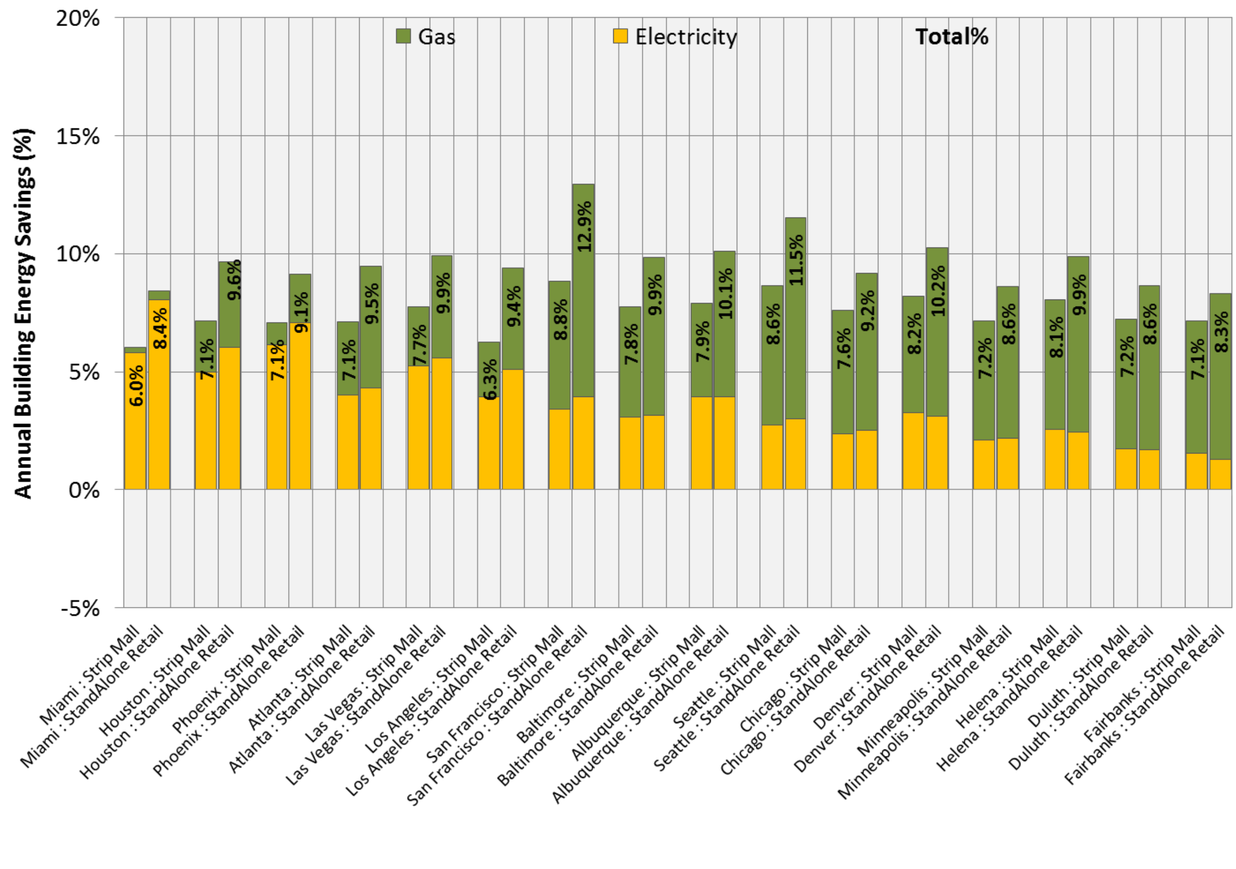

Figure A.7. Energy Savings: Measure 04 (C: Shorten HVAC Schedules)

A.5 Measure 05: Supply Air Temperature Reset

Figure A.8 shows the impact of an outdoor air temperature-based SAT reset and Figure A.9 shows the impact of a seasonal adjustment to the SAT setpoint. Both figures plot the same sample of three of the five building types affected by this measure. This measure achieves savings through the reduced use of heating in terminal box reheat coils. For buildings with economizers, the building can normally target the desired (warmer) SAT through modulation of the outdoor air damper; however, during very cold weather, warmer SATs may shift some of the heating to the AHU heating coil, which is the reason for gas increases in cold climates for the Medium Office prototype. Energy savings are strongest in mild climates with frequent cool weather. For most cities, the energy savings from a seasonal reset is very close in magnitude to savings from the outdoor air temperature-based reset; however, the seasonal reset strategy is expected to create more thermal discomfort during any periods of warm weather in the winter months. The weighted national site energy savings estimate among all building types and climates for the outdoor air temperature-based SAT reset is 4.4% (1.60% from electricity and 2.83% from natural gas).

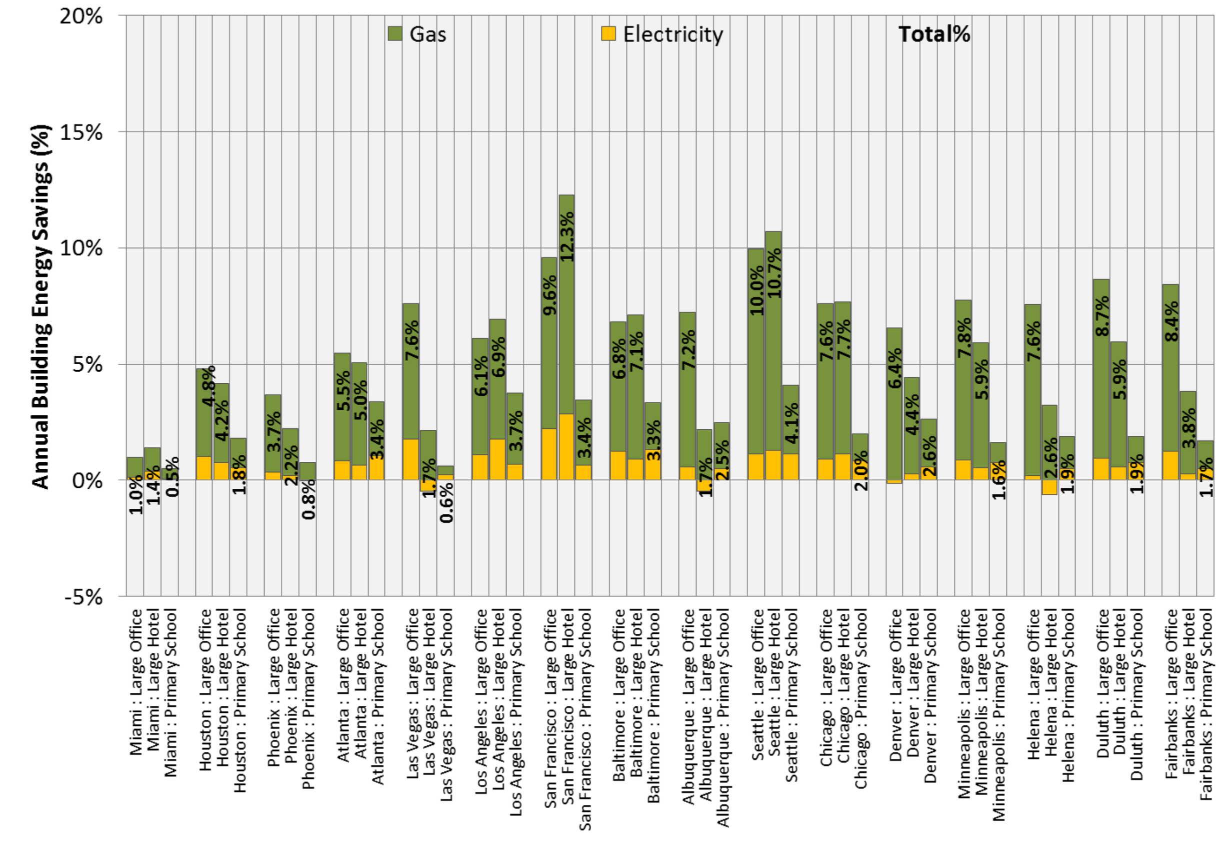

Figure A.8. Energy Savings: Measure 05 (Supply Air Temperature Reset): Outdoor Air Reset for Large Office, Large Hotel, and Primary School Prototypes

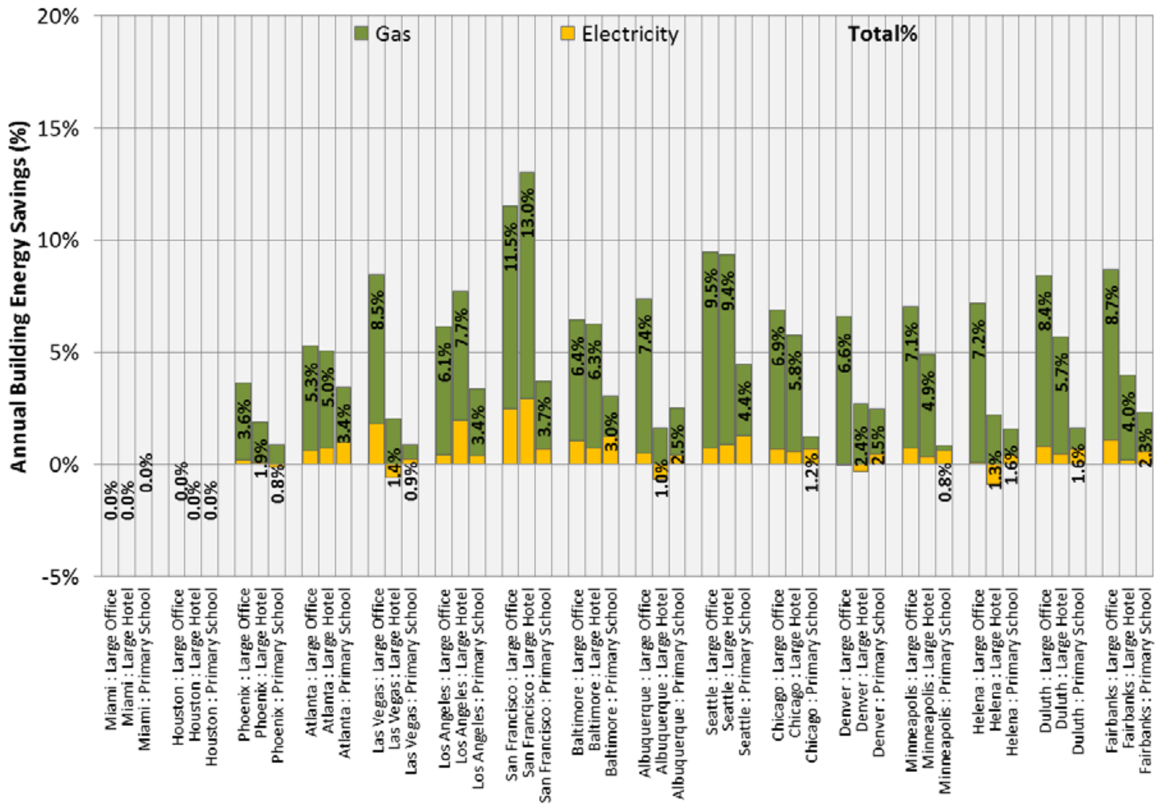

Figure A.9. Energy Savings: Measure 05 (Supply Air Temperature Reset): Seasonal Reset for Large Office, Large Hotel, and Primary School Prototypes

A.6 Measure 06: Outdoor Air Damper Faults and Control

Figure A.10 shows the impact of fixing damper seals and using zero minimum outdoor airflow during unoccupied periods in the three office prototypes, while Figure A.11 shows the savings for the two retail prototypes, and Figure A.12 shows the savings for the two school prototypes. The widely divergent savings can be addressed with the following explanations. Buildings with single-zone air distribution units (Small Office, Strip Mall, and StandAlone Retail) appear to reap significant gas savings, especially in cold climates. For VAV-centric buildings with low ventilation requirements (Medium and Large Office), there are minimal savings from this measure because achieving SAT setpoints of 55°F usually requires moderate amounts of outdoor air, and little is gained from allowing the dampers to close completely or to schedule zero minimum outdoor airflow. Some increase in electricity savings is also a possibility in mild climates, especially if economizing strategies are imperfect. Combining this measure with SAT reset is expected to improve this measure's performance in VAV-centric buildings. For buildings with very high ventilation rates and VAV systems (the two school prototypes), the baseline fault that limits the maximum outdoor airflow fraction to 70% limits ventilation rates in some areas of the building to below the design outdoor airflow rates. Correcting this fault leads to energy increases as a result of the increased maximum outdoor airflow rates that come from fixing damper seals. Although this leads to an increase in overall energy consumption, it is the right thing to do for occupant health and comfort. Because of the negative savings in these two prototypes, the weighted national site energy savings estimate among all building types and climates for this measure is -0.66% (-0.14% from electricity and -0.52% from natural gas).

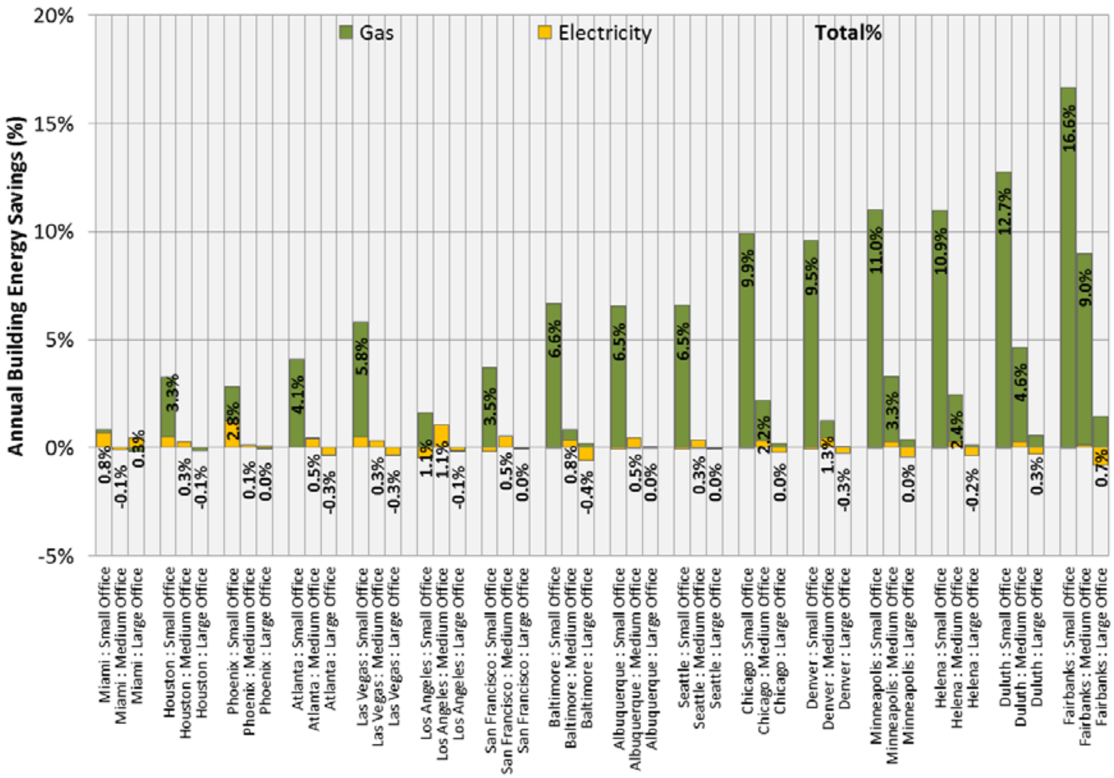

Figure A.10. Energy Savings: Measure 06 (Outdoor air Damper Faults and Control): Small, Medium, and Large Office Prototypes

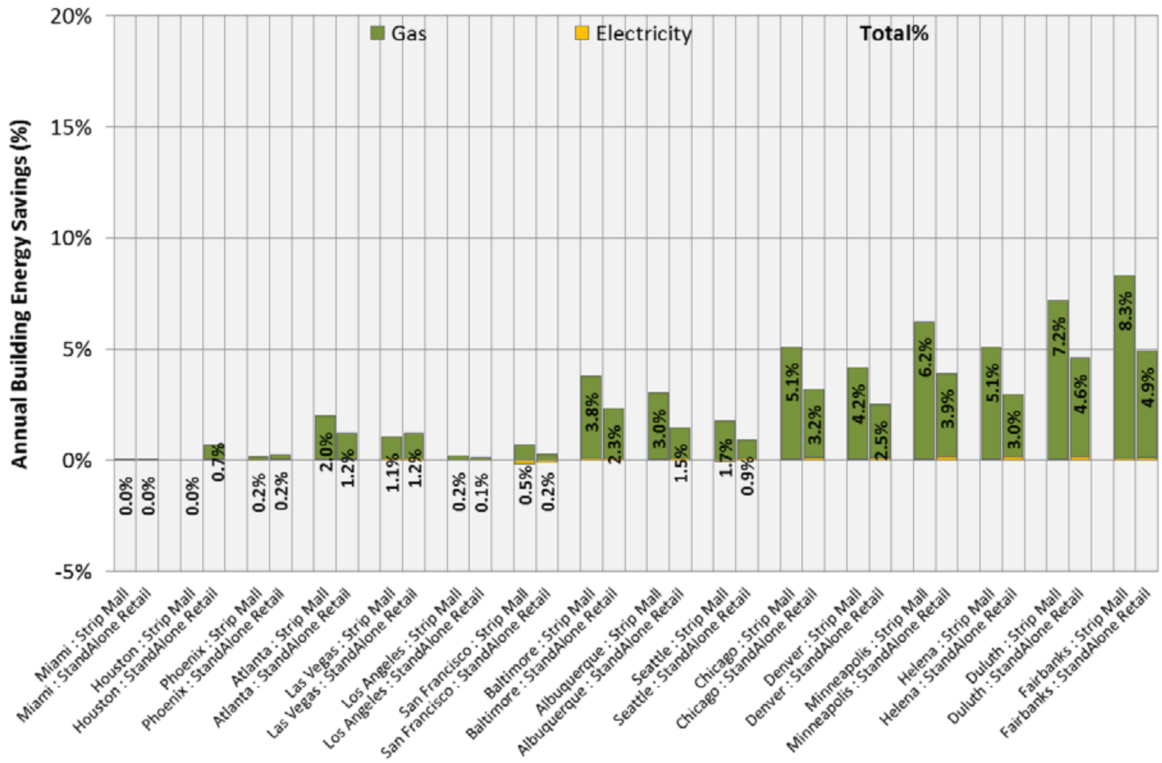

Figure A.11. Energy Savings: Measure 06 (Outdoor air Damper Faults and Control): Strip Mall and StandAlone Retail Prototypes

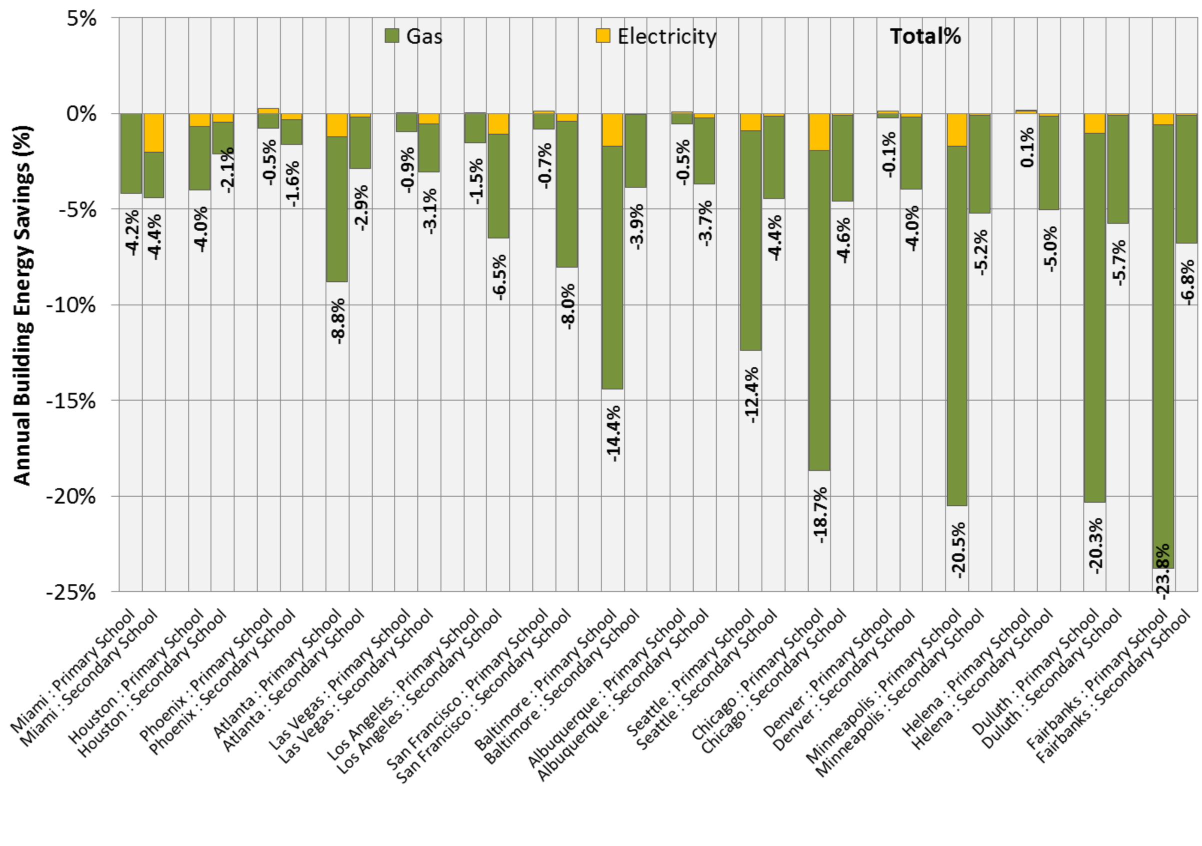

Figure A.12. Energy Savings: Measure 06 (Outdoor air Damper Faults and Control): Primary and Secondary School Prototypes

A.7 Measure 07: Exhaust Fan Control

Figure A.13 and Figure A.14 show the impact of shutting off bathroom exhaust fans at night in all six applicable prototypes. Although the fan electricity savings are very modest, the impact on heating savings through reduced induction of infiltration air at night is significant. Overall savings increase in colder climates. The weighted national site energy savings estimate among all building types and climates for this measure is 0.91% (0.29% from electricity and 0.62% from natural gas).

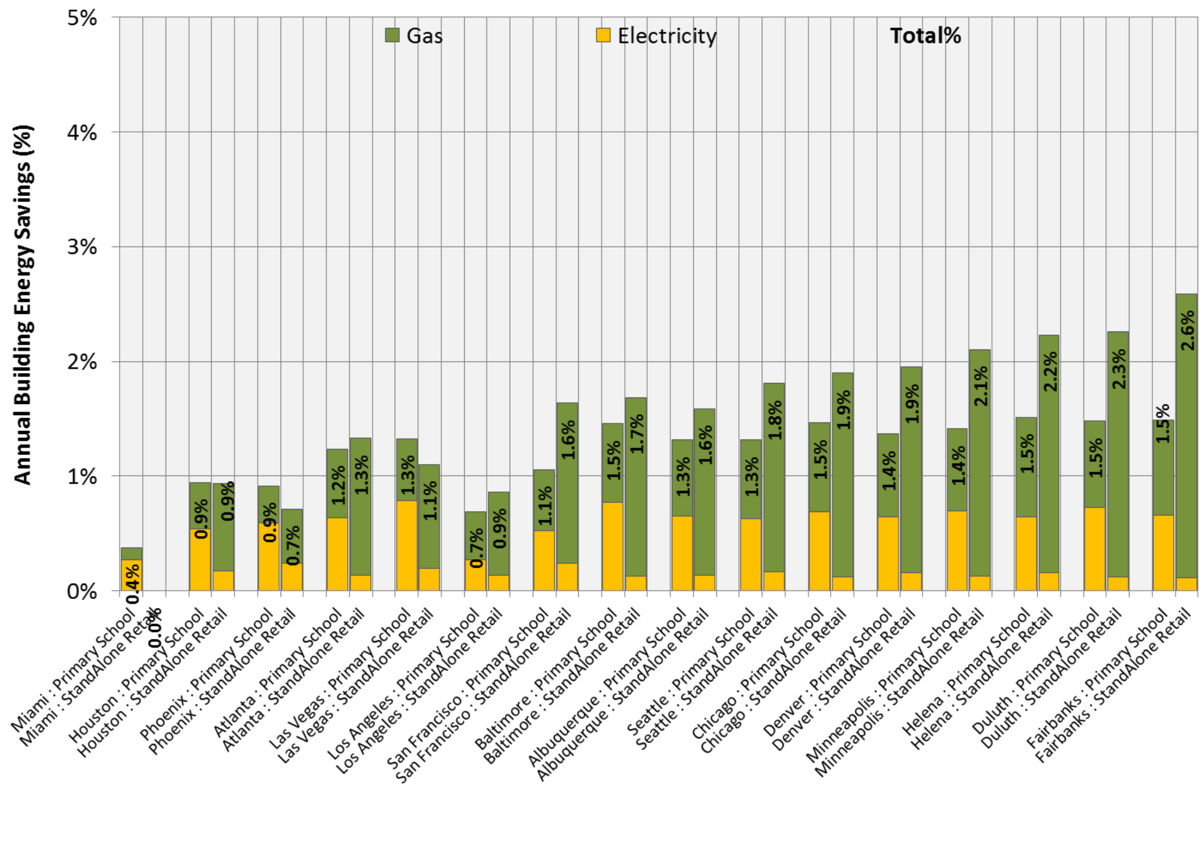

Figure A.13. Energy Savings: Measure 07 (Exhaust Fan Control) for Primary School, Secondary School, StandAlone Retail Prototypes

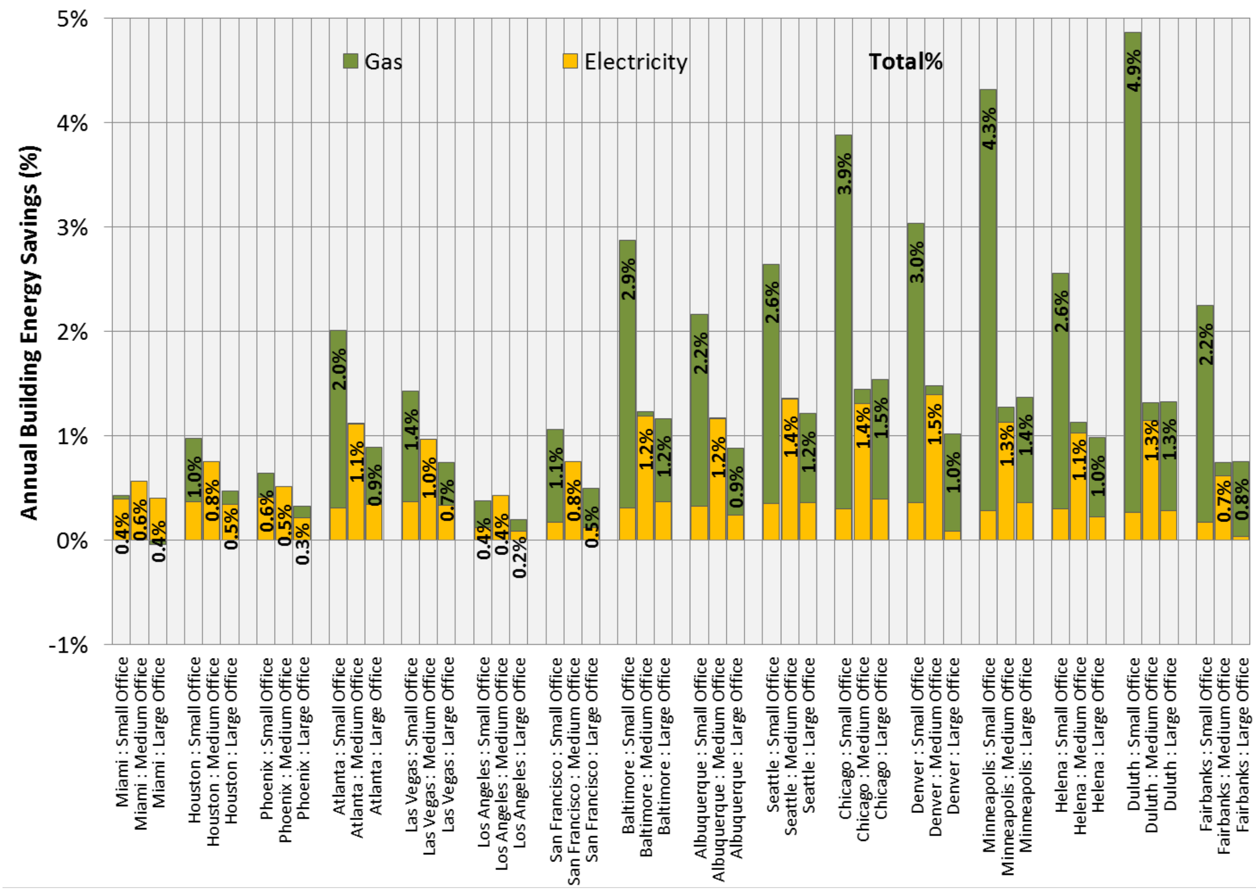

Figure A.14. Energy Savings: Measure 07 (Exhaust Fan Control) for the Three Office Prototypes

A.8 Measure 08: Static Pressure Reset

Figure A.15 and Figure A.16 show the impact of static pressure reset reductions based on VAV damper positions in all five applicable prototype buildings and Figure A.17 shows the impact of static pressure reset based on the time of day for the two office prototypes that can use this measure. Savings are relatively consistent across the board by climate and tend to be about twice as high for the VAV damper approach compared to the simpler time-of-day approach. Savings is smallest for the two school prototypes because high ventilation requirements tend to drive the VAV boxes toward being fully open most of the time and because there is a bigger increase for those building types in heating (natural gas) to compensate for reduced fan heat gains in the supply air stream.

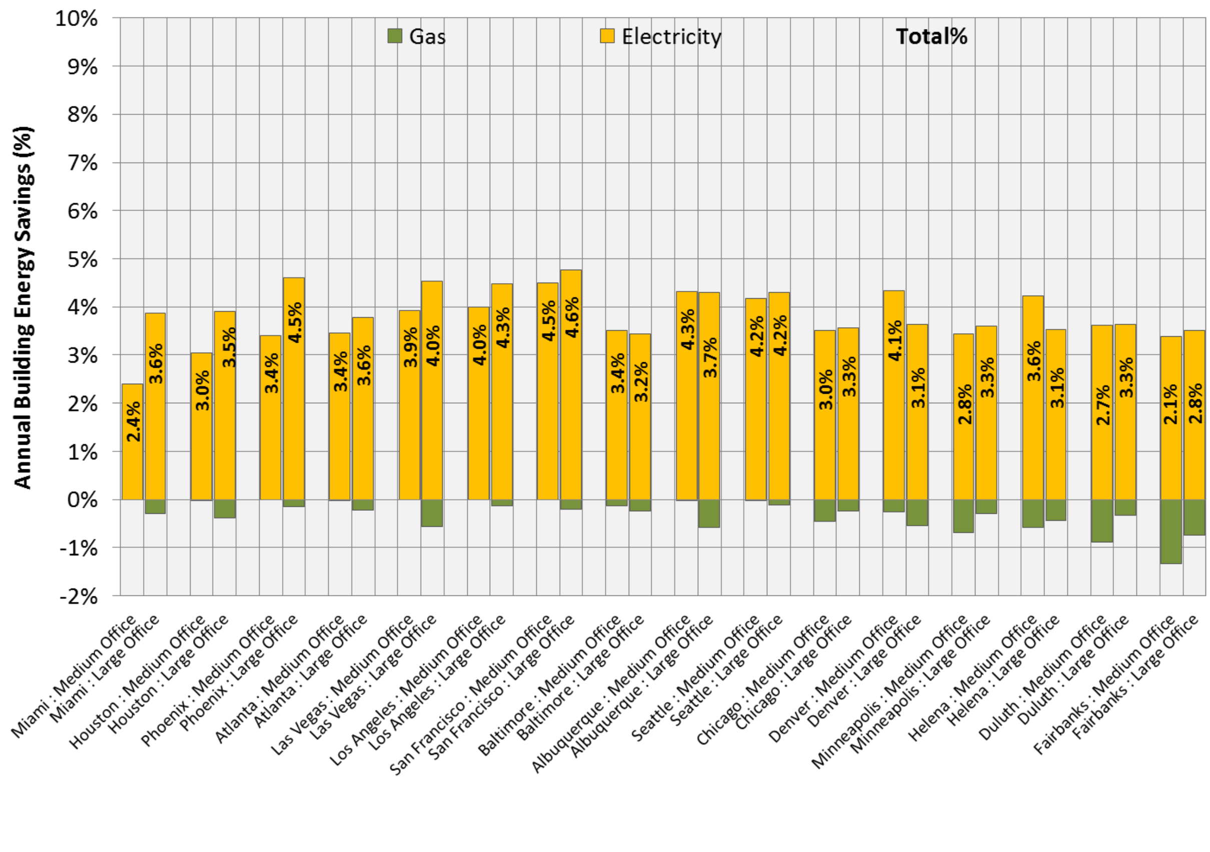

Figure A.15. Energy Savings: Measure 08 (Static Pressure Reset): VAV Damper Position Approach in Office Prototypes

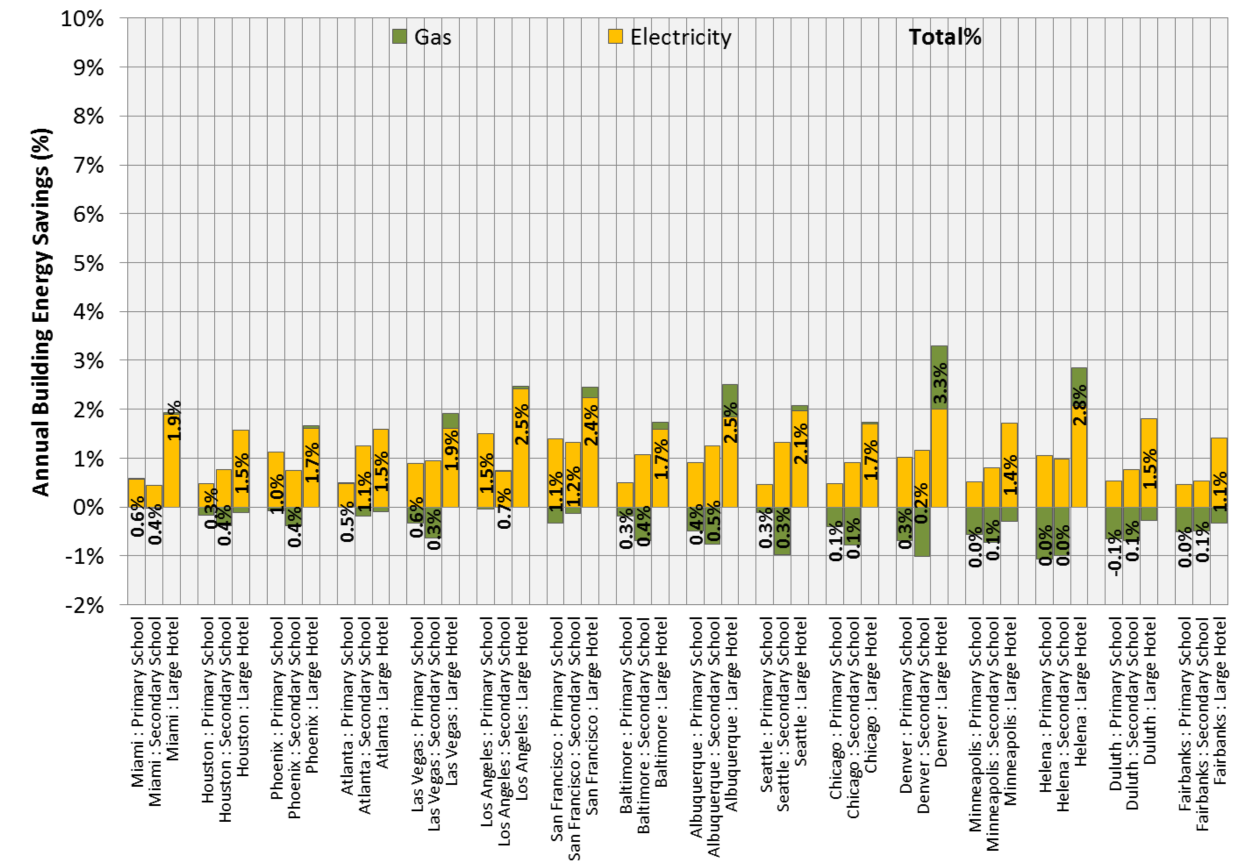

Figure A.16. Energy Savings: Measure 08 (Static Pressure Reset): VAV Damper Position Approach in School and Large Hotel Prototypes

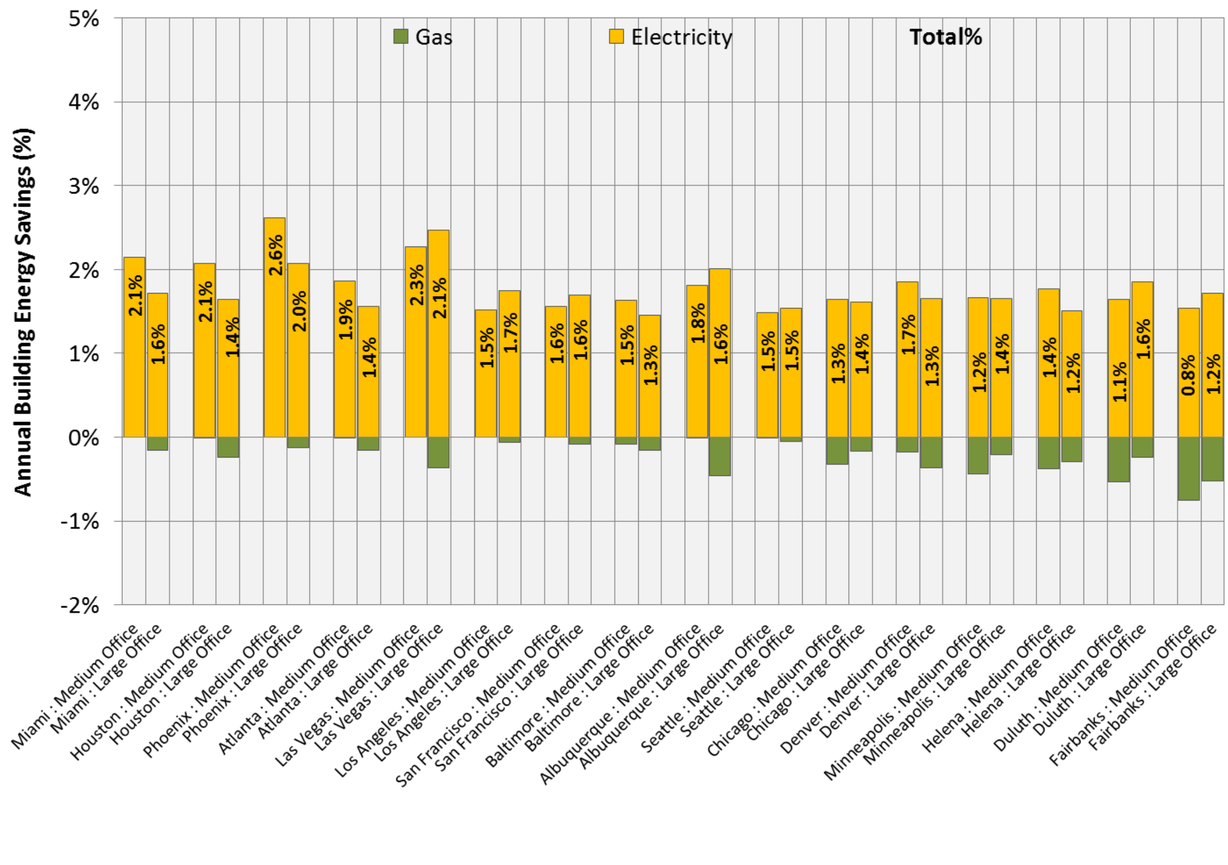

Figure A.17. Energy Savings: Measure 08 (Static Pressure Reset): Time-of-Day Approach in Medium and Large Office Buildings

A.9 Measure 9: Plant Shutdown When There Is No Load

Figure A.18 shows the energy savings from turning off secondary hot water pumps when there is no demand for hot water and shutting off secondary pumps when there is no demand for chilled water in the building. This measure could only be simulated for the Large Office prototype because of challenges in making the pumps operate according to the intent of this measure in the baseline model for other building types. The savings in the Large Office prototype is less than 1%, both from electricity to run the pumps and savings on natural gas from reduced circulation and standby losses (from hot water piping) of heat.

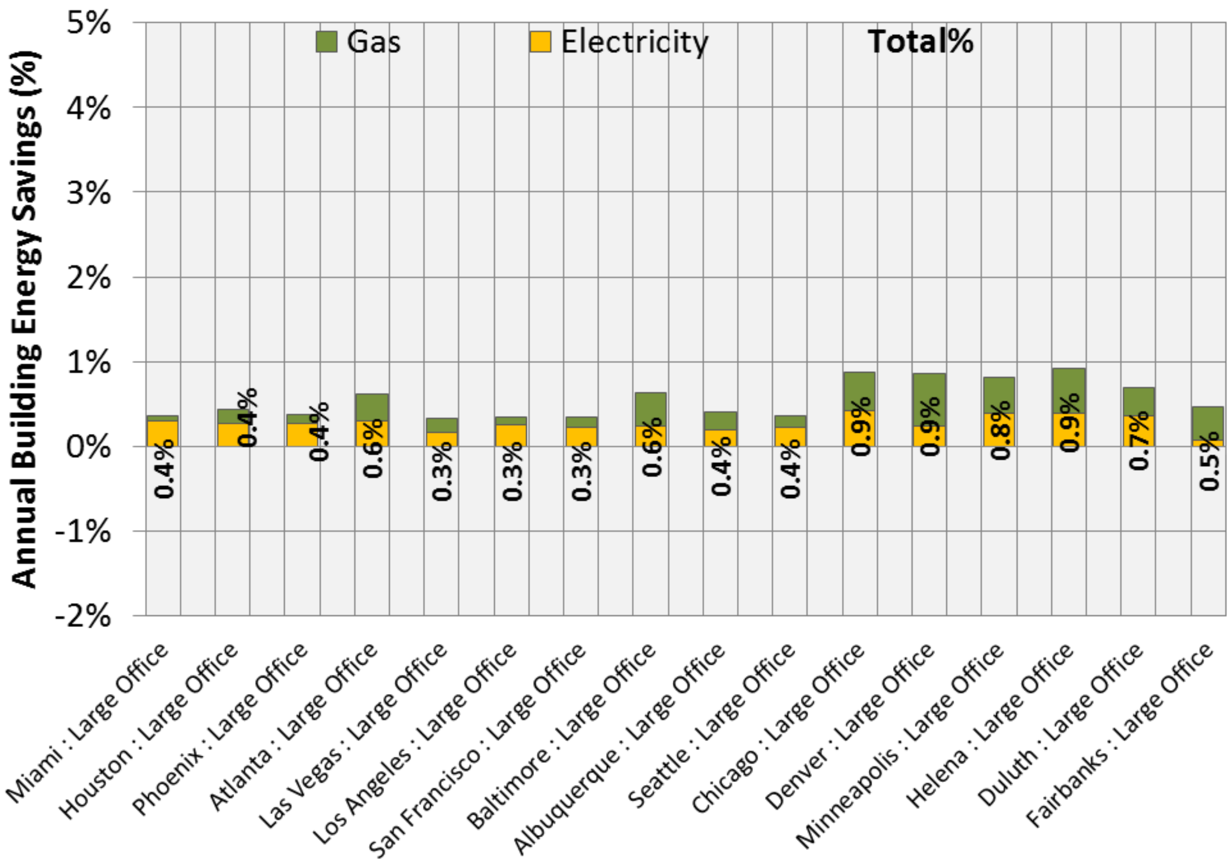

Figure A.18. Large Office Energy Savings: Measure 10 (Plant Shutdown When There Is No Load)

A.10 Measure 10: Chilled Water Differential Pressure Reset

Figure A.19 shows the savings from chilled water differential pressure reset in the three building types that have variable-speed chilled water pumping to the building (Large Office, Large Hotel, and Secondary School). The savings is relatively small (up to 0.3% of building energy consumption).

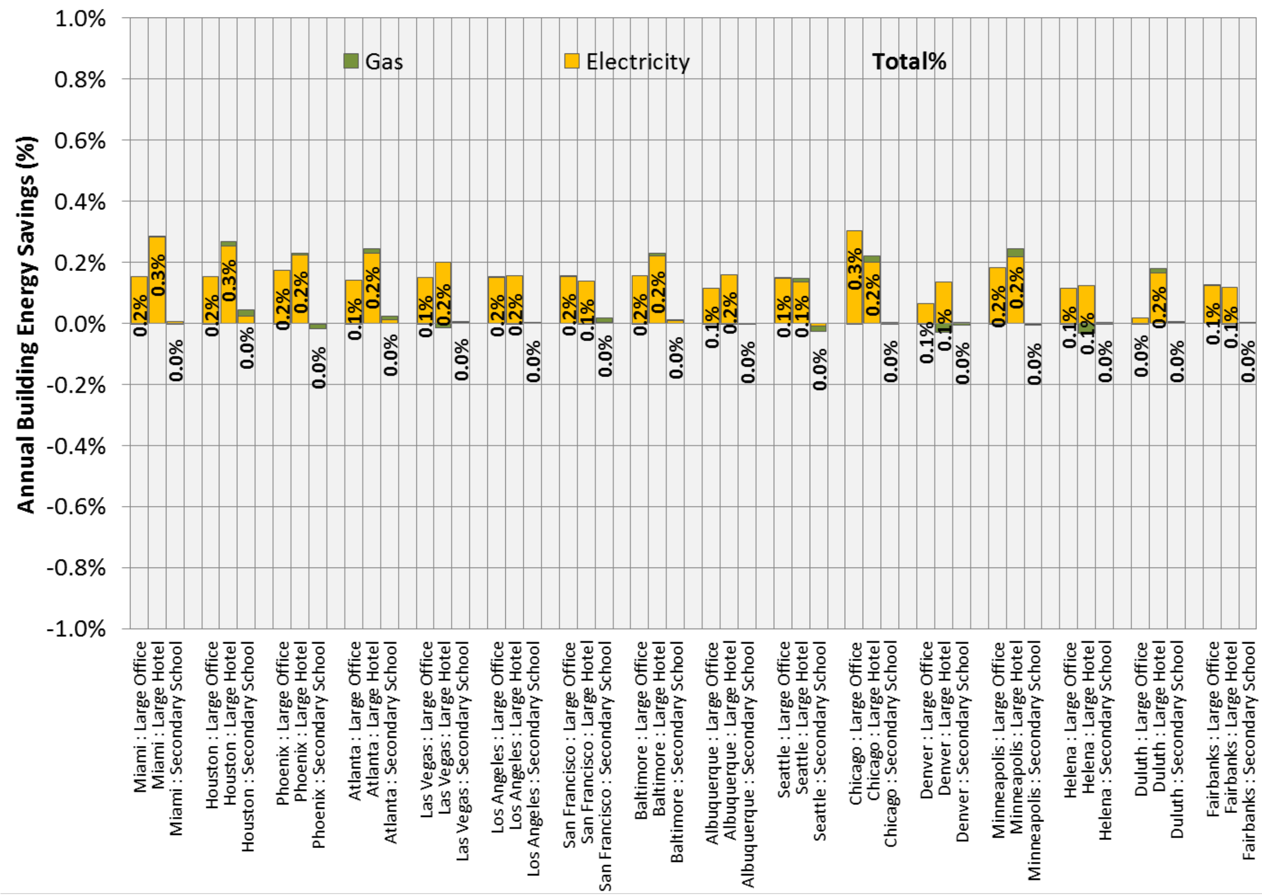

Figure A.19. Large Office Energy Savings: Measure 11 (Chilled Water Differential Pressure Reset)

A.11 Measure 11: Chilled Water Temperature Reset

Energy savings results for chilled water temperature reset (based on outdoor air temperature) are shown in Figure A.20 for all three applicable prototypes. The savings appear to be inconsistent and, at first glance, a bit perplexing because natural-gas savings are shown to be outstripping electricity savings for this measure. This result is an artifact of EnergyPlus's methodology for modeling AHUs. With an increase in chilled water temperature, EnergyPlus calculates that the chilled water coil is delivering less cooling to the air stream, and the fan compensates to meet the cooling load by increasing the fan flow rate and, therefore, fan power. So, the impact on total electricity ends up being more or less a wash because cooling energy savings are counteracted by fan power increases. The fan power increases lead to more waste heat in the air stream, which negates some of the need for heating, resulting in apparent natural-gas savings. In real buildings this would not happen. As the chilled water temperature increases, this would indeed reduce the cooling delivered by the cooling coil, but the control loop on the chilled water coil valve would respond by opening up to provide increased chilled water flow, quickly providing the same amount of cooling but without the need to increase the airflow (which would only happen if the zones served by the AHU began to get warmer, leading to increased airflow setpoints). Therefore, the results for chilled water temperature reset using EnergyPlus cannot be considered strictly accurate, especially in the breakdown of electricity versus natural-gas savings (the gas should be unaffected unless chilled water coil valves are often open near 100%, which is rare).

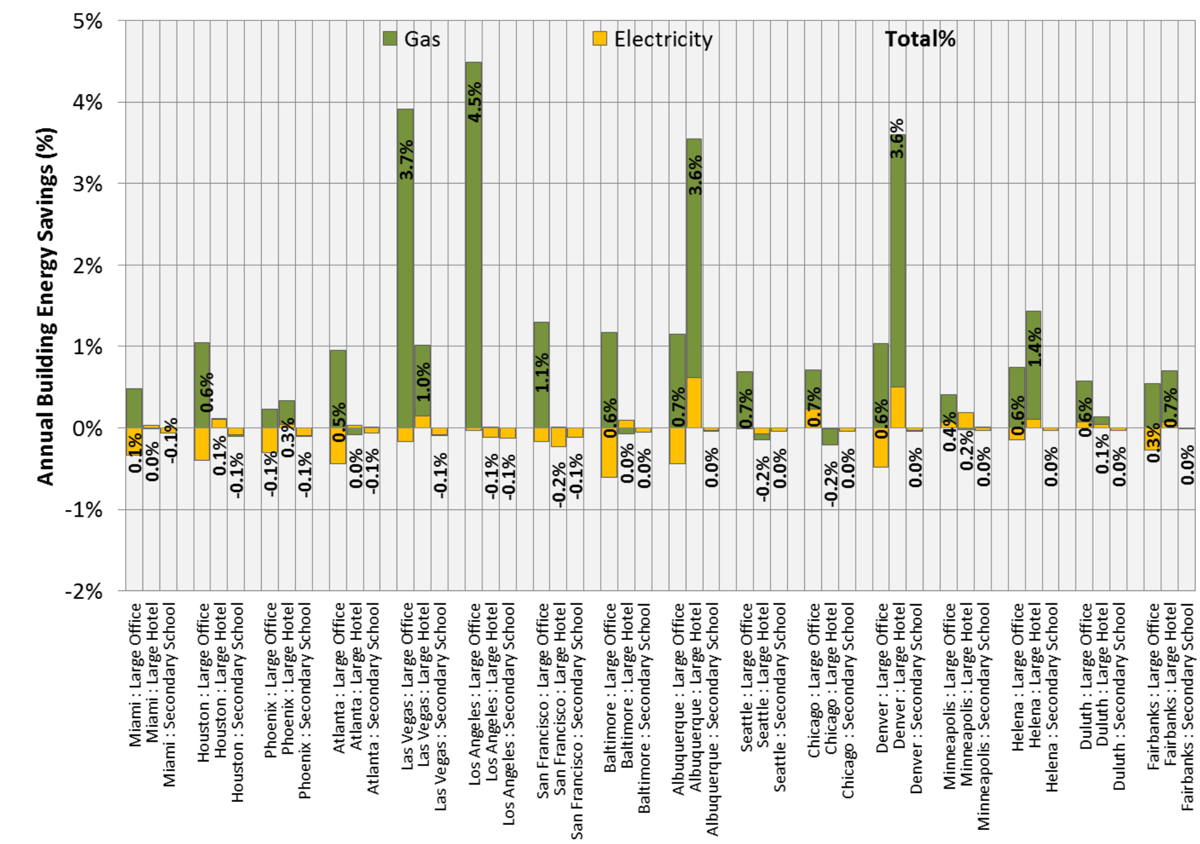

Figure A.20. Energy Savings: Measure 11 (Chilled Water Temperature Reset Based on Outdoor Air Temperature): Large Office, Large Hotel, and Secondary School Prototypes

A.12 Measure 12: Condenser Water Temperature Reset

Figure A.21 shows the savings from condenser water temperature reset in the only prototype model with water-cooled chillers (Large Office). The savings is strongest in warm (but not hot) climates, and can produce up to 0.6% building energy savings, all in electricity.

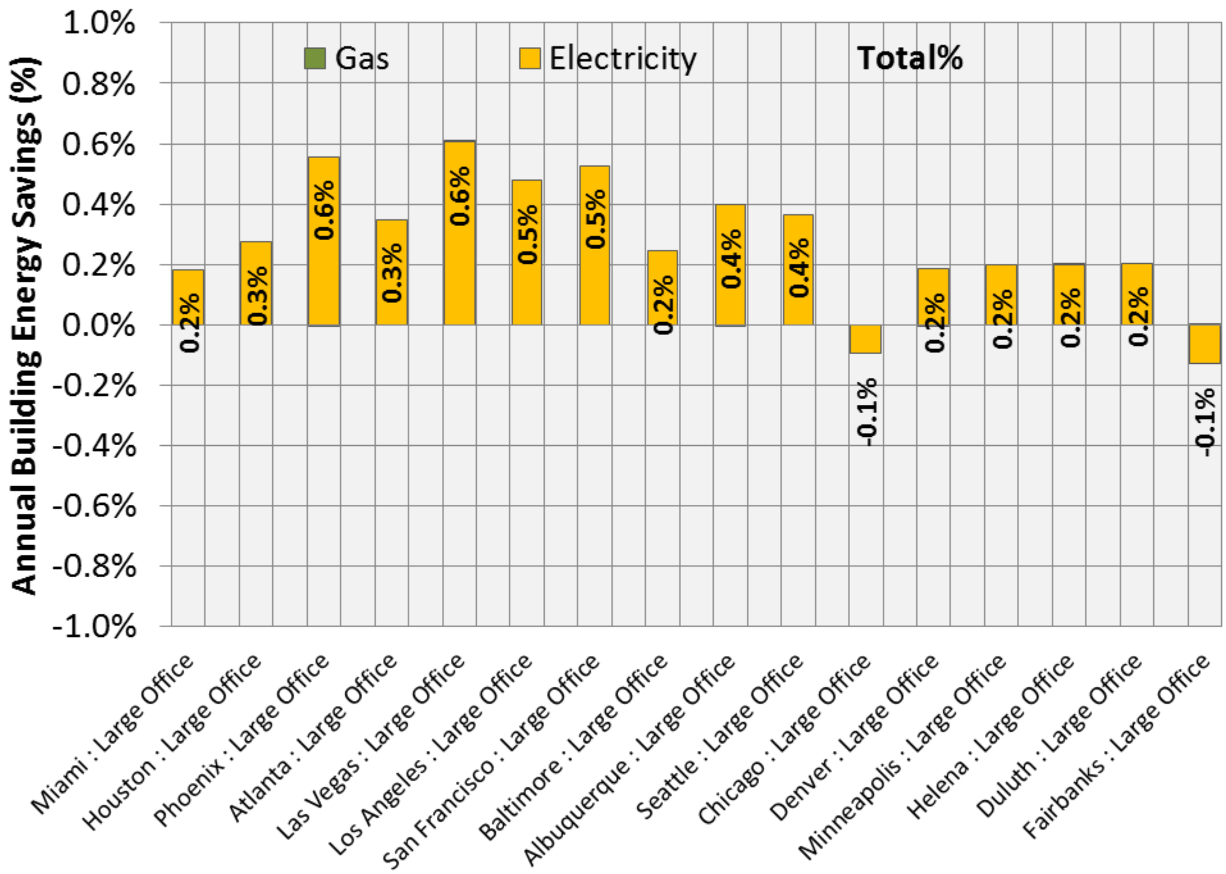

Figure A.21. Large Office Energy Savings: Measure 12 (Condenser Water Temperature Reset)

A.13 Measure 13: Hot Water Differential Pressure Reset

Figure A.22 shows the savings from hot water temperature reset in three of the four prototype buildings that have variable-speed building hot water pumps. In every case, the savings show the same pattern—very minor electricity savings and minor increases in natural gas consumption. Gas consumption increases because the saved pumping power is otherwise dissipated as heat in the hot water loop, so more gas heating is needed to get the loop up to the temperature setpoint. Electricity savings is very minor because hot water pumps are much smaller in size than chilled water pumps and the savings is proportionally less.

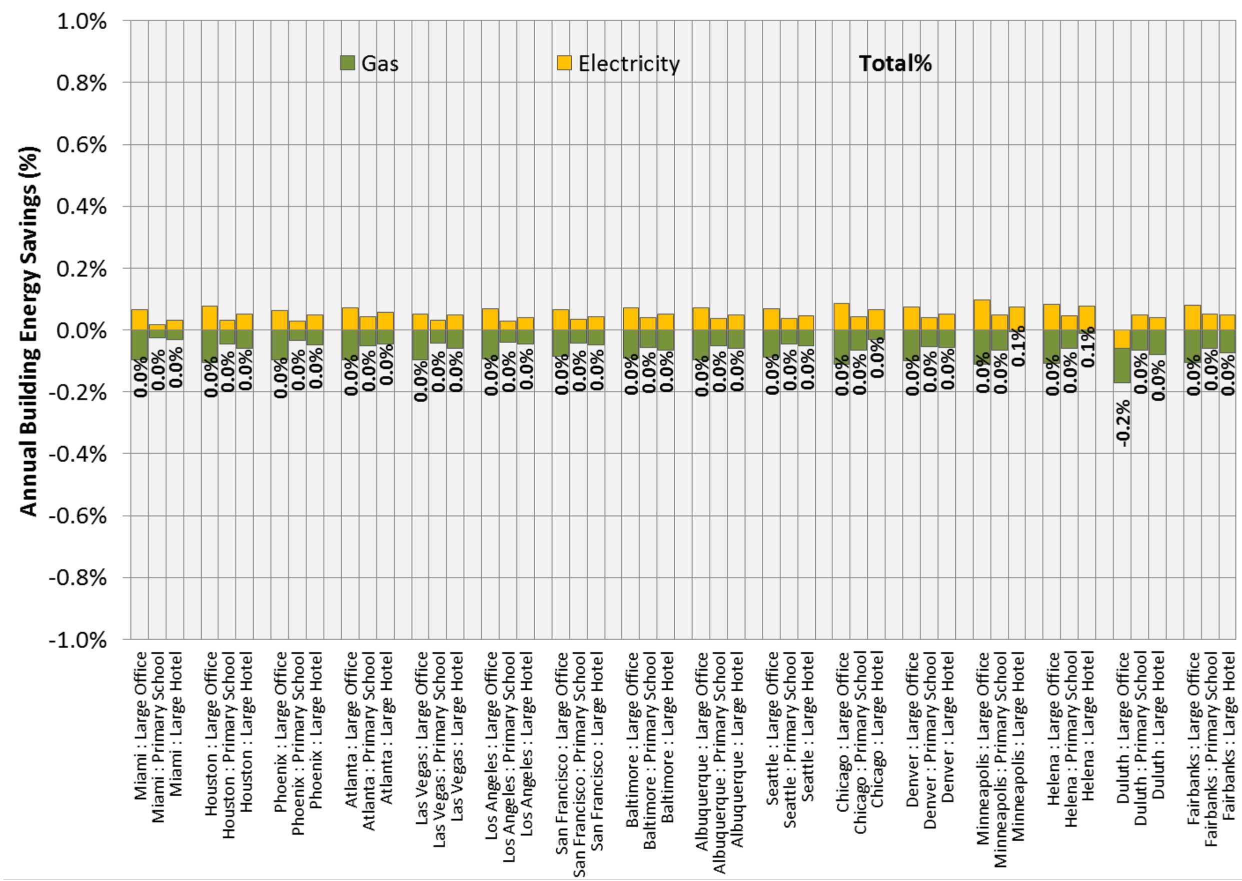

Figure A.22. Energy Savings: Measure 13 (Hot Water Differential Pressure Reset): Large Office, Primary School, and Large Hotel Prototypes

A.14 Measure 14: Hot Water Temperature Reset

Figure A.23 shows the savings from hot water temperature reset in three of the four prototype buildings with hot water loops (Large Office, Primary School, and Large Hotel). Modeled savings in all three cases is based on reduced standby losses in building hot water piping. Buildings with condensing boilers would reap significant additional gas savings from this measure. This measure is best suited for IECC Climate Zones 2 through 5. The savings was modeled as lower for the Large Office prototype because the hot water piping was specified as being located in unconditioned plenum zones, whereas the other prototypes were either single-story (schools) or did not have plenum spaces between floors (hotel). In the latter cases, when the hot water piping gives off heat to conditioned zones, the savings from hot water temperature reset can be as high as 3–5% of building energy consumption, mostly in natural gas, but this measure can also reduce the need for cooling to compensate for heat loss.

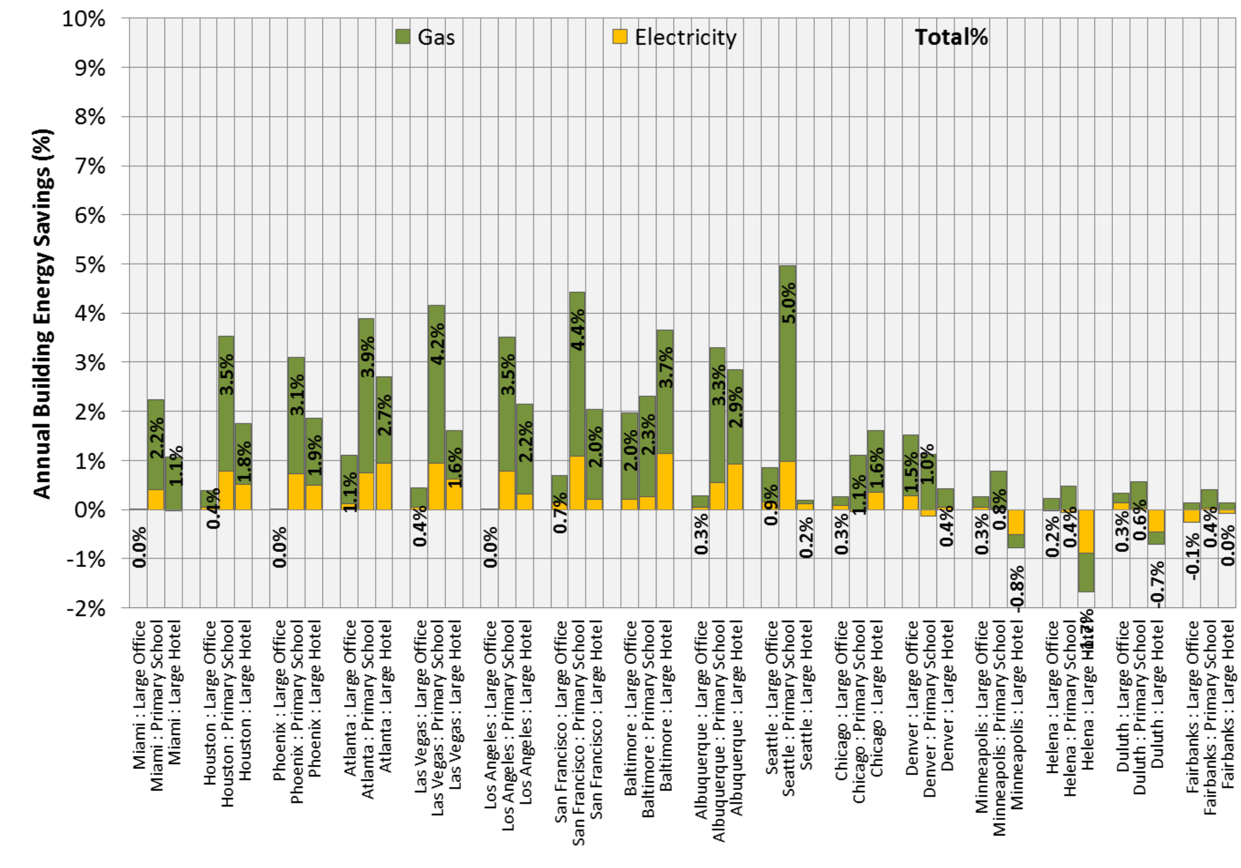

Figure A.23. Energy Savings: Measure 14 (Hot Water Temperature Reset): Large Office, Primary School, and Large Hotel Prototypes

A.15 Measure 15: Minimum VAV Terminal Box Damper Flow Reductions

Figure A.24 (Medium and Large Office) and Figure A.25 (Primary School, Secondary School, and Large Hotel) show the impact of reducing the minimum VAV terminal damper flow fraction from 40% to 25%. This has very large impacts on heating consumption because high minimum airflow setpoints, especially when combined with cool supply air temperatures, can induce a false heating load in the zones through delivery of too high of a volume of relatively cool air. This can force the reheat coils to come on, even in the summer, when there is no environmentally driven load. For most climates in the Medium Office, Large Office, and Large Hotel prototypes, the savings are between 15 and 20%, making this measure the most impactful measure for those prototypes. For the two school buildings, the high ventilation loads mean that many of the terminal boxes have to stay opened beyond 40% to maintain ventilation requirements, and the savings from this measure is less in those buildings, but is still substantial (generally 2–8% site energy savings).

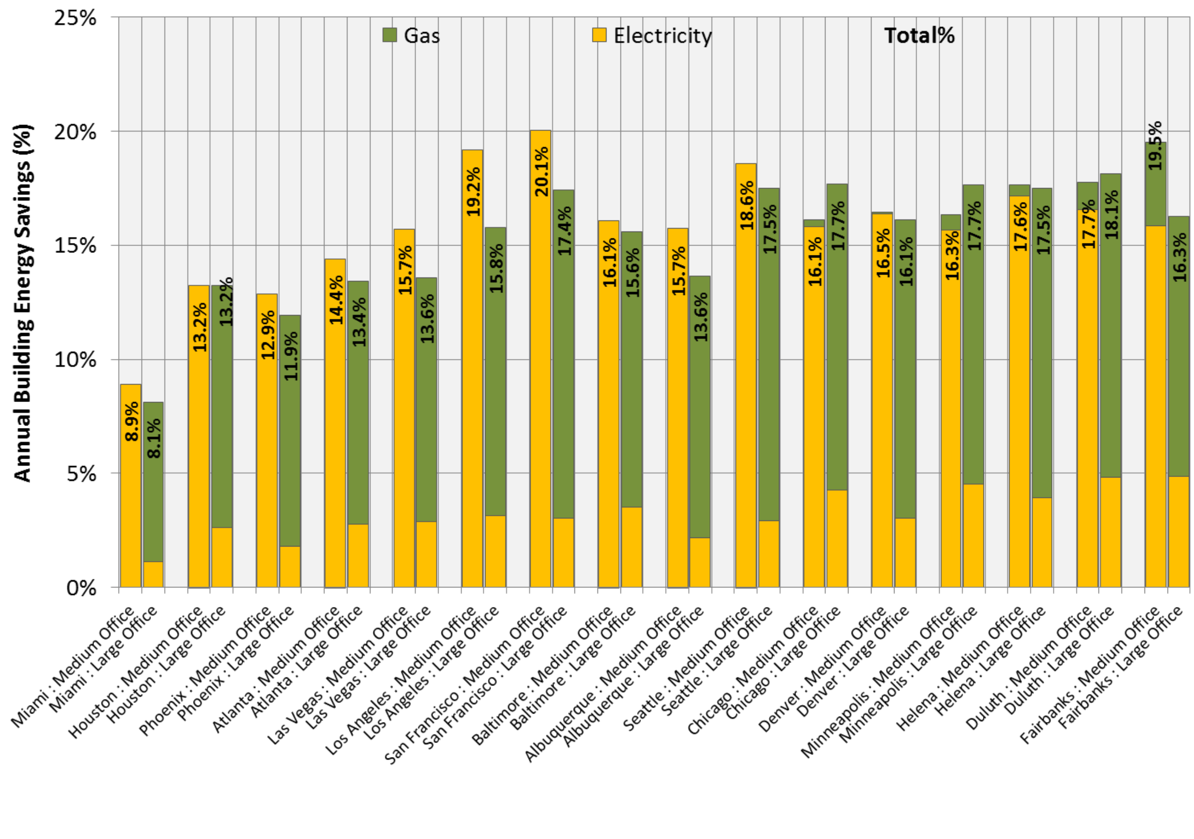

Figure A.24. Energy Savings: Measure 15 (Minimum VAV Terminal Box Damper Flow Reductions): Medium and Large Office Prototypes

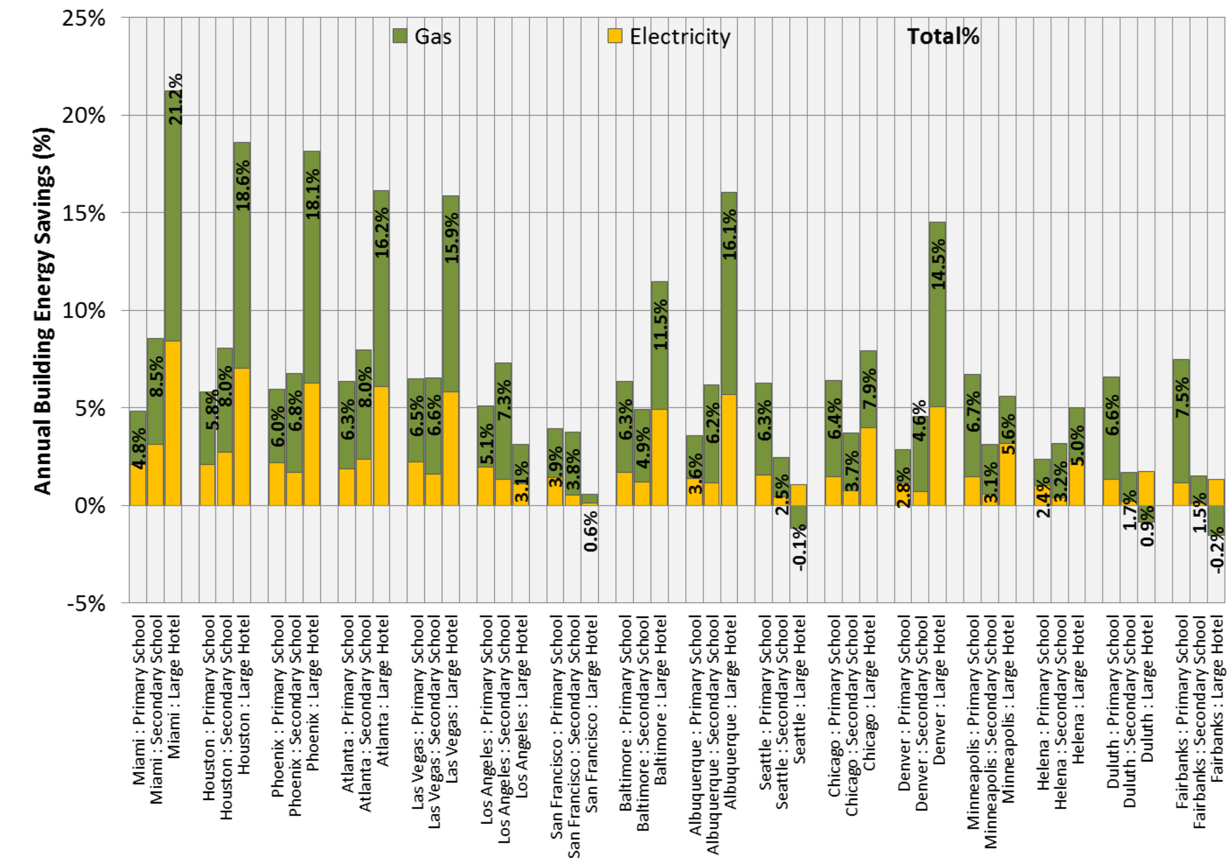

Figure A.25. Energy Savings: Measure 15 (Minimum VAV Terminal Box Damper Flow Reductions): Primary School, Secondary School, and Large Hotel Prototypes

A.16 Measure 16: Wider Deadbands and Night Setback

Figure A.26, Figure A.27, and Figure A.28 show the impact of increasing thermostat deadbands from +/- 1°F to +/-3°F and lowering the night setback temperature from 65°F to 60°F on all building prototypes. For most prototypes in most climates, the savings range from 5–15%. The high savings, combined with the broad applicability of this measure, make it the most impactful Re-tuning measure overall, but widening deadbands during occupied hours can have noticeable impacts on occupant comfort.

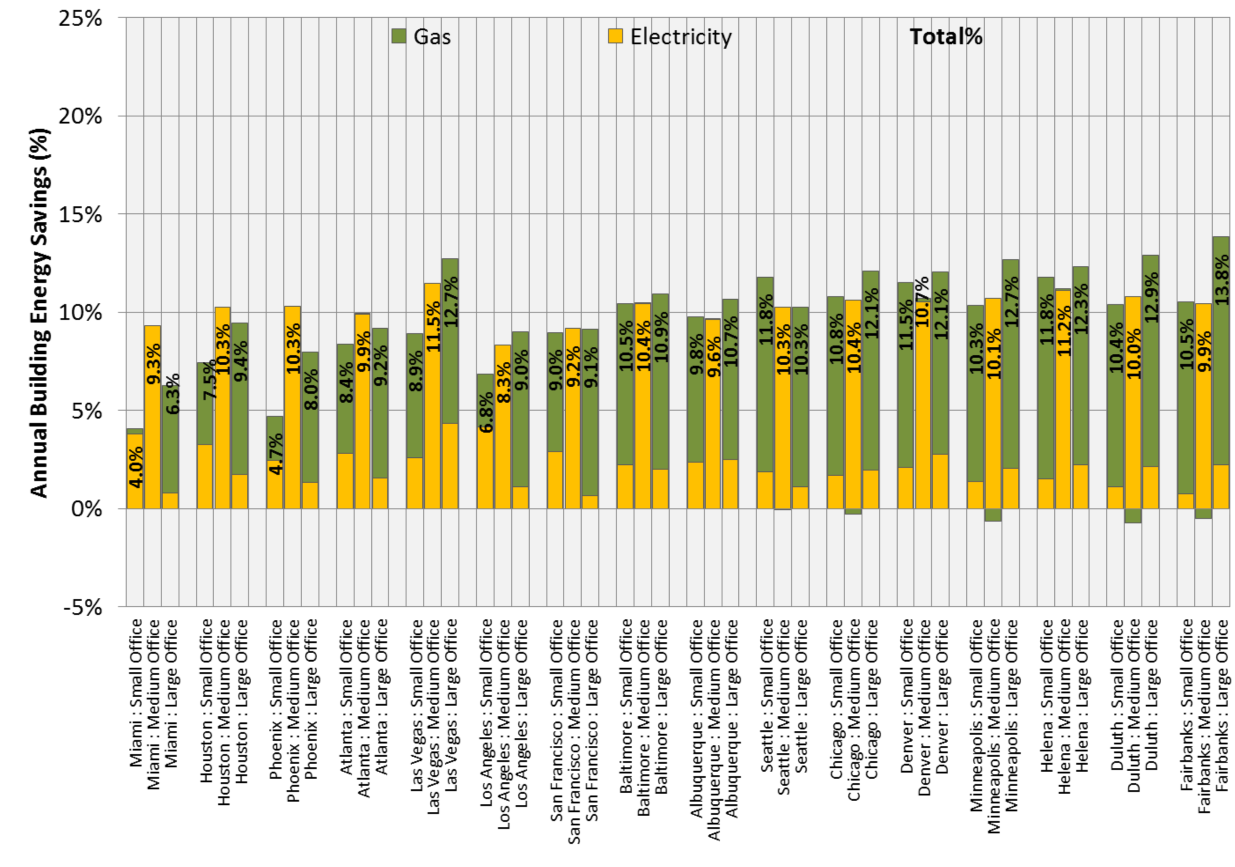

Figure A.26. Energy Savings: Measure 16 (Wider Deadbands and Night Setback): Office Prototypes

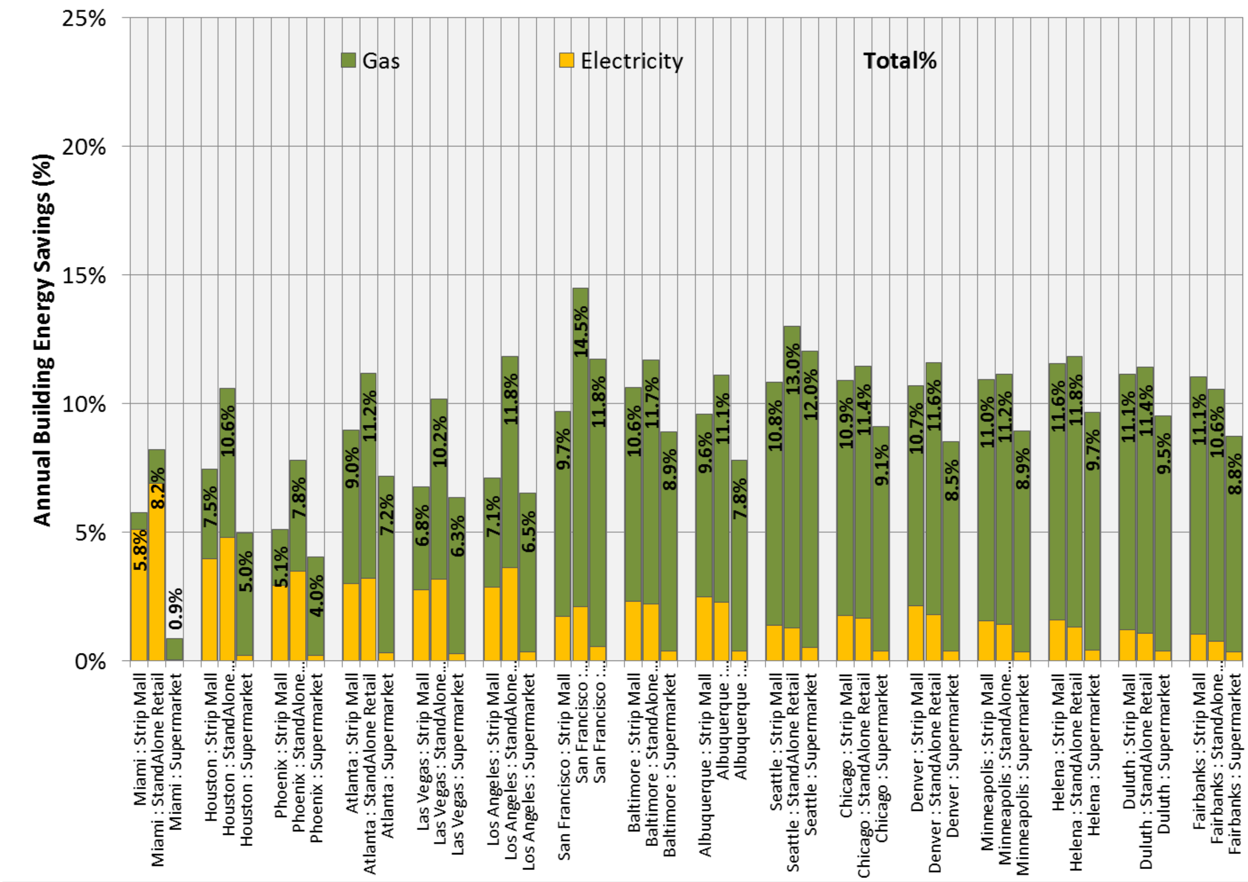

Figure A.27. Energy Savings: Measure 16 (Wider Deadbands and Night Setback): Strip Mall, StandAlone Retail, and Supermarket Prototypes

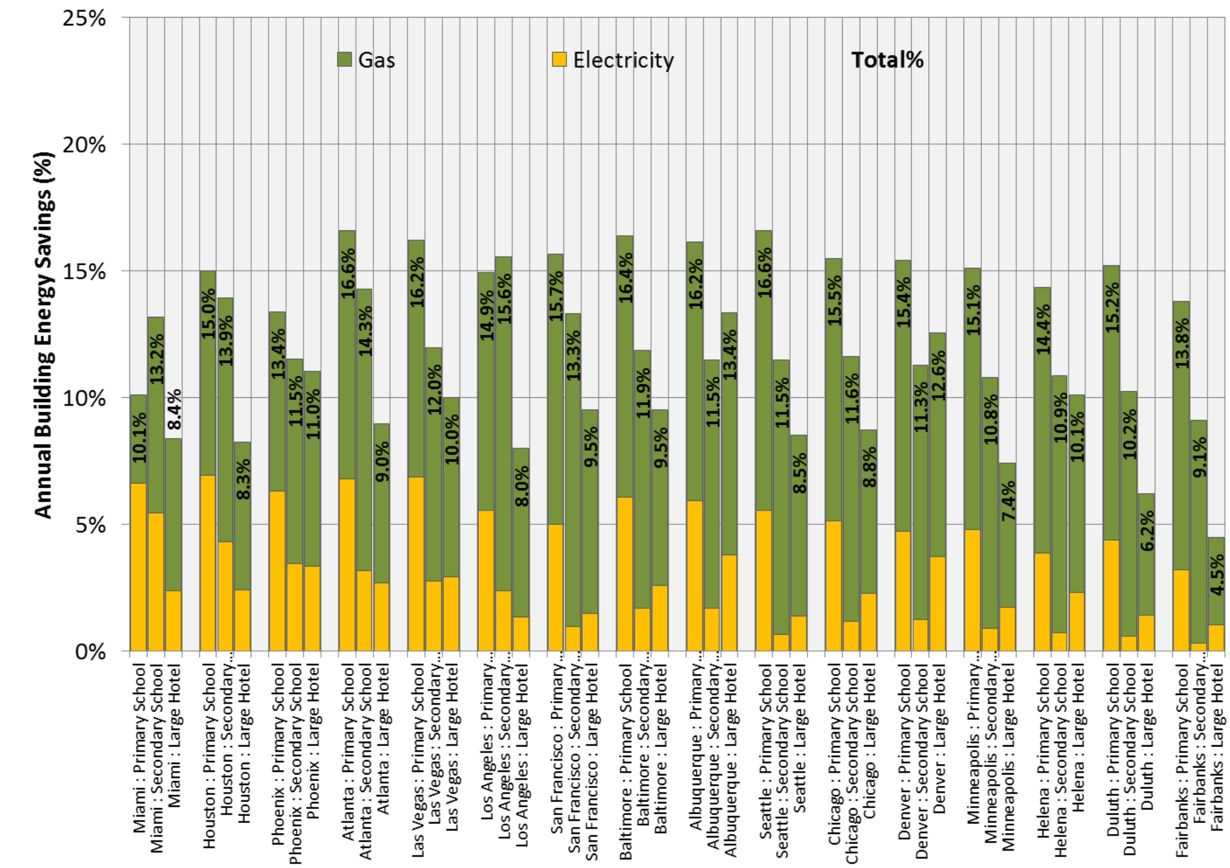

Figure A.28. Energy Savings: Measure 16 (Wider Deadbands and Night Setback): Primary and Secondary School and Large Hotel Prototypes

A.17 Measure 17: Demand Control Ventilation

Figure A.29, Figure A.30, and Figure A.31 show the impact of the use of demand control ventilation strategies on all applicable prototypes (excluding Large Hotel, for which this measure could not be simulated properly due to modeling issues). In prototypes that have very high occupancy rates at certain times, demand control ventilation can have an enormous savings impact (over 40% building energy savings in extreme cases). In buildings that have more constant and lower occupancy rates and no zone-by-zone CO_2 sensing and control (e.g., Medium and Large Office), the savings is much lower.

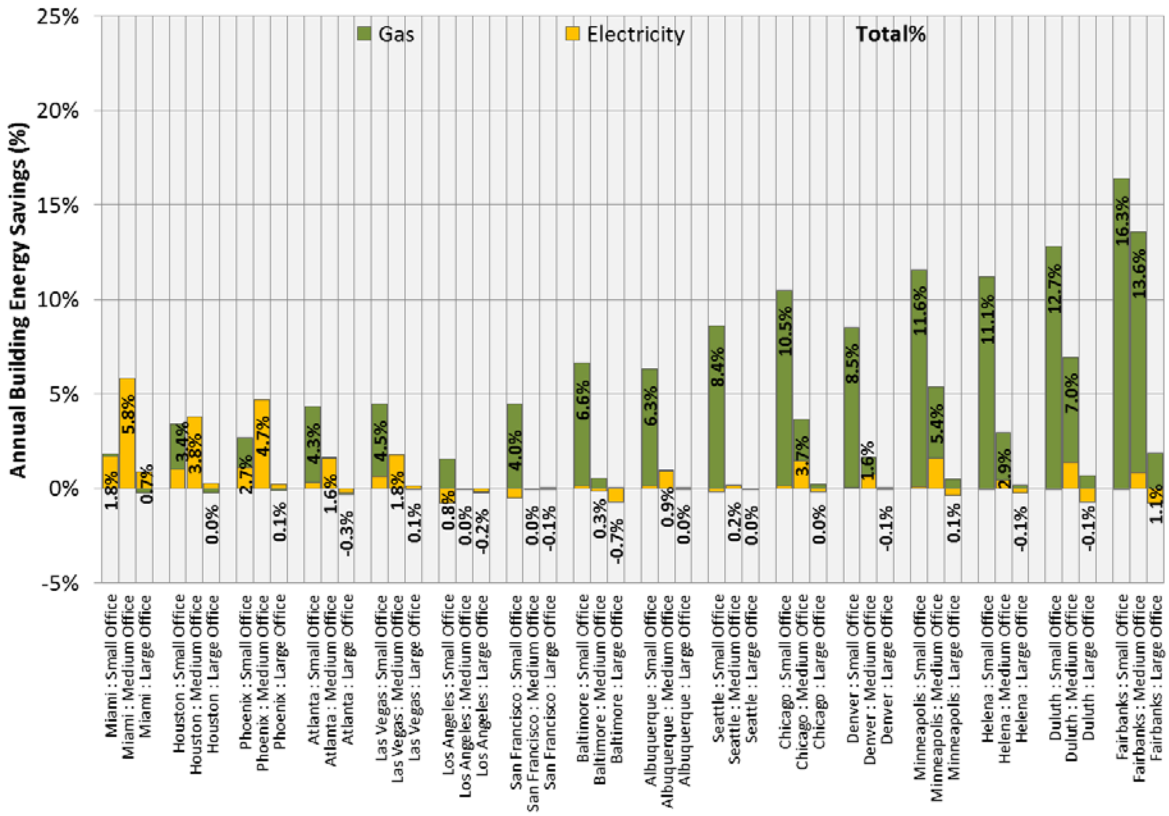

Figure A.29. Energy Savings: Measure 17 (Demand Control Ventilation): Office Prototypes

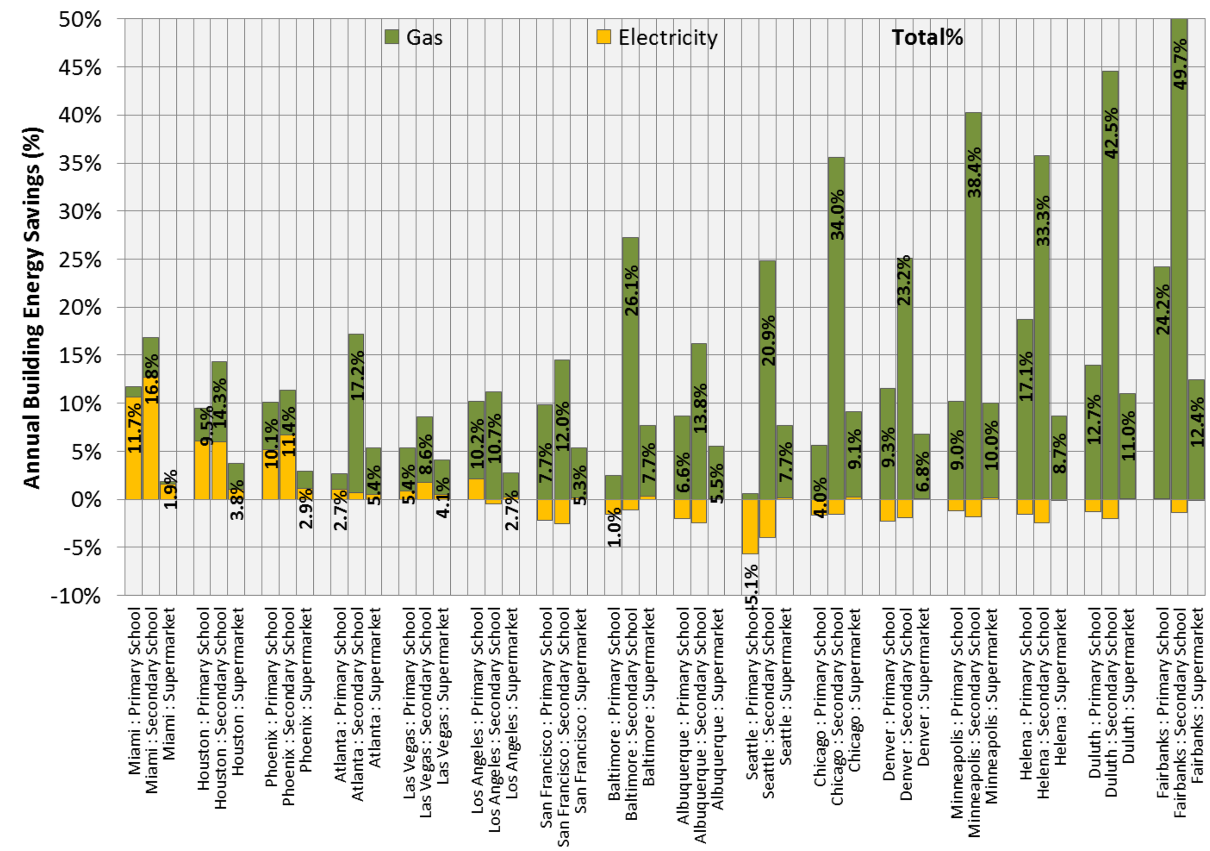

Figure A.30. Energy Savings: Measure 17 (Demand Control Ventilation): Primary and Secondary School and Supermarket Prototypes

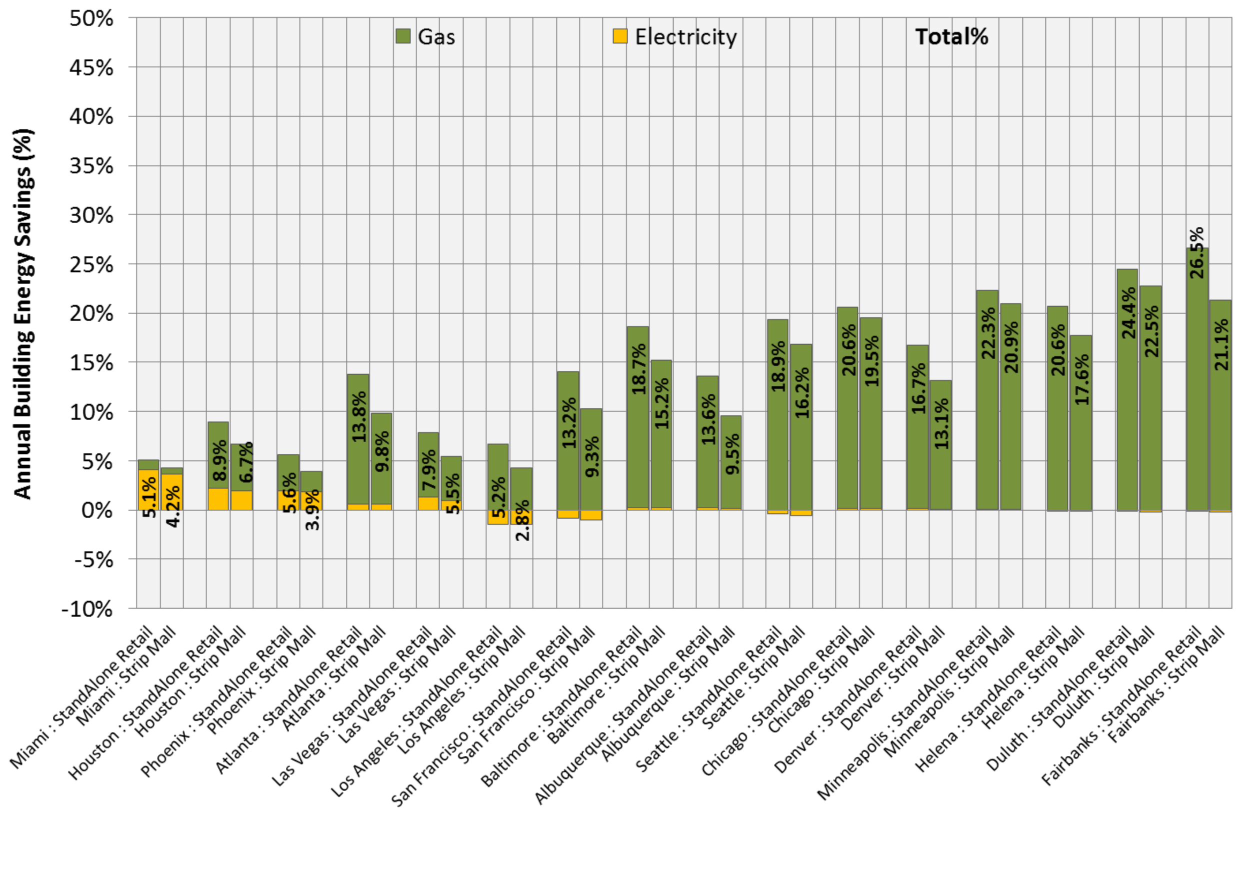

Figure A.31. Large Office Energy Savings: Measure 17 (Demand Control Ventilation): StandAlone Retail and Strip Mall Prototypes

A.18 Measure 18: Occupancy Sensors

Figure A.32, Figure A.33, and Figure A.34 show the impact of the use of occupancy sensors for lighting in all eight applicable prototypes. Savings is higher for building types that have a high density of applicable space types (especially office and schools; sales-oriented buildings only have a few spaces that can use these sensors). Electricity savings is stronger in warmer climates because the reduced heat gain from lights leads to a significant reduction in electricity for cooling as well. Also, because this measure reduces internal heat gains, it may increase the need for mechanical heating, especially in perimeter zones. Certain building types show higher modeled increase in natural gas for heating than others. In certain cases, especially in cold climates, the net effect on site energy use intensities is negative, although in terms of energy cost and primary energy consumption, this measure should always be a net positive because of its impact on electricity.

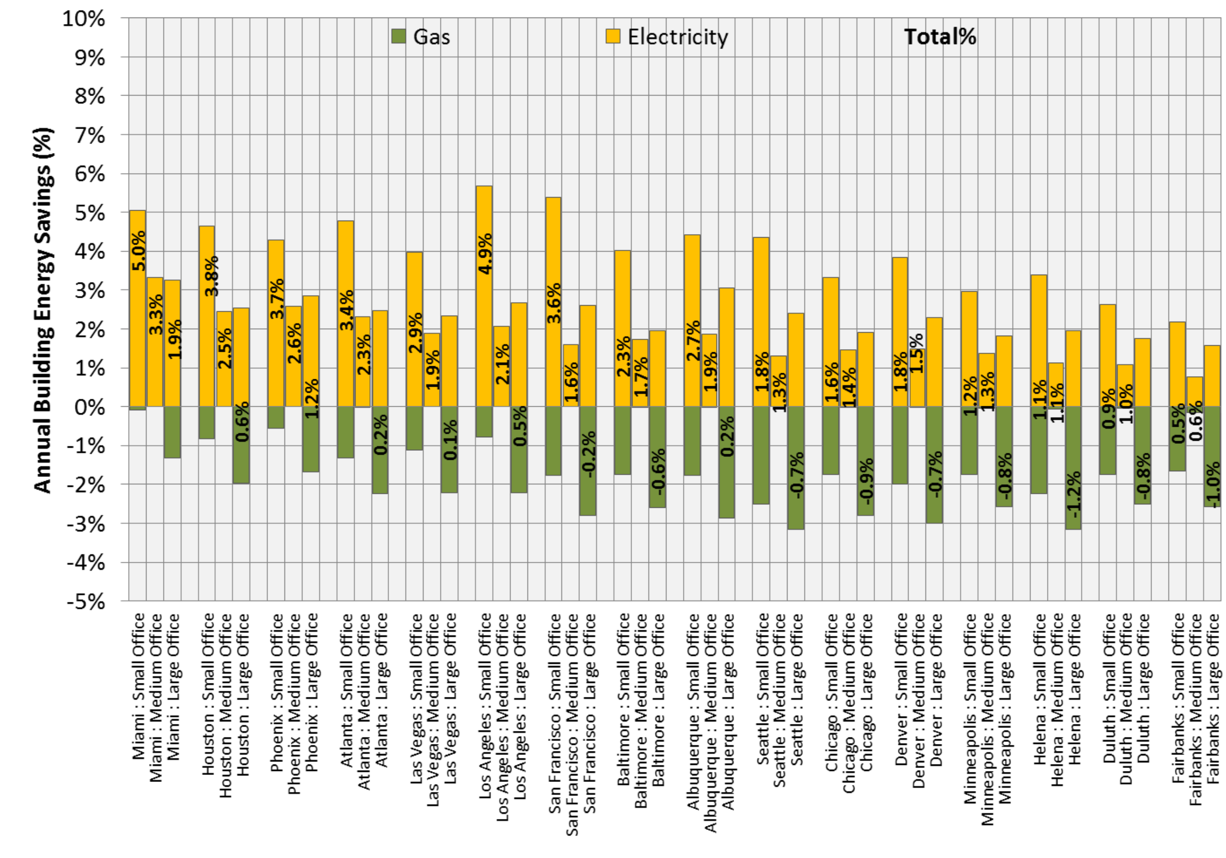

Figure A.32. Energy Savings: Measure 18 (Occupancy Sensors): Office Prototypes

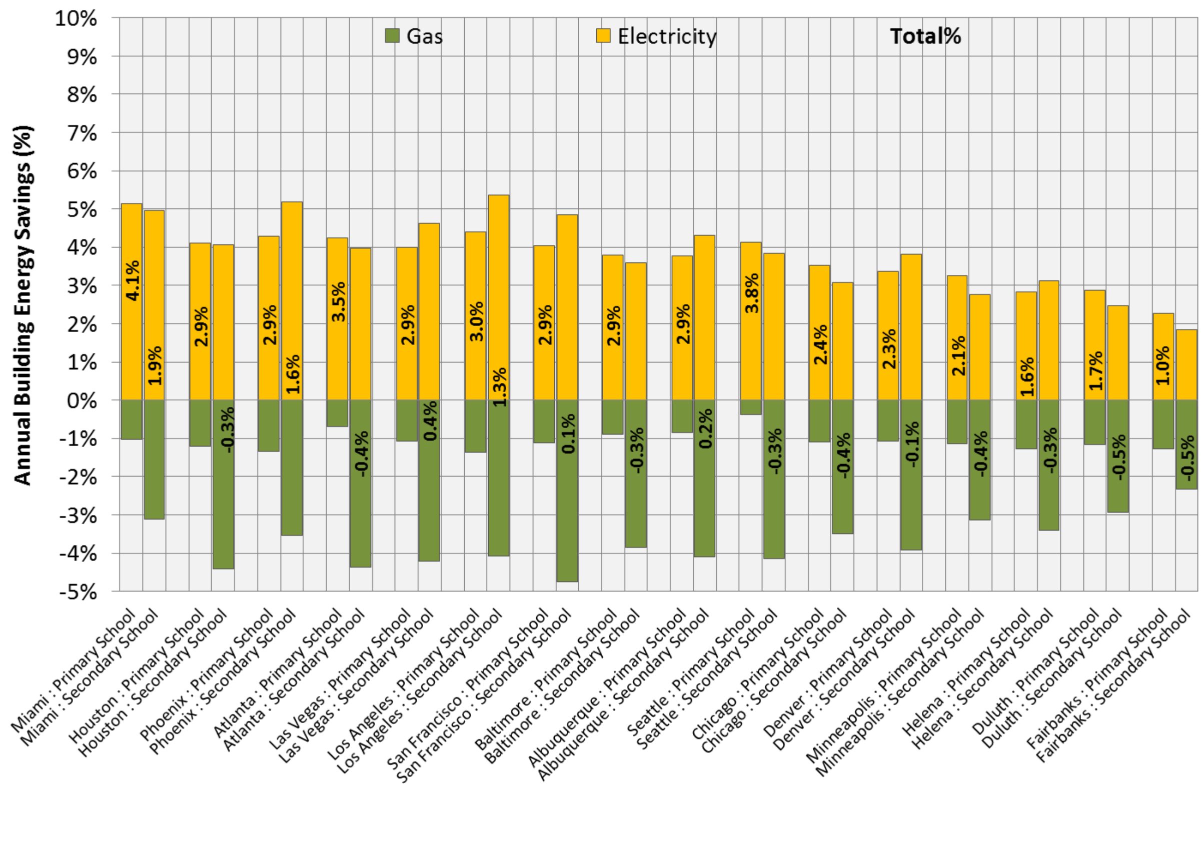

Figure A.33. Energy Savings: Measure 18 (Occupancy Sensors): Primary and Secondary School Prototypes

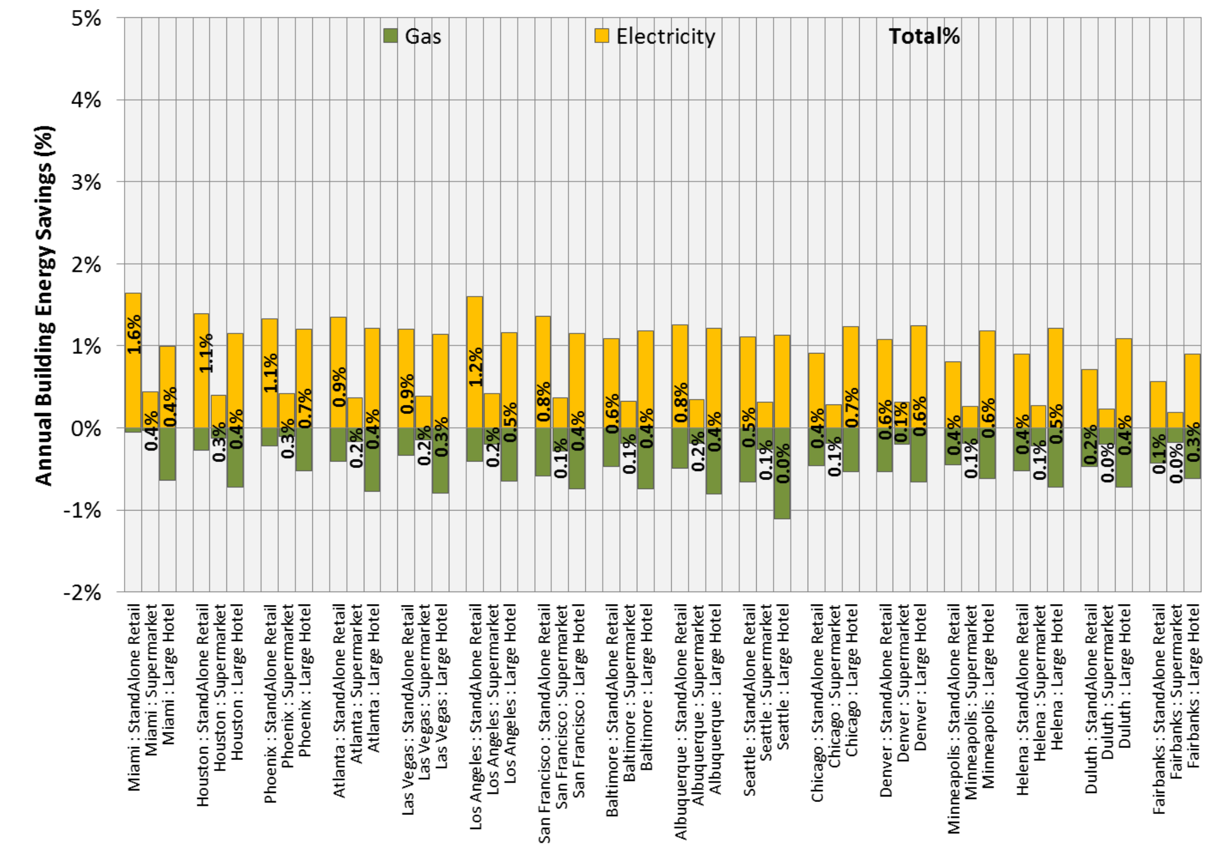

Figure A.34. Energy Savings: Measure 18 (Occupancy Sensors): StandAlone Retail, Supermarket, and Large Hotel Prototypes

A.19 Measure 19: Daylighting Controls

Figure A.35, Figure A.36, and Figure A.37 show the impact of the use of daylighting sensors in perimeter zones. Savings are greater for buildings like strip malls and small office buildings (typically 5–10%), for which perimeter zones represent a higher fraction of total floor space. Savings increase for locations closer to the equator, where there is more consistently strong daylight throughout the year during occupied hours. As was the case for occupancy sensors (Measure 18), the use of daylighting sensors also decreases the zone internal loads and has the same climate-driven impact on saving cooling energy and increasing natural gas for heating.

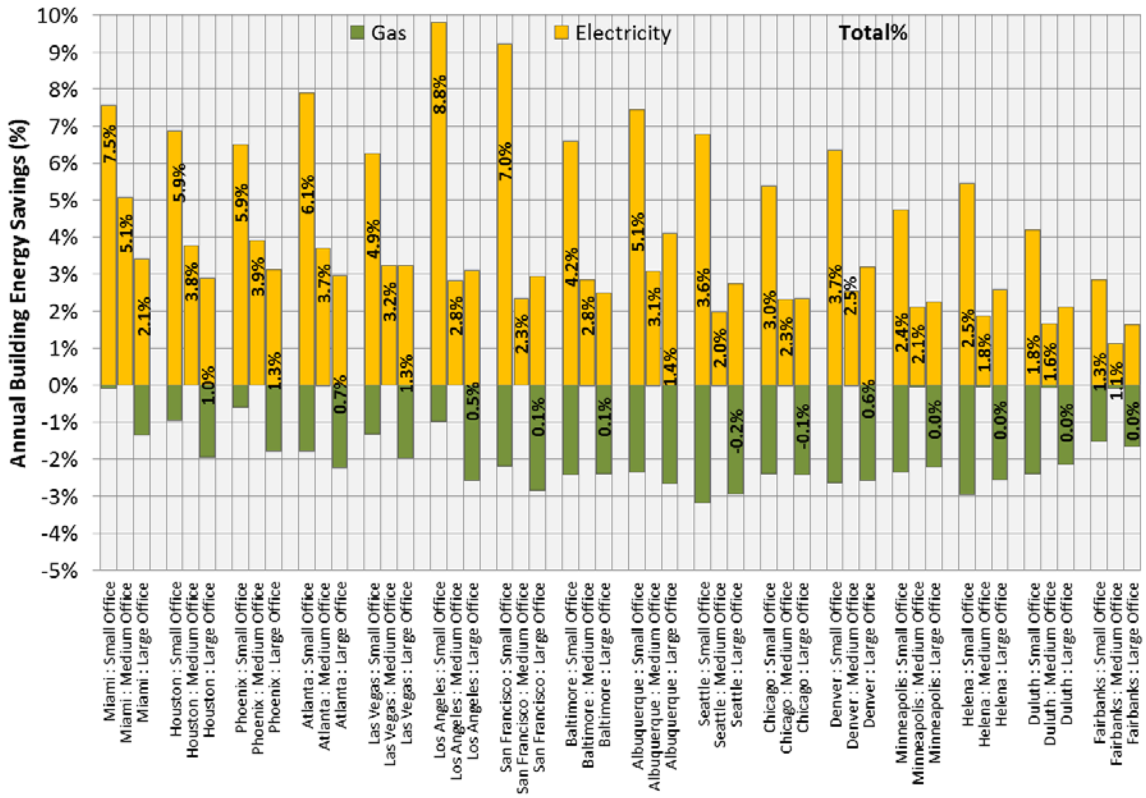

Figure A.35. Energy Savings: Measure 19 (Daylighting Controls): Office Prototypes

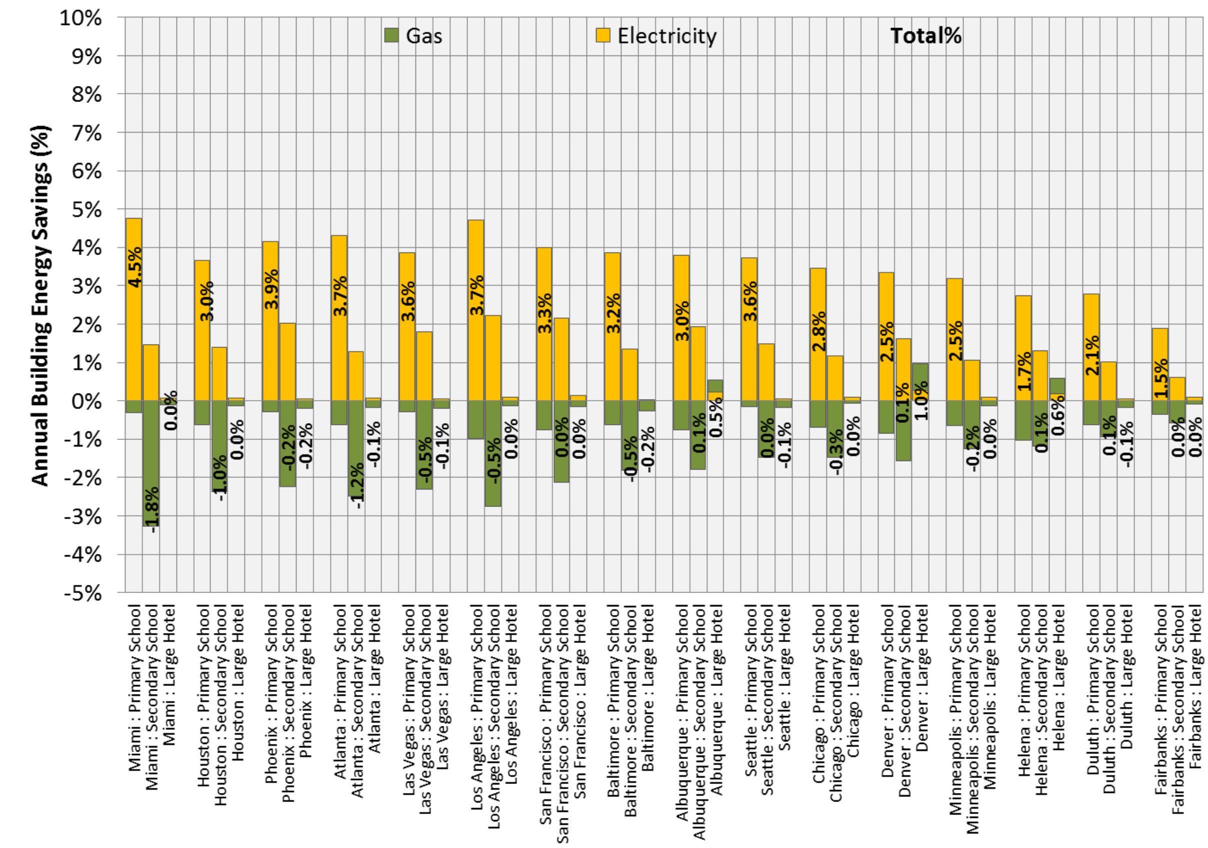

Figure A.36. Energy Savings: Measure 19 (Daylighting Controls): Primary and Secondary School and Large Hotel Prototypes

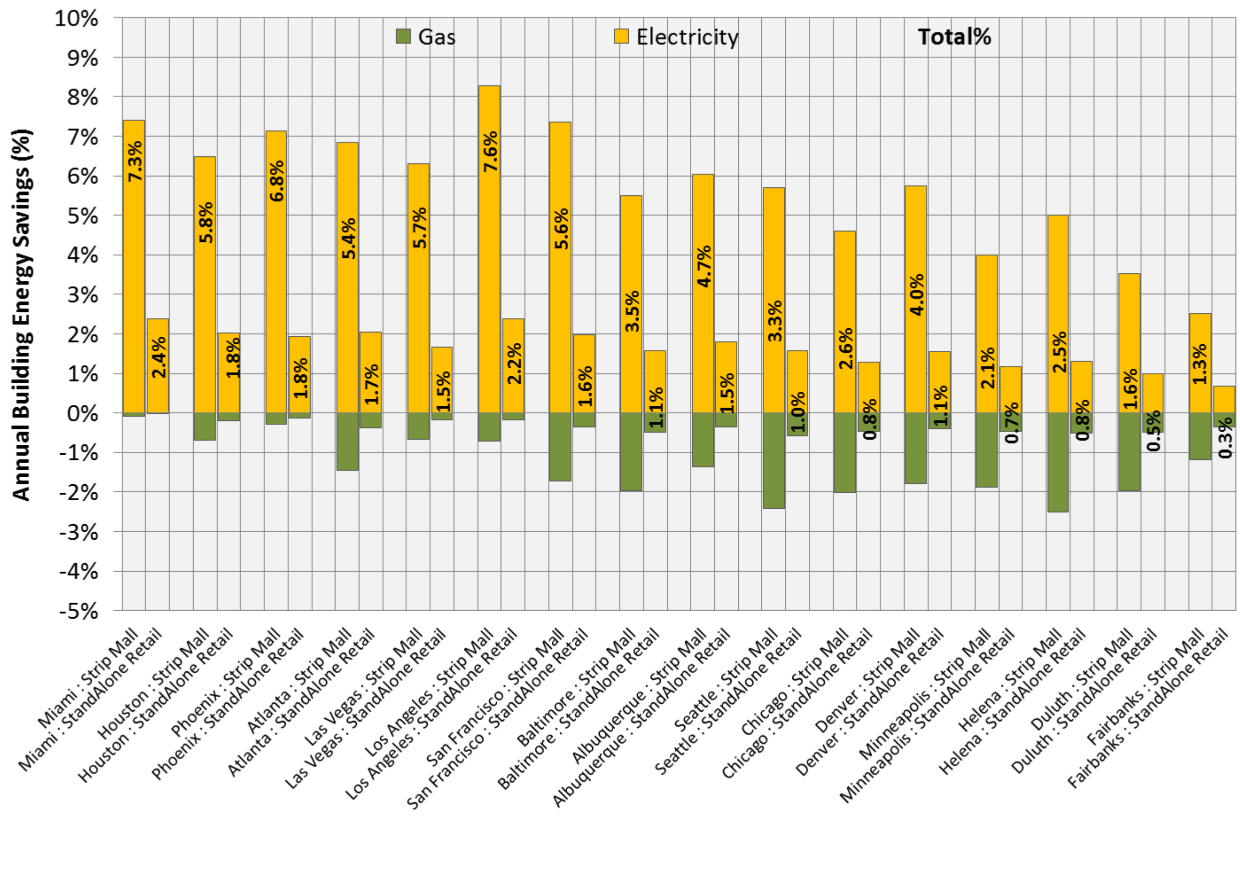

Figure A.37. Energy Savings: Measure 19 (Daylighting Controls): Strip Mall and StandAlone Retail Prototypes

A.20 Measure 20: Exterior Lighting Controls

Figure A.38 shows the impact of shutting 75% of parking lot lights off during the nighttime hours (leaving them all on only during times when it is dark and occupants are expected to be using the parking lot) for three selected building types. For any particular building, the magnitude of the savings is the same in all climates, but changes somewhat in percentage terms. The savings varies significantly by building type, based on the size of the parking lot.

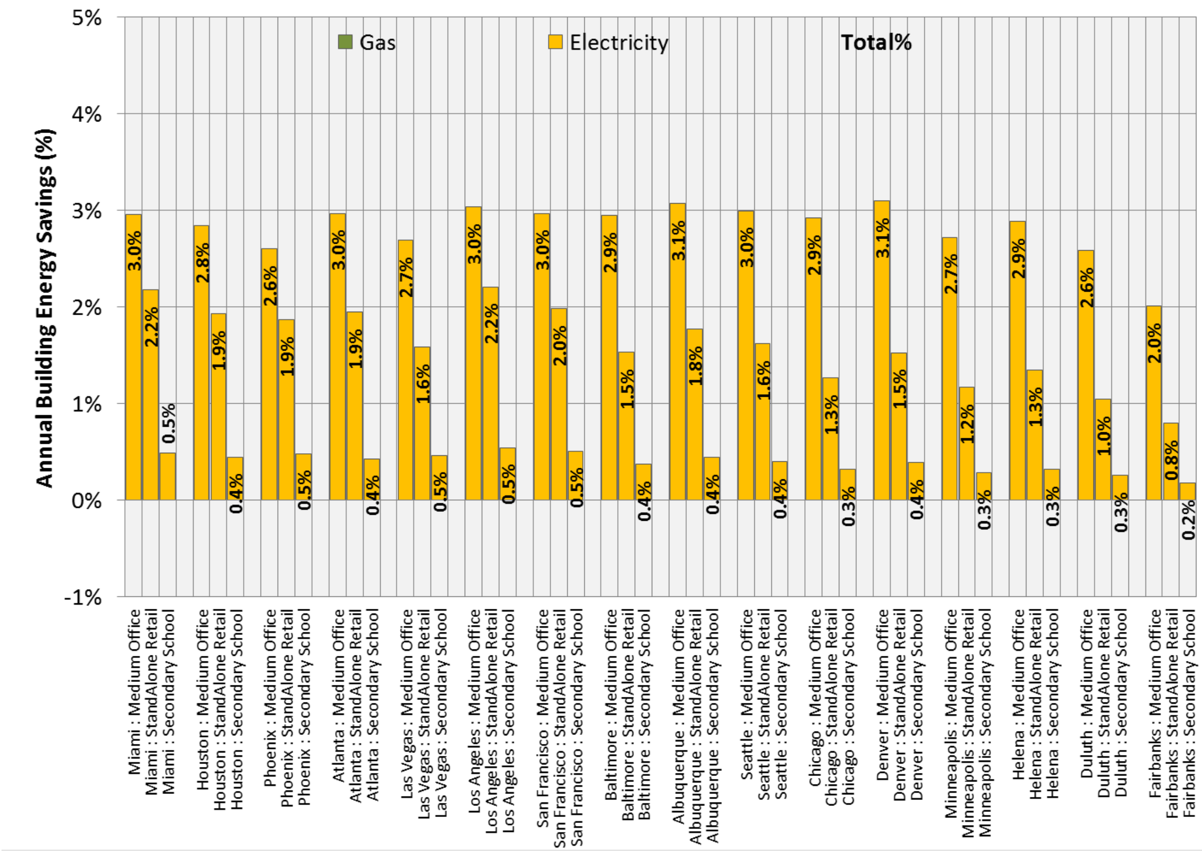

Figure A.38. Energy Savings: Measure 20: Exterior Lighting Controls: Medium Office, StandAlone Retail, and Secondary School Prototypes

A.21 Measure 21: Advanced Plug Load Controls

Figure A.39 shows the impact of advanced plug load control devices in the three applicable building types (offices). Up to a few percent savings are possible for this measure, but because the measure creates internal load reductions mostly at night, there is a strong rebound effect of heating usage in cold climates. Even in cold climates, where the overall savings are very small, electricity is much more valuable than natural gas, so the measure should still be considered worthwhile.

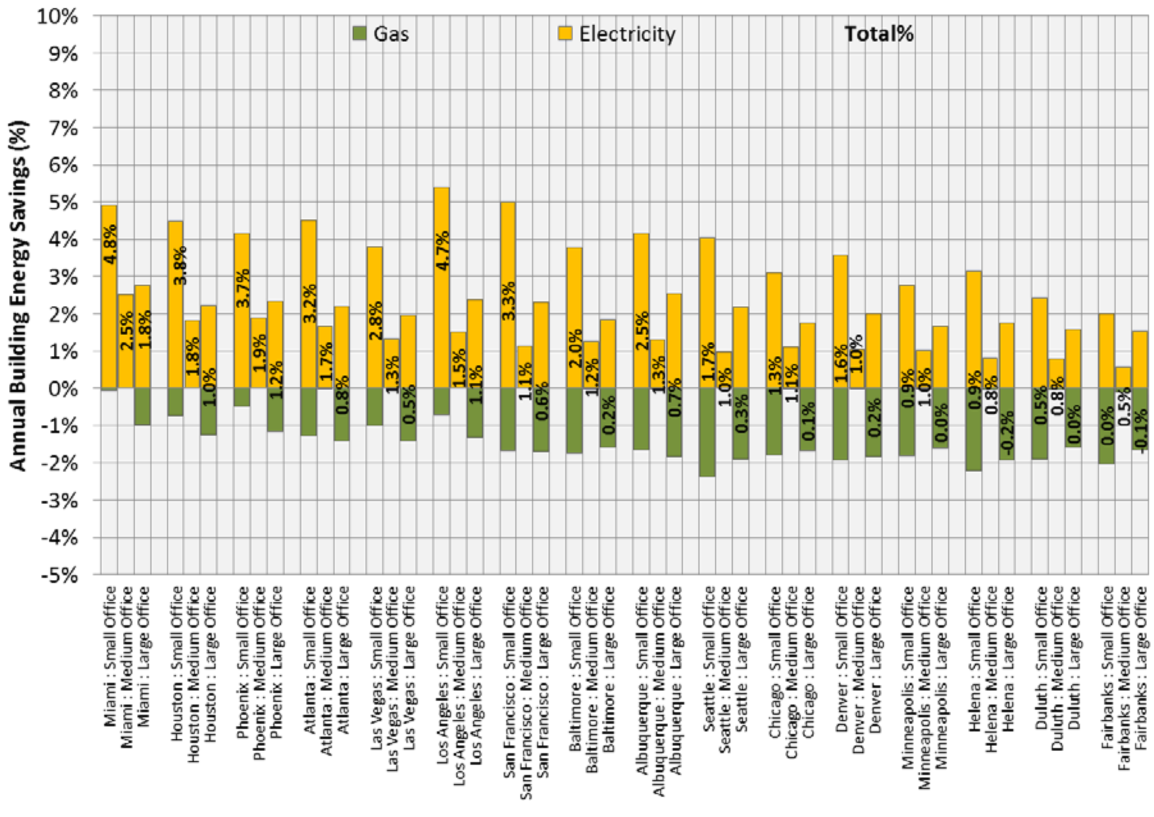

Figure A.39. Energy Savings: Measure 21 (Advanced Plug Load Controls): Office Prototypes

A.22 Measure 22: Night Purge

Figure A.40 shows the impact of night purge control strategies on three selected building types. Conventional wisdom dictates that this measure is usually only worth considering in dry climates with warm days and cool nights. The simulation indicates that there may be a wider range of climate zones in which this strategy could be applicable. The savings potential is fairly limited for most building types, and is typically below 0.5%. The Large Office (0.78% nationally) and StandAlone Retail (0.58% nationally) prototypes showed the most promising savings.

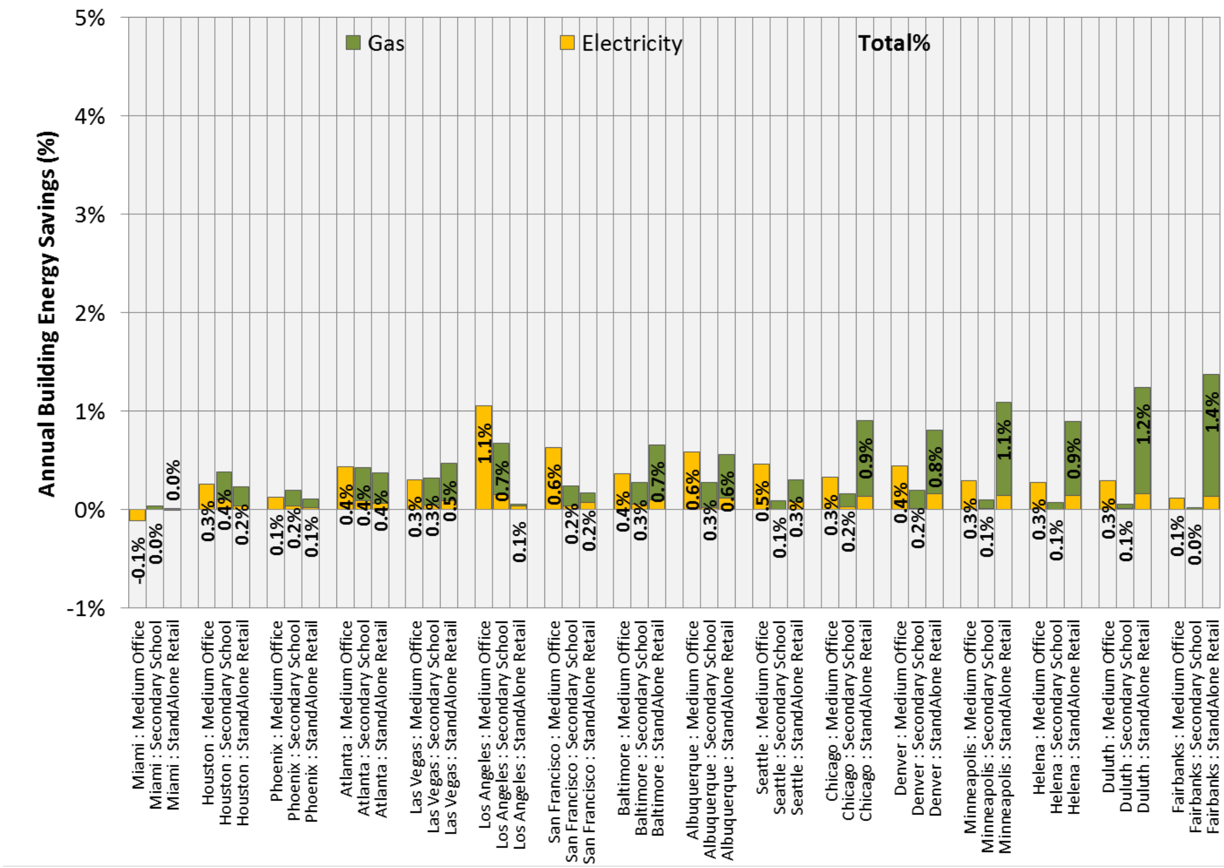

Figure A.40. Energy Savings: Measure 22 (Night Purge): Medium Office, Secondary School, and StandAlone Retail Prototypes

A.23 Measure 23: Advanced RTU Controls

Figure A.41 and Figure A.42 show the impact of advanced RTU controls that slow down RTU fans during certain operational modes. This measure generally produces strong electricity savings, but with a strong rebound effect on natural gas. Electricity savings ranges from 4 to 16% in buildings with full coverage of single-zone packaged units (Small Office, Strip Mall, and StandAlone Retail) and from 2% to 6% in buildings with partial coverage. Because of the overall increase in heating, overall energy savings is highest in the warm to hot climates and declines to near zero in the coldest climates.

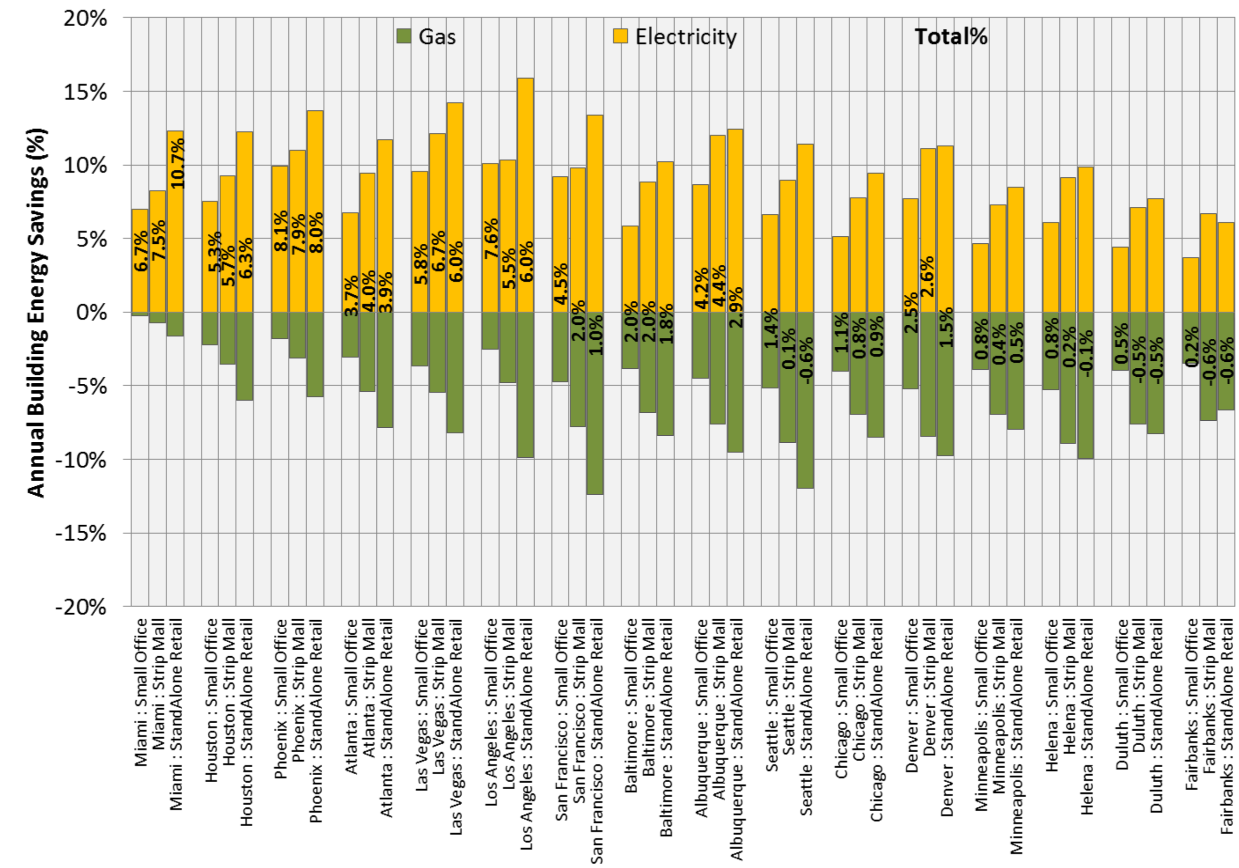

Figure A.41. Energy Savings: Measure 23 (Advanced RTU Controls): Small Office, Strip Mall, and StandAlone Retail Prototypes

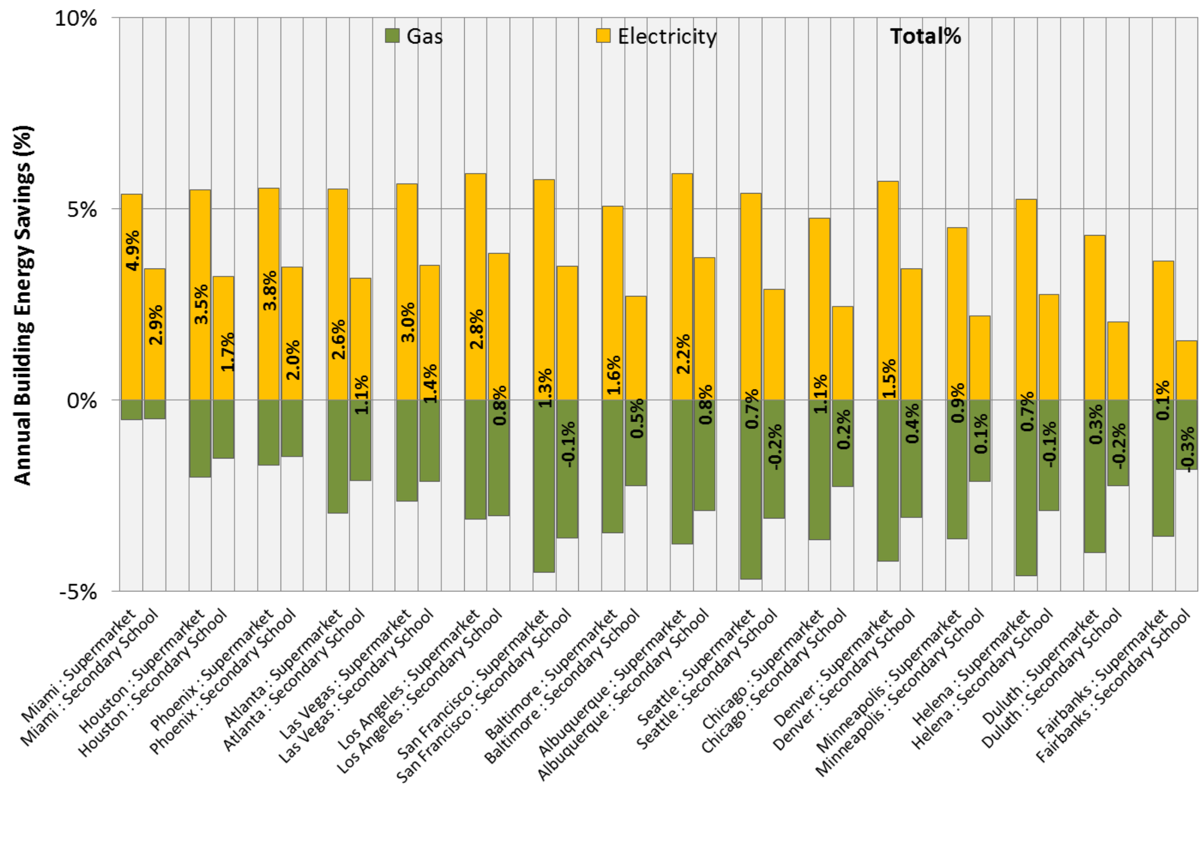

Figure A.42. Small Office Energy Savings: Measure 23 (Advanced RTU Controls): Supermarket and Secondary School Prototypes

A.24 Measure 24: Elevator Lighting and Ventilation Control

Figure A.43 shows the impact of elevator lighting and ventilation controls in the three prototype buildings that have elevators (Medium Office, Large Office, and Large Hotel). Minor savings of 0.1% to 0.2% (all in electricity) were modeled across the board.

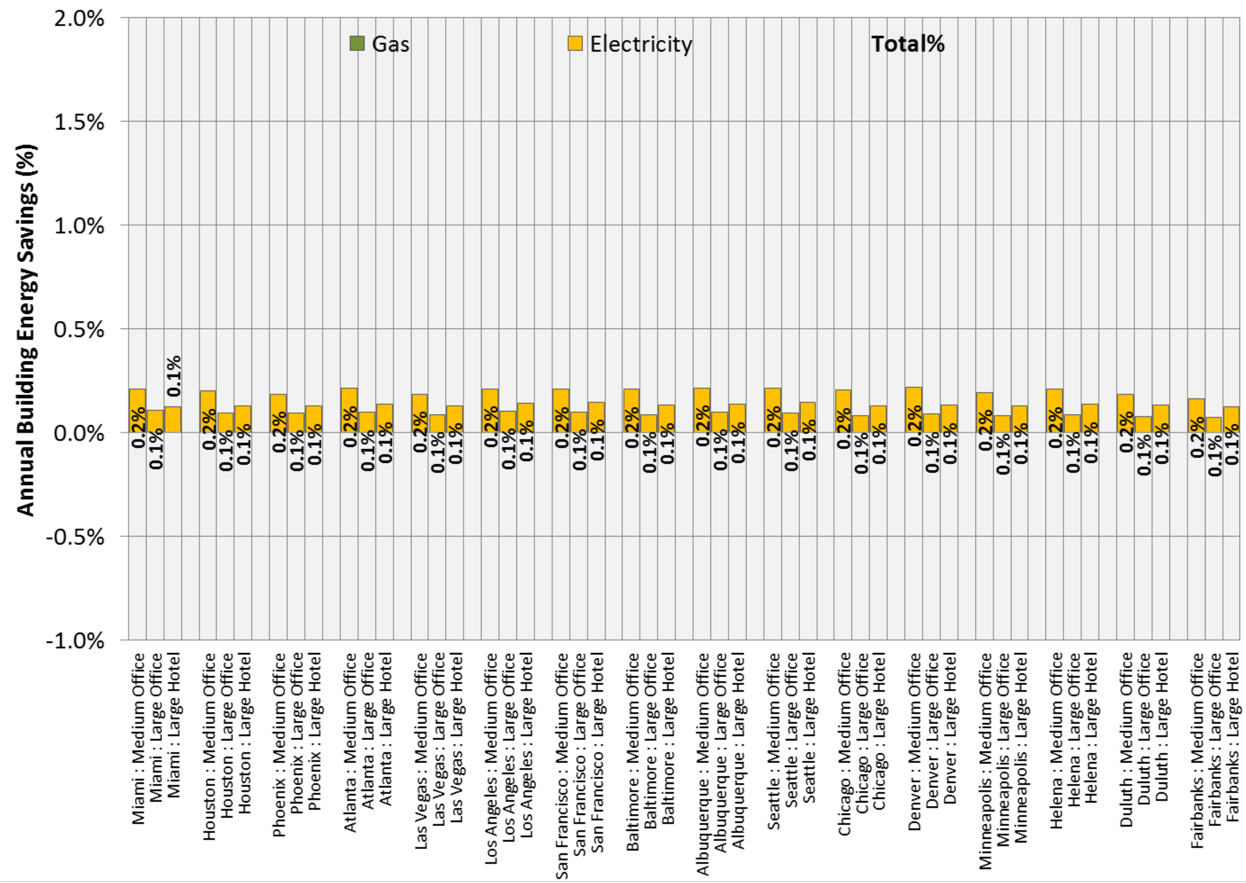

Figure A.43. Energy Savings: Measure 24 (Elevator Lighting and Ventilation Control): Medium and Large Office and Large Hotel Prototypes

A.25 Measure 25: Waterside Economizer

Figure A.44 shows the impact of enabling a previously disabled waterside economizer for the Large Office prototype. Waterside economizers are only useful in climates that regularly have wet-bulb temperatures below 40°F, so locations like Miami, Los Angeles, and San Francisco show no savings. The Large Office prototype also has airside economizing, so the additional benefit of a waterside economizer in cold climates (which are most favorable for using waterside economizers) is small.

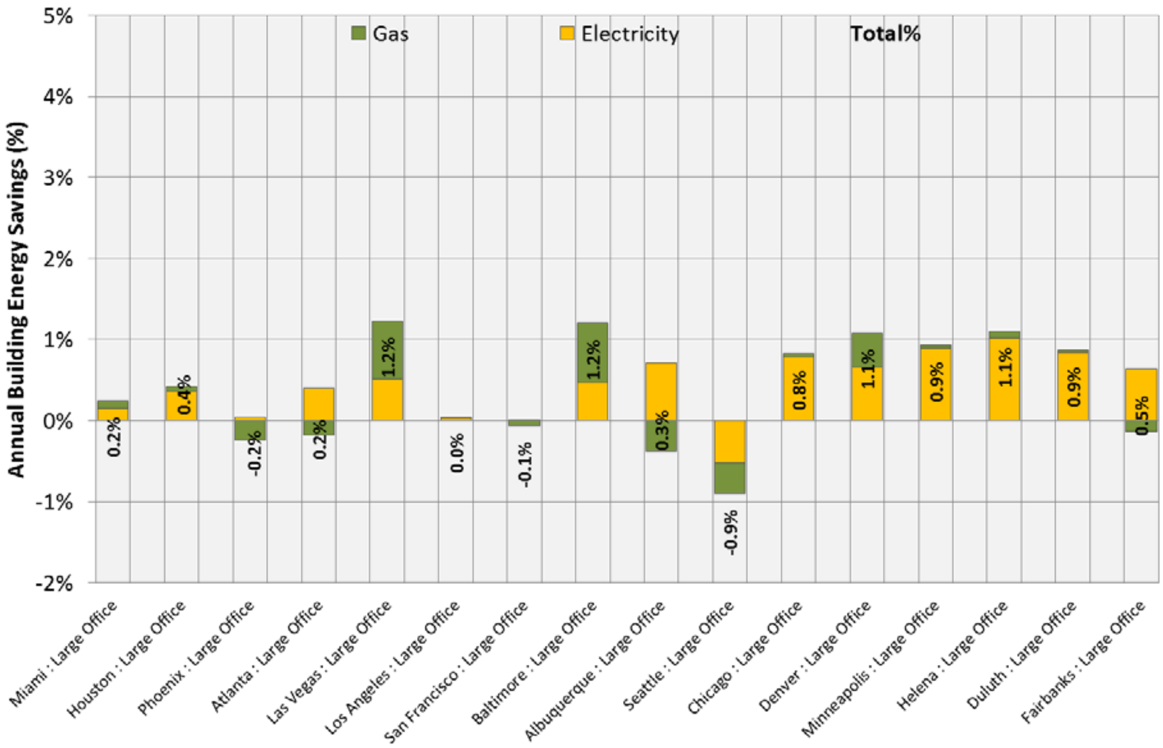

Figure A.44. Large Office Energy Savings: Measure 25 (Waterside Economizer Control)

A.26 Measure 26: Cooling Tower VFD Control

Figure A.45 shows the impact of adding VFDs to the cooling tower fans of single-speed cooling towers in the Large Office prototype (the only building that has cooling towers). This measure produces large electricity savings (generally 4–8% of building energy consumption).

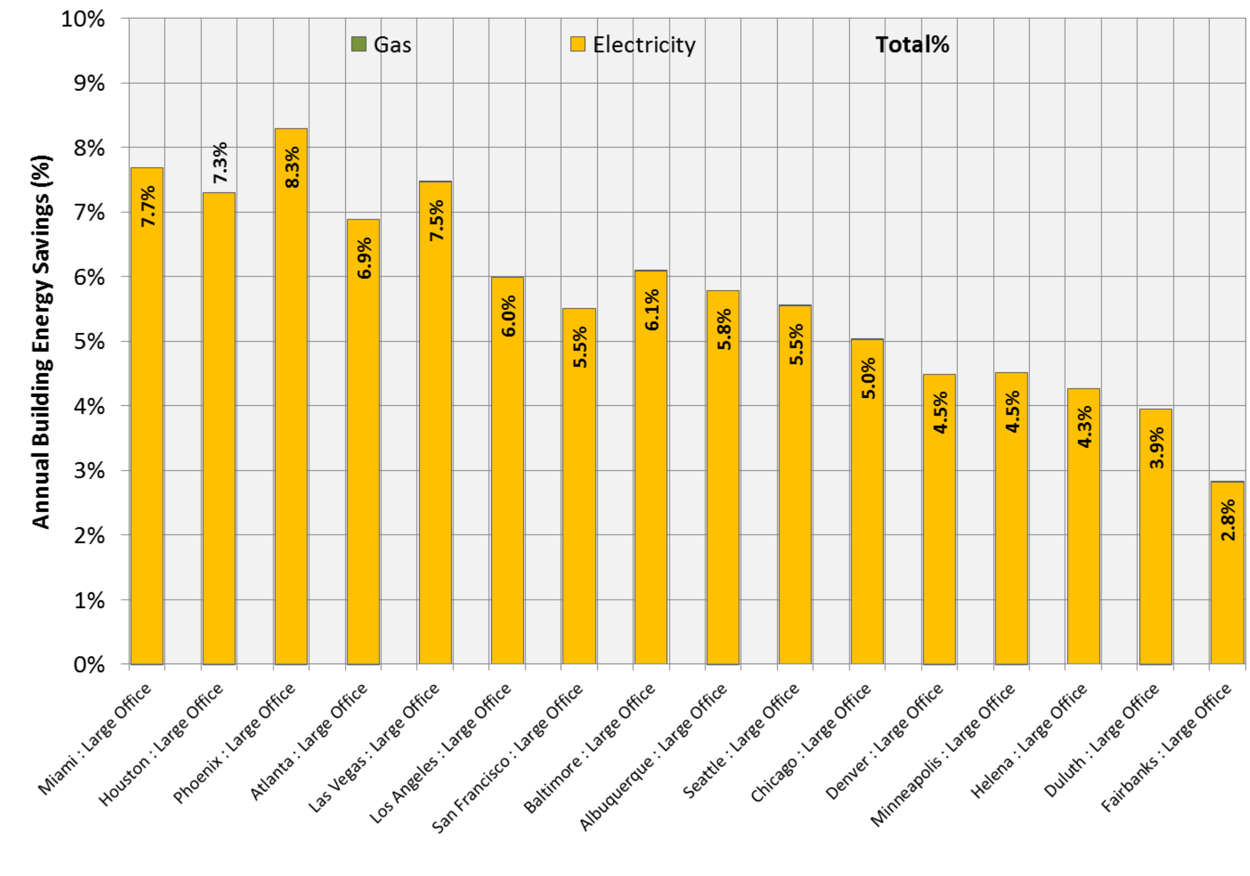

Figure A.45. Large Office Energy Savings: Measure 26 (Cooling Tower VFD Control)

A.27 Measure 27: Optimal Start

Figure A.46, Figure A.47, and Figure A.48 show the impact of Optimal Start in all eight building prototypes for which it is applicable (all except Large Hotel). The site energy savings estimate is very high—typically around 5–15%—for electricity and natural gas for nearly all buildings and in nearly all climates. This savings estimate is sensitive to assumptions about baseline operation. In this case, the modeled savings are compared to baseline operations for which the fans start three hours in advance of occupancy every day. Gas savings is typically higher than electricity in part because the deferred HVAC operations often coincide with the coldest part of the day (close to sunrise).

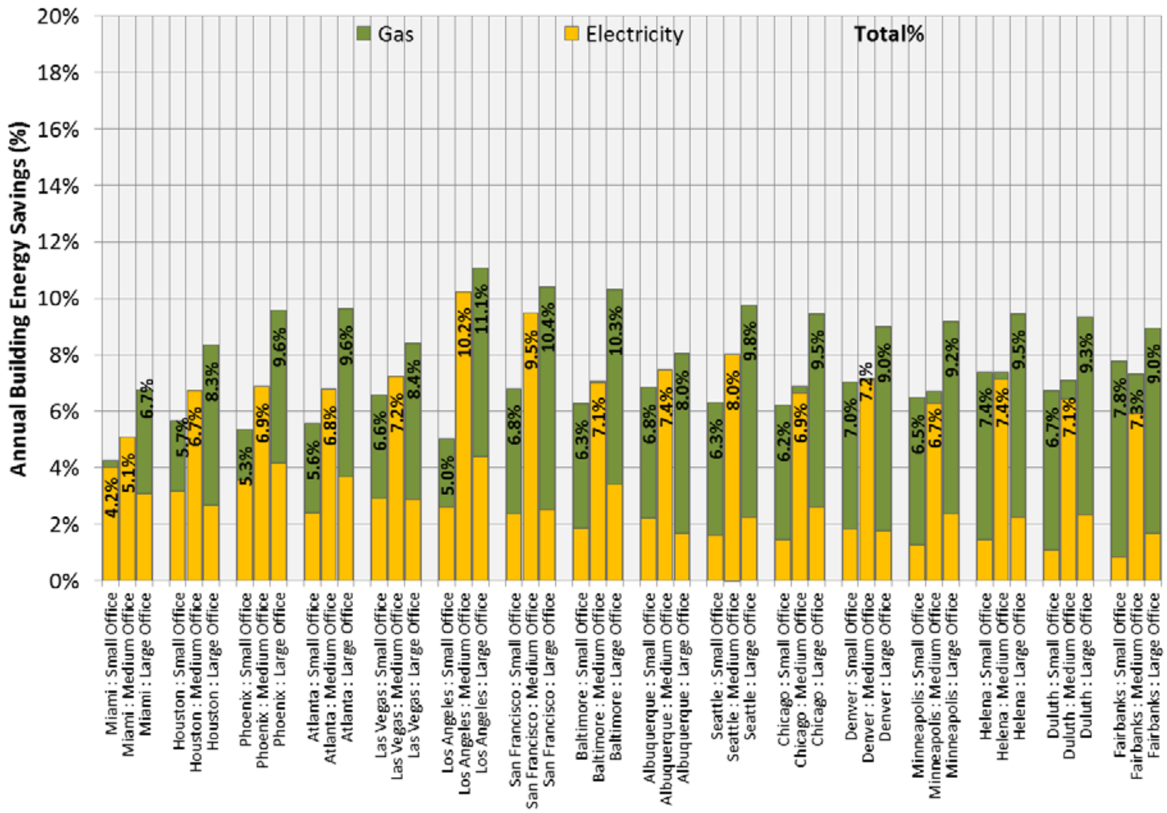

Figure A.46. Energy Savings: Measure 28 (Optimal Start): Office Prototypes

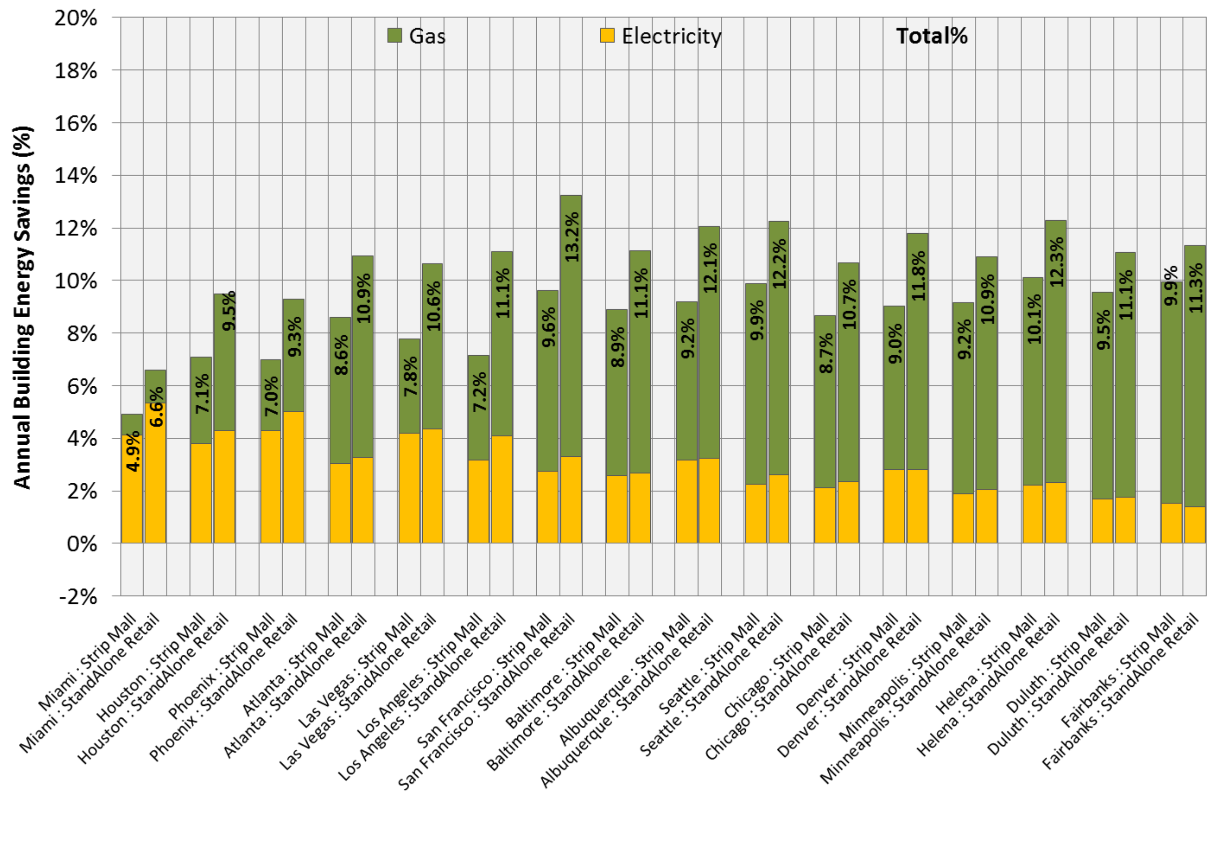

Figure A.47. Energy Savings: Measure 28 (Optimal Start): Strip Mall and StandAlone Retail Prototypes

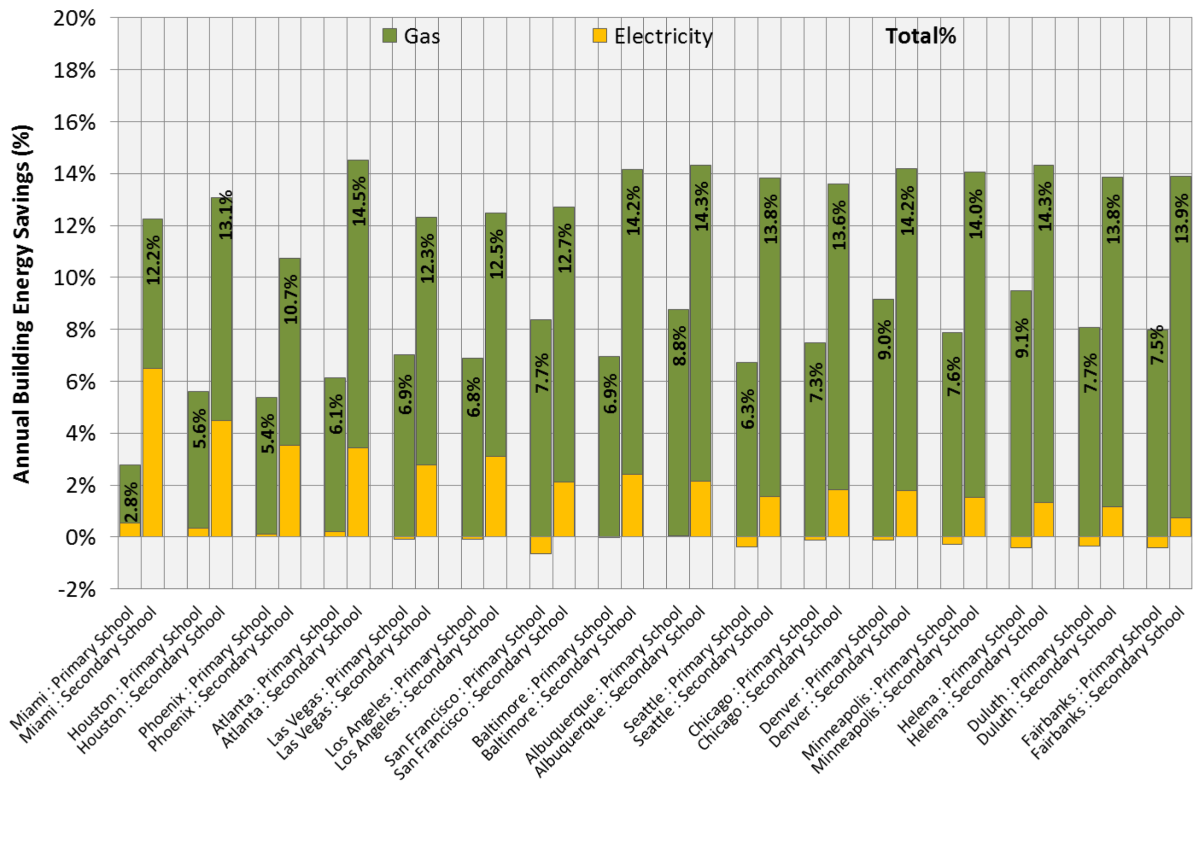

Figure A.48. Energy Savings: Measure 28 (Optimal Start): Primary and Secondary School Prototypes

A.28 Measure 28: Optimal Stop

Figure A.49 shows energy savings from Optimal Stop in three selected building prototypes (Large Office, Strip Mall, and Secondary School). Potential savings is generally below 2%, except in very mild climates, where the fan systems can often shut down close to a full hour in advance of the end of scheduled runtime.

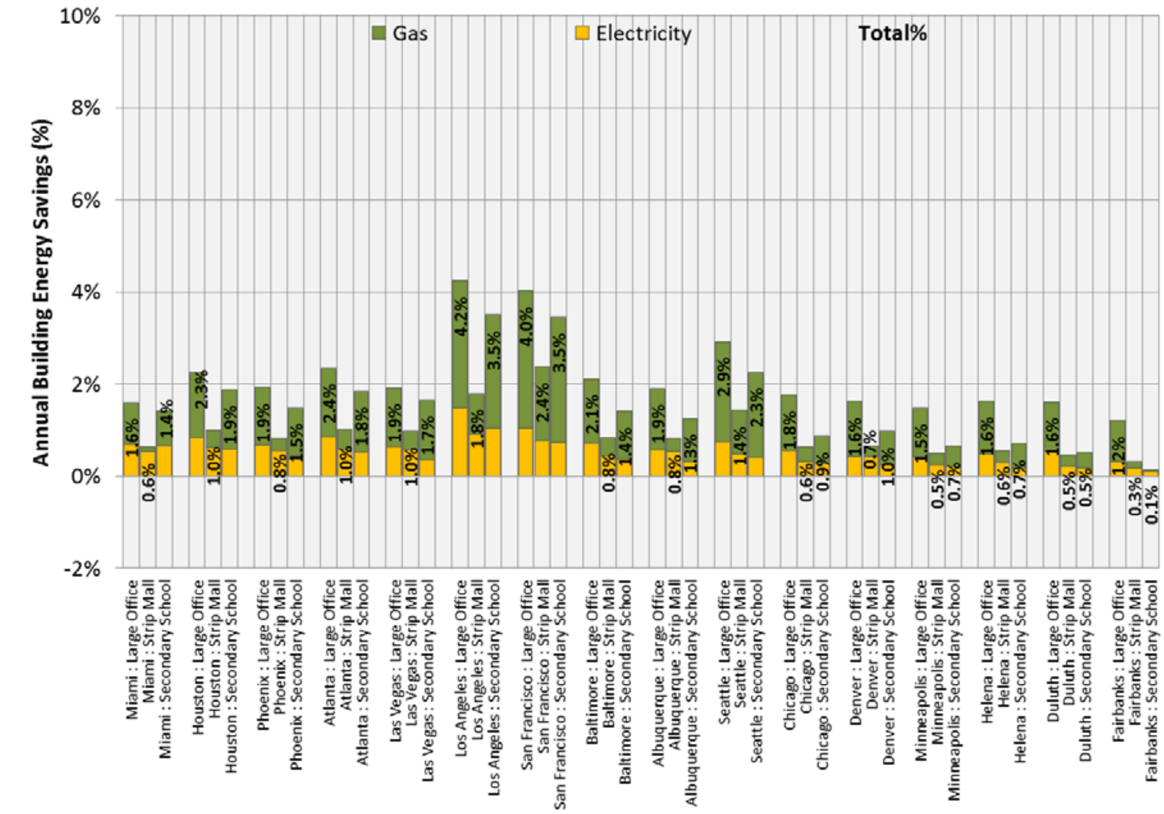

Figure A.49. Energy Savings: Measure 28 (Optimal Stop): Large Office, Strip Mall, and Secondary School Prototypes

A.29 Measure 29: Refrigerated Case Lighting Controls

Figure A.50 shows the energy savings from refrigerated case lighting controls in the Supermaket prototype. Electricity savings is generally around 1%, with higher cooling savings in warm climates and increases in space heating in warm climates.

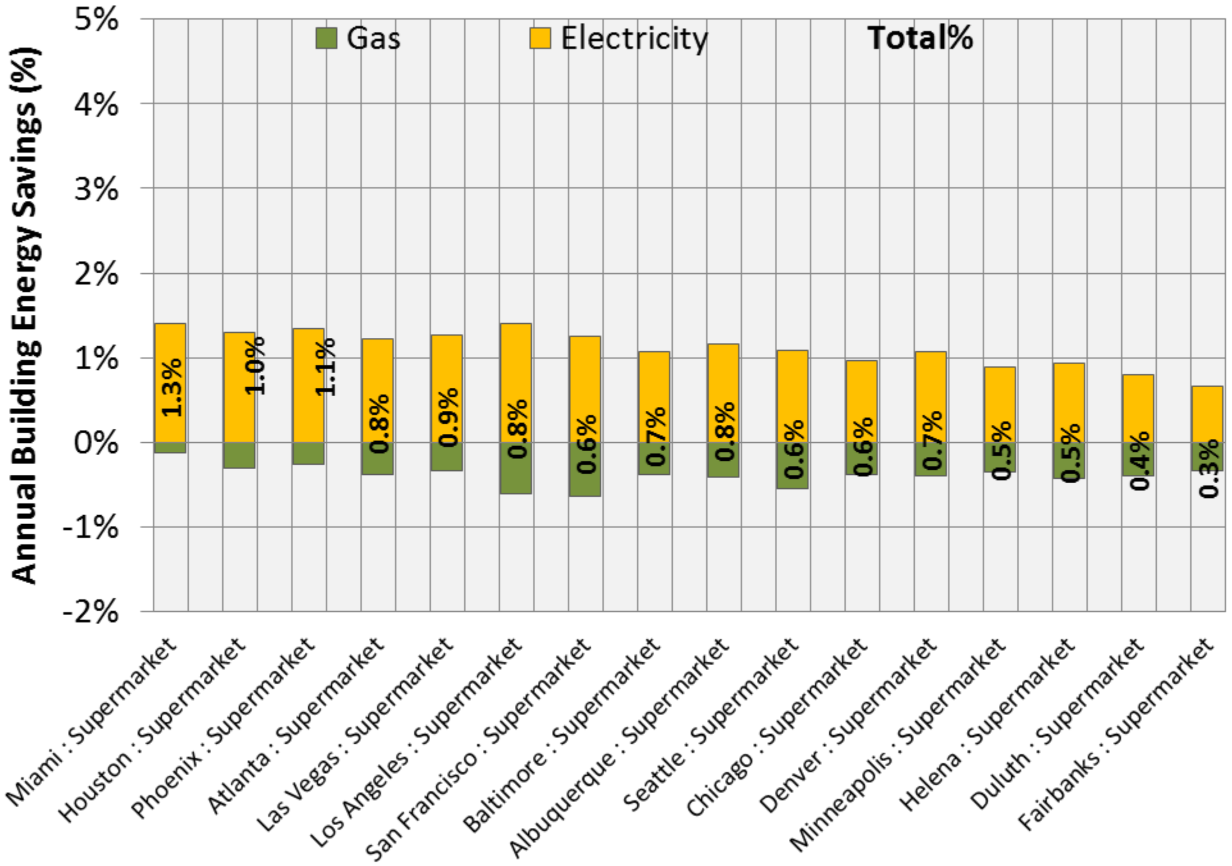

Figure A.50. Energy Savings: Measure 29 (Refrigerated Case Lighting Controls): Supermarket Prototype

A.30 Measure 30: Walk-Ins Lighting Control

Walk-in refrigerators/freezers represent a small fraction of the overall footprint of the Supermarket prototype and have relative small lighting loads. Figure A.51 shows that the savings is very small—0.1% for all climates.

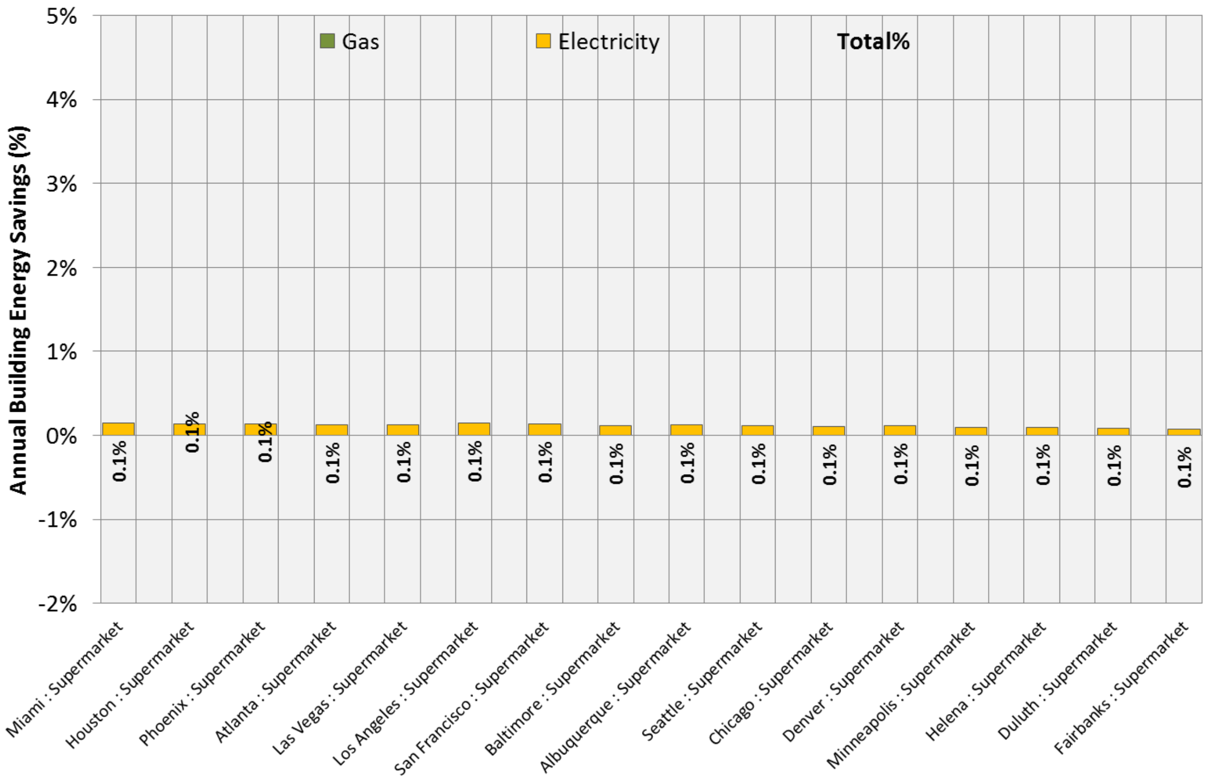

Figure A.51. Energy Savings: Measure 30 (Walk-Ins Lighting Control): Supermarket Prototype

A.31 Measure 31: Refrigeration: Floating Head Pressure Control

Floating head pressure control has the strongest energy savings potential of all EEMs geared toward saving energy in the refrigeration systems of supermarkets. Annual building energy savings is typically 2–4%, all in electricity, as shown in Figure A.52.

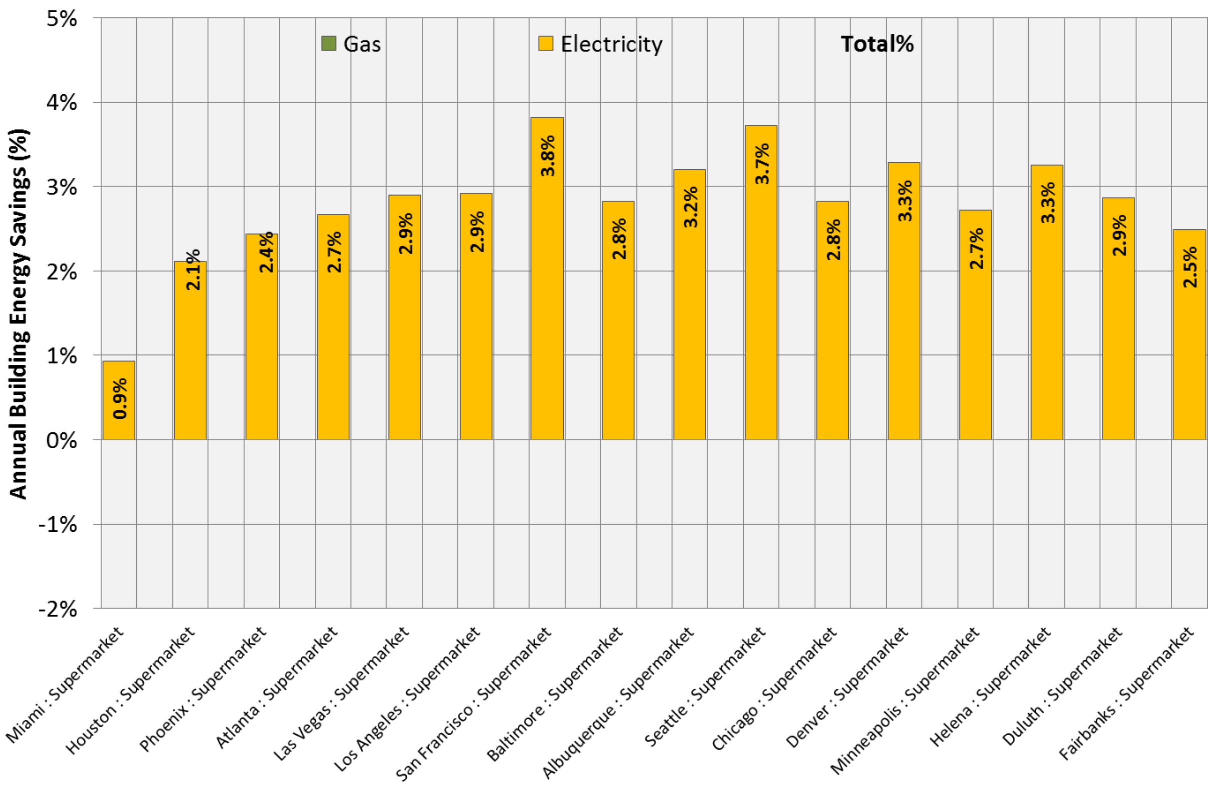

Figure A.52. Energy Savings: Measure 31 (Refrigeration: Floating Head Pressure Control): Supermarket Prototype

A.32 Measure 32: Refrigeration: Floating Suction Pressure Control

Figure A.53 shows the savings in the Supermarket prototype from floating suction pressure control. There is less potential for savings from floating suction pressure control than from floating head pressure control because the room for variation of the suction pressure is very small, in order to maintain constant freezer air temperatures.

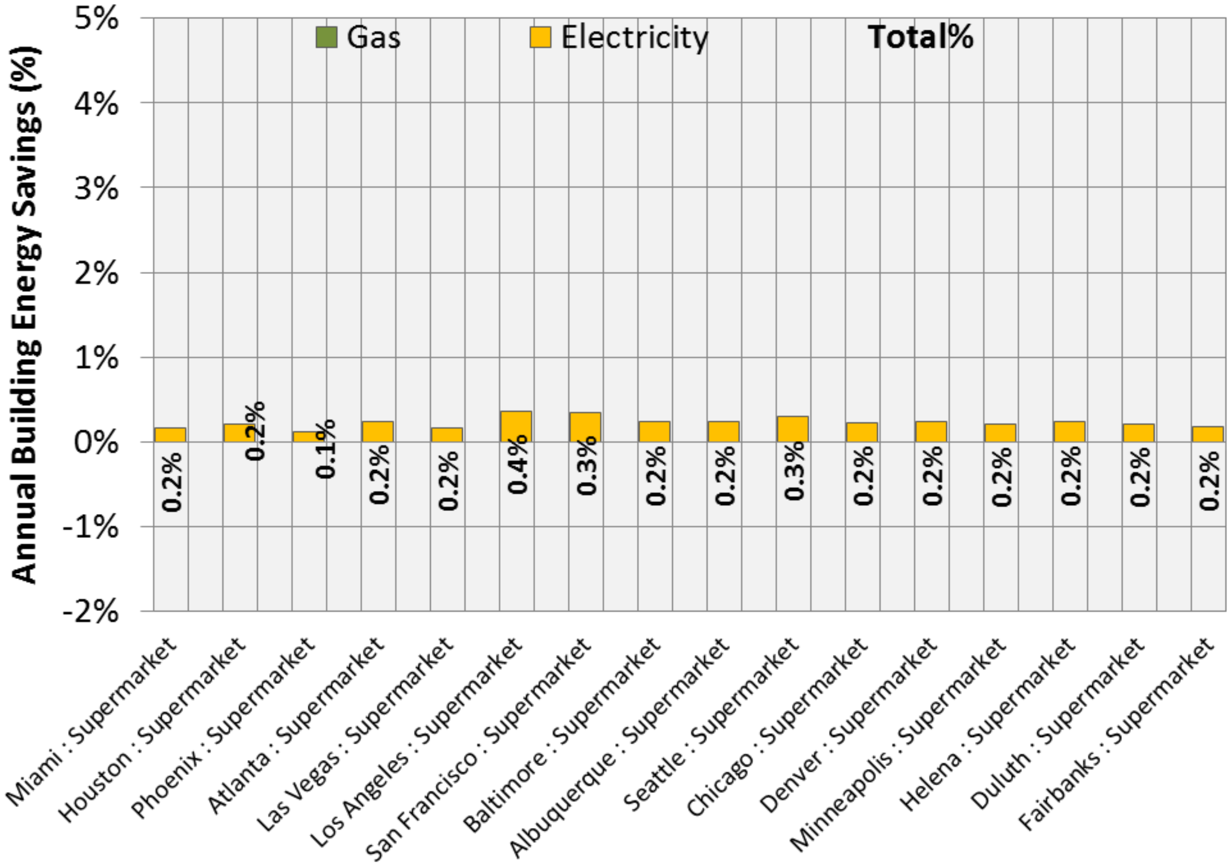

Figure A.53. Energy Savings: Measure 32 (Refrigeration: Floating Suction Pressure Control): Supermarket Prototype

A.33 Measure 33: Refrigerated Case Defrost Control

Figure A.54 shows that up to 1% of annual building energy consumption can be saved, all in electricity, by using demand-based defrost control. Savings is somewhat higher in dry climates than in humid climates.

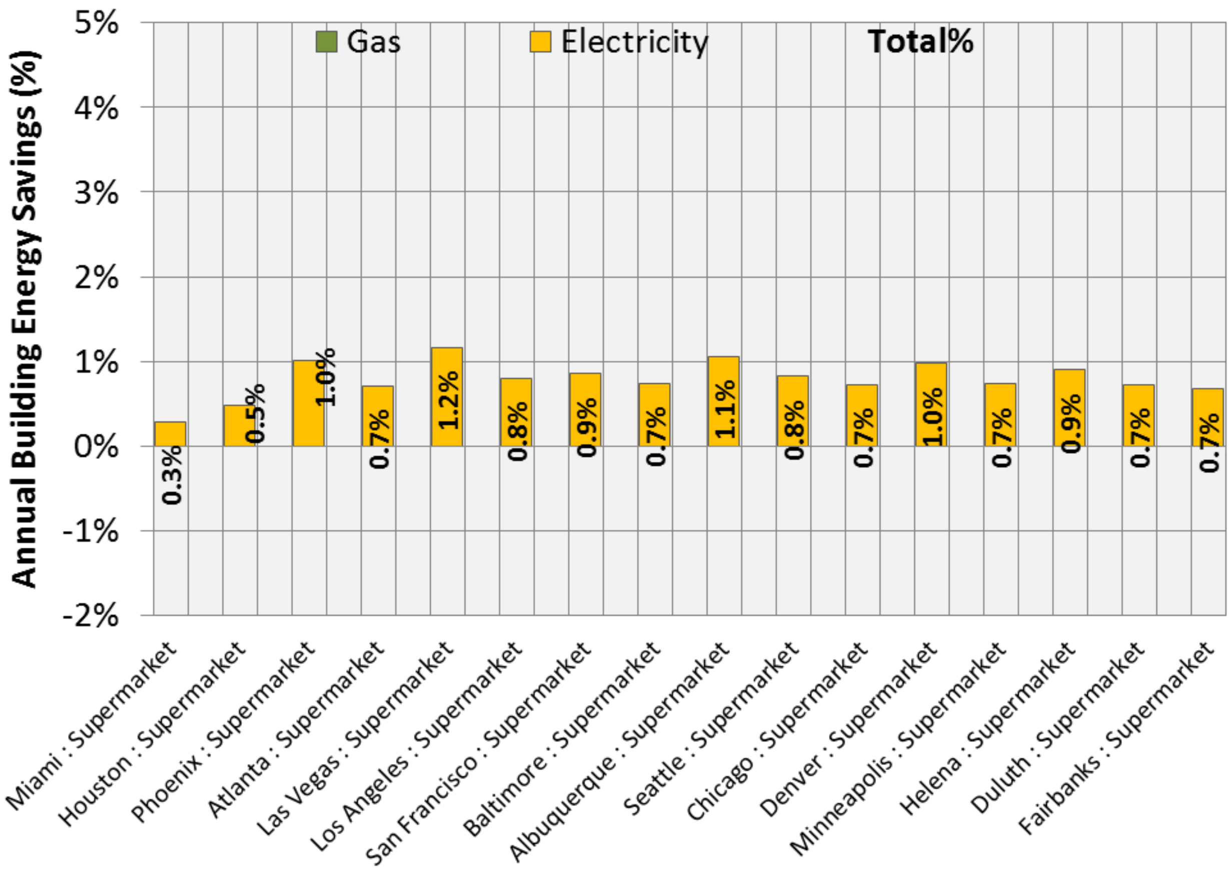

Figure A.54. Energy Savings: Measure 33 (Refrigerated Case Defrost Control): Supermarket Prototype

A.34 Measure 34: Refrigerated Case Anti-Sweat Heater Control

Figure A.55 shows the potential savings from anti-sweat heater control in supermarkets. Savings is generally 1–2% in humid climates and 2–3% in dry climates. All savings is in electricity, and there is a slight increase in natural gas consumption for heating to compensate.

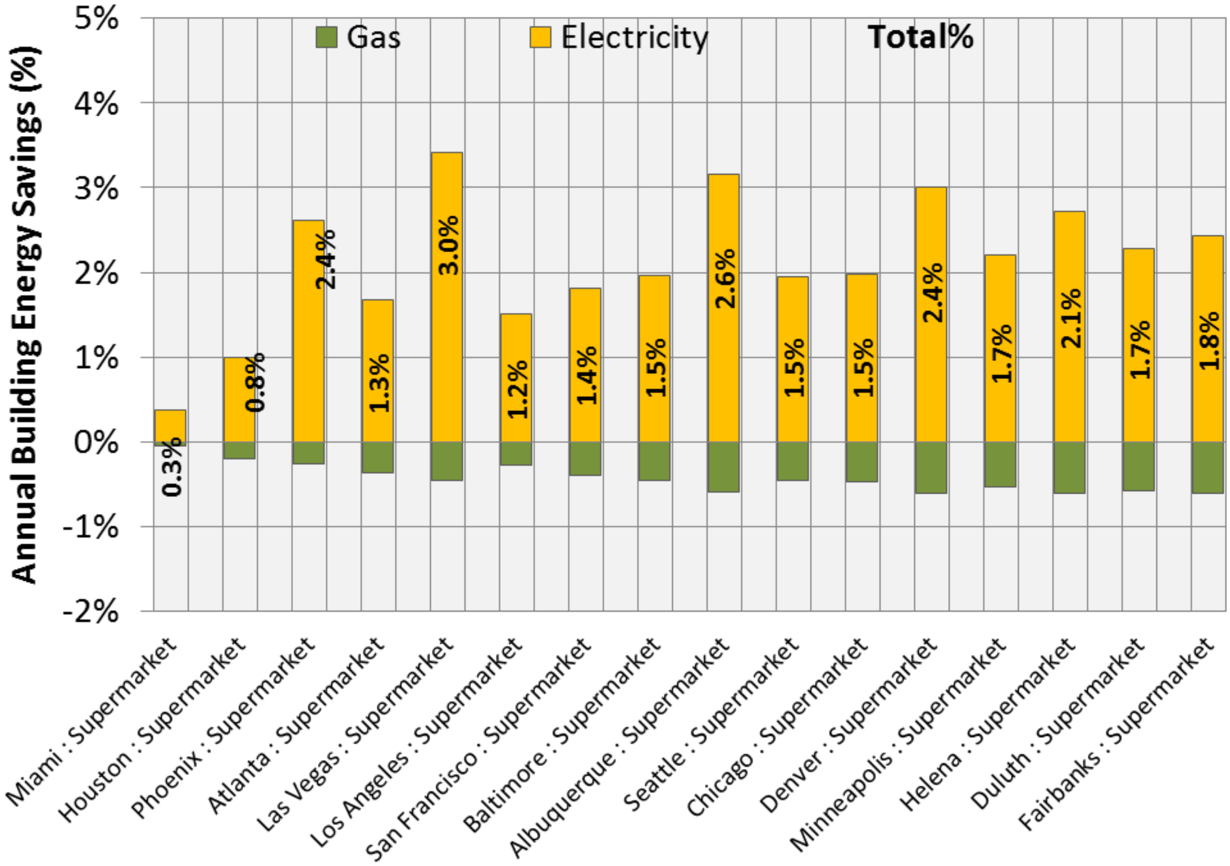

Figure A.55. Energy Savings: Measure 34 (Refrigerated Case Anti-Sweat Heater Control): Supermarket Prototype

A.35 Measure 35: Walk-Ins: Evaporator Fan Speed Control

Figure A.56 shows that a reduced speed of evaporator fans on walk-in refrigerators can save 0.2–0.3% of annual building energy consumption in supermarkets, all in electricity.

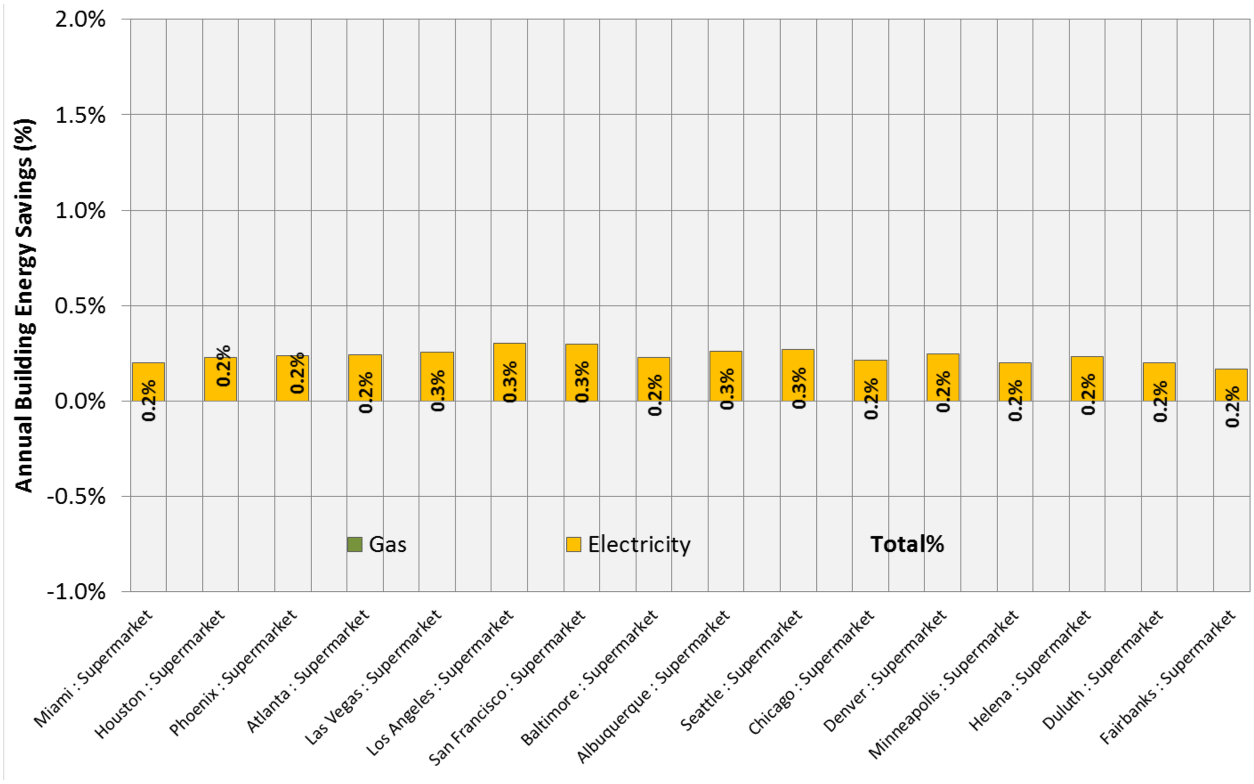

Figure A.56. Energy Savings: Measure 35 (Walk-Ins: Evaporator Fan Speed Control): Supermarket Prototype

A.36 Measure 36: Guest Room Occupancy Sensors for Lighting and HVAC

Figure A.57 shows the impact of occupancy sensors for automatic shut off of lights and setback of thermostats in hotel guest rooms. The modeling indicates that the potential savings is generally around 3% of building energy consumption and is mostly constant by climate. This measure most strongly affects electricity consumption. Some climates have slight increases or decreases in natural gas consumption. Gas savings from setting back thermostats competes in each climate with gas increases from reduced internal loads.

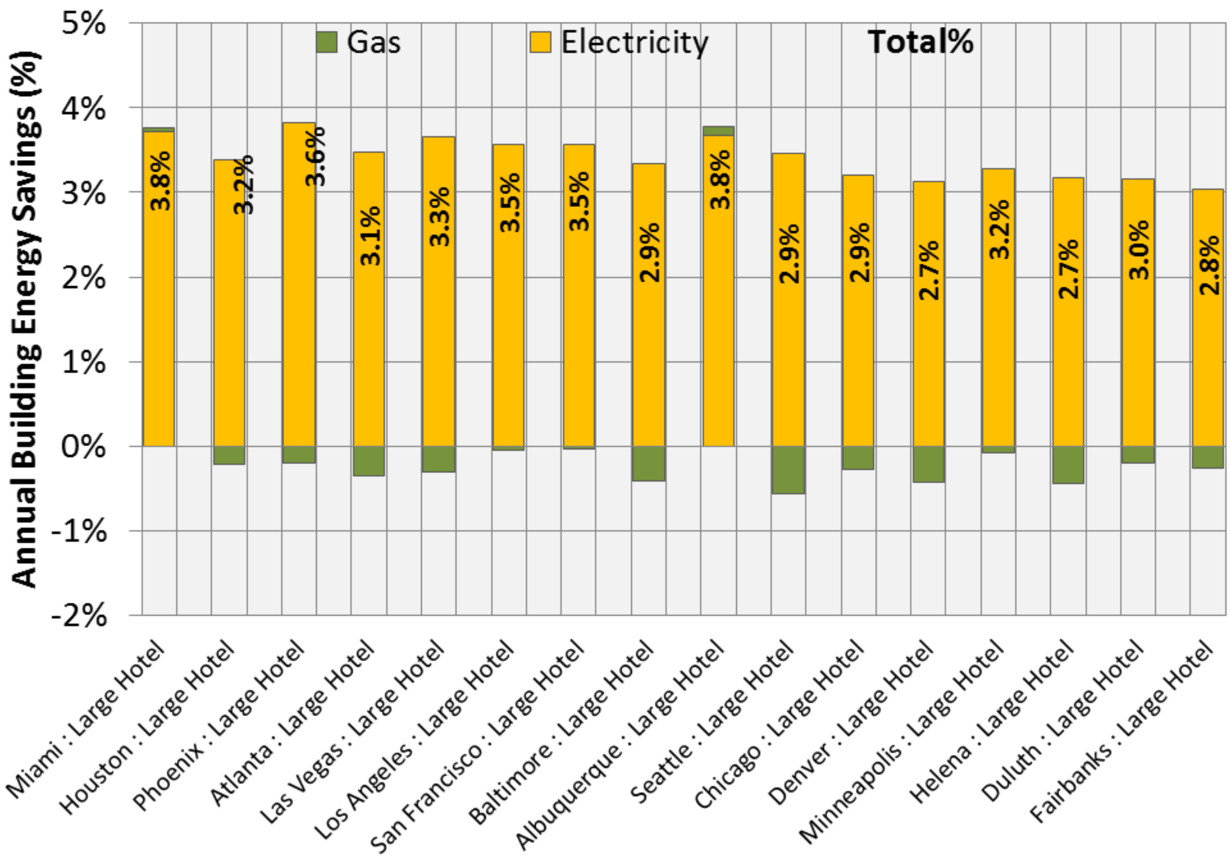

Figure A.57. Energy Savings: Measure 36 (Guest Room Occupancy Sensors for Lighting and HVAC): Large Hotel Prototype

A.37 Measure 37: Optimization of Heat Recovery Wheel

Figure A.58 shows the energy savings that can be achieved through optimization of the use of the heat recovery wheel. Bypassing the wheel when thermal energy savings is poor can save significant fan energy through reduced pressure drops in the DOAS ductwork. Building energy savings is up to 4% and is strongest for mild climates.

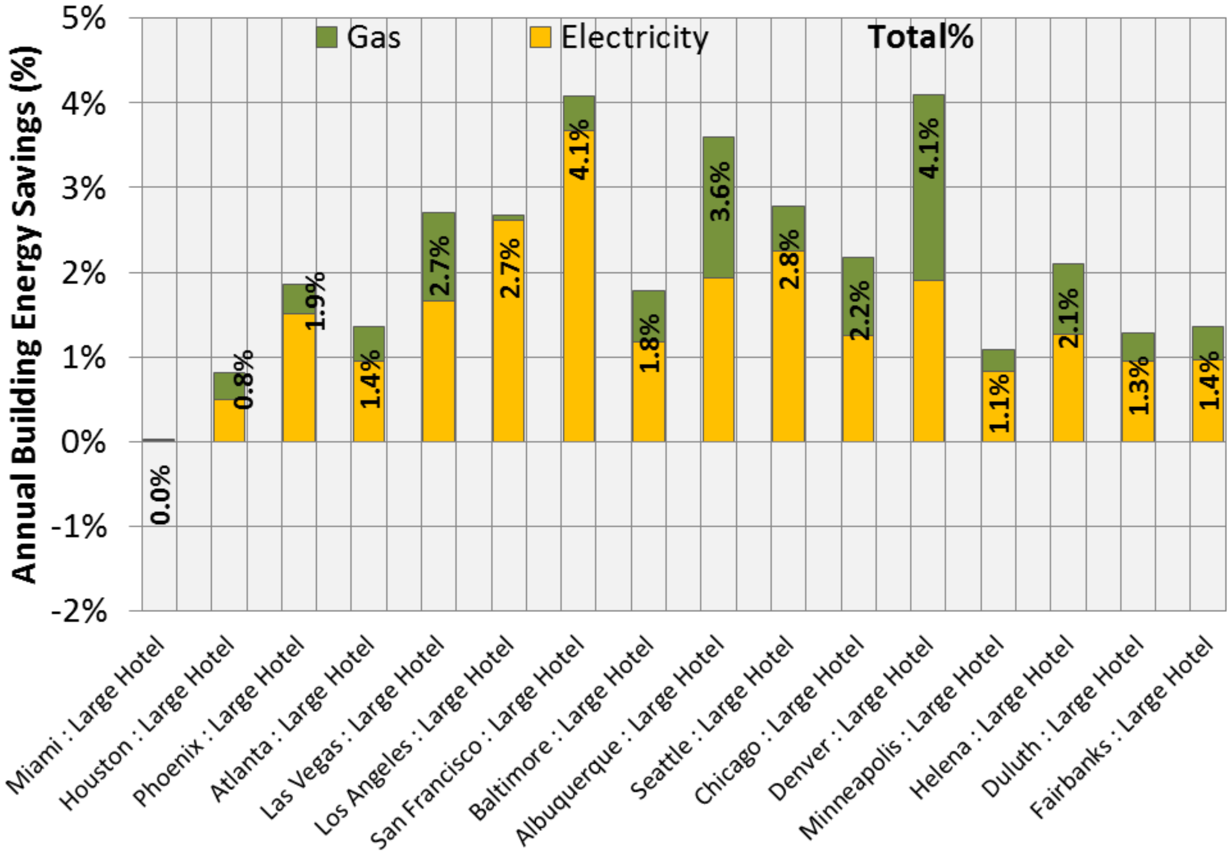

Figure A.58. Energy Savings: Measure 37 (Optimization of Heat Recovery Wheel): Large Hotel Prototype

Appendix B

EnergyPlus Users Guide to Measure Implementation

Appendix B

EnergyPlus Users Guide to Measure Implementation

This appendix contains sample EnergyPlus code as well as some discussion regarding the modeling strategy for selected measures—generally those measures for which the implementation strategy is not obvious.

B.1 Baseline: Addition of Indoor Pipe bjects

Large Office, Secondary School, and Large Hotel models are modified to include a run of indoor hot water piping that spans the long dimension of the building, located in the plenum space above each floor. Ninety percent of this pipe is insulated, while 10% is uninsulated (see two pipe objects below for the plenum spaces above the first floor of the Large Office model). The purpose of this addition is to more accurately model the effects of hot water temperature reset.

```
Pipe:Indoor,
 VAV_1_HeatC 1Demand Inlet Pipe 1,!- Name
 Hot Water Pipe Insulated,!- Construction Name
 VAV_1_HeatC 1Demand Inlet Node,!- Fluid Inlet Node Name
 VAV_1_HeatC 1Pipe 1 Outlet,!- Fluid Outlet Node Name
 Zone,!- Environment Type
 ZN_1_FLR_1_Plenum,!- Ambient Temperature Zone Name
,!- Ambient Temperature Schedule Name
,!- Ambient Air Velocity Schedule Name
 0.1524,!- Pipe Inside Diameter {m}
 75.17;!- Pipe Length {m}

Pipe:Indoor,
 VAV_1_HeatC 1Demand Inlet Pipe 2,!- Name
 Hot Water Pipe Uninsulated,!- Construction Name
 VAV_1_HeatC 1Pipe 1 Outlet,!- Fluid Inlet Node Name
 VAV_1_HeatC 1 Inlet Node,!- Fluid Outlet Node Name
 Zone,!- Environment Type
 ZN_1_FLR_1_Plenum,!- Ambient Temperature Zone Name
,!- Ambient Temperature Schedule Name
,!- Ambient Air Velocity Schedule Name
 0.1524,!- Pipe Inside Diameter {m}
 8.35;!- Pipe Length {m}
```

B.2 Measure 01: Re-calibrate Faulty Sensors

The following two EnergyPlus objects, taken from the Large Office prototype, demonstrate the use of the FaultModel:TemperatureSensor objects to simulate this fault. By switching the availability schedule to off, this measure (recalibration of the sensor) can be simulated.

```
FaultModel:TemperatureSensorOffset:OutdoorAir,
 VAV1 OA Sensor Bias,!- Name
 ALWAYS_ON,!- Availability Schedule Name
```

```
,!- Severity Schedule Name
 Controller:OutdoorAir,!- Controller Object Type
 VAV_1_OA_Controller,!- Controller Object Name
 3;!- Temperature Sensor Offset {deltaC}
FaultModel:TemperatureSensorOffset:ReturnAir,
 VAV1 RA Sensor Bias,!- Name
 ALWAYS_ON,!- Availability Schedule Name
,!- Severity Schedule Name
 Controller:OutdoorAir,!- Controller Object Type
 VAV_1_OA_Controller,!- Controller Object Name
 -3;!- Temperature Sensor Offset {deltaC}
```

B.3 Measure 03: Fix Leaking Heating Coil Valves

The following EnergyPlus objects, taken from the Large Office prototype, demonstrate the use of EMS objects to model the coil leakage fault. For brevity, the code has been shortened to only include one AHU. Sensors are defined for the mixed air temperature, the temperature setpoint at the cooling coil outlet, and for each of the VAV reheat coils. The actuator is the heating coil's outlet temperature setpoint. If any of the hot water reheat coils in the building are active, the flag variable HW_Flow is activated. Given that HW_Flow is active, if the mixed air temperature is colder than the cooling coil outlet temperature setpoint minus the minimum added temperature gain from coil leakage, the coil is considered to be in heating mode and will modulate open above and beyond the leakage amount to satisfy the heating setpoint. Otherwise, a fixed 2°C is added to the heating coil's temperature setpoint above the mixed air temperature. If HW_Flow is inactive, no change is made to the heating coil's temperature setpoint.

Note that the reheat coils are used instead of the hot water pump status to verify whether the hot water pump is on, because otherwise the pump would stay on all the time when the AHU heating coil is forced on by the EMS program.

```
EnergyManagementSystem:Sensor,
 VAV1_MA_Temp,
 VAV_1_OA-VAV_1_HeatC 1Node,
 System Node Temperature;

EnergyManagementSystem:Sensor,
 VAV1_CoolC_TempSP,
 VAV_1_CoolC 1-VAV_1_FanNode,
 System Node Setpoint Temperature;

EnergyManagementSystem:Sensor,
 VAV1_Sec1_Htg,
 ZN_1_FLR_1_SEC_1 VAV Box Reheat Coil,
 Heating Coil Heating Rate;

EnergyManagementSystem:Sensor,
 VAV1_Sec2_Htg,
 ZN_1_FLR_1_SEC_2 VAV Box Reheat Coil,
 Heating Coil Heating Rate;

EnergyManagementSystem:Sensor,
 VAV1_Sec3_Htg,
 ZN_1_FLR_1_SEC_3 VAV Box Reheat Coil,
 Heating Coil Heating Rate;
```

```
EnergyManagementSystem:Sensor,
 VAV1_Sec4_Htg,
 ZN_1_FLR_1_SEC_4 VAV Box Reheat Coil,
 Heating Coil Heating Rate;

EnergyManagementSystem:Sensor,
 VAV1_Sec5_Htg,
 ZN_1_FLR_1_SEC_5 VAV Box Reheat Coil,
 Heating Coil Heating Rate;

EnergyManagementSystem:Actuator,
 VAV1_HeatC_TempSP,
 VAV_1_HeatC 1-VAV_1_CoolC 1Node,
 System Node Setpoint,
 Temperature Setpoint;

EnergyManagementSystem:Program,
 LeakageHeat_Main,!- Name
 SET HW_Flow = 0,
 IF VAV1_Sec1_Htg > 0 || VAV1_Sec2_Htg > 0 || VAV1_Sec3_Htg > 0,
 SET HW_Flow = 1,
 ENDIF,
 IF VAV1_Sec4_Htg > 0 || VAV1_Sec5_Htg > 0,
 SET HW_Flow = 1,
 ENDIF,
 IF HW_Flow == 1,
 IF VAV1_MA_Temp < VAV1_CoolC_TempSP-2,
 SET VAV1_HeatC_TempSP = VAV1_CoolC_TempSP,
 ELSE,
 SET VAV1_HeatC_TempSP = VAV1_MA_Temp + 2,
 ENDIF,
 ELSE,
 SET VAV1_HeatC_TempSP = VAV1_CoolC_TempSP,
 ENDIF;
```

B.4 Measure 05: Supply Air Temperature (SAT) Reset

The following EnergyPlus code shows the implementation of the outdoor air temperature-based reset for the Large Office model.

```
EnergyManagementSystem:Sensor,
 T_amb,!- Name
 *,!- Output:Variable or Output:Meter Index Key Name
Site Outdoor Air DryBulb Temperature;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 HVACSch,!- Name
 HVACOperationSchd,!- Output:Variable or Output:Meter Index Key Name
 Schedule Value;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Actuator,
 SAT,!- Name
 Fixed-Supply-Air-Temp-Sch,!- Actuated Component Unique Name
```

```
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Program,
 SAT_RESET,!- Name
 If HVACSch==0 && T_amb<15.6,!- Program Line 1
 SET SAT=21.1,!- Program Line 2
 Else,!- A6
 SET SAT=12.8,!- A7
 ENDIF;!- A8
```

B.5 Measure 08: Static Pressure Reset (*Maximum Damper Position method*)

This control is performed using an EMS program. The custom program specifies each of the VAV boxes in the network as sensors and the fan pressure rise as the actuator. The program code for a typical VAV system (taken from the Large Office model) is reproduced below.

```
EnergyManagementSystem:Sensor,
       VAV1_1,!- Name
       ZN_1_FLR_1_SEC_1 VAV Box Component,!- Output:Variable or Output:Meter Index Key
Name
       Zone Air Terminal VAV Damper Position;!- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
 VAV1_2,!- Name
 ZN_1_FLR_1_SEC_2 VAV Box Component,!- Output:Variable or Output:Meter Index Key Name
 Zone Air Terminal VAV Damper Position;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 VAV1_3,!- Name
 ZN_1_FLR_1_SEC_3 VAV Box Component,!- Output:Variable or Output:Meter Index Key Name
 Zone Air Terminal VAV Damper Position;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 VAV1_4,!- Name
 ZN_1_FLR_1_SEC_4 VAV Box Component,!- Output:Variable or Output:Meter Index Key Name
 Zone Air Terminal VAV Damper Position;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 VAV1_5,!- Name
 ZN_1_FLR_1_SEC_5 VAV Box Component,!- Output:Variable or Output:Meter Index Key Name
 Zone Air Terminal VAV Damper Position;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Actuator,
 FPR_1,!- Name
 VAV_1_Fan,!- Actuated Component Unique Name
 Fan,!- Actuated Component Type
 Fan Pressure Rise;!- Actuated Component Control Type

EnergyManagementSystem:Program,
 SP_Reset,!- Name
 SET FPRMax1=1500,!- Program Line 1
 SET FPRMax2=1500,!- Program Line 2
```

```
 SET FPRMax3=1500,!- A4
 SET VAV1Max= @Max VAV1_1 VAV1_2,!- A5
 SET VAV1Max= @Max VAV1Max VAV1_3,!- A6
 SET VAV1Max= @Max VAV1Max VAV1_4,!- A7
 SET VAV1Max= @Max VAV1Max VAV1_5,!- A8
 SET FPR_1= FPRMax1*VAV1Max/0.95,!- A17
 SET FPR_1 = @Max FPR_1 FPRMax1*0.5,!- A18
 SET FPR_1 = @Min FPR_1 FPRMax1,!- A19
```

B.6 Measure 08: Static Pressure Reset (*Time of Day Reset*)

For Large and Medium Office prototypes, the time-of-day schedule for reduced static pressure setpoints is from 5:00 p.m. to 5:00 a.m., Monday through Friday, and from 1:00 p.m. Saturday to 5:00 a.m. Monday morning. During these times, the static pressure is reduced to half of its default value. The following EnergyPlus code shows the schedule and EnergyManagementSystem code used to control the setpoint.

```
Schedule:Compact,
 SP_Reset TOD Schedule,!- Name
 on/off,!- Schedule Type Limits Name
 Through: 12/31,!- Field 1
 For: Weekdays SummerDesignDay WinterDesignDay,!- Field 2
 Until: 05:00,!- Field 3
 0.0,!- Field 4
 Until: 17:00,!- Field 5
 1.0,!- Field 6
 Until: 24:00,!- Field 7
 0.0,!- Field 8
 For: Saturday,!- Field 9
 Until: 05:00,!- Field 10
 0.0,!- Field 11
 Until: 13:00,!- Field 12
 1.0,!- Field 13
 Until: 24:00,!- Field 14
 0.0,!- Field 15
 For: Sunday Holidays AllOtherDays,!- Field 16
 Until: 24:00,!- Field 17
 0.0;!- Field 18

EnergyManagementSystem:Sensor,
 SP_TOD,!- Name
 SP_Reset TOD Schedule,!- Output:Variable or Output:Meter Index Key Name
 Schedule Value;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Actuator,
 FPR_1,!- Name
 VAV_1_Fan,!- Actuated Component Unique Name
 Fan,!- Actuated Component Type
 Fan Pressure Rise;!- Actuated Component Control Type

EnergyManagementSystem:Program,
 SP_Reset,!- Name
 SET MaxFPR=1500,
 IF SP_TOD==1,
 SET FPR_1=MaxFPR,
```

```
 Else,
 SET FPR_1=MaxFPR*0.5,
 Endif;
```

B.7 Measure 9: Plant Shutdown When There is No Load

This measure relies on the use of custom EMS code to ensure that the secondary loop pumps are turned off whenever the lead equipment in the primary loop shuts off (this equipment in turn automatically shuts off when there is no load). The EMS code is shown below.

Although Large Office, Large Hotel, and Primary School prototypes all include secondary pumps for chilled and/or hot water loops, this measure could only be simulated as intended for the Large Office prototype. The custom EMS code did not work as intended in the other two prototypes.

```
EnergyManagementSystem:Sensor,
 VAV_1_Status,!- Name
 VAV_1_Fan,!- Output:Variable or Output:Meter Index Key Name
 Fan Electric Power;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 VAV_2_Status,!- Name
 VAV_2_Fan,!- Output:Variable or Output:Meter Index Key Name
 Fan Electric Power;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 VAV_3_Status,!- Name
 VAV_3_Fan,!- Output:Variable or Output:Meter Index Key Name
 Fan Electric Power;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 B1_pump_Status,!- Name
 HeatSys1 Pump Boiler 1,!- Output:Variable or Output:Meter Index Key Name
 Pump Electric Power;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Actuator,
 CoolSecLoopFlow,!- Name
 CoolSys1 Pump Secondary,!- Actuated Component Unique Name
 Pump,!- Actuated Component Type
 Pump Mass Flow Rate;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 HotSecLoopFlow,!- Name
 HeatSys1 Pump Secondary,!- Actuated Component Unique Name
 Pump,!- Actuated Component Type
 Pump Mass Flow Rate;!- Actuated Component Control Type

EnergyManagementSystem:Program,
 PumpRunCtl3,!- Name
 SET CoolSecLoopFlow = NULL,!- Program Line 1
 IF CH1_Status ==0,!- Program Line 2
 SET CoolSecLoopFlow = 0,!- A4
 ELSE,!- A5
 SET CoolSecLoopFlow = NULL,!- A6
```

```
ENDIF,!- A7
IF B1_pump_Status >0,!- A8
SET HotSecLoopFlow = NULL,!- A9
ELSE,!- A10
SET HotSecLoopFlow=0,!- A11
ENDIF;!- A12
```

B.8 Measure 10: Chilled Water Differential Pressure (DP) Reset

The two EnergyPlus objects below from the baseline Large Office model and the chilled water DP Reset model show the different set of coefficients used in the pump curve.

Baseline models

```
Pump:VariableSpeed,
 CoolSys1 Pump Secondary,!- Name
 CoolSys1 Demand Inlet Node,!- Inlet Node Name
 CoolSys1 Demand Pump Secondary-CoolSys1 Demand Mixer,!- Outlet Node Name
 autosize,!- Rated Flow Rate {m3/s}
 120000,!- Rated Pump Head {Pa}
 autosize,!- Rated Power Consumption {W}
 0.88,!- Motor Efficiency
 0,!- Fraction of Motor Inefficiencies to Fluid Stream
 0,!- Coefficient 1 of the Part Load Performance Curve
 0.5726,!- Coefficient 2 of the Part Load Performance Curve
 -0.301,!- Coefficient 3 of the Part Load Performance Curve
 0.7347,!- Coefficient 4 of the Part Load Performance Curve
 0.01249186,!- Minimum Flow Rate {m3/s}
 Intermittent,!- Pump Control Type
 PumpOperationSchd2;!- Pump Flow Rate Schedule Name
```

Measure 10

```
Pump:VariableSpeed,
 CoolSys1 Pump Secondary,!- Name
 CoolSys1 Demand Inlet Node,!- Inlet Node Name
 CoolSys1 Demand Pump Secondary-CoolSys1 Demand Mixer,!- Outlet Node Name
 autosize,!- Rated Flow Rate {m3/s}
 120000,!- Rated Pump Head {Pa}
 autosize,!- Rated Power Consumption {W}
 0.88,!- Motor Efficiency
 0,!- Fraction of Motor Inefficiencies to Fluid Stream
 0,!- Coefficient 1 of the Part Load Performance Curve
 0.0205,!- Coefficient 2 of the Part Load Performance Curve
 0.4101,!- Coefficient 3 of the Part Load Performance Curve
 0.5753,!- Coefficient 4 of the Part Load Performance Curve
 0.01249186,!- Minimum Flow Rate {m3/s}
 Intermittent,!- Pump Control Type
 PumpOperationSchd2;!- Pump Flow Rate Schedule Name
```

B.9 Measure 11: Chilled Water Temperature Reset (*Outdoor Air Temperature-Based Reset)*.

A simple EMS program is used to program this reset in EnergyPlus as shown below.

```
EnergyManagementSystem:Sensor,
 OAT,!- Name
 *,!- Output:Variable or Output:Meter Index Key Name
 Site Outdoor Air Drybulb Temperature;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Actuator,
 CHWSupplyTemp_actuator,!- Name
 COOLSYS1 SUPPLY OUTLET NODE,!- Actuated Component Unique Name
 System Node Setpoint,!- Actuated Component Type
 Temperature Setpoint;!- Actuated Component Control Type

EnergyManagementSystem:Program,
 CHWST_Reset,!- Name
 IF OAT<15.6,!- A6
 SET CHWSupplyTemp=10,
 ELSEIF OAT<26.7,
 SET CHWSupplyTemp=6.67+(26.7-OAT)/(26.7-15.6)*3.33,
 ELSE,
 SET CHWSupplyTemp=6.67,
 ENDIF;!- A10
```

B.10 Measure 12: Condenser Water Temperature Reset

An EMS program is used to model condenser water temperature reset, as shown below, using code from the Large Office model.

```
EnergyManagementSystem:Sensor,
 T_WB_OA,!- Name
,!- Output:Variable or Output:Meter Index Key Name
 Site Outdoor Air WetBulb Temperature;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Actuator,
 Tower_TempSP_Actuator,!- Name
 Tower Loop Setpoint Sched,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Program,

Tower_TempReset,!- Name
 IF (T_WB_OA + 4) >= 18.3,!- Program Line 1
      IF (T_WB_OA + 4) <= 26.7,!- Program Line 2
             SET Tower_TempSP_Actuator = T_WB_OA + 4,!- A4
      ELSE,!- A5
             SET Tower_TempSP_Actuator = 26.7,!- A6
      ENDIF,!- A7
 ELSE,!- A8
      SET Tower_TempSP_Actuator = 18.3,!- A9
```

```
 ENDIF;!- A10
```

B.11 Measure 14: Hot Water Temperature Reset

Although the temperature reset is very straightforward to implement in EnergyPlus, the impact of reductions in hot water temperature on energy savings achieved through reduced standby heat losses in hot water piping are very difficult to capture in an EnergyPlus model. For model prototypes with a hot water plant (Large Office, Large Hotel, Primary and Secondary School), however, the baseline has been modified to include a main trunk of indoor hot water piping that spans the long dimension of the building. In the case of the Large Office model, the piping is located in the plenum space above each floor. For buildings with two or fewer stories (Primary and Secondary School), the main hot water trunk is included on a single floor along the long dimension of the main building, and because these two prototypes contain "pod" wings, the main trunk is also extended to the ends of the wings. For the Large Hotel prototype, the hot water piping is simulated along the long dimension of the first floor, and also rises vertically through the center of the building in corridor spaces. An assumption is made that 90% of this pipe is insulated, while 10% is uninsulated (see two pipe objects below for the plenum spaces above the first floor of the Large Office model).

```
Pipe:Indoor,
 VAV_1_HeatC 1Demand Inlet Pipe 1,!- Name
 Hot Water Pipe Insulated,!- Construction Name
 VAV_1_HeatC 1Demand Inlet Node,!- Fluid Inlet Node Name
 VAV_1_HeatC 1Pipe 1 Outlet,!- Fluid Outlet Node Name
 Zone,!- Environment Type
 ZN_1_FLR_1_Plenum,!- Ambient Temperature Zone Name
,!- Ambient Temperature Schedule Name
,!- Ambient Air Velocity Schedule Name
 0.1524,!- Pipe Inside Diameter {m}
 75.17;!- Pipe Length {m}

Pipe:Indoor,
 VAV_2_HeatC 1Demand Inlet Pipe 2,!- Name
 Hot Water Pipe Uninsulated,!- Construction Name
 VAV_2_HeatC 1Pipe 1 Outlet,!- Fluid Inlet Node Name
 VAV_2_HeatC 1 Inlet Node,!- Fluid Outlet Node Name
 Zone,!- Environment Type
 ZN_1_FLR_2_Plenum,!- Ambient Temperature Zone Name
,!- Ambient Temperature Schedule Name
,!- Ambient Air Velocity Schedule Name
 0.1524,!- Pipe Inside Diameter {m}
 8.35;!- Pipe Length {m}
```

The hot water temperature reset uses a SetpointManager:OutsideAirReset object (see below) to reset the hot water temperature based on outdoor air temperature. At 65°F outdoor air temperature, the hot water supply temperature is set to 150°F and increases linearly to 180°F at 20°F outdoor air temperature. For non-condensing boilers, it is typically not feasible to lower the supply water temperature below ~150°F because this can lead to condensation, which can be damaging to these boilers.

```
SetpointManager:OutdoorAirReset,
 HeatSys1 Loop Setpoint Manager,!- Name
 Temperature,!- Control Variable
 82.2,!- Setpoint at Outdoor Low Temperature {C}
```

```
 -6.7,!- Outdoor Low Temperature {C}
 65.6,!- Setpoint at Outdoor High Temperature {C}
 18.3,!- Outdoor High Temperature {C}
```

B.12 Measure 15: Minimum VAV Terminal Box Damper Flow Reductions

A sample VAV terminal box object from the Medium Office prototype shows how the minimum airflow fraction, highlighted in red, can be reduced in EnergyPlus.

```
AirTerminal:SingleDuct:VAV:Reheat,
 Core_bottom VAV Box Component,!- Name
 ALWAYS_ON,!- Availability Schedule Name
 Core_bottom VAV Box Damper Node,!- Damper Air Outlet Node Name
 Core_bottom VAV Box Inlet Node,!- Air Inlet Node Name
 2.62223,!- Maximum Airflow Rate {m3/s}
 Constant,!- Zone Minimum Airflow Input Method
 0.25,!- Constant Minimum Airflow Fraction
,!- Fixed Minimum Airflow Rate {m3/s}
,!- Minimum Airflow Fraction Schedule Name
 Coil:Heating:Electric,!- Reheat Coil Object Type
 Core_bottom VAV Box Reheat Coil,!- Reheat Coil Name
 AUTOSIZE,!- Maximum Hot Water or Steam Flow Rate {m3/s}
 0.0,!- Minimum Hot Water or Steam Flow Rate {m3/s}
 Core_bottom VAV Box Outlet Node,!- Air Outlet Node Name
 0.001,!- Convergence Tolerance
 Normal;!- Damper Heating Action Results
```

B.13 Measure 17: Demand Control Ventilation *(Zone Sum method)*

```
Controller:OutdoorAir,
 VAV_1_OA_Controller,!- Name
 VAV_1_OARelief Node,!- Relief Air Outlet Node Name
 VAV_1 Supply Equipment Inlet Node,!- Return Air Node Name
 VAV_1_OA-VAV_1_HeatC 1Node,!- Mixed Air Node Name
 VAV_1_OAInlet Node,!- Actuator Node Name
 0,!- Minimum Outdoor Airflow Rate {m3/s}
 AUTOSIZE,!- Maximum Outdoor Airflow Rate {m3/s}
 NoEconomizer,!- Economizer Control Type
 ModulateFlow,!- Economizer Control Action Type
,!- Economizer Maximum Limit Dry-Bulb Temperature {C}
 55824,!- Economizer Maximum Limit Enthalpy {J/kg}
,!- Economizer Maximum Limit Dewpoint Temperature {C}
,!- Electronic Enthalpy Limit Curve Name
,!- Economizer Minimum Limit Dry-Bulb Temperature {C}
 NoLockout,!- Lockout Type
 FixedMinimum,!- Minimum Limit Type
 MinOA_Sched_Base,!- Minimum Outdoor Air Schedule Name
 MinOAFracSch_DCV,!- Minimum Fraction of Outdoor Air Schedule Name
 MaxOAFracSch_Adv,!- Maximum Fraction of Outdoor Air Schedule Name
 VAV_1_Vent_Controller,!- Mechanical Ventilation Controller Name
,!- Time of Day Economizer Control Schedule Name
```

```
,!- High Humidity Control
,!- Humidistat Control Zone Name
,!- High Humidity Outdoor Airflow Ratio
 No;!- Control High Indoor Humidity Based on Outdoor Humidity Ratio

Controller:MechanicalVentilation,
 VAV_1_Vent_Controller,!- Name
 DCV_Sched,!- Availability Schedule Name
 Yes,!- Demand Controlled Ventilation
 ZoneSum,!- System Outdoor Air Method
,!- Zone Maximum Outdoor Air Fraction {dimensionless}
 ZN_1_FLR_1_SEC_1,!- Zone 1 Name
 Zone Ventilation DCV,!- Design Specification Outdoor Air Object Name 1
 DCV ZADE,!- Design Specification Zone Air Distribution Object Name 1
 ZN_1_FLR_1_SEC_2,!- Zone 1 Name
 Zone Ventilation DCV,!- Design Specification Outdoor Air Object Name 1
 DCV ZADE,!- Design Specification Zone Air Distribution Object Name 1
 ZN_1_FLR_1_SEC_3,!- Zone 1 Name
 Zone Ventilation DCV,!- Design Specification Outdoor Air Object Name 1
 DCV ZADE,!- Design Specification Zone Air Distribution Object Name 1
 ZN_1_FLR_1_SEC_4,!- Zone 1 Name
 Zone Ventilation DCV,!- Design Specification Outdoor Air Object Name 1
 DCV ZADE,!- Design Specification Zone Air Distribution Object Name 1
 ZN_1_FLR_1_SEC_5,!- Zone 1 Name
 Zone Ventilation DCV,!- Design Specification Outdoor Air Object Name 1
 DCV ZADE;!- Design Specification Zone Air Distribution Object Name 1

DesignSpecification:ZoneAirDistribution,
 DCV ZADE,!- Name
 1.0,!- Zone Air Distribution Effectiveness in Cooling Mode
 0.8;!- Zone Air Distribution Effectiveness in Heating Mode

DesignSpecification:OutdoorAir,
 Zone Ventilation DCV,!- Name
 Sum,!- Outdoor Air Method
 0.00236,!- Outdoor Airflow per Person {m3/s-person}
 0.00031,!- Outdoor Airflow per Zone Floor Area {m3/s-m2}
 0.0;!- Outdoor Airflow per Zone {m3/s}

Schedule:Compact,
 DCV_Sched,!- Name
 On/Off,!- Schedule Type Limits Name
 Through: 12/31,!- Field 1
 For: Weekdays SummerDesignDay WinterDesignDay,!- Field 2
 Until: 07:00,!- Field 3
 0.0,!- Field 4
 Until: 22:00,!- Field 5
 1.0,!- Field 6
 Until: 24:00,!- Field 7
 0.0,!- Field 8
 For: Saturday,!- Field 9
 Until: 07:00,!- Field 10
 0.0,!- Field 11
 Until: 18:00,!- Field 12
 1.0,!- Field 13
```

```
 Until: 24:00,!- Field 14
 0.0,!- Field 15
 For: Sunday Holidays AllOtherDays,!- Field 16
 Until: 07:00,!- Field 17
 0.0,!- Field 18
 Until: 18:00,!- Field 19
 0.0,!- Field 20
 Until: 24:00,!- Field 21
 0.0;!- Field 22

Schedule:Compact,
 MinOAFracSch_DCV,!- Name
 Fraction,!- Schedule Type Limits Name
 Through: 12/31,!- Field 1
 For: Weekdays,!- Field 2
 Until: 05:00,!- Field 3
 0.10,!- Field 4
 Until: 22:00,!- Field 5
 0.10,!- Field 6
 Until: 24:00,!- Field 7
 0.10,!- Field 8
 For: Saturday,!- Field 9
 Until: 05:00,!- Field 10
 0.10,!- Field 11
 Until: 18:00,!- Field 12
 0.10,!- Field 13
 Until: 24:00,!- Field 14
 0.1,!- Field 15
 For: SummerDesignDay,!- Field 16
 Until: 24:00,!- Field 17
 0.15,!- Field 18
 For: WinterDesignDay,!- Field 19
 Until: 24:00,!- Field 20
 0.15,!- Field 21
 For: Sunday Holidays AllOtherDays,!- Field 22
 Until: 06:00,!- Field 23
 0.10,!- Field 24
 Until: 18:00,!- Field 25
 0.10,!- Field 26
 Until: 24:00,!- Field 27
 0.10;!- Field 28
```

B.14 Measure 17: Demand Control Ventilation *(CO_2 concentration method)*

In this procedure, EnergyPlus calculates the amount of outdoor air necessary to maintain the levels of indoor air CO_2 at or below the setpoint defined in the ZoneControl:ContaminantController object (1000 ppm; see below for EnergyPlus code used to control one packaged unit in the Small Office prototype).

```
ZoneAirContaminantBalance,
 Yes,!- Carbon Dioxide Concentration
 Outdoor CO2 Schedule;!- Outdoor Carbon Dioxide Schedule Name
```

```
Schedule:Compact,
 Outdoor CO2 Schedule,!- Name
 Any Number,!- Schedule Type Limits Name
 Through: 12/31,!- Field 1
 For: AllDays,!- Field 2
 Until: 24:00,!- Field 3
 400.0;!- Field 4
Schedule:Compact,
 CO2AvailSchedule,!- Name
 Any Number,!- Schedule Type Limits Name
 Through: 12/31,!- Field 1
 For: Weekdays SummerDesignDay,!- Field 2
 Until: 07:00,!- Field 3
 0.0,!- Field 4
 Until: 22:00,!- Field 5
 1.0,!- Field 6
 Until: 24:00,!- Field 7
 0.0,!- Field 8
 For: Saturday WinterDesignDay,!- Field 9
 Until: 07:00,!- Field 10
 0.0,!- Field 11
 Until: 18:00,!- Field 12
 1.0,!- Field 13
 Until: 24:00,!- Field 14
 0.0,!- Field 15
 For: AllOtherDays,!- Field 16
 Until: 24:00,!- Field 17
 0.0;!- Field 18

Schedule:Compact,
 CO2SetpointSchedule,!- Name
 Any Number,!- Schedule Type Limits Name
 Through: 12/31,!- Field 1
 For: AllDays,!- Field 2
 Until: 24:00,!- Field 3
 1000;!- Field 4

Schedule:Compact,
 MinOAFracSch_DCV,!- Name
 Fraction,!- Schedule Type Limits Name
 Through: 12/31,!- Field 1
 For: Weekdays,!- Field 2
 Until: 07:00,!- Field 3
 0.10,!- Field 4
 Until: 22:00,!- Field 5
 0.10,!- Field 6
 Until: 24:00,!- Field 7
 0.10,!- Field 8
 For: Saturday,!- Field 9
 Until: 07:00,!- Field 10
 0.10,!- Field 11
 Until: 18:00,!- Field 12
 0.10,!- Field 13
 Until: 24:00,!- Field 14
```

```
 0.10,!- Field 15
 For: SummerDesignDay WinterDesignDay,!- Field 16
 Until: 24:00,!- Field 21
 0.15,!- Field 22
 For: Sunday Holidays AllOtherDays,!- Field 23
 Until: 24:00,!- Field 28
 0.10;!- Field 29

DesignSpecification:ZoneAirDistribution,
 DCV ZADE,!- Name
 1.0,!- Zone Air Distribution Effectiveness in Cooling Mode
 0.8;!- Zone Air Distribution Effectiveness in Heating Mode

ZoneControl:ContaminantController,
 TS11 CO2 Controller,!- Name
 South Perim Spc TS11,!- Controlled Zone Name
 CO2AvailSchedule,!- Carbon Dioxide Control Availability Schedule Name
 CO2SetpointSchedule;!- Carbon Dioxide Setpoint Schedule Name

Controller:MechanicalVentilation,
 PSZ1 South F2 DCV,!- Name
 CO2AvailSchedule,!- Availability Schedule Name
 Yes,!- Demand Controlled Ventilation
 IndoorAirQualityProcedure,!- System Outdoor Air Method
,!- Zone Maximum Outdoor Air Fraction {dimensionless}
 South Perim Spc TS11,!- Zone 1 Name
 South Perim Spc TS11 DCV,!- Design Specification Outdoor Air Object Name 1
 DCV ZADE;!- Design Specification Zone Air Distribution Object Name 1
```

B.15 Measure 19: Daylighting Control

A sample EnergyPlus daylighting control object for a Large Office perimeter zone is shown below:

```
Daylighting:Controls,
 ZN_1_FLR_1_SEC_1,!- Zone Name
 1,!- Total Daylighting Reference Points
 41.757600,!- X-Coordinate of First Reference Point {m}
 4.100000,!- Y-Coordinate of First Reference Point {m}
 0.900000,!- Z-Coordinate of First Reference Point {m}
,!- X-Coordinate of Second Reference Point {m}
,!- Y-Coordinate of Second Reference Point {m}
,!- Z-Coordinate of Second Reference Point {m}
 0.75,!- Fraction of Zone Controlled by First Reference Point
 0.0,!- Fraction of Zone Controlled by Second Reference Point
 300,!- Illuminance Setpoint at First Reference Point {lux}
 300,!- Illuminance Setpoint at Second Reference Point {lux}
 1,!- Lighting Control Type
 180,!- Glare Calculation Azimuth Angle of View Direction Clockwise from Zone y-Axis
{deg}
 22.0,!- Maximum Allowable Discomfort Glare Index
 0.1,!- Minimum Input Power Fraction for Continuous Dimming Control
 0.1,!- Minimum Light Output Fraction for Continuous Dimming Control
 0,!- Number of Stepped Control Steps
 1.0,!- Probability Lighting will be Reset When Needed in Manual Stepped Control
```

```
 ALWAYS_ON;!- Availability Schedule Name
```

B.16 Measure 20: Exterior Lighting Control

A sample EnergyPlus schedule and exterior light control object is shown below.

```
Schedule:Compact,
 ParkingLightsSch,!- Name
 Fraction,!- Schedule Type Limits Name
 Through: 12/31,!- Field 1
 For: Weekdays,!- Field 2
 Until: 5:00,!- Field 3
 0.25,!- Field 4
 Until: 19:00,!- Field 5
 1.0,!- Field 6
 Until: 24:00,!- Field 7
 0.25,!- Field 8
 For: SummerDesignDay,!- Field 9
 Until: 24:00,!- Field 10
 1.0,!- Field 11
 For: Saturday,!- Field 12
 Until: 05:00,!- Field 13
 0.25,!- Field 14
 Until: 19:00,!- Field 15
 1.0,!- Field 16
 Until: 24:00,!- Field 17
 0.25,!- Field 18
 For: WinterDesignDay,!- Field 19
 Until: 24:00,!- Field 20
 1,!- Field 21
 For: Sunday Holidays AllOtherDays,!- Field 22
 Until: 24:00,!- Field 23
 0.25;!- Field 24

Exterior:Lights,
 ParkingLot_Lights,!- Name
 ParkingLightsSch,!- Schedule Name
 23516,!- Design Level {W}
 AstronomicalClock,!- Control Option
 General;!- End-Use Subcategory
```

B.17 Measure 22: Night Purge

EnergyPlus objects used for specification of night purge ventilation for one AHU are included below (from the Large Office prototype).

```
AvailabilityManager:NightVentilation,
 Night Purge VAV_1,!- Name
 Night Purge Availability,!- Applicability Schedule Name
 HVACOperationSchd,!- Fan Schedule Name
 NightPurge_HTGSETP_SCH,!- Ventilation Temperature Schedule Name
 2,!- Ventilation Temperature Difference {deltaC}
 15,!- Ventilation Temperature Low Limit {C}
```

```
 0.35,!- Night Venting Flow Fraction
 ZN_1_FLR_1_SEC_5;!- Control Zone Name

Schedule:Compact,
 NightPurge_HTGSETP_SCH,!- Name
 Temperature,!- Schedule Type Limits Name
 Through: 12/31,!- Field 1
 For: AllDays,!- Field 2
 Until: 24:00,!- Field 3
 21.7;!- Field 4

Schedule:Compact,
 Night Cycle Availability,!- Name
 On/Off,!- Schedule Type Limits Name
 Through: 12/31,!- Field 1
 For: Weekdays SummerDesignDay WinterDesignDay,!- Field 2
 Until: 04:00,!- Field 3
 1.0,!- Field 4
 Until: 5:00,!- Field 5
 0.0,!- Field 6
 Until: 24:00,!- Field 7
 1.0,!- Field 8
 For: Saturday,!- Field 9
 Until: 04:00,!- Field 10
 1.0,!- Field 11
 Until: 5:00,!- Field 12
 0.0,!- Field 13
 Until: 24:00,!- Field 14
 1.0,!- Field 15
 For: Sunday Holidays AllOtherDays,!- Field 16
 Until: 07:00,!- Field 17
 1.0,!- Field 18
 Until: 18:00,!- Field 19
 1.0,!- Field 20
 Until: 24:00,!- Field 21
 1.0;!- Field 22
FanPerformance:NightVentilation,
 VAV_1_Fan,!- Fan Name
 0.42,!- Fan Total Efficiency
 750,!- Pressure Rise {Pa}
 autosize,!- Maximum Flow Rate {m3/s}
 0.64,!- Motor Efficiency
 1;!- Motor in Airstream Fraction

EnergyManagementSystem:Sensor,
 OAT,!- Name
 *,!- Output:Variable or Output:Meter Index Key Name
 Site Outdoor Air Drybulb Temperature;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Actuator,
 NP_A,!- Name
 Night Purge Availability,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type
```

```
EnergyManagementSystem:Actuator,
 NC_A,!- Name
 Night Cycle Availability,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Program,
 Night_Purge_Availability,!- Name
 SET OATPrev2Days = @TrendAverage OAT_Trend 288,!- Program Line 1
 IF OATPrev2Days >15.6 && Hour>=4 && Hour<5,!- Program Line 2
 SET NP_A =1,!- A4
 SET NC_A =0,
 ELSE,!- A5
 SET NP_A=0,!- A6
 SET NC_A =1,
 ENDIF;!- A7

EnergyManagementSystem:TrendVariable,
 OAT_Trend,!- Name
 OAT,!- EMS Variable Name
 288;!- Number of Timesteps to be Logged

AvailabilityManagerAssignmentList,
 VAV_1 Availability Manager List,!- Name
 AvailabilityManager:NightCycle,!- Availability Manager 1 Object Type
 VAV_1 Availability Manager,!- Availability Manager 1 Name
 AvailabilityManager:NightVentilation,!- Availability Manager 2 Object Type
 Night Purge VAV_1;!- Availability Manager 2 Name

AvailabilityManager:NightCycle,
 VAV_1 Availability Manager,!- Name
 Night Cycle Availability,!- Applicability Schedule Name
 HVACOperationSchd,!- Fan Schedule Name
 CycleOnAny,!- Control Type
 1.0,!- Thermostat Tolerance {deltaC}
 1800;!- Cycling Run Time {s}
```

B.18 Measure 23: Advanced RTU Control

The EnergyPlus code used to specify this advanced RTU control is reproduced below for one RTU in the Small Office prototype.

```
EnergyManagementSystem:Program,
 Set_FanCtl_Par1,
 SET FanPwrExp = 2.2,
 SET HeatSpeed = 0.9,
 SET VenSpeed = 0.4,
 SET Stage1Speed = 0.9,!one stage cooling coil
 SET Stage2Speed = 0.9,
 SET EcoSpeed = 0.75;

EnergyManagementSystem:Program,
 Set_FanCtl_Par2,
 SET PSZ1_OADesignMass = 0.08,
```

```
EnergyManagementSystem:ProgramCallingManager,
 Fan_Parameter_manager,!- Name
 BeginNewEnvironment,!- EnergyPlus Model Calling Point
 Set_FanCtl_Par1,!- Program Name 1
 Set_FanCtl_Par2;!- Program Name 1

EnergyManagementSystem:InternalVariable,
 PSZ1_FanDesignPressure,!- Name
 PSZ-1 South F2 Supply Fan,!- Internal Data Index Key Name
 Fan Nominal Pressure Rise;!- Internal Data Type

EnergyManagementSystem:InternalVariable,
 PSZ1_DesignFlowMass,!- Name
 PSZ-1 SOUTH F2 OA CONTROLLER,!- Internal Data Index Key Name
 Outdoor Air Controller Maximum Mass Flow Rate;!- Internal Data Type

EnergyManagementSystem:Sensor,
 PSZ1_OASch,
 MinOA_Sched,! This schedule name may be changed for measure combinations
 Schedule Value;

EnergyManagementSystem:Sensor,
 PSZ1_OAFracSch,
 MinOAFracSch_Base,! This schedule name may be changed for measure combinations
 Schedule Value;

EnergyManagementSystem:Sensor,
 PSZ1_OAFlowMass,
 PSZ-1 South F2 Outside Air Inlet,
 System Node Mass Flow Rate;

EnergyManagementSystem:Sensor,
 PSZ1_HtgRTF,
 PSZ-1 South F2 Heating Coil,
 Heating Coil Runtime Fraction;

EnergyManagementSystem:Sensor,
 PSZ1_ClgRTF,
 PSZ-1 South F2 Cooling Coil,
 Cooling Coil Runtime Fraction;

EnergyManagementSystem:Actuator,
 PSZ1_FanPressure,! Name
 PSZ-1 South F2 Supply Fan,! Actuated Component Unique Name
 Fan,! Actuated Component Type
 Fan Pressure Rise;! Actuated Component Control Type

EnergyManagementSystem:Program,
 PSZ1_FanControl,!- Name
 IF PSZ1_HtgRTF > 0,
 SET PSZ1_Htg = PSZ1_HtgRTF,!Percent of time in heating mode
 SET PSZ1_Ven = 1 - PSZ1_HtgRTF,!Percent of time in ventilation mode
 SET PSZ1_Eco = 0,!Percent of time in economize mode
```

```
 SET PSZ1_Stage1 = 0,!Percent of time on 1st stage DX cooling
 SET PSZ1_Stage2 = 0,!Percent of time on 2nd stage DX cooling
 ELSE,
 SET PSZ1_Htg = 0,
 SET PSZ1_MinOA1 = PSZ1_OADesignMass * PSZ1_OASch,
 SET PSZ1_MinOA2 = PSZ1_DesignFlowMass * PSZ1_OAFracSch,
 SET PSZ1_MinOA = @Max PSZ1_MinOA1 PSZ1_MinOA2,
 IF PSZ1_ClgRTF > 0,! Mechanical cooling is on
 SET PSZ1_Stage1 = PSZ1_ClgRTF,
 SET PSZ1_Stage2 = 0,
 IF PSZ1_OAFlowMass > PSZ1_MinOA,! Integrated Economzing mode
 SET PSZ1_Eco = 1-PSZ1_ClgRTF,
 SET PSZ1_Ven = 0,
 ELSE,
 SET PSZ1_Eco = 0,
 SET PSZ1_Ven = 1-PSZ1_ClgRTF,
 ENDIF,
 ELSE,! Mechanical cooling is off
 SET PSZ1_Stage1 = 0,
 SET PSZ1_Stage2 = 0,
 IF PSZ1_OAFlowMass > PSZ1_MinOA,!Economzing mode
 SET PSZ1_Eco = 1.0,
 SET PSZ1_Ven = 0,
 ELSE,
 SET PSZ1_Eco = 0,
 SET PSZ1_Ven = 1.0,
 ENDIF,
 ENDIF,
 ENDIF,

! For each mode, (percent time in mode) * (fanSpeer^PwrExp) is the contribution to
weighted fan power over time step

 SET PSZ1_FPR = PSZ1_Ven * (VenSpeed ^ FanPwrExp),
 SET PSZ1_FPR = PSZ1_FPR + PSZ1_Eco * (EcoSpeed ^ FanPwrExp),
 SET PSZ1_FPR1 = PSZ1_Stage1 * (Stage1Speed ^ FanPwrExp),
 SET PSZ1_FPR = PSZ1_FPR + PSZ1_FPR1,
 SET PSZ1_FPR2 = PSZ1_Stage2 * (Stage2Speed ^ FanPwrExp),
 SET PSZ1_FPR = PSZ1_FPR + PSZ1_FPR2,
 SET PSZ1_FPR3 = PSZ1_Htg * (HeatSpeed ^ FanPwrExp),
 SET PSZ1_FanPwrRatio = PSZ1_FPR + PSZ1_FPR3,
 SET PSZ1_FanPressure = PSZ1_FanDesignPressure * PSZ1_FanPwrRatio;
```

B.19 Measure 25: Waterside Economizer

The EnergyPlus code used to specify the waterside economizer, its control, and plant-side connections are reproduced below. This measure is implemented only for the Large Office prototype, which is the only one with a condenser water loop.

```
Schedule:Constant,
 Waterside Economizer Schedule,!- Name
 On/Off,!- Schedule Type Limits Name
 1;!- Hourly Value
```

```
HeatExchanger:FluidToFluid,
 Waterside Economizer,!- Name
 Waterside Economizer Schedule,!- Availability Schedule Name
 Waterside Economizer Condenser Inlet Node,!- Loop Demand Side Inlet Node Name
 Waterside Economizer Condenser Outlet Node,!- Loop Demand Side Outlet Node Name
 autosize,!- Loop Demand Side Design Flow Rate {m3/s}
 Waterside Economizer ChW Inlet Node,!- Loop Supply Side Inlet Node Name
 Waterside Economizer ChW Outlet Node,!- Loop Supply Side Outlet Node Name
 autosize,!- Loop Supply Side Design Flow Rate {m3/s}
 CounterFlow,!- Heat Exchange Model Type
 autosize,!- Heat Exchanger U-Factor Times Area Value {W/k}
 UncontrolledOn,!- Control Type
,!- Heat Exchanger Setpoint Node Name
 5,!- Minimum Temperature Difference to Activate Heat Exchanger {deltaC}
 FreeCooling,!- Heat Transfer Metering End Use Type
,!- Component Override Loop Supply Side Inlet Node Name
,!- Component Override Loop Demand Side Inlet Node Name
 Loop,!- Component Override Cooling Control Temperature Mode
 1;!- Sizing Factor

EnergyManagementSystem:Program,
 WSE_Control,!- Name
 IF TWb<6,!- Program Line 1
 SET WSE=1,!- Program Line 2
 SET ChWT = @Max Twb+4.5 6.67,!- A4
 SET TowerT= ChWT-0.5,!- A5
 ELSE,!- A6
 SET WSE=0,!- A7
 SET TowerT=26.7,!- A8
 SET ChWT=6.67,!- A9
 ENDIF;!- A10

EnergyManagementSystem:Sensor,
 TWb,!- Name
 *,!- Output:Variable or Output:Meter Index Key Name
 Site Outdoor Air WetBulb Temperature;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Actuator,
 WSE,!- Name
 Waterside Economizer Schedule,!- Actuated Component Unique Name
 Schedule:Constant,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 TowerT,!- Name
 Tower Loop Setpoint Sched,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 ChwT,!- Name
 CoolSys1 Loop Setpoint Sched,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 SChedule Value;!- Actuated Component Control Type
```

```
Branch,
 CoolSys1 Supply Equipment Branch 1,!- Name
,!- Maximum Flow Rate {m3/s}
,!- Pressure Drop Curve Name
 HeatExchanger:FluidToFluid,!- Component 1 Object Type
 Waterside Economizer,!- Component 1 Name
 Waterside Economizer ChW Inlet Node,!- Component 1 Inlet Node Name
 Waterside Economizer ChW Outlet Node,!- Component 1 Outlet Node Name
 Active,!- Component 1 Branch Control Type
 Chiller:Electric:ReformulatedEIR,!- Component 2 Object Type
 CoolSys1 Chiller1,!- Component 2 Name
 Waterside Economizer ChW Outlet Node,!- Component 2 Inlet Node Name
 CoolSys1 Chiller 1 Outlet,!- Component 2 Outlet Node Name
 Active,!- Component 2 Branch Control Type
 Pump:ConstantSpeed,!- Component 3 Object Type
 CoolSys1 Primary Pump Chiller 1,!- Component 3 Name
 COOLSYS1 CHILLER 1 OUTLET,!- Component 3 Inlet Node Name
 CoolSys1 Supply Equipment Outlet Node 1,!- Component 3 Outlet Node Name
 Active;!- Component 3 Branch Control Type

Branch,
 Waterside Economizer Condenser Branch,!- Name
 autosize,!- Maximum Flow Rate {m3/s}
,!- Pressure Drop Curve Name
 HeatExchanger:FluidToFluid,!- Component 1 Object Type
 Waterside Economizer,!- Component 1 Name
 Waterside Economizer Condenser Inlet Node,!- Component 1 Inlet Node Name
 Waterside Economizer Condenser Outlet Node,!- Component 1 Outlet Node Name
 Active;!- Component 1 Branch Control Type

BranchList,
 CoolSys1 Chiller TowerSys Demand Branches,!- Name
 CoolSys1 Chiller TowerSys Demand Inlet Branch,!- Branch 1 Name
 Waterside Economizer Condenser Branch,!- Branch 2 Name
 CoolSys1 Chiller TowerSys Demand Load Branch 1,!- Branch 3 Name
 CoolSys1 Chiller TowerSys Demand Load Branch 2,!- Branch 4 Name
 CoolSys1 Chiller TowerSys Demand Bypass Branch,!- Branch 5 Name
 CoolSys1 Chiller TowerSys Demand Outlet Branch;!- Branch 6 Name

Connector:Splitter,
 CoolSys1 Chiller TowerSys Demand Splitter,!- Name
 CoolSys1 Chiller TowerSys Demand Inlet Branch,!- Inlet Branch Name
 Waterside Economizer Condenser Branch,!- Outlet Branch 1 Name
 CoolSys1 Chiller TowerSys Demand Load Branch 1,!- Outlet Branch 2 Name
 CoolSys1 Chiller TowerSys Demand Load Branch 2,!- Outlet Branch 3 Name
 CoolSys1 Chiller TowerSys Demand Bypass Branch;!- Outlet Branch 4 Name

Connector:Mixer,
 CoolSys1 Chiller TowerSys Demand Mixer,!- Name
 CoolSys1 Chiller TowerSys Demand Outlet Branch,!- Outlet Branch Name
 Waterside Economizer Condenser Branch,!- Inlet Branch 1 Name
 CoolSys1 Chiller TowerSys Demand Load Branch 1,!- Inlet Branch 2 Name
 CoolSys1 Chiller TowerSys Demand Load Branch 2,!- Inlet Branch 3 Name
 CoolSys1 Chiller TowerSys Demand Bypass Branch;!- Inlet Branch 4 Name
```

```
Chiller:Electric:ReformulatedEIR,
 CoolSys1 Chiller1,!- Name
 641136.064875,!- Reference Capacity {W}
 5.2,!- Reference COP {W/W}
 6.6700,!- Reference Leaving Chilled Water Temperature {C}
 34.4,!- Reference Leaving Condenser Water Temperature {C}
 0.02708495,!- Reference Chilled Water Flow Rate {m3/s}
 autosize,!- Reference Condenser Water Flow Rate {m3/s}
 CoolSys1 Chiller ClgCapFuncTempCurve,!- Cooling Capacity Function of Temperature
Curve Name
 CoolSys1 Chiller EirFuncTempCurve,!- Electric Input to Cooling Output Ratio Function
of Temperature Curve Name
 Taylor_Base_Change,!- Electric Input to Cooling Output Ratio Function of Part Load
Ratio Curve Name
 0.10,!- Minimum Part Load Ratio
 1.0,!- Maximum Part Load Ratio
 1.0000,!- Optimum Part Load Ratio
 0.1000,!- Minimum Unloading Ratio
 Waterside Economizer ChW Outlet Node,!- Chilled Water Inlet Node Name
 COOLSYS1 CHILLER 1 OUTLET,!- Chilled Water Outlet Node Name
 CoolSys1 Chiller1 Water Inlet Node,!- Condenser Inlet Node Name
 CoolSys1 Chiller1 Water Outlet Node,!- Condenser Outlet Node Name
 1.0,!- Fraction of Compressor Electric Consumption Rejected by Condenser
 2.0,!- Leaving Chilled Water Lower Temperature Limit {C}
 ConstantFlow,!- Chiller Flow Mode Type
 0.0;!- Design Heat Recovery Water Flow Rate {m3/s}

CoolingTower:VariableSpeed,
 CoolSys1 Chiller TowerSys CoolTower 1,!- Name
 CoolSys1 Chiller TowerSys Pump-CoolSys1 Chiller TowerSys CoolTower1Node,!- Water
Inlet Node Name
 CoolSys1 Tower 1 CndW Outlet,!- Water Outlet Node Name
 YorkCalc,!- Model Type
,!- Model Coefficient Name
 25.6,!- Design Inlet Air Wet-Bulb Temperature {C}
 3.9,!- Design Approach Temperature {deltaC}
 5.6,!- Design Range Temperature {deltaC}
 0.12949,!- Design Water Flow Rate {m3/s}
 84.1943,!- Design Airflow Rate {m3/s}
 31823.50835,!- Design Fan Power {W}
 TowerVDFCurve,!- Fan Power Ratio Function of Airflow Rate Ratio Curve Name
 0.2,!- Minimum Airflow Rate Ratio
 0.125,!- Fraction of Tower Capacity in Free Convection Regime
,!- Basin Heater Capacity {W/K}
 2,!- Basin Heater Setpoint Temperature {C}
,!- Basin Heater Operating Schedule Name
,!- Evaporation Loss Mode
 0.2,!- Evaporation Loss Factor {percent/K}
 0.008,!- Drift Loss Percent {percent}
 ConcentrationRatio,!- Blowdown Calculation Mode
 3,!- Blowdown Concentration Ratio
,!- Blowdown Makeup Water Usage Schedule Name
,!- Supply Water Storage Tank Name
 CoolSys1 Chiller TowerSys CoolTower1 OA ref Node,!- Outdoor Air Inlet Node Name
 1,!- Number of Cells
```

```
 MinimalCell,!- Cell Control
 0.33,!- Cell Minimum Water Flow Rate Fraction
 2.5,!- Cell Maximum Water Flow Rate Fraction
 1;!- Sizing Factor

Curve:Cubic,
 TowerVDFCurve,!- Name
 0.070428852,!- Coefficient1 Constant
 0.385330201,!- Coefficient2 x
 -.460864118,!- Coefficient3 x**2
 1.00920344,!- Coefficient4 x**3
 0.2,!- Minimum Value of x
 1,!- Maximum Value of x
 0,!- Minimum Curve Output
 1.1,!- Maximum Curve Output
 Dimensionless,!- Input Unit Type for X
 Dimensionless;!- Output Unit Type
```

B.20 Measure 27: Optimal Start

The set of objects used to define optimal start for one air handler in the Large Office model is shown below

```
Schedule:Compact,
 Night Cycle Availability,!- Name
 On/Off,!- Schedule Type Limits Name
 Through: 12/31,!- Field 1
 For: Weekdays SummerDesignDay WinterDesignDay,!- Field 2
 Until: 05:00,!- Field 3
 1.0,!- Field 4
 Until: 8:00,!- Field 5
 0.0,!- Field 6
 Until: 24:00,!- Field 7
 1.0,!- Field 8
 For: Saturday,!- Field 9
 Until: 05:00,!- Field 10
 1.0,!- Field 11
 Until: 8:00,!- Field 12
 0.0,!- Field 13
 Until: 24:00,!- Field 14
 1.0,!- Field 15
 For: Sunday Holidays AllOtherDays,!- Field 16
 Until: 07:00,!- Field 17
 1.0,!- Field 18
 Until: 18:00,!- Field 19
 1.0,!- Field 20
 Until: 24:00,!- Field 21
 1.0;!- Field 22

ZoneList,
 OptStartZoneList VAV_1,!- Name
 ZN_1_FLR_1_SEC_1,!- Zone 1 Name
 ZN_1_FLR_1_SEC_2,!- Zone 2 Name
 ZN_1_FLR_1_SEC_3,!- Zone 3 Name
```

```
 ZN_1_FLR_1_SEC_4,!- Zone 4 Name
 ZN_1_FLR_1_SEC_5;!- Zone 5 Name

AvailabilityManager:OptimumStart,
 VAV_1 Optimal Start,!- Name
 Optimal Start Availability Schd,!- Applicability Schedule Name
 HVACOperationSchd VAV_1,!- Fan Schedule Name
 MaximumofZoneList,!- Control Type
 ZN_1_FLR_1_SEC_1,!- Control Zone Name
 OptStartZoneList VAV_1,!- Zone List Name
 3,!- Maximum Value for Optimum Start Time {hr}
 AdaptiveASHRAE,!- Control Algorithm
 3,!- Constant Temperature Gradient during Cooling {deltaC/hr}
 2,!- Constant Temperature Gradient during Heating {deltaC/hr}
 3,!- Initial Temperature Gradient during Cooling {deltaC/hr}
 2,!- Initial Temperature Gradient during Heating {deltaC/hr}
,!- Constant Start Time {hr}
 2;!- Number of Previous Days {days}

AvailabilityManager:NightCycle,
 VAV_1 Availability Manager,!- Name
 Night Cycle Availability,!- Applicability Schedule Name
 HVACOperationSchd VAV_1,!- Fan Schedule Nam
 CycleOnAny,!- Control Type
 1.0,!- Thermostat Tolerance {deltaC}
 1800;!- Cycling Run Time {s}

AvailabilityManagerAssignmentList,
 VAV_1 Availability Manager List,!- Name
 AvailabilityManager:NightCycle,!- Availability Manager 1 Object Type
 VAV_1 Availability Manager,!- Availability Manager 1 Name
 AvailabilityManager:OptimumStart,!- Availability Manager 2 Object Type
 VAV_1 Optimal Start;!- Availability Manager 2 Name
```

B.21 Measure 28: Optimal Stop

There is no object or set of objects for modeling Optimal Stop in EnergyPlus, so a custom EMS code was developed to implement a form of Optimal Stop that is controlled based on outdoor air temperatures alone.

```
EnergyManagementSystem:Sensor,
 OAT,!- Name
 *,!- Output:Variable or Output:Meter Index Key Name
 Site Outdoor Air Drybulb Temperature;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Actuator,
 HVAC_Op,!- Name
 HVACOperationSchd,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 HSet,!- Name
 HTGSETP_SCH_Base_ExtendedHVAC,!- Actuated Component Unique Name
```

```
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 CSet,!- Name
 CLGSETP_SCH_Base_ExtendedHVAC,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 MinOA,
 MinOAFracSch_Base,
 Schedule:Compact,
 Schedule Value;

EnergyManagementSystem:Actuator,
 Infil,
 INFIL_SCH_Base,
 Schedule:Compact,
 Schedule Value;

EnergyManagementSystem:Program,
 Optimal_Stop,!- Name
 SET SaturdayHVACEnd=18-DaylightSavings,!- Program Line 1
 SET WeekdayHVACEnd=22-DaylightSavings,!- Program Line 2
 SET MinimumEarlyStop=1,!- A4
 SET HSetpOcc=21.7,!- A5
 SET HSetback=18.3,!- A6
 SET CSetpOcc=22.8,!- A7
 SET CSetback=26.7,!- A8
 IF DayOfWeek==7,!- A9
 SET MinimumStop=SaturdayHVACEnd-MinimumEarlyStop,!- A10
 ENDIF,!- A11
 IF DayOfWeek<7 && DayOfWeek>1 && Holiday==0,!- A12
 SET MinimumStop=WeekdayHVACEnd-MinimumEarlyStop,!- A13
 ENDIF,!- A14
 SET HVAC_OP=NULL,!- A15
 SET HSet=NULL,!- A16
 SET CSet=Null,!- A17
 SET MinOA=Null,
 SET Infil=Null,
 IF CurrentTime>=MinimumStop && DayOfWeek>1 && Holiday==0,!- A18
 IF OAT<=2 || OAT>28,!- A19
 SET HourPlus=MinimumEarlyStop,!- A20
 ELSEIF OAT<=12,!- A21
 SET HourPlus= MinimumEarlyStop*(12-OAT)/10,!- A22
 ELSEIF OAT<=18,!- A23
 SET HourPlus=0,!- A24
 ELSE,!- A25
 SET HourPlus = MinimumEarlyStop*(OAT-18)/10,!- A26
 ENDIF,!- A27
 IF CurrentTime<=MinimumStop+HourPlus,!- A28
 SET HVAC_OP=1,!- A29
 SET HSet=HSetpOcc,!- A30
 SET CSet=CSetpOcc,!- A31
```

```
SET Infil=0.25,
SET MinOA=0.15,
ELSE,!- A32
SET HVAC_OP=0,!- A33
SET HSet=HSetback,!- A34
SET CSet=CSetback,!- A35
SET Infil=1,
SET MinOA=0.1,
ENDIF,!- A36
ENDIF;!- A37
```

B.22 Measure 31: Refrigeration Floating Head Pressure.

This measure is simulated in EnergyPlus by reducing the minimum condenser temperature in each Refrigerator:System object from 26.7°C to 15.6°C, and by switching from constant speed control of the air-cooled refrigeration condensers to variable-speed control (see EnergyPlus objects below for one refrigeration rack). EMS code is used to reset the minimum condensing temperature for each Refrigerator:System object based on the outdoor air dry-bulb temperature with an offset of 10°F and 15°F for low-temperature and medium-temperature refrigeration systems, respectively. The condensing temperature setpoint is subject to a range between 60°F and 95°F.

```
Refrigeration:System,
 Rack A,!- Name
 Rack A Case and Walk-In List,!- Refrigerated Case or Walkin or CaseAndWalkInList Name
,!- Refrigeration Transfer Load or TransferLoad List Name
 Rack A Condenser,!- Refrigeration Condenser Name
 Rack A Compressor List,!- Compressor or CompressorList Name
 15.6,!- Minimum Condensing Temperature {C}
 R404A,!- Refrigeration System Working Fluid Type
 ConstantSuctionTemperature,!- Suction Temperature Control Type
,!- Mechanical Subcooler Name
,!- Liquid Suction Heat Exchanger Subcooler Name
 5.8,!- Sum UA Suction Piping {W/K}
 MainSales,!- Suction Piping Zone Name
,!- End-Use Subcategory
 1,!- Number of Compressor Stages
 None;!- Intercooler Type

Refrigeration:Condenser:AirCooled,
 Rack A Condenser,!- Name
 Rack A Cond Curve,!- Rated Effective Total Heat Rejection Rate Curve Name
 0,!- Rated Subcooling Temperature Difference {DeltaC}
 VariableSpeed,!- Condenser Fan Speed Control Type
 4057.070672,!- Rated Fan Power {W}
 0.1,!- Minimum Fan Airflow Ratio {dimensionless}
 Rack A Cond Node;!- Air Inlet Node Name or Zone Name
```

B.23 Measure 32: Refrigeration Floating Suction Pressure.

This measure is simulated in EnergyPlus by switching the “Suction Temperature Control Type” in each of the “Refrigeration:System” objects from “ConstantSuctionTemperature” to “FloatSuctionTemperature” (see EnergyPlus object below for one system). The EnergyPlus Engineering Reference (EnergyPlus 2015) describes how this control type is modeled internally in EnergyPlus under the “Variable Evaporator Temperature” section.

```
Refrigeration:System,
 Rack D,!- Name
 Rack D Case and Walk-In List,!- Refrigerated Case or Walkin or CaseAndWalkInList Name
,!- Refrigeration Transfer Load or TransferLoad List Name
 Rack D Condenser,!- Refrigeration Condenser Name
 Rack D Compressor List,!- Compressor or CompressorList Name
 26.7,!- Minimum Condensing Temperature {C}
 R404A,!- Refrigeration System Working Fluid Type
 FloatSuctionTemperature,!- Suction Temperature Control Type
,!- Mechanical Subcooler Name
,!- Liquid Suction Heat Exchanger Subcooler Name
 5.8,!- Sum UA Suction Piping {W/K}
 MainSales,!- Suction Piping Zone Name
,!- End-Use Subcategory
 1,!- Number of Compressor Stages
 None;!- Intercooler Type
```

B.24 Measure 33: Optimize Defrost Strategy

This type of control is available as a standard feature in the refrigerated case and refrigerated walk-in objects in EnergyPlus. The control requires user-defined curves that map the required defrost time to the indoor dewpoint temperature. The EnergyPlus object for a refrigerated case is shown below. In red, the case defrost type for this measure is “ElectricWithTemperatureTermimation,” and the curve specified is “Glass Door Defrost Curve.”

```
Refrigeration:Case,
 A01 Ice Cream Reach-Ins,!- Name
 Always_On,!- Availability Schedule Name
 MainSales,!- Zone Name
 23.9,!- Rated Ambient Temperature {C}
 55,!- Rated Ambient Relative Humidity {percent}
 617.5,!- Rated Total Cooling Capacity per Unit Length {W/m}
 0.1,!- Rated Latent Heat Ratio
 0.85,!- Rated Runtime Fraction
 14.6,!- Case Length {m}
 -24.4,!- Case Operating Temperature {C}
 DewpointMethod,!- Latent Case Credit Curve Type
 Glass Door Latent Curve,!- Latent Case Credit Curve Name
 70.2,!- Standard Case Fan Power per Unit Length {W/m}
 70.2,!- Operating Case Fan Power per Unit Length {W/m}
 99.1,!- Standard Case Lighting Power per Unit Length {W/m}
 99.1,!- Installed Case Lighting Power per Unit Length {W/m}
 Always_On,!- Case Lighting Schedule Name
 0.5,!- Fraction of Lighting Energy to Case
 286.9,!- Case Anti-Sweat Heater Power per Unit Length {W/m}
 286.9,!- Minimum Anti-Sweat Heater Power per Unit Length {W/m}
 Constant,!- Anti-Sweat Heater Control Type
,!- Humidity at Zero Anti-Sweat Heater Energy {percent}
,!- Case Height {m}
 0.7,!- Fraction of Anti-Sweat Heater Energy to Case
 1221.5,!- Case Defrost Power per Unit Length {W/m}
 ElectricwithTemperatureTermination,!- Case Defrost Type
 A01 Defrost Sch,!- Case Defrost Schedule Name
 A01 Drip-Down Sch,!- Case Defrost Drip-Down Schedule Name
 DewpointMethod,!- Defrost Energy Correction Curve Type
 Glass Door Defrost Curve,!- Defrost Energy Correction Curve Name
 0,!- Under Case HVAC Return Air Fraction
 Always_Off,!- Refrigerated Case Restocking Schedule Name
 Always_On,!- Case Credit Fraction Schedule Name
 -28.3;!- Design Evaporator Temperature or Brine Inlet Temperature {C}
```

```
Curve:Cubic,
 Glass Door Defrost Curve,!- Name
 0.3475,!- Coefficient1 Constant
 0.0296,!- Coefficient2 x
 0.0007,!- Coefficient3 x**2
 3e-005,!- Coefficient4 x**3
 -55,!- Minimum Value of x
 55;!- Maximum Value of x
```

B.25 Measure 34: Anti-Sweat Heater Control

Anti-sweat heater control is modeled internally in EnergyPlus through the specification of anti-sweat heater strategy in the Refrigeration:Case object (one is reproduced below showing the control type in red). In the baseline, the control type is constant and the minimum anti-sweat heater power is set equal to the maximum power. For Measure 34, the dewpoint method of control is selected and the minimum anti-sweat heater power is set to 0. The EnergyPlus Engineering Reference (EnergyPlus 2015) describes how this control type is modeled internally in EnergyPlus under the “Anti-Sweat Heater Performance” section.

```
Refrigeration:Case,
 A01 Ice Cream Reach-Ins,!- Name
 Always_On,!- Availability Schedule Name
 MainSales,!- Zone Name
 23.9,!- Rated Ambient Temperature {C}
 55,!- Rated Ambient Relative Humidity {percent}
 617.5,!- Rated Total Cooling Capacity per Unit Length {W/m}
 0.1,!- Rated Latent Heat Ratio
 0.85,!- Rated Runtime Fraction
 14.6,!- Case Length {m}
 -24.4,!- Case Operating Temperature {C}
 DewpointMethod,!- Latent Case Credit Curve Type
 Glass Door Latent Curve,!- Latent Case Credit Curve Name
 70.2,!- Standard Case Fan Power per Unit Length {W/m}
 70.2,!- Operating Case Fan Power per Unit Length {W/m}
 99.1,!- Standard Case Lighting Power per Unit Length {W/m}
 99.1,!- Installed Case Lighting Power per Unit Length {W/m}
 Always_On,!- Case Lighting Schedule Name
 0.5,!- Fraction of Lighting Energy to Case
 286.9,!- Case Anti-Sweat Heater Power per Unit Length {W/m}
 0,!- Minimum Anti-Sweat Heater Power per Unit Length {W/m}
 DewpointMethod,!- Anti-Sweat Heater Control Type
,!- Humidity at Zero Anti-Sweat Heater Energy {percent}
,!- Case Height {m}
 0.7,!- Fraction of Anti-Sweat Heater Energy to Case
 1221.5,!- Case Defrost Power per Unit Length {W/m}
 Electric,!- Case Defrost Type
 A01 Defrost Sch,!- Case Defrost Schedule Name
 A01 Drip-Down Sch,!- Case Defrost Drip-Down Schedule Name
 DewpointMethod,!- Defrost Energy Correction Curve Type
 Glass Door Defrost Curve,!- Defrost Energy Correction Curve Name
 0,!- Under Case HVAC Return Air Fraction
 Always_Off,!- Refrigerated Case Restocking Schedule Name
 Always_On,!- Case Credit Fraction Schedule Name
 -28.3;!- Design Evaporator Temperature or Brine Inlet Temperature {C}
```

B.26 Measure 35: Evaporator Fan Speed Control

This control is modeled using an EMS program in EnergyPlus. In the model, the valve position is represented by the evaporator's actual cooling rate as the percentage of its design cooling rate. The EMS code is shown below for three of the walk-ins. Note that EMS does not have an actuator that can directly change the fan power for the walk-in evaporators, so this measure cannot be modeled within the simulation. Instead, the EMS program calculates the fan power savings, and the aggregated savings are externally calculated for this study. Unfortunately, this means that any additional cooling savings from reducing fan power heat gain cannot be captured.

```
EnergyManagementSystem:GlobalVariable,
 SavedWalkInFan,!- Erl Variable 1 Name
 A05CC,!Rated cooling capacity
 B04CC,
 C10CC,
EnergyManagementSystem:Sensor,
 A05Cooling,!- Name
 A05 Grocery Freezer,!- Output:Variable or Output:Meter Index Key Name
 Refrigeration Walk In Evaporator Total Cooling Rate;!- Output:Variable or
Output:Meter Name

EnergyManagementSystem:Sensor,
 B04Cooling,!- Name
 B04 Bakery Freezer,!- Output:Variable or Output:Meter Index Key Name
 Refrigeration Walk In Evaporator Total Cooling Rate;!- Output:Variable or
Output:Meter Name

EnergyManagementSystem:Sensor,
 C10Cooling,!- Name
 C10 Dairy Cooler,!- Output:Variable or Output:Meter Index Key Name
 Refrigeration Walk In Evaporator Total Cooling Rate;!- Output:Variable or
Output:Meter Name
EnergyManagementSystem:Sensor,
 A05Fan,!- Name
 A05 Grocery Freezer,!- Output:Variable or Output:Meter Index Key Name
 Refrigeration Walk In Fan Electric Energy;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 B04Fan,!- Name
 B04 Bakery Freezer,!- Output:Variable or Output:Meter Index Key Name
 Refrigeration Walk In Fan Electric Energy;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 C10Fan,!- Name
 C10 Dairy Cooler,!- Output:Variable or Output:Meter Index Key Name
 Refrigeration Walk In Fan Electric Energy;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Program,
 WalkInCCInit,!- Name
 SET A05CC = 8826,
 SET B04CC = 3030,
 SET C10CC = 12626,

EnergyManagementSystem:Program,
 WalkInFanCtrl,!- Name
 SET SavedWalkInFan = 0,
 SET EEVPosition = A05Cooling/A05CC,
 IF EEVPosition <= 0.5,
 SET SavedWalkInFan = SavedWalkInFan + A05Fan * (1 - (0.8^2.5)),
 ENDIF,
```

```
 SET EEVPosition = B04Cooling/B04CC,
 IF EEVPosition <= 0.5,
 SET SavedWalkInFan = SavedWalkInFan + B04Fan * (1 - (0.8^2.5)),
 ENDIF,
 SET EEVPosition = C10Cooling/C10CC,
 IF EEVPosition <= 0.5,
 SET SavedWalkInFan = SavedWalkInFan + C10Fan * (1 - (0.8^2.5)),
 ENDIF,

EnergyManagementSystem:ProgramCallingManager,
 WalkInFanCtrl_Manager,!- Name
 InsideHVACSystemIterationLoop,!- EnergyPlus Model Calling Point
 WalkInFanCtrl;!- Program Name

EnergyManagementSystem:ProgramCallingManager,
 WalkInCCInit_Manager,!- Name
 BeginNewEnvironment,!- EnergyPlus Model Calling Point
 WalkInCCInit;!- Program Name
```

B.27 Measure 36: Occupancy Sensors for Thermostats and Room Lighting

To simulate this measure, as described in the building description for the Large Hotel prototype, all guest rooms were carefully reassigned individual on/off occupancy schedules, rather than grouped, fractional occupancy schedules. Lighting schedules and thermostat schedules that were initially general were also duplicated and assigned to individual guest rooms. An EMS program was developed to shut off all lights and set back the thermostat to “standby” setpoints of 67°F for heating and 76°F for cooling. These setpoints are wide enough to achieve savings, but narrow enough to avoid the risk of making guest rooms too hot or too cold (long recovery times) upon re-entry. A portion of the EMS code covering three guest rooms is shown below.

```
EnergyManagementSystem:Sensor,
 Occ1,!- Name
 Room_1_Flr_3 Occ Sch,!- Output:Variable or Output:Meter Index Key Name
 Schedule Value;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 Occ2,!- Name
 Room_2_Flr_3 Occ Sch,!- Output:Variable or Output:Meter Index Key Name
 Schedule Value;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 Occ3,!- Name
 Room_3_Flr_3 Occ Sch,!- Output:Variable or Output:Meter Index Key Name
 Schedule Value;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Actuator,
 Light1,!- Name
 BLDG_LIGHT_GUESTROOM_SCH_1,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 Light2,!- Name
 BLDG_LIGHT_GUESTROOM_SCH_2,!- Actuated Component Unique Name
```

```
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 Light3,!- Name
 BLDG_LIGHT_GUESTROOM_SCH_3,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 Cool1,!- Name
 Guest_Cooling_3_1,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 Cool2,!- Name
 Guest_Cooling_3_2,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 Cool3,!- Name
 Guest_Cooling_2_1,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 Heat1,!- Name
 Guest_Heating_3_1,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 Heat2,!- Name
 Guest_Heating_3_2,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 Heat3,!- Name
 Guest_Heating_2_1,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Program,
 Room_Occ_Sensors,!- Name
 If Occ1==0,!- Program Line 1
 SET Light1=0,!- Program Line 2
 Set Heat1= 19.44,!- A4
 Set Cool1= 24.44,!- A5
 Else,!- A6
 Set Light1= Null,!- A7
 Set Heat1= Null,!- A8
 Set Cool1 = Null,!- A9
```

```
 Endif,!- A10
 If Occ2==0,!- A11
 SET Light2=0,!- A12
 Set Heat2= 19.44,!- A13
 Set Cool2= 24.44,!- A14
 Else,!- A15
 Set Light2= Null,!- A16
 Set Heat2= Null,!- A17
 Set Cool2 = Null,!- A18
 Endif,!- A19
 If Occ3==0,!- A20
 SET Light3=0,!- A21
 Set Heat3= 19.44,!- A22
 Set Cool3= 24.44,!- A23
 Else,!- A24
 Set Light3= Null,!- A25
 Set Heat3= Null,!- A26
 Set Cool3 = Null,!- A27
 Endif,!- A28
```

B.28 Measure 37: Optimized Use of Heat Recovery Wheel

The EMS code below uses psychrometric functions to forecast the cooling coil and heating coil thermal energy, then uses rough assumptions about boiler and chiller efficiency to forecast the electric or natural-gas energy that would be saved by the use of the ERV at outdoor and return air temperatures, humidities, and flows. When the forecast saved energy is less than the forecast added energy from the ERV, the ERV wheel is disabled. Note that heating energy saved is divided by 3.0 to roughly account for primary energy differences between natural gas and electricity. In other words, 3 units of natural gas would need to be saved to justify the addition of 1 unit of electricity. Comments are added in red to help explain what the code is doing.

```
EnergyManagementSystem:Sensor,
 MFR_VAV,!- Name
 VAV WITH REHEAT Supply Equipment Outlet Node,!- Output:Variable or Output:Meter Index
Key Name
 System Node Mass Flow Rate;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 T_RA_VAV,!- Name
 VAV WITH REHEAT_OARelief Node,!- Output:Variable or Output:Meter Index Key Name
 System Node Temperature;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 T_SAsp,!- Name
 VAV WITH REHEAT Supply Equipment Outlet Node,!- Output:Variable or Output:Meter Index
Key Name
 System Node Setpoint Temperature;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 H_RA_VAV,!- Name
 VAV WITH REHEAT_OARelief Node,!- Output:Variable or Output:Meter Index Key Name
 System Node Enthalpy;!- Output:Variable or Output:Meter Name
```

```
EnergyManagementSystem:Sensor,
 W_OA,!- Name
 *,!- Output:Variable or Output:Meter Index Key Name
 Site Outdoor Air Humidity Ratio;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 W_RA_VAV,!- Name
 VAV WITH REHEAT_OARelief Node,!- Output:Variable or Output:Meter Index Key Name
 System Node Humidity Ratio;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Actuator,
 VAV_w_a,!- Name
 VAV Wheel Availability,!- Actuated Component Unique Name
 Schedule:Constant,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Program,
 ERV_Wheel_Lockout_VAV,!- Name
 SET P_VAV_exp= 372+ (MFR_VAV*1.2*3.28*3.28*3.28*60/0.61165/6.356),!expected power in
W, given the flow rate of supply air in kg/s
 SET CA_VAV_exp=0.7*(T_RA_VAV-OAT)+OAT,!- expected conditioned temperature (supply air
outlet from wheel), given 70% sensible effectiveness of ERV
 IF OAT< T_SAsp,!- If outdoor air temp is less than DOAS SAT setpoint
 IF CA_VAV_exp>T_SAsp,!- If expected conditioned temperature is greater than DOAS SAT
setpoint
 SET CA_VAV_exp=T_SAsp,!- The wheel will switch to variable-speed mode in this case
and target the SAT setpoint
 ENDIF,!- A8
 IF CA_VAV_exp==T_SAsp,!- A9
 SET P_withwheel=0,!- In this case, with the wheel running, there will be no power
consumption due to the use of heating or cooling coils.
 ELSE,!- A11
 SET H_CA = @HFnTdbW CA_VAV_exp W_OA,!- Psychrometric function for enthalpy of
conditioned air, at the expected wheel outlet temperature and at the humidity ratio of
outdoor air
 SET H_SA= @HFnTdbW T_SAsp W_OA,!- Psychrometric function for enthalpy of the DOAS
supply air, at the SAT setpoint and at the humidity ratio of outdoor air
 SET P_withwheel= MFR_VAV*(H_SA-H_CA),!- In this case, the wheel alone is insufficient
to meet the SAT setpoint. This calculates additional heating load.
 ENDIF,!- A15
 SET H_SA= @HFnTdbW T_SAsp W_OA,!- Calculates supply air enthalpy if heated sensibly
from OA condition
 SET H_OA= @HFnTdbW OAT W_OA,!- Calculates outdoor air enthalpy
 SET P_withoutwheel= MFR_VAV*(H_SA-H_OA),!- Thermal energy required for heating coil
 SET P_savings=P_withoutwheel-P_withwheel,!- Thermal energy savings from using wheel
 SET P_savings_adj=P_savings/(n_boiler*3),!- Estimate natural gas consumption, divide
by three for comparison with electricity
 ELSE,!- Else if outdoor air is warmer than SAT setpoint
 IF CA_VAV_exp<T_SAsp,!- A23 If expected conditioned temperature is less than DOAS SAT
setpoint
 SET CA_VAV_exp=T_SAsp,!- A24 The wheel will switch to variable-speed mode in this
case and target the SAT setpoint
 ENDIF,!- A25
 IF CA_VAV_exp==T_SAsp,!- A26
 SET P_withwheel=0,!- A27
```

```
 ELSE,!- If wheel would run full speed for cooling
 SET EFF1=0.6,!- Wheel latent effectiveness
 SET EFF2=0.7,!- Wheel Sensible effectiveness
 SET W_CA=W_OA+(EFF1*(W_RA_VAV-W_OA)),!- Calculate humidity ratio of dehumidified
conditioned air leaving the wheel
 SET T_CA=OAT+(EFF2*(T_RA_VAV-OAT)),!- Calculate temperature of conditioned air
leaving the wheel
 SET H_CA= @HFnTdbW T_cA W_CA,!- Calculate conditioned air enthalpy
 SET W_OA= @WFnTdbH OAT H_OA,!- Calculate outdoor air humidity ratio
 SET W_SAmax= @WFnTdbRhPb T_SAsp 100 101000,!- maximum supply air humidity ratio (100%
relative humidity at SAT setpoint)
 SET W_SAtarget= @min W_CA W_SAmax,!- Supply air humidity ratio
 SET H_SA= @HFnTdbW T_SAsp W_SAtarget,!- Supply air enthalpy
 SET P_withwheel= MFR_VAV*(H_CA-H_SA),!- A38
 ENDIF,!- A39
 SET W_OA= @WFnTdbH OAT H_OA,!- A40
 SET W_SAmax= @WFnTdbRhPb T_SAsp 100 101000,!- A41
 SET W_SAtarget= @min W_OA W_SAmax,!- A42
 SET H_SA= @HFnTdbW T_SAsp W_SAtarget,!- A43
 SET H_OA= @HFnTdbW OAT W_OA,!- A44
 SET P_withoutwheel= MFR_VAV*(H_OA-H_SA),!- A45
 SET P_savings=P_withoutwheel-P_withwheel,!- A46
 SET n_chiller= 2.8,!- Chiller COP (rated)
 SET P_savings_adj=P_savings/(n_chiller),!- Expected electricity savings to cool
supply air from using wheel
 ENDIF,!- A49
 IF P_savings_adj<P_VAV_exp,!- If cooling/heating savings is less than added fan power
 SET VAV_w_a=0,!- Set schedule to disable wheel
 ELSE,!- A52
 SET VAV_w_a=1,!- A53
 ENDIF;!- A54
```

B.29 Measure 38: Demand-Response-SetpointChanges

Implementing this CPP event requires loading a pre-defined schedule file that contains hour-by-hour definitions of CPP events, based on an analysis of daily high temperatures in each weather file. The cooling thermostat can then be adjusted by an EMS program that is cued off of the CPP event schedule.

```
Schedule:File,
 DR_Event,!- Name
 Any Number,!- Schedule Type Limits Name
 /phome/comstd/CtrlBenefit/simulation/DR_ScheduleFiles/BaltimoreDR.csv,!- File Name
 1,!- Column Number
 0,!- Rows to Skip at Top
 8760,!- Number of Hours of Data
 Comma,!- Column Separator
 No,!- Interpolate to Timestep
 60;!- Minutes per Item

EnergyManagementSystem:Sensor,
 CPP_Event_Sensor,!- Name
 DR_Event,!- Output:Variable or Output:Meter Index Key Name
 Schedule Value;!- Output:Variable or Output:Meter Name
```

```
EnergyManagementSystem:Actuator,
 Cool_Tstat,!- Name
 CLGSETP_SCH_Base_ExtendedHVAC,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:ProgramCallingManager,
 DR_ManagerSetPoint,!- Name
 BeginTimestepBeforePredictor,!- EnergyPlus Model Calling Point
 SetPointChanges;!- Program Name 2

EnergyManagementSystem:Program,
 SetPointChanges,!- Name
 IF CPP_Event_Sensor==1,!- Program Line 2
 SET Cool_Tstat = 25.8,!- A4
 Else,!- A5
 SET Cool_Tstat= Null,!- A6
 Endif,!- A7
 SET DemandKW = Demand*20/3600;!- A8
```

B.30 Measure 39: Demand-Response-Pre-Cooling

The following EnergyPlus code demonstrates the implementation of a pre-cooling DR. The CPP_Event_Sensor refers to coded hourly values in the DR_Event schedule file. The code 2 is used for three hours prior to a DR event, the code 3 is used for two hours prior, the code 4 is used for one hour prior, and the code 1 for the event itself. The cooling thermostat can then be adjusted by an EMS program that is cued off of the CPP event schedule.

```
Schedule:File,

 DR_Event,!- Name
 Any Number,!- Schedule Type Limits Name
 /phome/comstd/CtrlBenefit/simulation/DR_ScheduleFiles/BaltimoreDR.csv,!- File Name
 1,!- Column Number
 0,!- Rows to Skip at Top
 8760,!- Number of Hours of Data
 Comma,!- Column Separator
 No,!- Interpolate to Timestep
 60;!- Minutes per Item

EnergyManagementSystem:Actuator,
 Cool_Tstat,!- Name
 CLGSETP_SCH_Base_ExtendedHVAC,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

!- PART3: EEM35_GridDR_MECH_precool: insert schedule line 14502-14512
EnergyManagementSystem:Actuator,
 Heat_Tstat,!- Name
 HTGSETP_SCH_Base_ExtendedHVAC,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type
```

```
EnergyManagementSystem:ProgramCallingManager,
 DR_ManagerPreCool,!- Name
 BeginTimestepBeforePredictor,!- EnergyPlus Model Calling Point
 PreCool;!- Program Name 2

EnergyManagementSystem:Program,
 PreCool,!- Name
 IF CPP_Event_Sensor==2,!- Program Line 1
 SET Cool_Tstat = 21.8,!- Program Line 2
 SET Heat_Tstat = 10,!- A4
 Elseif CPP_Event_Sensor==3,!- A5
 SET Cool_Tstat = 20.8,!- A6
 SET Heat_Tstat = 10,!- A7
 Elseif CPP_Event_Sensor==4,!- A8
 SET Cool_Tstat = 19.8,!- A9
 SET Heat_Tstat = 10,!- A10
 Elseif CPP_Event_Sensor==1,!- A11
 SET Cool_Tstat = 25.8,!- A12
 SET Heat_Tstat = 10,!- A13
 ELSE,!- A14
 SET Cool_Tstat= Null,!- A15
 SET Heat_Tstat = Null,!- A16
 Endif,!- A17
 SET DemandKW = Demand* 12 /3600;!- A18
```

B.31 Measure 40: Demand-Response-Duty Cycle

This control is accomplished in EnergyPlus (see code below for Small Office) by assigning one of three thermostats evenly to all zones served under each air system (in this case only one zone per air system). Two EMS programs are used. A program called DutyCycleCount maintains a running count of timesteps (five per hour) and resets after three hourly duty cycles. The second program, called DutyCycle, decides based on that count which duty cycle is active and selects one of three cooling thermostat schedules to switch to 50°C. This setpoint is so high that it is equivalent to locking out the cooling coil.

```
Schedule:Constant,
 DutyCycleTimestepCount,!- Name
 Number,!- Schedule Type Limits Name
 1;!- Hourly Value
ZoneControl:Thermostat,
 South Perim Spc GS1 Thermostat,!- Name
 South Perim Spc GS1,!- Zone or ZoneList Name
 COMPACT HVAC-ALWAYS 4,!- Control Type Schedule Name
 ThermostatSetpoint:DualSetpoint,!- Control 1 Object Type
 Thermostat 1 Dual SP Control;!- Control 1 Name

ZoneControl:Thermostat,
 South Perim Spc TS11 Thermostat,!- Name
 South Perim Spc TS11,!- Zone or ZoneList Name
 COMPACT HVAC-ALWAYS 4,!- Control Type Schedule Name
 ThermostatSetpoint:DualSetpoint,!- Control 1 Object Type
 Thermostat 2 Dual SP Control;!- Control 1 Name

ZoneControl:Thermostat,
```

```
 East Perim Spc GE2 Thermostat,!- Name
 East Perim Spc GE2,!- Zone or ZoneList Name
 COMPACT HVAC-ALWAYS 4,!- Control Type Schedule Name
 ThermostatSetpoint:DualSetpoint,!- Control 1 Object Type
 Thermostat 3 Dual SP Control;!- Control 1 Name

EnergyManagementSystem:Sensor,
 DutyCycleNumSensor,!- Name
 DutyCycleTimestepCount,!- Output:Variable or Output:Meter Index Key Name
 Schedule Value;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Actuator,
 DutyCycleNumActuator,!- Name
 DutyCycleTimestepCount,!- Actuated Component Unique Name
 Schedule:Constant,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 Cool_Tstat1,!- Name
 Cool 1/0,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 Cool_Tstat2,!- Name
 Cool 1/0 2,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 Cool_Tstat3,!- Name
 Cool 1/0 3,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:TrendVariable,
 DutyCycleTrend,!- Name
 DutyCycleNumSensor,!- EMS Variable Name
 3;!- Number of Timesteps to be Logged

EnergyManagementSystem:GlobalVariable,
 DutyCycleLength;!- Erl Variable 1 Name

EnergyManagementSystem:Program,
 DutyCycle,!- Name
 SET CurrCycle = DutyCycleNumSensor,!- Program Line 1
 IF CPP_Event_Sensor == 1 && CurrCycle <= DutyCycleLength,!- Program Line 2
 SET Cool_Tstat1 = 50,!- A4
 Else,!- A5
 SET Cool_Tstat1= Null,!- A6
 Endif,!- A7
 IF CPP_Event_Sensor == 1 && CurrCycle > DutyCycleLength && CurrCycle <=
2*DutyCycleLength,!- A8
 SET Cool_Tstat2 = 50,!- A9
 Else,!- A10
```

```
 SET Cool_Tstat2= Null,!- A11
 Endif,!- A12
 IF CPP_Event_Sensor == 1 && CurrCycle > (2*DutyCycleLength),!- A13
 SET Cool_Tstat3 = 50,!- A14
 Else,!- A15
 SET Cool_Tstat3= Null,!- A16
 Endif,!- A17
 SET DemandKW = Demand*12/3600;!- A18

EnergyManagementSystem:Program,
 DutyCycleCount,!- Name
 SET DutyCycleLength = 5,!- Program Line 1
 SET CurrDutyCycle = DutyCycleTrend 1,!- Program Line 2
 SET DutyCycleNumActuator = CurrDutyCycle+ 1,!- A4
 IF DutyCycleNumActuator > DutyCycleLength*3,!- A5
 SET DutyCycleNumActuator = 1,!- A6
 Endif;!- A7
```

B.32 Measure 41: Demand-Response-Lighting

Implementation of this strategy in EnergyPlus is demonstrated below for the Small Office prototype.

```
EnergyManagementSystem:Sensor,
 LtgSch_Sensor,!- Name
 Lgt 1/0_Copy,!- Output:Variable or Output:Meter Index Key Name
 Schedule Value;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Actuator,
 Ltg_Reset,!- Name
 Lgt 1/0,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:ProgramCallingManager,
 DR_LtgManager,!- Name
 BeginTimestepBeforePredictor,!- EnergyPlus Model Calling Point
 DR_Ltg;!- Program Name 2

EnergyManagementSystem:Program,
 DR_Ltg,!- Name
 IF CPP_Event_Sensor==1,!- Program Line 1
 SET Ltg_Reset = LtgSch_Sensor * 0.9,!- Program Line 2
 Else,!- A4
 SET Ltg_Reset = Null,!- A5
 Endif;!- A6
```

B.33 Measure 42 Demand-Response-Chilled Water Temperature Reset

EnergyPlus objects used to specify this DR strategy are reproduced below.

```
Schedule:Constant,
 PreviousFlow1,!- Name
 Any Number,!- Schedule Type Limits Name
```

```
 1;!- Hourly Value

Schedule:Constant,
 PreviousFlow2,!- Name
 Any Number,!- Schedule Type Limits Name
 1;!- Hourly Value

Schedule:Constant,
 PreviousFlow3,!- Name
 Any Number,!- Schedule Type Limits Name
 1;!- Hourly Value

nergyManagementSystem:Sensor,
 VAV1_FlowSensor,!- Name
 VAV_1 Supply Equipment Outlet Node,!- Output:Variable or Output:Meter Index Key Name
 System Node Mass Flow Rate;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 VAV2_FlowSensor,!- Name
 VAV_2 Supply Equipment Outlet Node,!- Output:Variable or Output:Meter Index Key Name
 System Node Mass Flow Rate;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 VAV3_FlowSensor,!- Name
 VAV_3 Supply Equipment Outlet Node,!- Output:Variable or Output:Meter Index Key Name
 System Node Mass Flow Rate;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 PrevFlow1_S,!- Name
 PreviousFlow1,!- Output:Variable or Output:Meter Index Key Name
 Schedule Value;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 PrevFlow2_S,!- Name
 PreviousFlow2,!- Output:Variable or Output:Meter Index Key Name
 Schedule Value;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 PrevFlow3_S,!- Name
 PreviousFlow3,!- Output:Variable or Output:Meter Index Key Name
 Schedule Value;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Actuator,
 CHWT_Reset,!- Name
 CoolSys1 Loop Setpoint Sched,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 VAV1_FlowReset,!- Name
 VAV_1_FAN,!- Actuated Component Unique Name
 Fan,!- Actuated Component Type
 Fan Air Mass Flow Rate;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
```

```
 VAV2_FlowReset,!- Name
 VAV_2_FAN,!- Actuated Component Unique Name
 Fan,!- Actuated Component Type
 Fan Air Mass Flow Rate;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 VAV3_FlowReset,!- Name
 VAV_3_FAN,!- Actuated Component Unique Name
 Fan,!- Actuated Component Type
 Fan Air Mass Flow Rate;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 PrevFlow1_A,!- Name
 PreviousFlow1,!- Actuated Component Unique Name
 Schedule:Constant,!- Actuated Component Type
 Schedule value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 PrevFlow2_A,!- Name
 PreviousFlow2,!- Actuated Component Unique Name
 Schedule:Constant,!- Actuated Component Type
 Schedule value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 PrevFlow3_A,!- Name
 PreviousFlow3,!- Actuated Component Unique Name
 Schedule:Constant,!- Actuated Component Type
 Schedule value;!- Actuated Component Control Type

EnergyManagementSystem:ProgramCallingManager,
 DR_CHWT_ResetManager,!- Name
 AfterPredictorBeforeHVACManagers,
 DR_CHWT_Reset;!- Program Name 2

EnergyManagementSystem:ProgramCallingManager,
 PrevFlowMan,!- Name
 EndOfSystemTimestepAfterHVACReporting,!- EnergyPlus Model Calling Point
 SetPrevFlow;!- Program Name 1

EnergyManagementSystem:Program,
 DR_CHWT_Reset,!- Name
 SET PrevFlow1=PrevFlow1_S,!- Program Line 1
 SET PrevFlow2=PrevFlow2_S,!- Program Line 1
 SET PrevFlow3=PrevFlow3_S,!- Program Line 1
 IF CPP_Event_Sensor==1,!- Program Line 1
 SET CHWT_Reset = 10,!- Program Line 2
 SET VAV1_FlowReset = PrevFlow1,
 SET VAV2_FlowReset = PrevFlow2,
 SET VAV3_FlowReset = PrevFlow3,
 Else,!- A4
 SET CHWT_Reset = Null,!- A5
 SET VAV1_FlowReset = NULL,
 SET VAV2_FlowReset = NULL,
 SET VAV3_FlowReset = NULL,
 Endif;!- A6
```

```
EnergyManagementSystem:Program,
 SetPrevFlow,!- Name
 SET PrevFlow1_A= VAV1_FlowSensor,!- Program Line 1
 SET PrevFlow2_A= VAV2_FlowSensor,!- Program Line 2
 SET PrevFlow3_A= VAV3_FlowSensor;!- A4
```

B.34 Measure 43 Demand-Response- Refrigeration

The EnergyPlus EMS code controlling this measure is reproduced below.

```
EnergyManagementSystem:Program,
 DR_Post_Process,!- Name
 SET DR_Demand = 0,
 SET DR_Pre_Demand=0,
 SET DR_Post_Demand=0,
 IF CPP_Event_Sensor==1,!- Program Line 2
 SET DR_Demand = Demand /(ZoneTimeStep*3600),!- A8
 SET DR_Demand = DR_Demand - A01ASH - A02ASH - A03ASH - A04ASH,
 SET DR_Demand = DR_Demand - B01ASH - B02ASH - B03ASH,
 ELSE,
 SET DR_Demand = 0,
 ENDIF,
 IF CPP_Event_Sensor>0,
 IF CPP_Event_Sensor==1,
 SET DR_FullDay = Demand /(ZoneTimeStep*3600),!- A8
 SET DR_FullDay = DR_FullDay - A01ASH - A02ASH - A03ASH - A04ASH,
 SET DR_FullDay = DR_FullDay - B01ASH - B02ASH - B03ASH,
 ELSE,
 SET DR_FullDay = Demand /(ZoneTimeStep*3600),!- A8
 ENDIF,
 ELSE,
 SET DR_FullDay = 0,
 ENDIF;

EnergyManagementSystem:Actuator,
 CaseLtgCtrl,!- Name
 CaseLtgSchOrig,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 A01DefrostCtrl,!- Name
 A01 Defrost Sch,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 A02DefrostCtrl,!- Name
 A02 Defrost Sch,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
```

```
 A03DefrostCtrl,!- Name
 A03 Defrost Sch,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 A04DefrostCtrl,!- Name
 A04 Defrost Sch,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 B01DefrostCtrl,!- Name
 B01 Defrost Sch,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 B02DefrostCtrl,!- Name
 B02 Defrost Sch,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 B03DefrostCtrl,!- Name
 B03 Defrost Sch,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 A05DefrostCtrl,!- Name
 A05 Defrost Sch,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 B04DefrostCtrl,!- Name
 B04 Defrost Sch,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 D11DefrostCtrl,!- Name
 D11 Defrost Sch,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 D13DefrostCtrl,!- Name
 D13 Defrost Sch,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Actuator,
 D16DefrostCtrl,!- Name
```

```
 D16 Defrost Sch,!- Actuated Component Unique Name
 Schedule:Compact,!- Actuated Component Type
 Schedule Value;!- Actuated Component Control Type

EnergyManagementSystem:Sensor,
 A01ASH,!- Name
 A01 Ice Cream Reach-Ins,!- Output:Variable or Output:Meter Index Key Name
 Refrigeration Case Anti Sweat Electric Power;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 A02ASH,!- Name
 A02 Ice Cream Reach-Ins,!- Output:Variable or Output:Meter Index Key Name
 Refrigeration Case Anti Sweat Electric Power;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 A03ASH,!- Name
 A03 Ice Cream Reach-Ins,!- Output:Variable or Output:Meter Index Key Name
 Refrigeration Case Anti Sweat Electric Power;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 A04ASH,!- Name
 A04 Ice Cream Coffins,!- Output:Variable or Output:Meter Index Key Name
 Refrigeration Case Anti Sweat Electric Power;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 B01ASH,!- Name
 B01 Frozen Food Reach-Ins,!- Output:Variable or Output:Meter Index Key Name
 Refrigeration Case Anti Sweat Electric Power;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 B02ASH,!- Name
 B02 Frozen Food Reach-Ins,!- Output:Variable or Output:Meter Index Key Name
 Refrigeration Case Anti Sweat Electric Power;!- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
 B03ASH,!- Name
 B03 Frozen Food Reach-Ins,!- Output:Variable or Output:Meter Index Key Name
 Refrigeration Case Anti Sweat Electric Power;!- Output:Variable or Output:Meter Name


EnergyManagementSystem:ProgramCallingManager,
 DR_ManagerRefCase,!- Name
! BeginTimestepBeforePredictor,!- EnergyPlus Model Calling Point
 InsideHVACSystemIterationLoop,!- EnergyPlus Model Calling Point
 RefCaseCtrl;!- Program Name 1

EnergyManagementSystem:Program,
 RefCaseCtrl,!- Name
 IF CPP_Event_Sensor==1,!- Program Line 1
 SET CaseLtgCtrl = 0,!- Program Line 2
 SET A01DefrostCtrl = 0,!- Program Line 2
 SET A02DefrostCtrl = 0,!- Program Line 2
 SET A03DefrostCtrl = 0,!- Program Line 2
 SET A04DefrostCtrl = 0,!- Program Line 2
 SET B01DefrostCtrl = 0,!- Program Line 2
```

```
SET B02DefrostCtrl = 0,!- Program Line 2
SET B03DefrostCtrl = 0,!- Program Line 2
SET A05DefrostCtrl = 0,!- Program Line 2
SET B04DefrostCtrl = 0,!- Program Line 2
SET D11DefrostCtrl = 0,!- Program Line 2
SET D13DefrostCtrl = 0,!- Program Line 2
SET D16DefrostCtrl = 0,!- Program Line 2
ELSE,
SET CaseLtgCtrl = NULL,!- Program Line 2
SET A01DefrostCtrl = NULL,!- Program Line 2
SET A02DefrostCtrl = NULL,!- Program Line 2
SET A03DefrostCtrl = NULL,!- Program Line 2
SET A04DefrostCtrl = NULL,!- Program Line 2
SET B01DefrostCtrl = NULL,!- Program Line 2
SET B02DefrostCtrl = NULL,!- Program Line 2
SET B03DefrostCtrl = NULL,!- Program Line 2
SET A05DefrostCtrl = NULL,!- Program Line 2
SET B04DefrostCtrl = NULL,!- Program Line 2
SET D11DefrostCtrl = NULL,!- Program Line 2
SET D13DefrostCtrl = NULL,!- Program Line 2
SET D16DefrostCtrl = NULL,!- Program Line 2
ENDIF;
```

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