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Energy Savings and Peak Load Reduction Benefits from Building Controls Measures in Seattle, Washington

May 2017

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Abstract

Many commercial buildings consume more energy than they should, while also simultaneously failing to maintain adequate comfort of occupants. The inability to adequately sense, monitor, and control buildings effectively leads to significant energy waste. This study was initiated to systematically estimate and document the potential savings from improving building operations. The purpose of the study was to quantify 1) the technical energy savings potential from deployment of accurate sensors, proper and advanced controls, and automated fault detection and diagnostics in the commercial building sector and 2) lowered commercial peak electric demand by using demand-response measures. These estimations were performed via simulation of individual measures as well as packages of measures using the U.S. Department of Energy's (DOE's) EnergyPlus building energy modeling software. This report documents the results relevant to the climate in Seattle, Washington.

In this report, each of the 38 individual energy efficiency measures (EEMs) and 6 demand-response (DR) measures that were considered are described, including details regarding how each measure was modeled in EnergyPlus. Three packages of EEMs were created to estimate city-wide savings by building type for the set of measures included in Seattle's Tune-Ups mandate. Two packages of DR measures were also created. Detailed total site energy savings, natural gas savings, and electricity savings are reported both for individual EEMs and for packages of measures by building type in Seattle. The electricity demand savings resulting from DR measures and the savings estimates of the packages of measures are also presented.

The total site savings from individual EEMs varied significantly by building type, ranging between -12% and 21%. Some individual measures had negative savings because correcting an underlying operational problem (e.g., inadequate ventilation) resulted in an increase in energy consumption.

The three packages of EEMs, created to estimate the whole-building energy and electricity savings potential from the Seattle Building Tune-Ups mandate, represented 1) an efficient building, 2) a typical building, and 3) an inefficient building. The efficient building package only includes a few (or in some cases no) EEMs because the buildings to which this package applies (~30% of the building stock) are considered to be efficient with little possibility of improvement. The inefficient building package is assumed to offer significant savings opportunity (all EEMs) because it is considered to be inefficient (applies to 20% of the building stock), and the typical building package is in between the two packages in opportunity and prevalence (50% of the building stock). The total site energy savings for the efficient building package, typical building package, and inefficient building package, respectively, ranged from 0% to 18%, 17% to 39%, and 19% to 45%. Applying estimated weights to each of the packages, the annual building energy savings is estimated to be between 14% and 32%, by building type, including electricity savings between 4% and 20% and natural gas savings between 20% and 65%.

Summary

Commercial buildings in the United States use about 18 Quadrillion British thermal units (Quads) of primary energy annually.[1] Studies have shown that as much as 30% of building energy consumption can be avoided by using more accurate sensing, using existing controls better, and deploying advanced controls; hence, the motivation for the work described in this report. Studies also have shown that 10% to 20% of the commercial building peak load can be temporarily managed/curtailed to provide grid services. Although many studies have indicated significant potential for reducing the energy consumption in commercial buildings, very few have documented the actual measured savings. The studies that did so only provided savings at the whole-building level, which makes it difficult to assess the savings potential of each individual measure deployed.

Study Purpose

Pacific Northwest National Laboratory (PNNL) conducted a study for the U.S. Department of Energy (DOE) to systematically estimate and document the potential savings using detailed simulation of individual measures and packages of measures using DOE's EnergyPlus building energy modeling software and considering Re-tuning™ opportunities (Fernandez et al. 2017). This report is a customization of the DOE study, specifically for the City of Seattle, Washington and Seattle City Light.

In 2016, the city of Seattle approved through its council, a mandate called the Seattle Building Tune-Ups mandate (Seattle Building Tune-Ups Ordinance 2016). Beginning in 2018, commercial buildings over 50,000 ft^2 will be required to undergo periodic "tune-ups", aimed at optimizing energy and water performance by identifying no or low-cost actions related to building operations and maintenance, focusing on actions that typically pay back within three years. The mandate includes a "Director's Rule" (Seattle Office of Sustainability and Environment 2016) that identifies in Section 11 (Table 1) required and voluntary corrective actions (potential EEMs) if deficiencies are found in buildings. This report attempts to reshape the approach to the national energy savings to the specific requirements of the Seattle Building Tune-Ups mandate.

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 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 energy waste 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 measures simulated during the study. For each building type, the study's two-fold purpose was to quantify two impacts relative to their potential savings:

- the impact of deploying accurate sensors, proper and advanced controls, and automated fault detection and diagnostics by estimating the energy savings potential of these Re-tuning approaches in the commercial building sector; and
- the impact of demand-response (DR) measures to lower commercial building electric demand during critical peak pricing (CPP) events. This load reduction potential can help to facilitate the performance

[1] DOE Energy Information Administration. *Annual Energy Outlook 2016*. See Table 2, accessed September 8, 2016: https://www.eia.gov/forecasts/aeo/tables_ref.cfm

of grid services by buildings that may be of particular benefit under a scenario of higher penetration of renewables (e.g., solar photovoltaics).

Methodology for Calculating Savings

Estimation of the energy savings derived by adopting Re-tuning and DR measures involved the simulation of individual and packages of energy savings and DR measures in nine DOE prototype building models, using a typical meteorological year 3 (TMY3) weather input file for Seattle. 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 were simulated for the 9 prototypical buildings in Seattle. 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. The savings were calculated for each individual EEM, and each relevant building type; a summary, ranking the measures by impact for each building type, was also included. To estimate savings from the set of measures included in the Seattle Building Tune-Ups mandate, a set of packages were also created—those designed for 1) efficient buildings, 2) "typical" buildings, and 3) "inefficient" buildings. The savings calculated for the individual measures were also calculated for the packaged measures.

Building Prototype Models

Nine EnergyPlus building prototype models (described below) were used to simulate each of the Re-tuning and DR measures simulated in this report. The models were derived directly from the commercial building prototypes developed by DOE for the Building Energy Codes Program,[1] or from other further refinements of these models. They served as a starting point for development of the baseline models used in this study, and each model underwent changes to enable proper estimation of the savings derived from the full suite of Re-tuning measures that were investigated. Descriptions and accompanying figures of each prototype model include the total square footage, building external and internal construction, and operating systems, including HVAC, electricity/lighting, and water. Changes/faults added to the baseline models are also described. All building types were modified to represent the existing building stock based on an assumed vintage of the 1990s. This most notably includes wall, roof, and window construction adhering to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 90.1-1999 according to the climate and construction type of the building, as listed below.

- Small Office – The EnergyPlus model for the Small Office was developed by modifying the prototype model used in the Advanced Energy Design Guide. The model is a two-story building with 20,000 ft2 of total floor area, using packaged single-zone rooftop air-conditioning units with natural gas heating coils and direct expansion (DX) cooling coils for HVAC.
- Medium Office – The EnergyPlus model for the Medium Office was developed by modifying the prototype model used in the Advanced Energy Design Guide. The model is a three-story building with 53,600 ft2 of total floor area, using packaged multi-zone variable-air-volume (VAV) air-conditioning units with natural gas heating coils and DX cooling coils for HVAC. VAV terminal boxes have electric reheat capability.
- Large Office – The Large Office prototype is a four-story building with 200,000 ft2 of total floor area that uses a central boiler plant and water-cooled chiller plant for generation of hot water and chilled water that are used in built-up VAV air-handling units (AHUs) with terminal box hot water reheat.

[1] http://energy.gov/eere/buildings/commercial-reference-buildings

- Large Hotel – The prototype Large Hotel building consists of six stories aboveground, plus a conditioned basement floor, totaling 122,132 ft2 of total floor area. The building uses a central boiler plant and air-cooled chiller plant for generation of hot water and chilled water. Guest rooms are conditioned with four-pipe fan-coil units with a dedicated outdoor air system for ventilation. Other public zones are conditioned via a single built-up AHU with a hot water and chilled water coil and hot water reheat at the terminal boxes.
- StandAlone Retail – The EnergyPlus model for StandAlone Retail was developed by modifying the prototype model used in the Advanced Energy Design Guide. It is a single-story building with a rectangular footprint, covering 24,695 ft2 of total floor area. The building uses packaged single-zone rooftop air-conditioning units with natural gas heating coils and DX cooling coils for HVAC.
- Strip Mall Retail – The EnergyPlus model for Strip Mall Retail was developed by modifying the prototype model used in the Advanced Energy Design Guide. The model is a one-story building with 22,500 ft2 of total floor area and 10 retail stores. The building uses packaged single-zone rooftop air-conditioning units with natural gas heating coils and DX cooling coils for HVAC.
- Primary School – The Primary School model was developed based on the DOE commercial building prototype model. It is a one-story building, totaling 73,960 ft2 of total floor area. The building uses a central boiler plant for generation of hot water. Most zones, including classrooms are conditioned with built-up VAV AHUs, with DX cooling coils and hot water reheat at the terminal boxes. A gym, kitchen, and cafeteria, however, are conditioned and ventilated using packaged single-zone units with DX cooling coils and gas heating coils.
- Secondary School – The Secondary School model was developed based on the DOE commercial building prototype model and represents buildings constructed in the 1990s. It is a two-story building, totaling 210,900 ft2 of total floor area. The building uses a central boiler plant and air-cooled chiller plant for generation of hot water and chilled water. Most zones, including classrooms, are conditioned with built-up VAV AHUs, with chilled water for cooling and hot water reheat at the terminal boxes. Two gyms, an auditorium, a kitchen, and cafeteria, however, are conditioned and ventilated using packaged single-zone units with DX cooling coils and gas heating coils.
- Supermarket – The Supermarket building prototype model is based on a Grocery Store 50% Energy Savings model with some modifications. It is a standalone, one-floor building with 45,000 ft^2 of total floor area. The building has a refrigeration loop with two low-temperature and two medium-temperature racks that serve many refrigerated display cases and walk-in refrigerators and freezers. The building uses packaged single-zone rooftop air-conditioning units with natural gas heating coils and DX cooling coils for HVAC.

Energy Savings and Demand-Response Control Measures

Forty-three energy savings and DR control measures were designed to produce annual energy savings or be used for DR to reduce power during CPP events. Not all measures were applicable to each building prototype, because the physical or control infrastructure needed to implement the measure was lacking (see Table S.1). The purpose of each measure listed in Table S.1 is briefly described below the table. Note that these measures include a full set of Re-tuning and small capital project measures typically recommended and/or implemented by PNNL’s Re-tuning process. Only a subset of these measures is required as laid out in Section 11B of the Director’s Rule for the City of Seattle Building Tune-Ups mandate (Seattle Office of Sustainability and Environment 2016).

Table S.1. List of Energy Savings and Demand-Response Control Measures and Applicability to Each Prototype

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	●	●	●		●	●	●	●	●
Occupancy Sensors for Lighting	18	●	●	●	●	●		●	●	●
Daylighting Controls	19	●	●	●		●	●	●	●	

Measure	Measure Number	Small Office	Medium Office	Large Office	Large Hotel	StandAlone Retail	Strip Mall Retail	Primary School	Secondary School	Supermarket
Exterior Lighting Control	20	●	●	●		●	●	●	●	●
Advanced Plug Load Controls	21	●	●	●						
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				●					
Heating and Cooling Lockouts	38	●	●	●	●	●	●	●	●	●
Demand Response: Setpoint Changes	39	●	●	●	●	●	●	●	●	●
Demand Response: Pre-Cool	40	●	●	●	●	●	●	●	●	●
Demand Response: Duty Cycle	41	●	●	●		●	●	●	●	●
Demand Response: Lighting	42	●	●	●	●	●	●	●	●	

Measure	Measure Number	Small Office	Medium Office	Large Office	Large Hotel	StandAlone Retail	Strip Mall Retail	Primary School	Secondary School	Supermarket
Demand Response: Chilled Water Temperature Reset	43			●	●				●	
Demand Response: Refrigeration	44									●

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 that are used to control the buildings' air handlers have constant temperature bias faults. This baseline fault is applied to all air-side systems in each prototype that have economizers.

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. This measure is applied to all packaged AHUs and rooftop units (RTUs).

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.

Measure 04: Shorten HVAC Operation Schedules. This measure simulates the correction of HVAC schedules that are applied more widely than necessary. This pertains to the management of the scheduling of HVAC equipment, but is classified as a fault in this context to the extent that the schedules are applied inappropriately or have been neglected.

Measure 05: Supply Air Temperature (SAT) Reset. This measure includes three alternative strategies for SAT control for all buildings with VAV systems for air distribution. *Outdoor Air Temperature-Based Reset* is a simple method for automatic control of SAT; *Seasonal Control* is often applied in buildings without access to building automation system (BAS) programing to automatically reset the SAT; and *Night-Cycle Mode SAT Reset* enables operators to raise the setpoint so that air is only being recirculated in the building, and only heated where there is a heating load.

Measure 06: Outdoor Air Damper Faults and Control. This measure restores proper outdoor air damper operation and control in two ways: 1) 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, and 2) it controls to zero minimum outdoor air during unoccupied periods.

Measure 07: Exhaust Fan Control. This measure synchronizes exhaust fan schedules (for bathroom exhausts) with the HVAC operation schedule used for AHUs so that bathroom exhaust fans shut off at night and when the building is otherwise unoccupied.

Measure 08: Static Pressure Reset. This measure simulates the reset of supply fan static pressure setpoints for VAV systems. Two methods of static pressure reset are modeled. The *Maximum Damper*

Position method simulates control of static pressure setpoints in response to the most open damper position in the VAV network. The *Time of Day Reset* is an alternative strategy that is often implemented in buildings that have pneumatically controlled VAV boxes.

Measure 09: Plant Shutdown When There is No Load. This measure simulates shutting off the secondary loop pumps in central plant systems when there is no load from any of the hot water or chilled water coils in the building.

Measure 10: Chilled Water Differential Pressure (DP) Reset. This measure simulates the reset of the chilled water secondary loop pump's DP setpoint in response to chilled water valve coil positions. DP reset for chilled water loops is a possibility for buildings that have variable-speed chilled water pumps.

Measure 11: Chilled Water Temperature Reset. Two strategies are modeled for this measure: 1) A *Seasonal Reset* simulates the use of a summer chilled water temperature setpoint of 44°F and a winter setpoint of 48°F. 2) An *Outdoor Air Temperature-Based Reset* resets the chilled water temperature from 44°F when the outdoor air temperature is above 80°F to 50°F when the outdoor air temperature is below 60°F with a linear reset of the chilled water temperature setpoint for outdoor temperatures between 80°F and 50°F.

Measure 12: Condenser Water Temperature Reset: This measure maintains the condenser water temperature setpoint at a 4°C approach temperature to the outdoor air wet-bulb temperature. It was 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 DP reset is handled the same way as for chilled water DP reset—by adjusting pump curves for hot water loop secondary loop pumps using the same changes in pump power curve coefficients. Hot water temperature reset was modeled for all buildings with variable-speed hot water loop pumps.

Measure 14: Hot Water Temperature Reset. This measure is applicable to all prototypes with hot water loops and resets the hot water temperature linearly from 150°F to 180°F based on outdoor air temperatures of 65°F to 25°F, respectively. Reset strategies for condensing boilers can make use of cooler minimum hot water temperatures.

Measure 15: Minimum VAV Terminal Box Damper Flow Reductions. This measure is applicable to all prototypes with multi-zone VAV systems. For all VAV-served zones, this measure reduces the constant minimum air flow fractions to 25% of the maximum air flow rate.

Measure 16: Wider Thermostat Deadbands and Night Setback. This measure encompasses two strategies that affect thermostat setpoints: 1) it widens the deadbands between the effective heating and effective cooling setpoints to +/-3°F, for an effective heating setpoint of 69°F and an effective cooling setpoint of 75°F; and 2) it expands heating night setback limits for individual zones from 65°F to 60°F.

Measure 17: Demand Control Ventilation (DCV). Minimum outdoor air requirements for buildings are typically set based on design occupancy. Two different strategies for DCV were modeled depending on building type. The *Zone Sum* Procedure, used for multi-zone VAV systems, simulates a ventilation scheme that dynamically complies with ASHRAE Standard 62.1 ventilation requirements. The *Indoor Air Quality Procedure,* used for single-zone packaged equipment, uses an estimation of zone carbon dioxide (CO_2) concentration to drive the minimum outdoor air requirements.

Measure 18: Occupancy Sensors for Lighting. This measure simulates the use of occupancy sensors in applicable spaces by adjusting lighting schedules according to the anticipated fraction of lighting that will shut off, and it is implemented by zone type.

Measure 19: Daylighting Control. This measure simulates the use of daylighting controls for perimeter zone lighting. The measure dims lights in the 15 ft area closest to the windows in perimeter zones using a light sensor that maintains an illuminance setpoint of 300 lux.

Measure 20: Exterior Lighting Control. This measure uses a simulated photocell to shut parking lot lights off during the day, and only keeps all of the parking lot lights on at night during building occupied hours (plus an additional hour before and after occupancy). When parking lot lights shut off at night, 25% remain on for safety.

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.

Measure 22: Night Purge. This measure simulates the use of a special early morning cycle of the AHUs that makes use of full air-side economizing to pre-cool the building in advance of occupancy.

Measure 23: Advanced RTU Controls. 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 (e.g., cooling, heating, ventilating, economizing). This measure is simulated for all packaged single-zone RTUs.

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.

Measure 25: Waterside Economizer. This measure simulates the impact of using a waterside economizer for free cooling, and was implemented only for the Large Office prototype—the only one that has a condenser water loop.

Measure 26: Cooling Tower Controls (Variable-Speed Fan). This measure simulates the addition of variable-frequency drives (VFDs) to cooling towers.

Measure 27: Optimal Start. This measure simulates the use of predictive controls that are often used to control the scheduled morning startup of AHUs. Optimal start is commonly available as a configurable module within BASs supplied by most vendors.

Measure 28: Optimal Stop. This 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."

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 closes until 1 hour prior to the store opening.

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), 7 days per week.

Measure 31: Refrigeration Floating Head Pressure. This measure pertains only to the Supermarket prototype and is geared toward saving energy by lowering the compressor lift (pressure difference between condenser and evaporator) on the main refrigeration system that serves refrigerated cases and displays throughout the sales area. Floating head pressure control optimizes the high pressure setpoint for the refrigeration loop by dynamically setting the “head pressure” setpoint according to ambient conditions.

Measure 32: Refrigeration Floating Suction Pressure. This measure pertains only to the Supermarket prototype and is geared toward saving energy by lowering compressor lift on the main refrigeration system that serves refrigerated cases and displays throughout the sales area. 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 a demand-based control of the defrost heaters on freezer display cases and walk-in freezers. The strategy used is conceptually based on a “time-temperature control” method that uses a temperature sensor on the evaporator to determine when the frost has melted and the defrost cycle can be terminated.

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. 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. Evaporator fans are slowed down when the evaporator coil serving the walk-in area is operating at a lower 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 shut off lighting and set back the thermostats in the room when the guests leave.

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 using a heat recovery wheel. This measure disables the wheel (and diverts 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.

Measure 38: Heating and Cooling Lockouts. This measure locks out space heating (including reheat in VAV systems) when the outdoor air temperature is greater than 65°F, and locks out space cooling (including AHU cooling coils) when the outdoor air temperature is less than 50°F.

Measure 39: Demand Response-Setpoint Changes. This DR measure automatically raises the cooling setpoint temperatures throughout the building during a DR event from 75°F to 78.4°F. DR events have been defined as CPP periods in 4-hour windows from 2:00 p.m. to 6:00 p.m. during the eight hottest weekdays of the year in each climate location.

Measure 40: Demand Response-Pre-Cooling. This DR measure is a variation of Measure 38 that anticipates the near-term future occurrence of a CPP event and responds proactively by pre-cooling the building in the 3 hours in advance of the CPP event to cooler-than-normal setpoints. During the CPP event, the thermostat setpoint is then raised to the same level as Measure 38.

Measure 41: Demand Response-Duty Cycle. For this DR measure, cooling demand is mitigated by limiting the number of cooling coils that are active. One out of every three air systems in the building has its cooling coil disabled, and the specific disabled coils are rotated once per hour.

Measure 42: Demand Response-Lighting. This DR measure reduces the power input to the building lights by 10% starting at the beginning of a CPP event and returns lighting to normal levels at the end of the event. This could be done through either dimmable lighting or through specific lighting circuits that are shut off entirely.

Measure 43: Demand Response-Chilled Water Temperature Reset. This DR measure responds to a CPP event 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.

Measure 44: Demand Response-Refrigeration. This DR measure responds to a CPP event 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.

Packages of Re-tuning and Demand-Response Measures

Seattle's new Building Tune-Ups mandate contains a list of requirements. For this reason, packages of Re-tuning measures were created to estimate the national savings potential of Re-tuning. 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 buildings packages are for

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

Table S.2 lists the EEMs in each package. EEMs with over 50% observed prevalence of opportunity are considered nearly universally applicable, and are not already present in any of the three building packages. PNNL defines the "observed prevalence of opportunity" as "the fraction of buildings for which each measure has been recommended for implementation among a set of 130 buildings surveyed by PNNL over the past 10 years for the Re-tuning program." EEMs with between 25% and 50% prevalence of opportunity are considered to be already present in efficient buildings, but not in typical or inefficient buildings. EEMs with less than 25% prevalence of opportunity are considered to be widely applied already, and are only applicable as remaining opportunities in the inefficient buildings. For measures that are not applicable to office-type buildings, no prevalence of opportunity is provided, and PNNL used professional judgment to place them into the three packages. To make the overall prevalence of each measure in the national savings estimates like the observed prevalence from PNNL's Re-tuning experience, the packages were weighted as indicated in columns 4–6 of Table S.2. Savings are estimated by comparing the energy consumption of the package of interest to an ideal building that has all the remaining measures implemented.

Table S.2. Packages of EEMs Used to Estimate Savings from Re-tuning Measures

Energy Efficiency Measure	Prevalence of Opportunity[(a)]	Reference Case (Ideal Building)[(b)]	Efficient Building (30%)	Typical Building (50%)	Inefficient Building (20%)
EEM01: Re-calibrate Faulty Sensors	30%	✓	✓		
EEM04: Shorten HVAC Schedules	48%	✓	✓		
EEM05: Supply Air Temperature Reset	79%	✓			
EEM07: Exhaust Fan Control	44%	✓	✓		
EEM08: Static Pressure Reset	76%	✓			
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%	✓	✓		
EEM27: Optimal Start	48%	✓	✓		
EEM28: Optimal Stop	48%	✓	✓		
EEM38: Heating and Cooling Lockouts	**Unknown**	✓	✓	✓	

(a) The observed prevalence of opportunity indicates the fraction of buildings for which each measure has been recommended for implementation among a set of 130 buildings surveyed by PNNL in the past 10 years for the Re-tuning program.

(b) Energy consumption from each of the three packages is compared to the energy consumption from a modeled "ideal" building 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.

Two DR packages were developed to estimate whole-building and national level electric demand savings derived by implementing a set of DR measures simultaneously during the CPP events. The "reactive" package can be implemented immediately upon initiation of a CPP event, without any prior knowledge or planning for the timing of the event. The predictive package can be implemented if there is advanced warning (at least 4 hours ahead of time) of an impending CPP event, and if the building has the ability to prepare for the event by pre-cooling interior spaces and the building's thermal mass in advance. In both cases, only one measure designed to limit cooling demand is applied, to avoid major thermal comfort disruptions.

Simulation Results

Simulation results and findings for the individual Re-tuning and DR control measures and for the packages of measures are highlighted below. The percent savings reported are the percent of the total site energy consumption. This is broken out into the contribution to that total from electricity and natural gas.

Energy Savings from Individual Measures by Building Type

Table S.3 shows a summary of the range of savings modeled among the set of applicable EEMs for each building type. 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 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, EEM17: demand control ventilation, or EEM05: Supply Air Temperature Reset.

Table S.3. Energy Savings from Individual Measures by Building Type

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	-0.2	6.8	-5.2	9.9	0.0	11.8	EEM19: Daylighting Controls	EEM16: Wider Deadbands and Night Setbacks
Medium Office	-0.1	18.6	-0.2	0.0	-0.1	18.6	EEM15: Minimum VAV Terminal Box Damper Flow Reductions	EEM17: Demand Control Ventilation
Large Office	-0.5	4.3	-3.2	14.6	-0.9	17.5	EEM08: Static Pressure Reset	EEM15: Minimum VAV Terminal Box Damper Flow Reductions
Stripmall Retail	-0.6	9.0	-8.9	16.8	0.0	16.2	EEM23: Advanced RTU Controls	EEM17: Demand Control Ventilation
StandAlone Retail	-0.4	11.4	-12.0	19.3	-0.6	18.9	EEM23: Advanced RTU Controls	EEM17: Demand Control Ventilation
Primary School	-5.7	5.3	-11.5	11.2	-5.0	16.4	EEM16: Wider Deadbands and Night Setbacks	EEM16: Wider Deadbands and Night Setbacks
Secondary School	-3.9	3.8	-4.2	24.8	-4.5	20.9	EEM18: Lighting Occupancy Sensors	EEM17: Demand Control Ventilation
Large Hotel	-0.1	3.5	-1.2	9.4	-0.2	10.7	EEM36: Occupancy Sensors for Thermostats and Room Lighting	EEM05: Supply Air Temperature Reset
Supermarket	0.0	5.4	-4.7	11.5	0.0	12.0	EEM23: Advanced RTU Controls	EEM16: Wider Deadbands and Night Setbacks

Energy Savings from a Package 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 0% to 18%, 17% to 39%, and 19% to 45%, respectively. Based on the weighting of these three efficiency levels, the expected savings from the required measures in the Seattle Building Tune-Ups mandate for each set of building types were also estimated. For most building types, the potential total site savings ranged from 14% to 19%, except for Large Hotel (26%), Secondary School (32%), and Standalone Retail/Dealership (27%). Figure S.1 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 shows the savings in electricity from these packages as well as the overall electricity savings for each building type. The results show that larger buildings are the best candidates for this package of control measures. Savings ranged from 19% for Supermarket to 43% for Secondary School. The package of measures in the Seattle Building Tune-Ups package is particularly well suited for buildings dominated by VAV systems. Most of the top Re-tuning measures for Supermarkets (generally affecting refrigeration systems) are not included in this package, and the savings for this building type were lower.

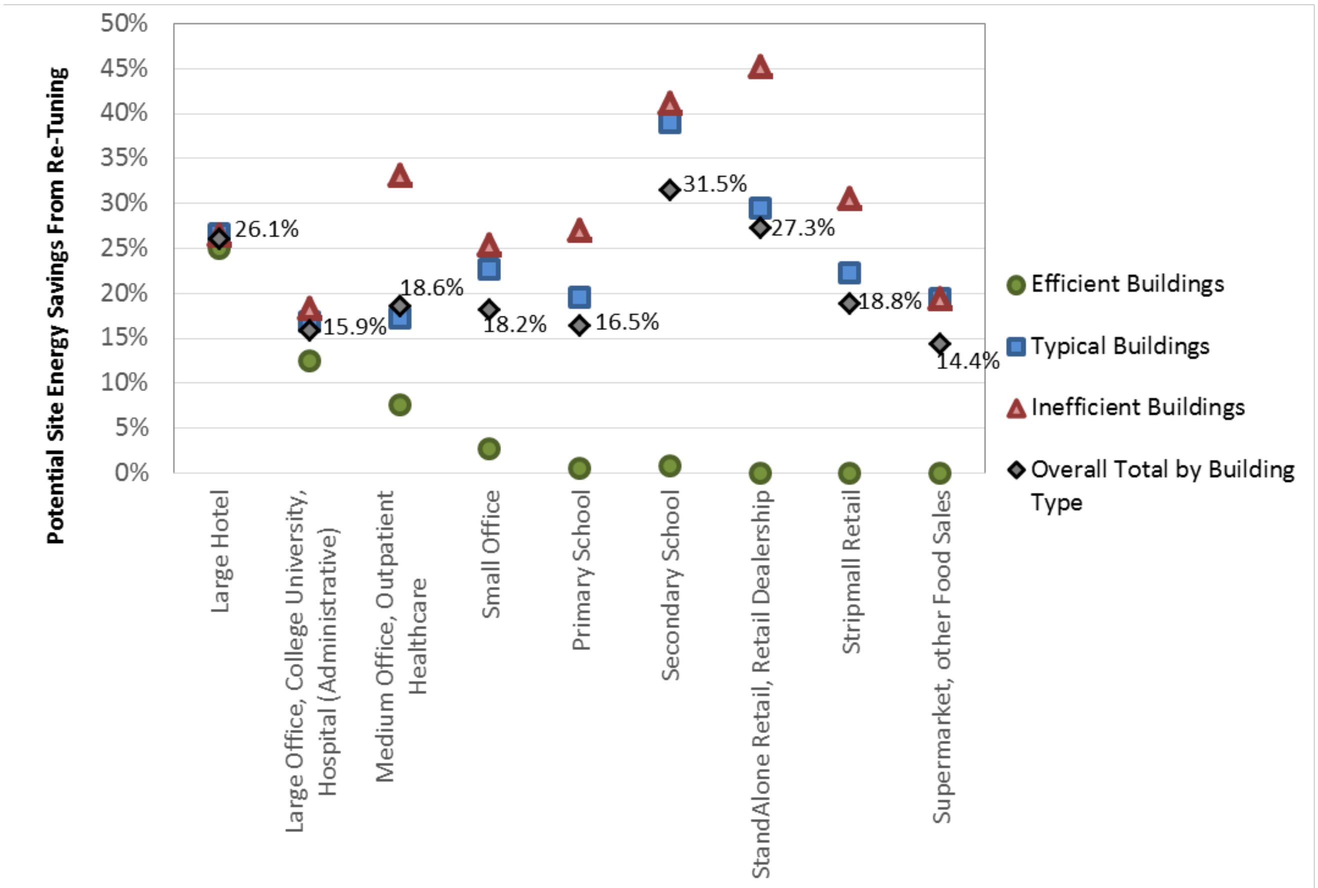

Figure S.1. Whole-Building Energy Savings from Packages of Measures by Building Type

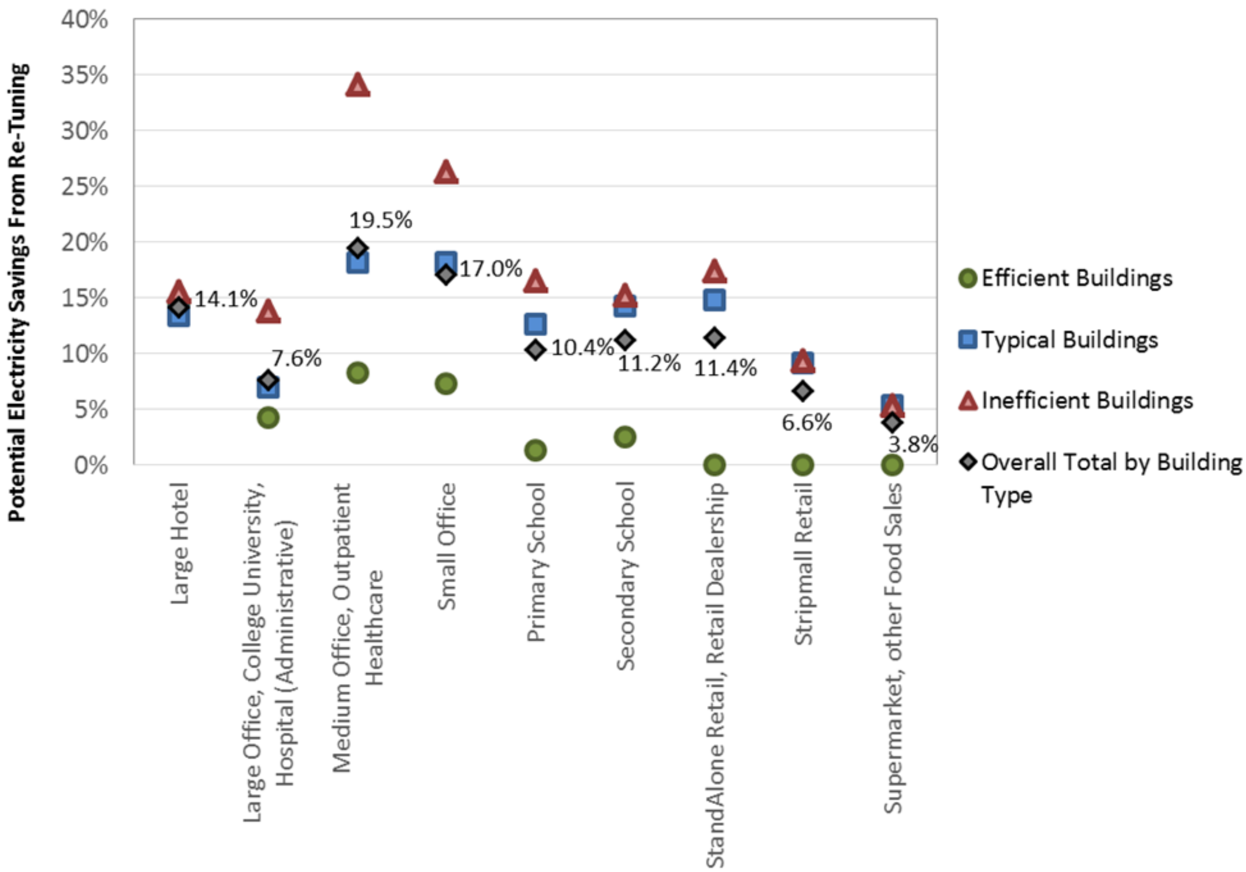

Figure S.2. Electricity Savings from Packages of Measures by Building Type

Peak Reductions from Individual Demand-Response Measures by Building Type

The peak reductions for each of six DR measures were estimated for each of the nine primary building types in Seattle. Because the CPP utility rate is one of the commonly implemented DR rates in California and other parts of the United States, a series of measures was created to estimate the possible peak reduction. The measures included

- thermostat setpoint adjustments during the CPP event
- pre-cooling the building prior to the CPP event, then making thermostat setpoint adjustments during the CPP event
- duty-cycling sets of cooling coils off
- reducing lighting
- raising the chilled water temperature setpoint while holding the fan speeds constant
- a suite of refrigeration system DR measures specifically for supermarkets.

The reductions varied across the building types for each measure. The duty cycle measure resulted in an increase in demand rather than a decrease when applied to supermarkets.

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 4–30% depending on the building type for the reactive package and 6–31% depending on the building type for the predictive package. Figure S.3 shows the modeled electric demand savings during the CPP events for the predictive DR package in each building type for Seattle.

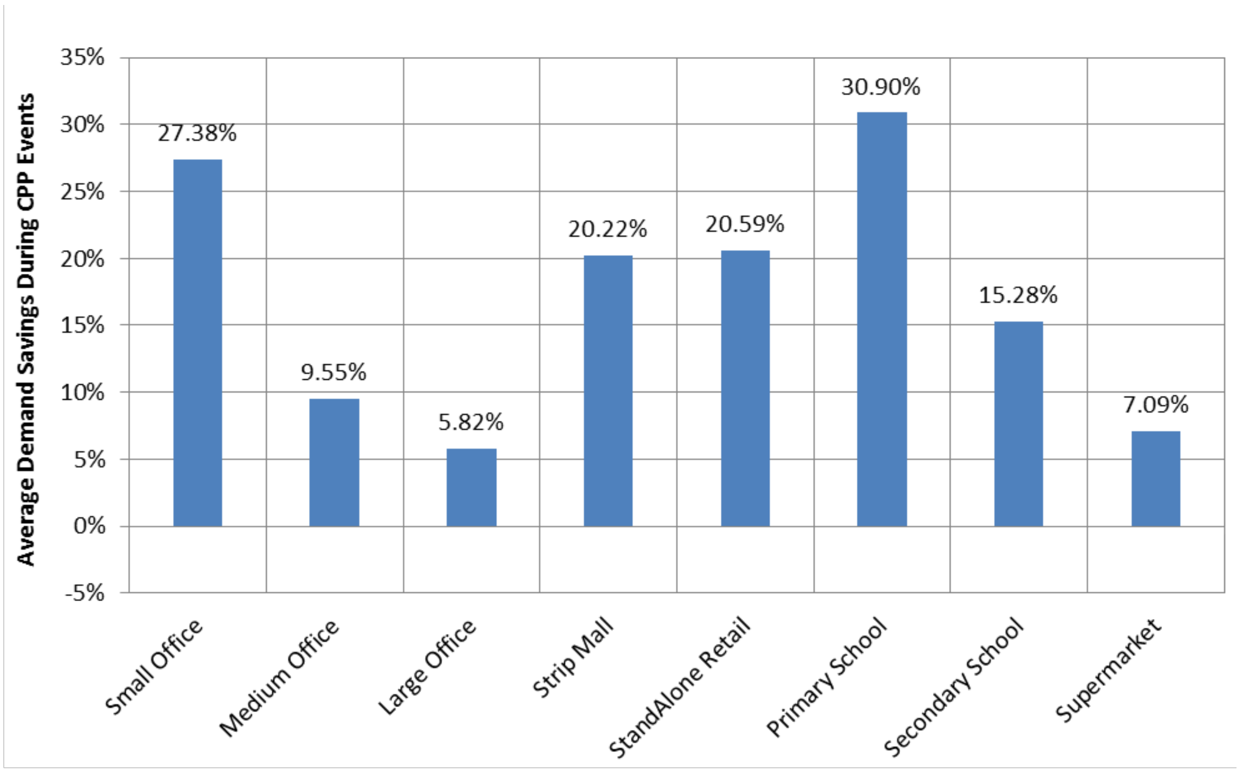

Figure S.3. Demand Response: Aggregate National Savings by Measure and Package

Conclusions, Gaps, and Recommendations

This study investigated the potential energy savings from implementation of common and advanced controls measures in the Seattle climate. 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 BASs, such as enhanced communication capabilities and installation of variable-speed drives on certain fans and pumps in specific buildings. This study simulated 38 EEMs and 6 DR measures in 9 commercial building types and extends (by analogy) to another 5 building types. The energy modeling also relied on packages of measures that represent a of the current status of building controls (inefficient, typical, and efficient); these packages were compared 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 38 EEMs simulated, 6 measures, when simulated individually, showed the potential for over 6% savings in at least 3 building types. These measures included wider deadbands and night setbacks (9 building types), shortened HVAC schedules (8), optimal start (7), demand control ventilation (5), supply air temperature reset (3), and minimum VAV terminal damper flow reductions. The two most impactful measures on electricity savings—achieving over 5% whole-building energy savings in electricity in at least three building types—were not included in the previous list of six measures (which all primarily affected natural gas savings for heating). These two measures are advanced RTU controls (4 building types) and daylighting sensors (3).

Although the study was expansive, there were some limitations and research gaps.

- The set of modeled buildings represents just over half of the commercial building sector square footage. This was confirmed nationally and is expected to represent a similar fraction for Seattle as well.
- 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 many faults and the severity of the fault levels for almost all faults are completely unknown. Therefore, some assumptions for which no data exist in the literature are guesses at best, and savings from their correction could use significant refinement, aided by additional research.
- Another major research gap that needs to be addressed is benchmarking. Several questions need to be investigated. For example, it needs to be determined to what extent the 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, control parameter settings, etc.
- Some available data were used to estimate the prevalence of opportunities for deploying various control measures, especially in office buildings. However, more extensive research on the state of controls across the commercial building sector would greatly improve this picture and aid in the weighting of EEMs within packages.
- 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 to further “push the envelope” of energy savings.

Acknowledgments

The authors acknowledge the Washington State Attorney General's Office and the Buildings Technologies Office of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy for supporting this research and development effort. The authors would also like to thank Ted Brown and Joseph Fernandi at Seattle City Light for their valuable comments and feedback.

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
cfm	cubic foot(feet) per minute
CO_2	carbon dioxide
COP	coefficient of performance
CPP	critical peak pricing
DCV	demand control ventilation
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
hr	hour(s)
HVAC	heating, ventilation, and air-conditioning
IECC	International Energy Conservation Code
in.	inch(es)
kW	kilowatt(s)
Pa	pascal(s)
PBA	principal building activity
Quad	Quadrillion British thermal units
RCx	retro-commissioning
RD&D	research, development, and deployment

RTU	rooftop unit
SAT	Supply Air Temperature
SHGC	Solar Heat Gain Coefficient
VAV	variable air volume
VFD	variable-frequency drive
W	watt(s)

Contents

Figures

Tables

1.0 Introduction

Many commercial buildings consume more energy than they should, yet they cannot maintain adequate comfort for occupants. The inability to adequately sense, monitor, and control buildings effectively leads to significant energy waste. For example, over 85% of buildings do not have an adequate control infrastructure (CBECS 2012); many of these buildings 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, thereby 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, as well as by fully deploying advanced controls measures (Fernandez et al. 2012, 2014). This savings is in addition to estimated savings of between 30% and 50% that can be achieved through deep energy retrofits (combined savings is estimated to be between 40% and 60%).

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. Technologies are needed to perform smart and automatic control of building systems so that these systems can be based on open standards, be of low cost, and be reliable. The technologies include inexpensive, reliable sensors; open, standard, and reliable controls infrastructure; and solutions that scale. Often technologies like BASs that can be deployed to accommodate Re-tuning measures are very expensive to purchase and operate for smaller buildings. In many cases, the industry has been slow to respond to these needs, and the solutions offered to date do not scale well, except to large buildings. The anticipated path to achieving high penetration of intelligent building control requires

- making controls infrastructure a commodity product that building owners and operators can purchase and easily set up and install on their buildings without the need for custom programming by specialized technicians;
- conducting research, development, and deployment (RD&D) of sensors, monitoring, diagnostics, and control systems on a large scale; and
- conducting research to quantify the benefits from the use of sensors, controls, and diagnostics in order to justify the RD&D investments.

This study was initiated to systematically estimate and document the potential savings through detailed simulation. The two-fold purpose of this study is to quantify 1) the impact of deploying accurate sensors, proper and advanced controls, and automated fault detection and diagnostics by estimating the energy savings potential of these Re-tuning approaches in the commercial building sector of Seattle, Washington; and 2) the impact of demand-response (DR) measures to lower commercial building electric demand during critical peak pricing (CPP) events. This load reduction potential can help to facilitate the performance of grid services by buildings that may be of benefit under a scenario of higher penetration of renewables (e.g., wind and solar photovoltaics). Both tasks reported here rely on the simulation of individual measures as well as packages of measures in the U.S. Department of Energy's (DOE's) EnergyPlus building energy modeling software (DOE 2012).

The city of Seattle legislature recently approved a new ordinance called the Building Tune-Ups mandate (Seattle Building Tune-Ups Ordinance 2016). Beginning in 2018, commercial buildings over 50,000 ft^2 will be required to undergo periodic "tune-ups", aimed at optimizing energy and water performance by identifying no or low-cost actions related to building operations and maintenance, focusing on actions that typically pay back within three years. The mandate includes a "Director's Rule" document (Seattle Office of Sustainability and Environment 2016) that identifies in Section 11 (Table 1) required and voluntary corrective actions (potential EEMs) if deficiencies are found.

1.1 Approach

The approach to estimating the impact of Re-tuning and DR measures involves the simulation of individual and packages of energy savings and DR measures using nine different DOE prototype building models for the Seattle climate. The nine prototype buildings (and similar building types) include the following.

- Small Office: A small office building at 5,000 ft^2, representing office buildings smaller than 25,000 ft^2. This square footage is below that covered by the Seattle Building Tune-Ups mandate.
- Medium Office: A mid-sized office building at 53,000 ft^2, representing office buildings between 25,000 and 100,000 ft^2, as well as outpatient health care buildings.
- Large Office: A larger office building at 200,000 ft^2, meant to represent office buildings over 100,000 ft^2. PNNL has determined that this model also represents the administrative portion of hospitals (~69% of hospital floor area) fairly well, as well as most college and university buildings.
- Large Hotel: A multistory hotel at 122,132 ft^2, similar to most large chain hotels.
- StandAlone Retail: A large retail building likely only representing big box stores and retail dealerships that would have large enough square footage to be subject to the mandate. Most stand-alone retail stores—especially in the city—will be well under the square footage requirement of the Seattle Building Tune-Ups mandate. This prototype model is 24,695 ft^2.
- Strip Mall Retail: An outdoor strip of 10 connected retail stores, covering 22,500 ft^2. Individual stores average 2,250 ft^2 and stores of this type are unlikely to be covered by the Seattle Building Tune-Ups mandate.
- Primary School: A 73,960 ft^2 school building representing elementary schools.
- Secondary School: A 210,900 ft^2 school building representing middle and high schools.
- Supermarket: A 45,000 ft^2 grocery store meant to represent supermarkets and convenience stores. Note that many supermarkets—especially those in the city core—may be below the 50,000 ft^2 threshold.

In this document, packages of measures are developed based on Pacific Northwest National Laboratory's (PNNL's) internal documentation of the prevalence of opportunities to implement individual measures on over 130 buildings that have been surveyed by PNNL in the past 10 years for its Re-tuning program (Katipamula 2016). This program included projects funded by the State of Washington and by the U.S. General Services Administration. Three packages were developed that are intended to represent buildings with different energy footprints: (1) an efficient building with most common and some advanced Re-tuning measures already in place, (2) a typical building with a handful of obvious and/or easy-to-implement measures in place, and (3) an inefficient or wasteful building with none of the control measures in place. Savings are evaluated by comparing the energy consumption of each of these buildings to an “ideal” building that has all of the Re-tuning measures implemented (excluding a few that PNNL expects to not be economically sound/worthwhile investments based on the simulation results for individual measures). Because these packages, which were developed for a broader DOE study, contain many additional control measures that are not called for in Seattle’s Building Tune-Ups mandate, a fourth package of measures is included in this study, combining the specific set of measures that conform to the requirements of the ordinance. This package is compared to a baseline building with none of the measures implemented to understand the maximum savings that buildings of each type should expect to see as a result of the mandate.

Some of the Re-tuning measures are geared toward the correction of operational faults, and the baseline models representing the inefficient buildings are created through modification of the prototype models to include those faults. 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 (DOE 2012), 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 temporarily curtail energy-intensive processes associated with maintaining refrigeration systems (applicable to only one building type). DR packages are created by selecting the top-performing cooling energy reduction measure and pairing it with either the lighting measure or the refrigeration measure, as applicable by building type. Packaging more than one cooling energy reduction measure together is expected to cause unacceptable disruptions in occupant comfort.

1.2 Report Contents and Organization

This report consists of nine sections (including this introduction). Section 2.0 describes 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). Section 3.0 describes each of the individual Re-tuning and DR measures considered for this study, including details about how each measure was modeled in EnergyPlus. Section 4.0 describes the distribution of individual EEMs within three packages of measures used to calculate the overall savings potential by building type in Seattle. Section 5.0 presents the results of the simulations—first describing the savings from individual EEMs by measure and by building type, then describing the electricity demand savings derived from Demand-Response measures, and finally presenting the savings estimates derived from simulation of the packages of measures. Section 6.0 summarizes the results. The conclusions and recommendations are presented in section 7.0 and a list of references is included in section 8.0.

2.0 Building Prototype Models

This section describes each of the EnergyPlus building models that were used for the simulation of each of the Re-tuning and DR measures simulated in this report. In general, the models were either taken directly from the commercial building prototypes (DOE 2016) developed by DOE for the Building Energy Codes Program, or from other further iterations of these models—for example, from the set of Advanced Energy Design Guides (AEDG 2008, 2011, 2015) published by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) with significant financial support from DOE. These models formed a starting point for 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 Re-tuning measures that were investigated. This section describes in detail each of the source models and the changes that were made for this study.

2.1 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 2.1 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 is intended to represent buildings constructed in the 1990s. The code used for wall, roof, and window construction is ASHRAE Standard 90.1-1999, as shown in Table 2.1. The original intent was to use performance requirements specified in ASHRAE Standard 90.1-1989. 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 work. 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.

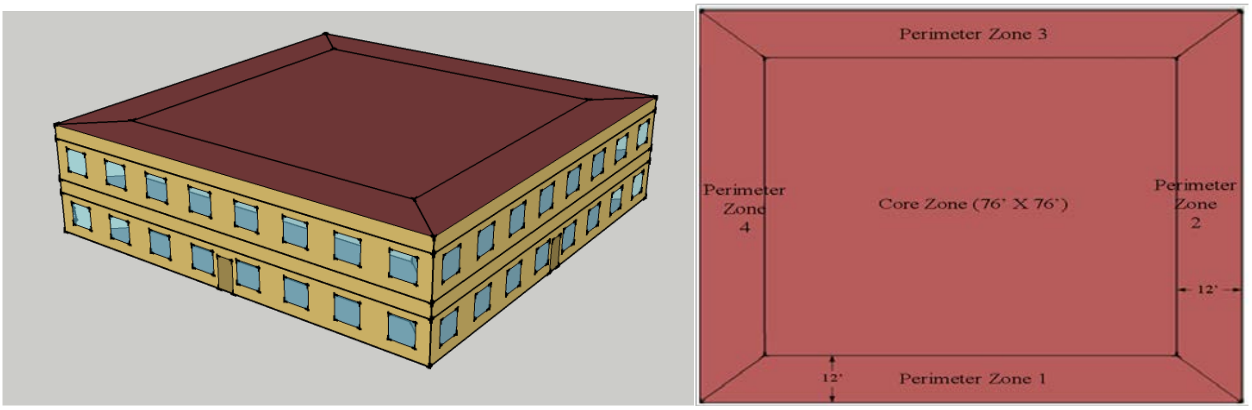

Figure 2.1. Small Office Prototype Building Shape and Zoning Diagram

Table 2.1. 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[1] 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.[2] Lighting, equipment, and occupancy schedules on weekdays, Saturdays, and Sundays are shown in Figure 2.2. Exterior lighting includes 4.89 kW of parking lot lights and 3.29 kW of other exterior building lights on photocell sensors.

[1] 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.

[2] 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.

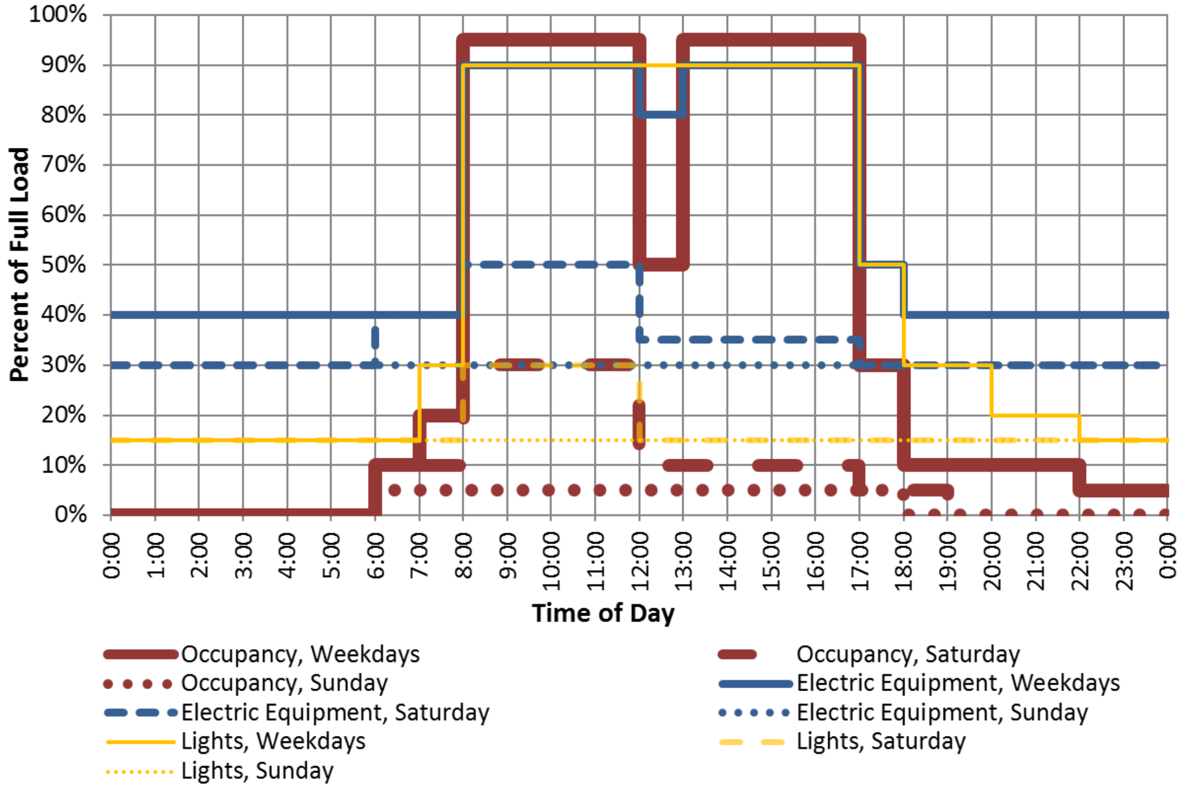

Figure 2.2. Small, Medium and Large Office – Schedules of Internal Loads

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[1] 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.[2] 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 International Energy Conservation Code (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.[3] 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 the purpose of 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 Re-tuning measures. These include 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

[1] 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.

[2] 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.

[3] 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 affect the economizer operation only. To simulate poor damper seals, the maximum outdoor air fraction is limited to 70%.

Some additional advanced control has been 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 for AHUs is to establish a differential between outdoor air flow and relief air flow, 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 2 of the Small Office's 10 AHUs come on to maintain zone temperatures, the infiltration fraction will drop from 100% to 85%. If 8 of the 10 AHUs come on, the infiltration fraction will drop to 40%. On top of this, 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.

2.2 Medium Office

The EnergyPlus model for Medium Office was developed by modifying the prototype model used in the AEDG (2011). The Medium Office prototype is a three-story building with 53,600 ft^2 of total floor area. Figure 2.3 is an axonometric projection of the building shape and Figure 2.4 is a diagram of floor zoning, which is identical on all three floors. Figure 2.3 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 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 the description of 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 the scheduled shutdown of VAV system fans. When the fans are on, infiltration rates drop to one-quarter of this level.

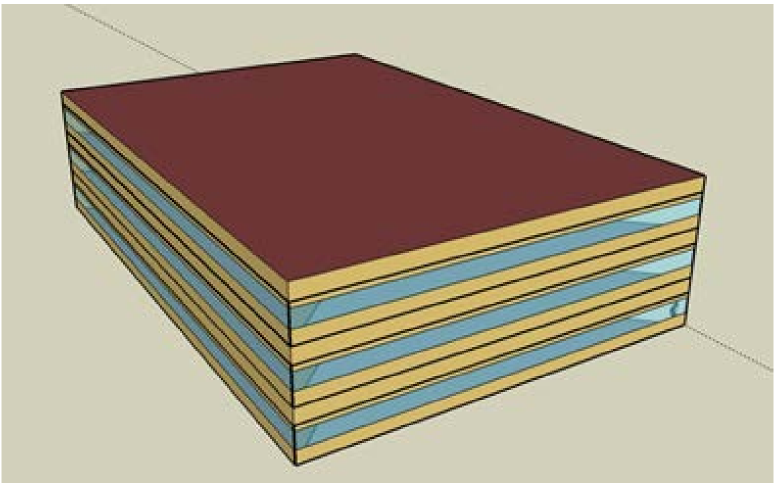

Figure 2.3. Medium Office Prototype Building Shape

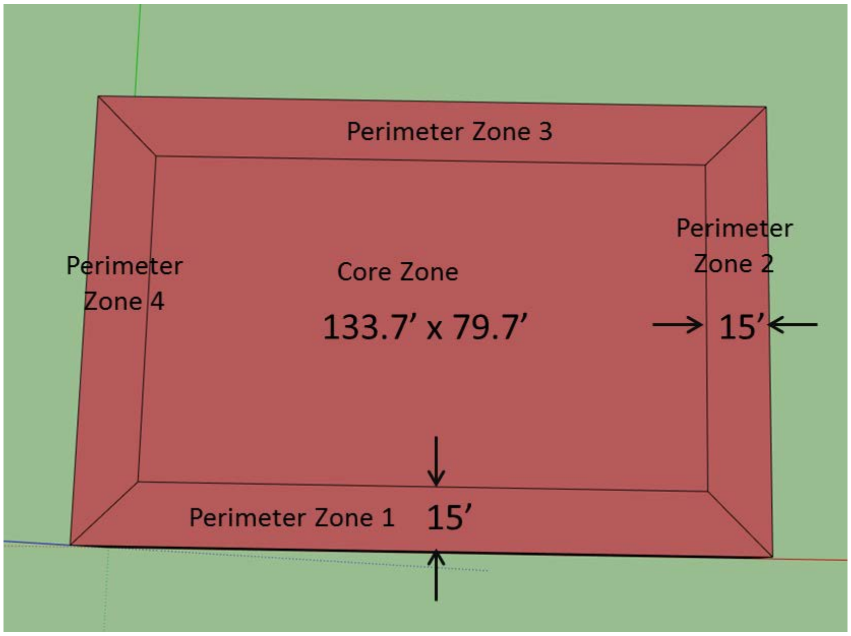

Figure 2.4. Medium Office Thermal Zoning

Internal loads include lighting at a density of 1.36 W/ft^2 [1] 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 2.2. 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[2] and gas heating coils with a rated thermal efficiency

[1] 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.

[2] 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 air flow 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.[1] 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.[2] 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 are added to the Medium Office baseline model to facilitate simulation of several fault correction Re-tuning 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 in the description of the Small Office building prototype.

2.3 Large Office

The Large Office prototype is a four-story building with 200,000 ft^2 of total floor area. Figure 2.5 is an axonometric projection of the building shape and Figure 2.6 is a diagram of floor zoning, which is identical on all four floors. Figure 2.5 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 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 the description of the Small Office model. 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.

[1] 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.

[2] 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.

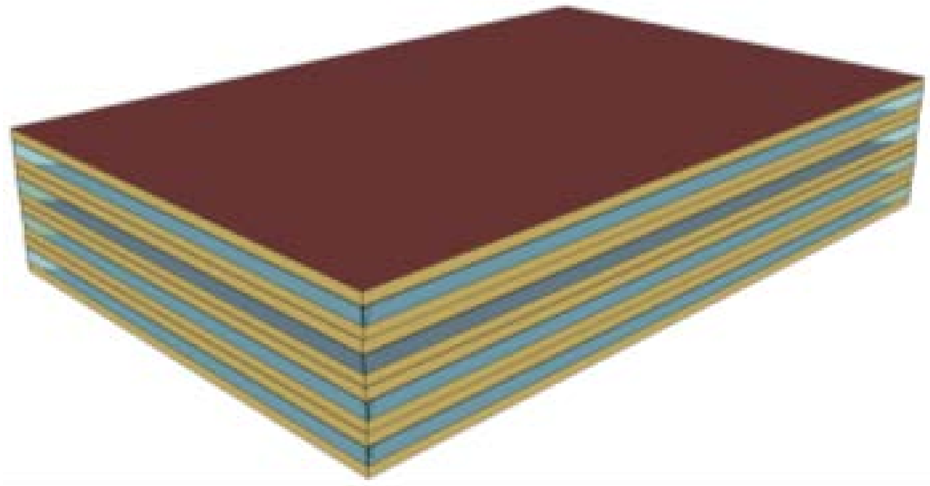

Figure 2.5. Large Office Building Shape

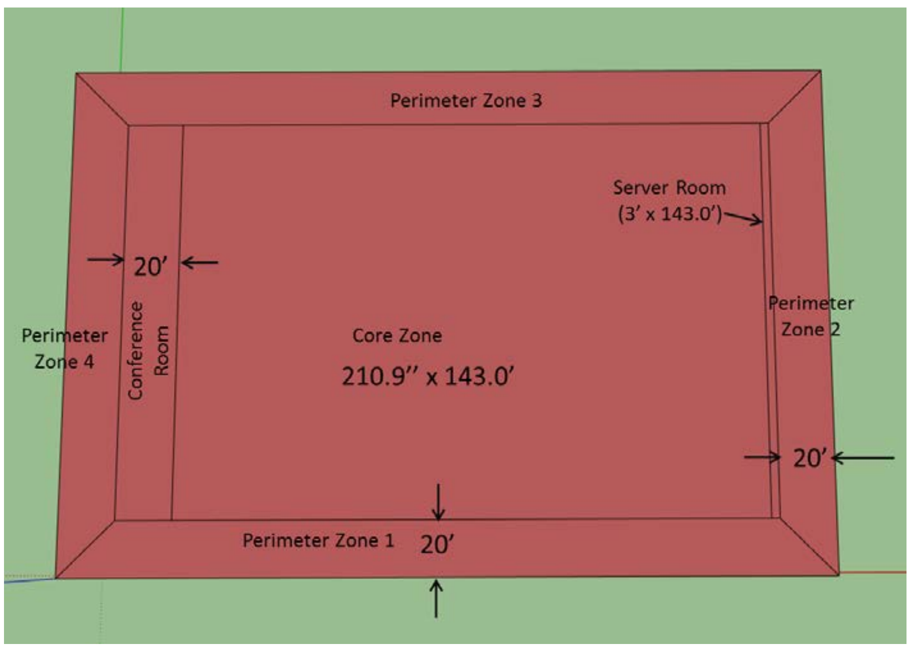

Figure 2.6. Large Office Thermal Zoning

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 2.2. 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 air flow 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.[1]

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. Bathroom exhaust fans are located in each of the core zones of the model with constant "on" schedules.

Some additional faults were added to the Large Office baseline model to facilitate simulation of several fault correction Re-tuning 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 (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
```

[1] 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.

```
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}
```

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.

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 in the description of the Small Office building prototype.

2.4 Large Hotel

The prototype Large Hotel building consists of six stories aboveground, plus a conditioned basement floor, totaling 122,132 ft^2 of total floor area. Figure 2.7 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 Re-tuning 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 the description of the Small Office model. 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%.

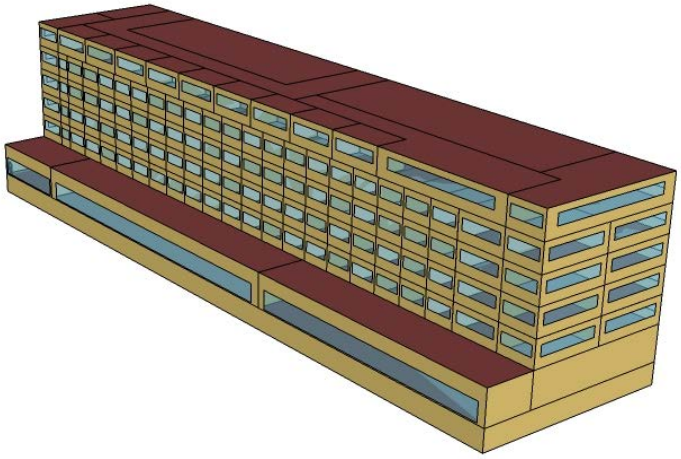

Figure 2.7. Large Hotel Building Shape

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 2.8 and Figure 2.9, respectively. Exterior lighting includes 23.52 kW of parking lot lights and 10.12 kW of other exterior building lights on photocell sensors.

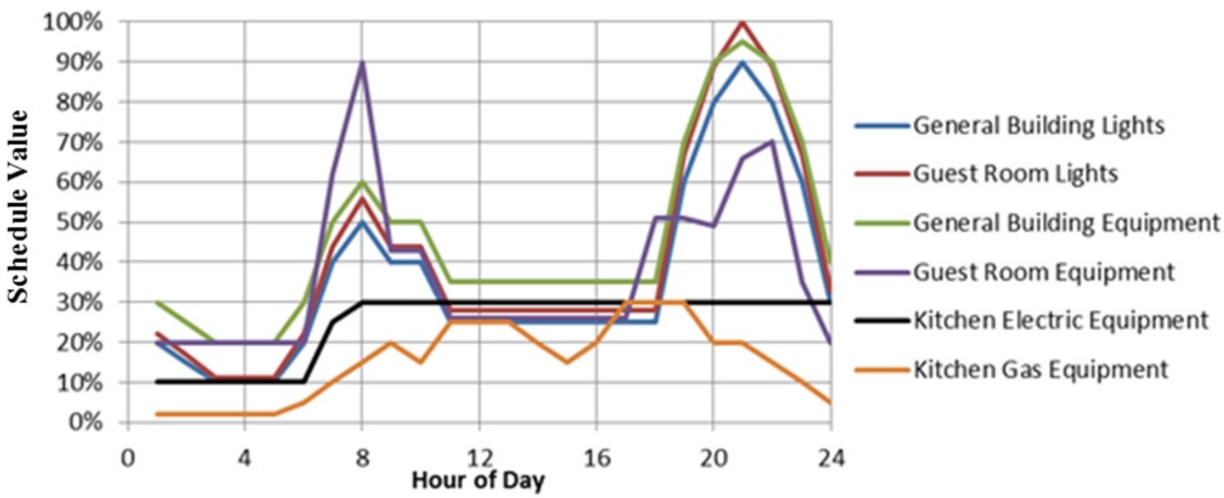

Figure 2.8. Weekday Schedules for Lighting and Equipment in Large Hotel Prototype

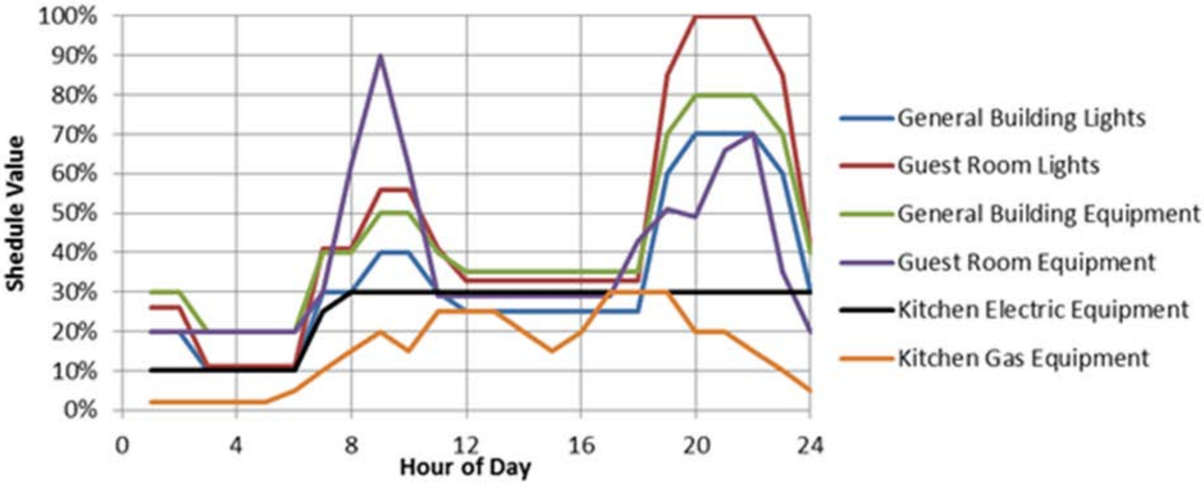

Figure 2.9. Weekend Schedules for Lighting and Equipment in the Large Hotel Prototype

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 air flow 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 the building description for the Large Office prototype, 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.

2.5 StandAlone Retail

The EnergyPlus model for StandAlone Retail was developed by modifying the prototype model used in the AEDG (2008). The StandAlone Retail prototype is a single-story building with a rectangular footprint, covering 24,695 ft^2 of total floor area, and with a floor-to-ceiling height of 20 ft. Figure 2.10 is an axonometric projection of the building and Figure 2.11 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 2.12.

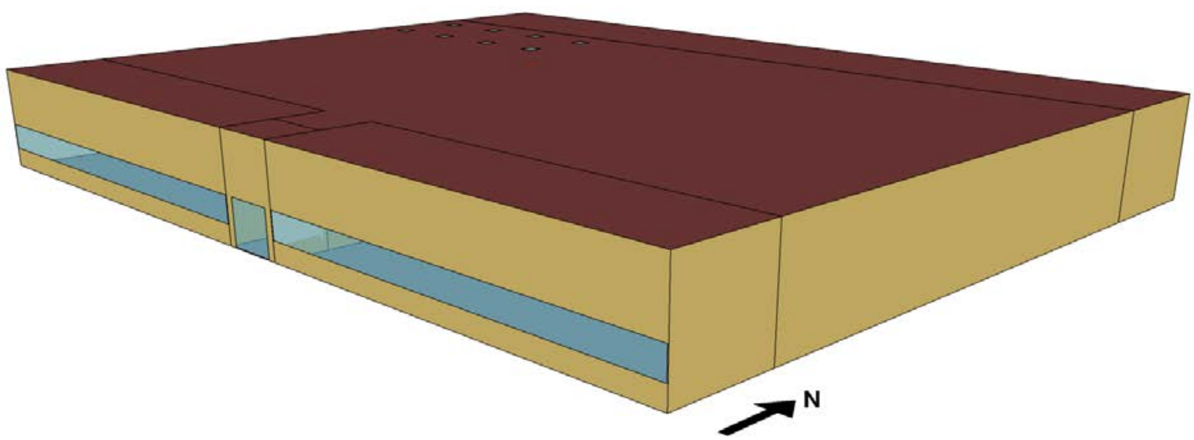

Figure 2.10. StandAlone Retail Building Shape

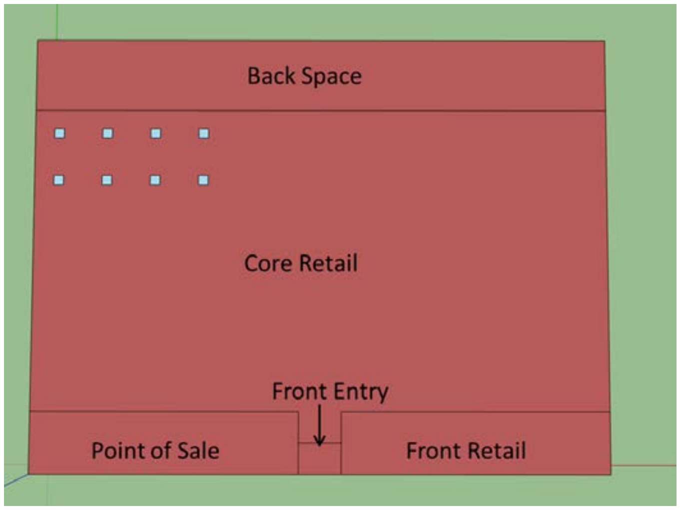

Figure 2.11. StandAlone Retail Thermal Zoning

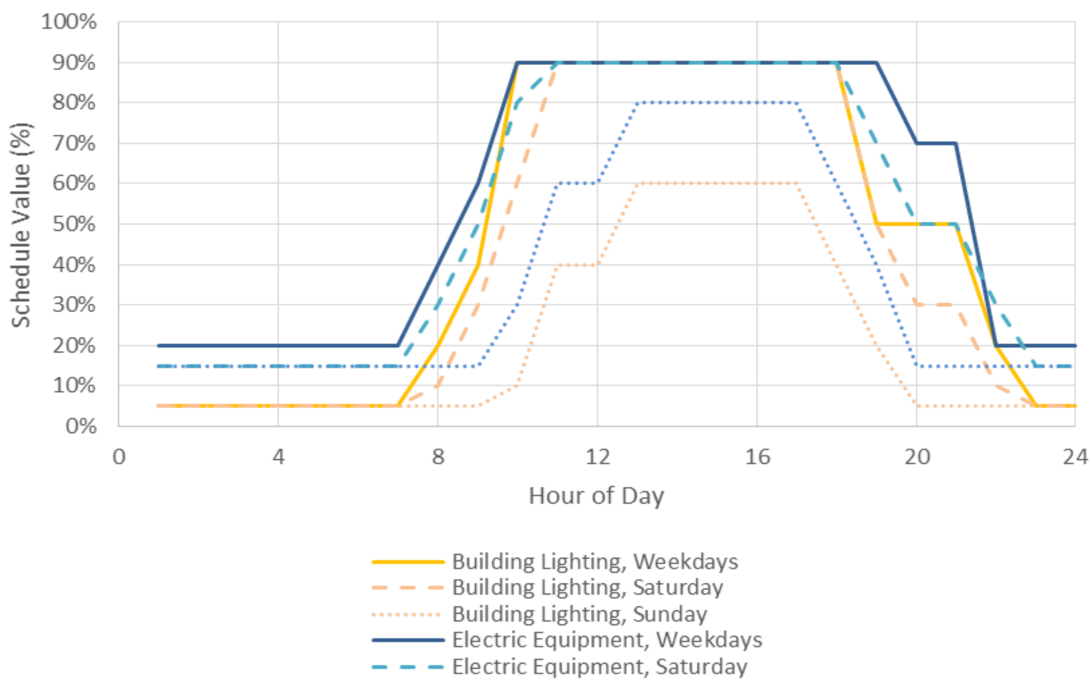

Figure 2.12. Lighting and Plug Load Schedules for Weekday and Weekends in the StandAlone Retail Model

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 4 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. through

1:00 a.m. (20 hours) Monday through Friday, from 5:00 a.m. through 2:00 a.m. on Saturday, and from 7:00 a.m. through 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 air flow 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 for the Small Office model, 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. 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.

2.6 Strip Mall Retail

The EnergyPlus model for Strip Mall Retail was developed by modifying the prototype model used in the AEDG (2008). The Strip Mall prototype is a one-story building with 22,500 ft^2 of total floor area. Figure 2.13 is an axonometric projection of the building shape and Figure 2.14 is a diagram of floor zoning, including all 10 retail stores. The floor-to-ceiling height of the building is 17 ft and it has a total window-to-wall fraction of 10.5%.

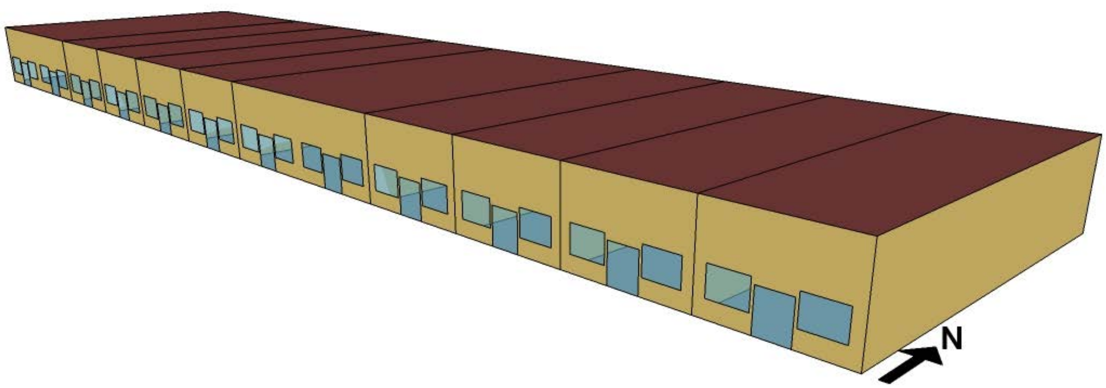

Figure 2.13. Strip Mall Building Shape

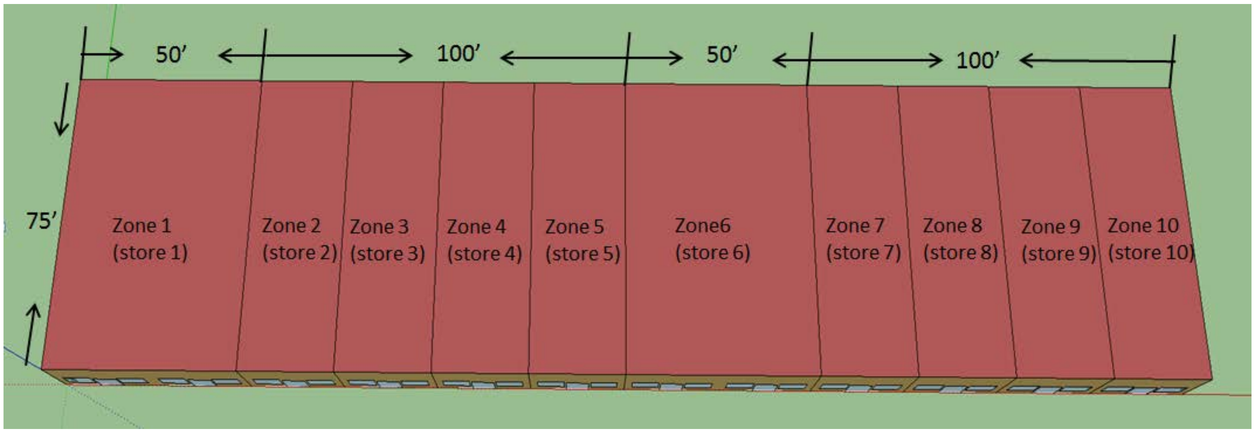

Figure 2.14. Strip Mall Thermal Zoning

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 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 the description of 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 tanks for seven of the stores.

Some additional faults are added to the Strip Mall baseline model to facilitate simulation of several fault correction Re-tuning 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.

2.7 Primary School

The Primary School model was developed based on the DOE commercial building protoype model (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 2.15 is an axonometric projection of the building and Figure 2.16 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 constructions include an outer roof membrane above insulation and a metal deck.

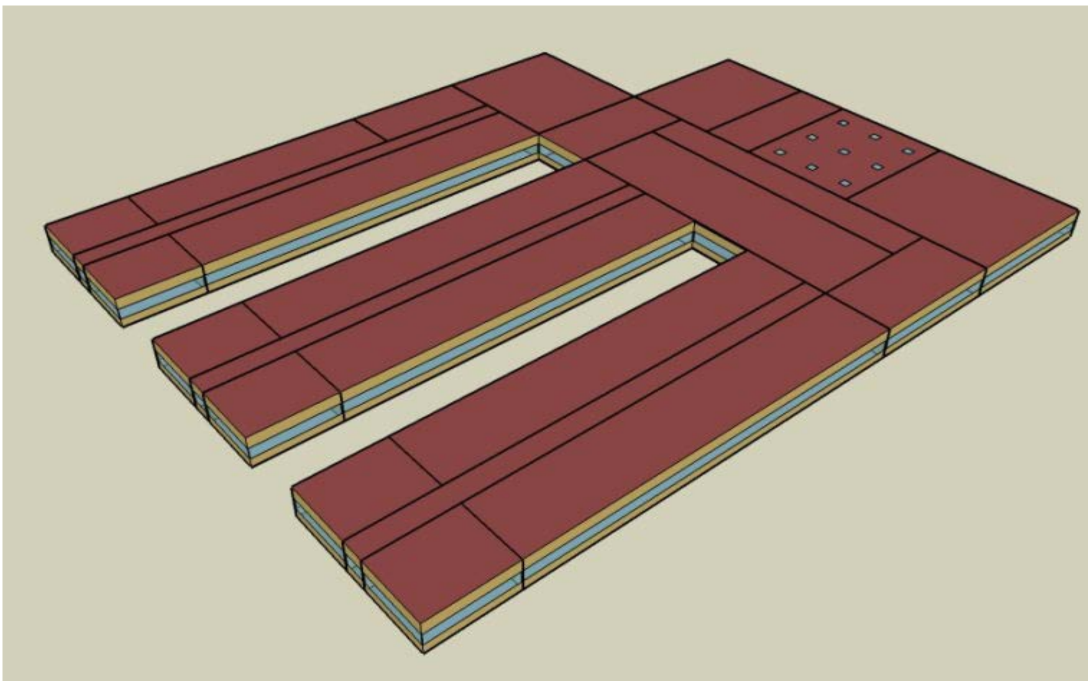

Figure 2.15. Primary School Building Shape

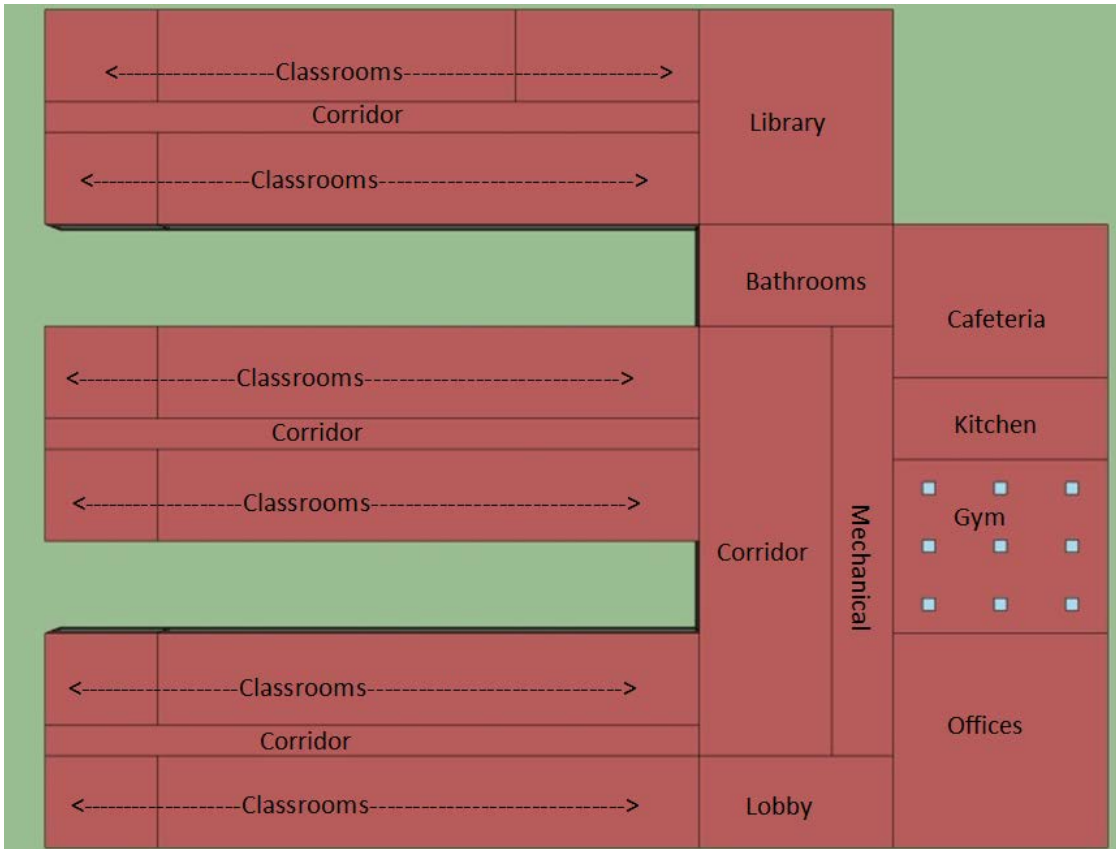

Figure 2.16. Primary School Thermal Zoning

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. Study periods (January through June and September through December) have schedules shown in Figure 2.17 and summer schedules (July and August) are shown in Figure 2.18.

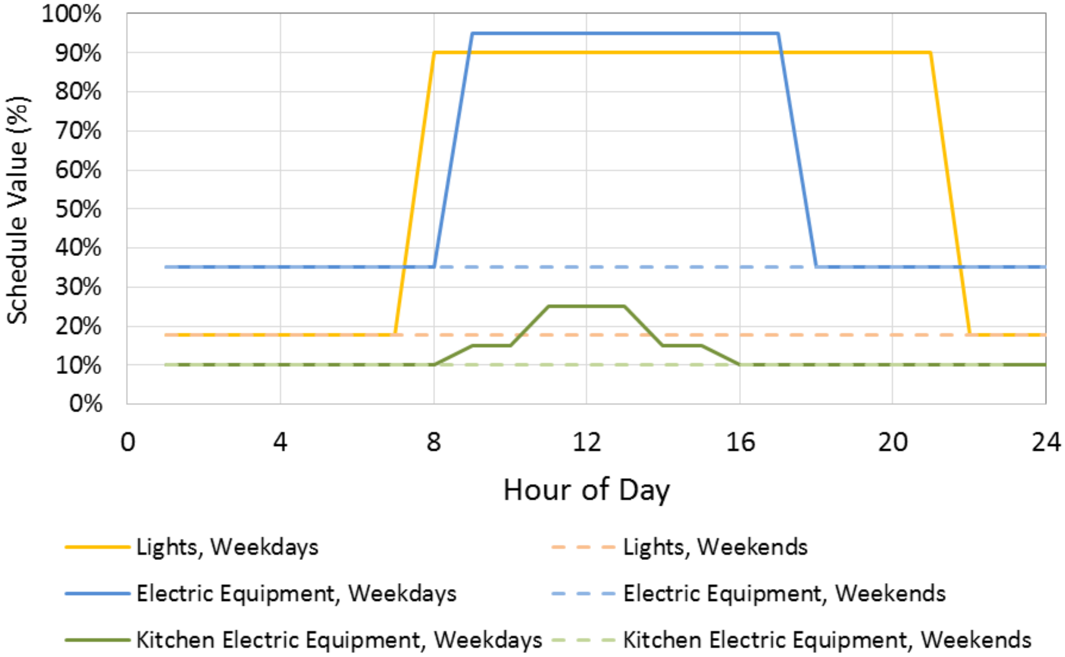

Figure 2.17. Lighting and Plug Load Schedules for Weekday and Weekends during the Study Period (January–June and September–December) in the Primary School Model

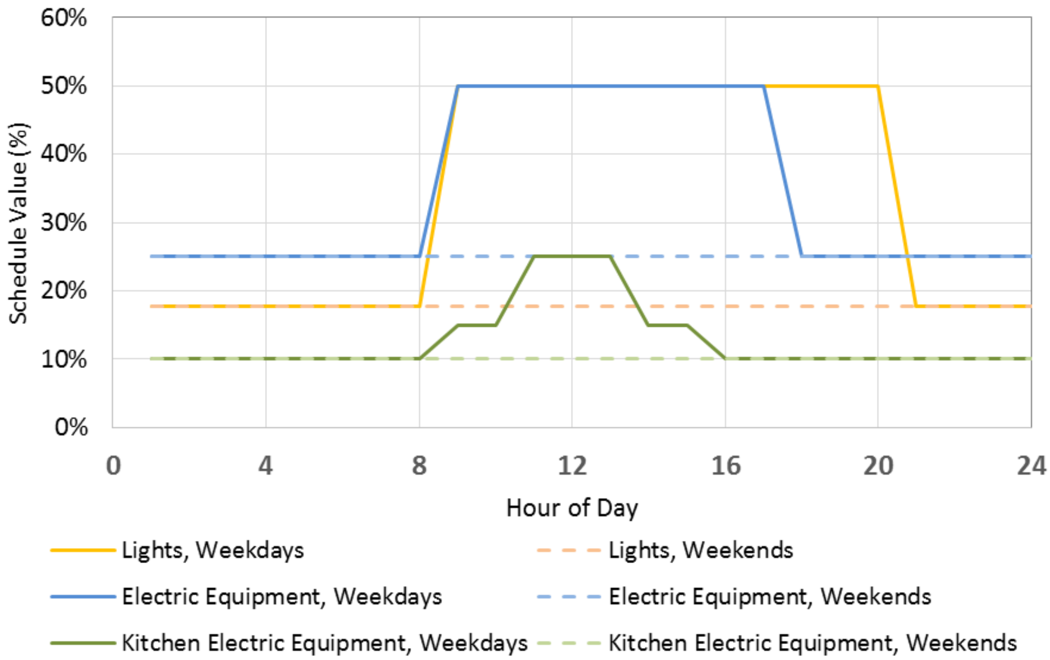

Figure 2.18. Lighting and Plug Load Schedules for Weekday and Weekends during the Study Period (July and August) in the Primary School Model

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 the Small Office model description. 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 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 4 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 for the Small Office model, 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 the building description for the Large Office prototype, 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. The bathroom exhaust fan flow rate has been increased from 600 cfm to 2,100 cfm to reflect minimum bathroom fixture requirements from the state of California,[1] which requires for males, 1 toilet per 50 people and 1 urinal per 100 people and for females, 1 toilet per 30 people. 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, 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.

2.8 Secondary School

The Secondary School model was developed based on the DOE commercial building protoype model (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 2.19 is an axonometric projection of the building and Figure 2.20 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, the Secondary School model also contains three classroom pods, zoned similarly. Windows run in a continuous band around the exterior of the building,

[1] http://www.cde.ca.gov/ls/fa/sf/toiletrequire.asp

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 construction includes 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 2.19). This model contains a total of 46 conditioned zones, most of which are classrooms. The floor-to-ceiling height of the building is 13 ft and it has a total window-to-wall fraction of 33%.

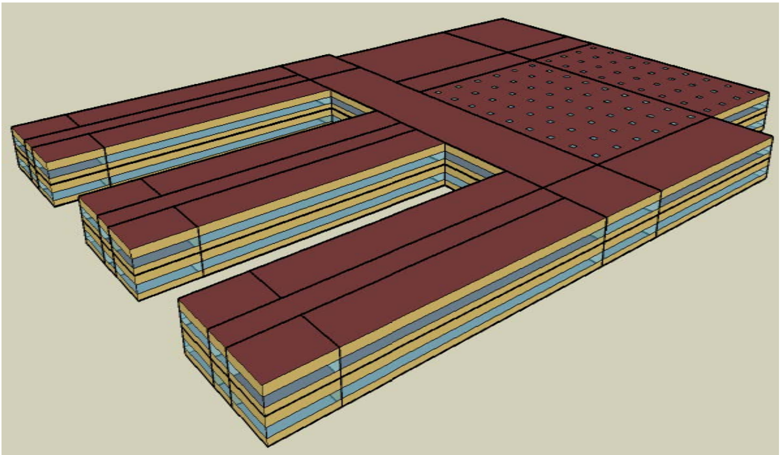

Figure 2.19. Secondary School Building Shape

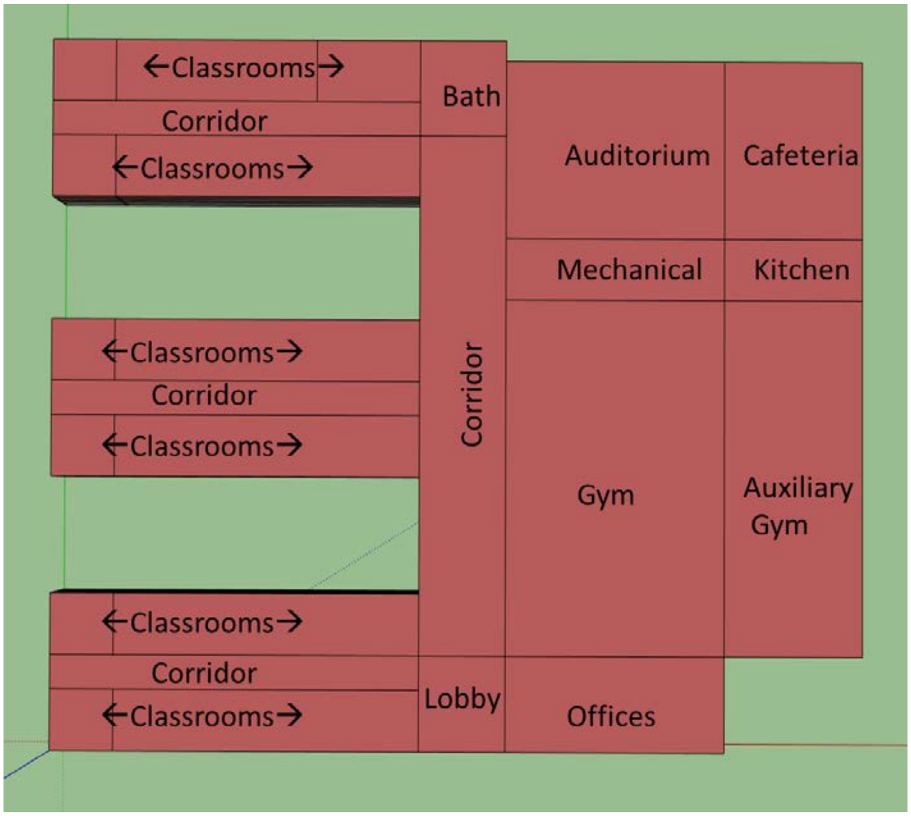

Figure 2.20. Second Floor Zoning for Secondary School

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. Study periods (January through June and September through December) have schedules shown in Figure 2.17 and summer schedules (July and August) are shown in Figure 2.18 (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, and the classrooms are divided into two categories 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 no occupancy is 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 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. 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 4 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, 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 the building description for the Large Office prototype, 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 infiltration objects are applied at a uniform rate to each exterior wall as a function of its area. As described for the Large Office prototype, 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.

2.9 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 2.21 shows the store layout.

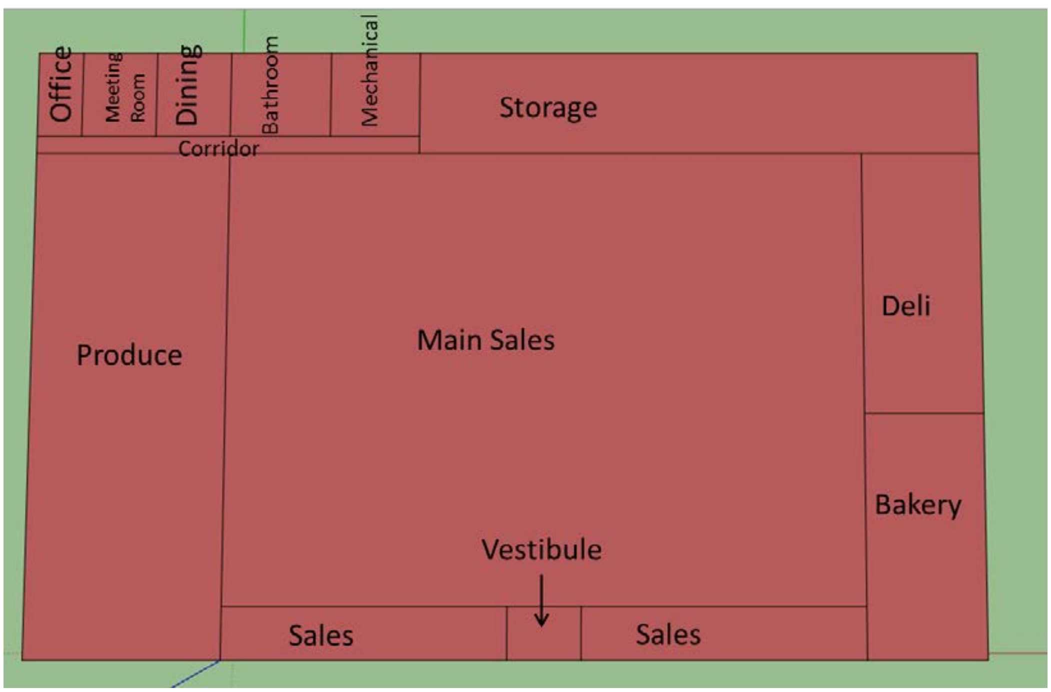

Figure 2.21. Floor Plan/Zoning for the Supermarket Building Prototype

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 are modeled the same as those in the original model (Leach et al. 2009), which can be referred to for more details. Each space in Figure 2.21 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.

3.0 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 either to produce annual energy savings or to be used for DR to reduce power during CPP grid events. Table 3.1 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 as a result 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.

Table 3.1. List of Energy Savings and Demand-Response Control Measures and Applicability to Each Prototype

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			●	●			●	●	

Measure	Measure Number	Small Office	Medium Office	Large Office	Large Hotel	StandAlone Retail	Strip Mall Retail	Primary School	Secondary School	Supermarket
Minimum VAV Terminal Box Damper Flow Reductions	15		●	●	●			●	●	
Wider Deadbands and Night Setback	16	●	●	●	●	●	●	●	●	●
Demand Control Ventilation	17	●	●	●		●	●	●	●	●
Occupancy Sensors for Lighting	18	●	●	●	●	●		●	●	●
Daylighting Controls	19	●	●	●		●	●	●	●	
Exterior Lighting Control	20	●	●	●		●	●	●	●	●
Advanced Plug Load Controls	21	●	●	●						
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				●					

Measure	Measure Number	Small Office	Medium Office	Large Office	Large Hotel	StandAlone Retail	Strip Mall Retail	Primary School	Secondary School	Supermarket
Optimized Use of Heat Recovery Wheel	37				●					
Heating and Cooling Lockouts	38	●	●	●	●	●	●	●	●	●
Demand Response: Setpoint Changes	39	●	●	●	●	●	●	●	●	●
Demand Response: Pre-Cool	40	●	●	●	●	●	●	●	●	●
Demand Response: Duty Cycle	41	●	●	●		●	●	●	●	●
Demand Response: Lighting	42	●	●	●	●	●	●	●	●	
Demand Response: Chilled Water Temperature Reset	43			●	●				●	
Demand Response: Refrigeration	44									●

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 (e.g., 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 also 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 of 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 air-side systems in each prototype that has economizers. This excludes the Large Hotel prototype, which does not have modulating air-side economizers due to the 100% outdoor air requirements for ventilation.

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 caused by either 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 3.2.

Table 3.2. 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 air flow 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; 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 3.3 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 3.3. 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 Auditorium; Study Period Alt Baseline (2 hr)	6:00 a.m.–11:00 p.m.	Off	Off
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

Prototype Model	Weekday Schedule	Saturday Schedule	Sunday Schedule
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 automatically reset 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 3.4. 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 to be 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 the purpose of 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 3.4. Seasonal Switch Dates for SAT 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 it implicitly fixes any problems with damper sealing. These changes are accomplished through simple schedule changes in the controller:outdoorair 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 3.3. This measure pertains to all prototypes except for Large Hotel, which is continuously occupied, and therefore cannot 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 air flow rates. During most operating conditions, however, reduced overall air flow demands mean that the static pressure setpoint can be reduced without compromising air flow for any of the VAV boxes.

Accurate modeling of air flow 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, so the air flow rates at each terminal box are not affected by the specified “fan pressure rise” (i.e., static pressure), nor are they affected by the air flow demands elsewhere in the VAV network. Although EnergyPlus does track VAV terminal unit damper positions, these positions are calculated as the ratio of current air flow rates to design air flow 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 air flow 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 DP setpoint in response to chilled water valve coil positons. As was the case for static pressure setpoints for the VAV systems, the chilled water DP 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 DP 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. DP 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 DP resets as well. There is no feedback of pump head to cooling coil valve positions. In the case of DP 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 DP. 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 DPs 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 of the code. Figure 3.1 shows the two curves graphically along with the relative savings from the baseline to the DP reset measure.

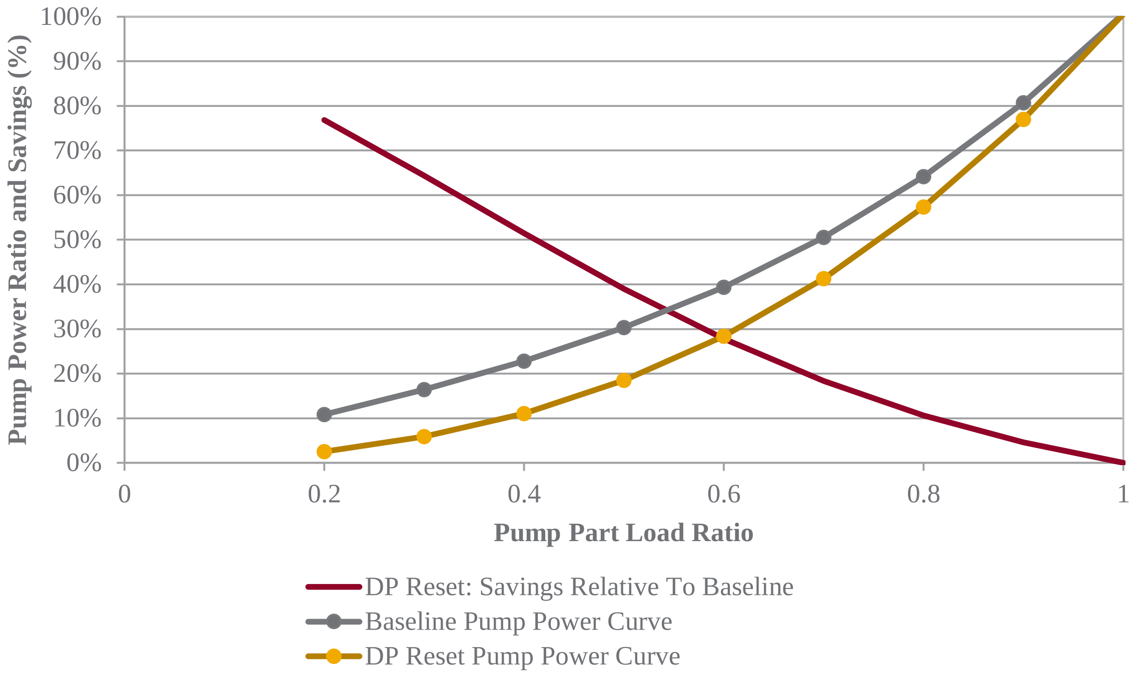

Figure 3.1. Comparison of Baseline and DP Reset Pump Power Curves and Energy Savings

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 3.4.
- *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 DP reset is handled the same way as for chilled water DP 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°F) to low-demand setpoints (as low as 90–100°F). None of the prototype models, however, currently include condensing boilers and 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 air flow 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 air flow to the zone anyway. As a consequence, high minimum air flow setpoints tend to be unnecessary and are counterproductive to energy performance. High minimum air flow rates force the zone to accept too much relatively cool supply air from the AHU, forcing the zone into heating mode. Lowering the minimum air flow rates reduces the aggregate air flow 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 air flow fractions are reduced to 25% of the maximum air flow 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 that affect 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 setpoint 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, 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 (ANSI/ASHRAE 2016) 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 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 Sensors for Lighting. This measure simulates the use of occupancy 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 3.5 by zone type. Table 3.5 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 3.6 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 School. 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 3.5. Lighting Savings Assumptions in Applicable Zones for Lighting Occupancy Sensors

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

Type of Zone	Day Savings (Occupied)	Night Savings	Source	Assumption
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 3.6. Occupancy Sensor Application by Prototype Model

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 controls on. 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 are shown for all applicable prototypes in Table 3.7.

Table 3.7. 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)		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 3.2 shows these changes graphically for weekdays, Saturdays, and Sundays.

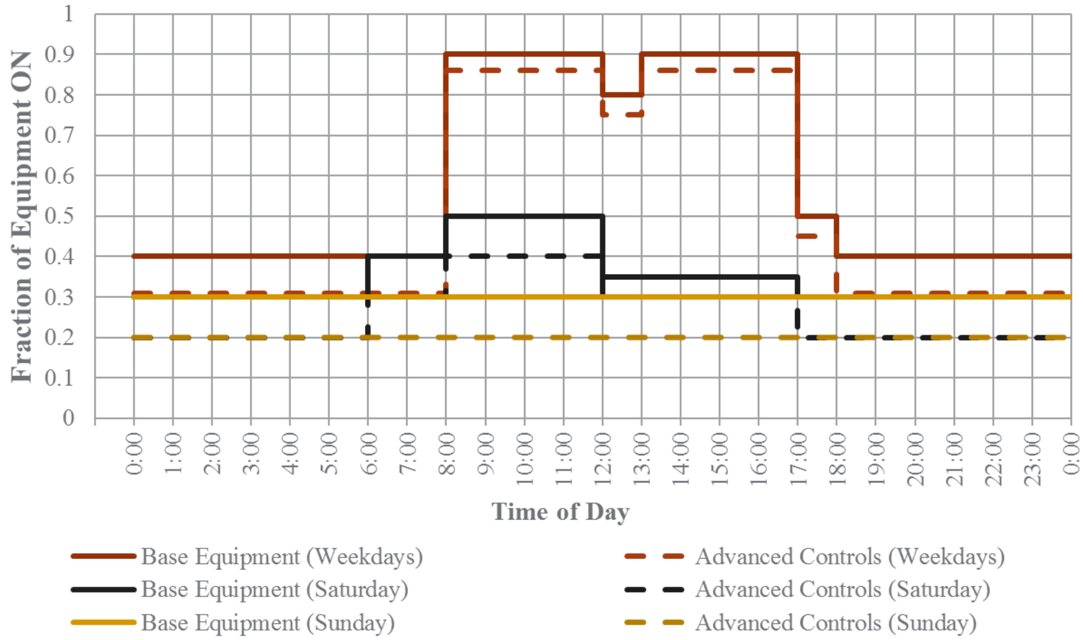

Figure 3.2. Schedule Changes to Plug Load Fraction with Measure 21

Measure 22: Night Purge. This measure simulates the use of a special early morning cycle of the AHUs that make use of full air-side 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 otherwise occur 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 3.8. 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) or 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 3.8. Advanced RTU Control Definitions

Mode of Operation	Fraction of time Definition	Fan Speed Fraction	Fan Power Reduction
Economizer	If outdoor air flow is greater than minimum outdoor air flow, fraction of time not in cooling mode	0.75	47%
Ventilation	If actual outdoor air flow equals minimum outdoor air flow, 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%
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 3.3.

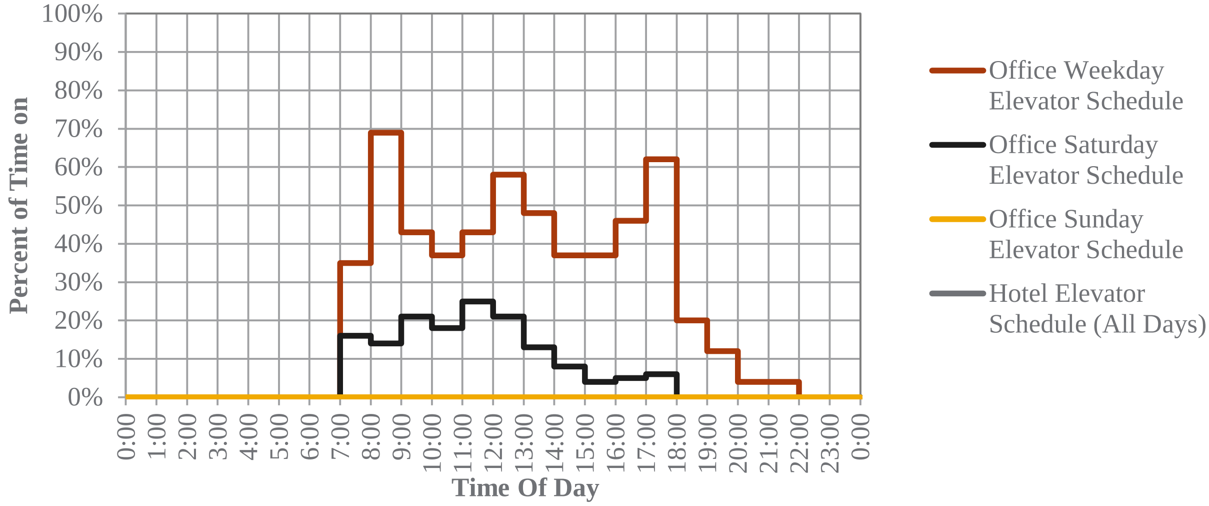

Figure 3.3. Schedule for Elevator Cab Fan and Lights Using Occupancy Sensor

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 air-side economizers. In this study, air-side economizers were not used in several of the warmer climate zones. For buildings that already have air-side 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 startup 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 3.4 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 adjusts heating and cooling setpoints, minimum air flow 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.

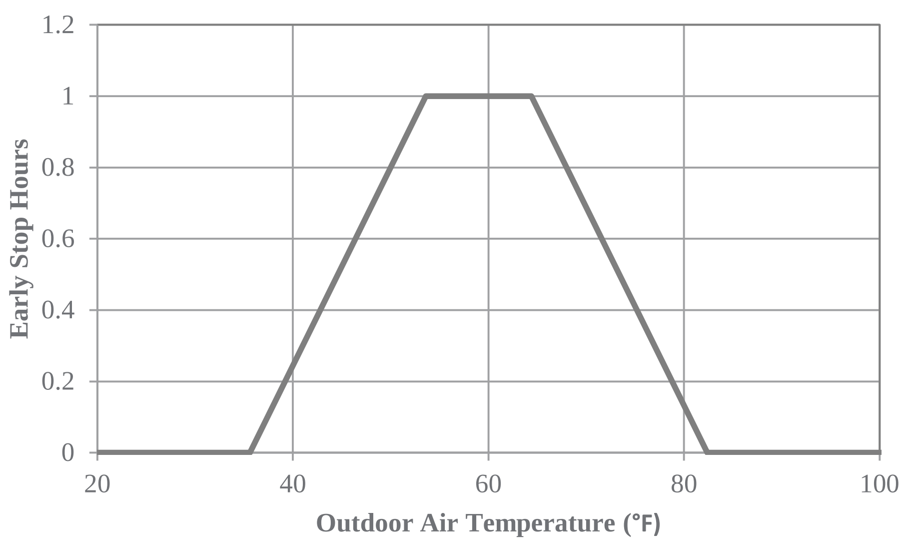

Figure 3.4. Optimal Stop: Early Stop Hours Subtracted from Evening HVAC Schedules

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. 7 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), 7 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°C 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 the conventional fixed head pressure control discussed for 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 3.5 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 the “off-cycle” for defrost control. In those cases, there is no energy benefit to shortening the defrost cycle.

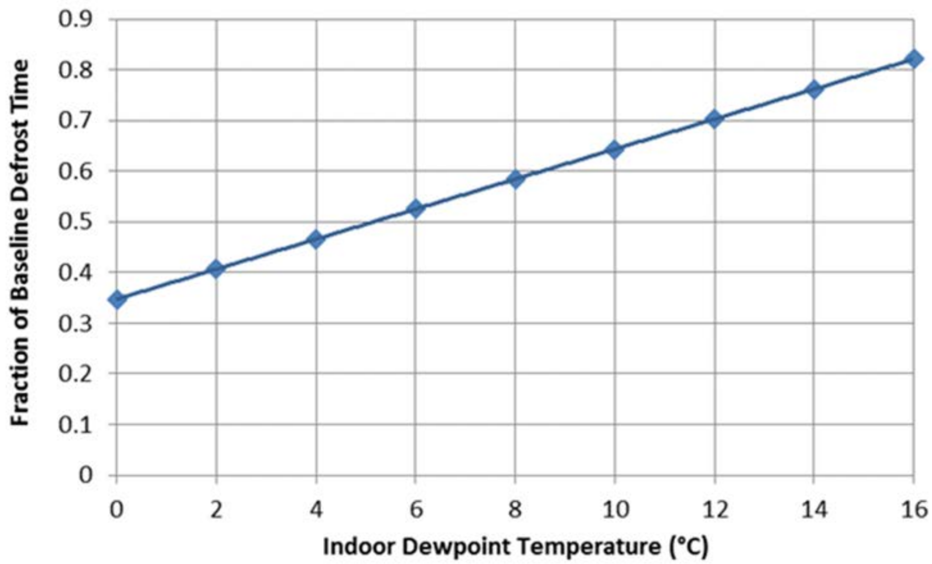

Figure 3.5. Defrost Time Fraction for Optimal Defrost Control

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 to shut off lighting and set 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.

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 air flow 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: Heating and Cooling Lockouts. This measure creates outdoor air temperature-dependent lockouts on both the heating and cooling systems in all buildings. While some buildings are able to successfully implement a single lockout setpoint below which cooling is locked out and above which heating is locked out, for most buildings a more realistic and conservative scenario is to lock out heating based on a setpoint that is warmer than the lockout for cooling, such that there is a band of temperatures in between where both heating and cooling are enabled. In this case, 50°F was chosen for the cooling system lockouts and 65°F was chosen for the heating system lockouts. For buildings with water loops for heating and cooling, this locks out the boilers and chillers, while for buildings with single-zone equipment, this involves lockout of the heating and cooling coils in the RTU serving the zone.

For buildings with functioning air-side economizers, there is generally no concern with locking out cooling during cold weather. Locking out heating during warm weather, however, can create comfort issues in some buildings that use VAV systems for air distribution. Correcting these comfort issues is possible in most cases through more intelligent control of SAT setpoints (e.g., SAT reset) and minimum VAV airflow setpoints.

Measure 39: Demand Response-Setpoint Changes: 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 4-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 40: 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 41: 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 air-side 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 42: 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 the description for Measure 38) and returns lighting to normal levels at the end of the event.

Measure 43 Demand Response-Chilled Water Temperature Reset: This DR measure responds to a CPP event (see definition of CPP event in the 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 44 Demand Response- Refrigeration: This DR measure responds to a CPP event (see definition of CPP event in the 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 the 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.

4.0 Packages of Re-tuning and Demand-Response Measures

Three packages of measures have been created to estimate the overall energy savings (and overall electricity savings) of the required measures in the Seattle Building Tune-Ups mandate.

These packages combine all the measures that adhere to the specific actions required in the Building Tune-Up Assessments—as laid out in Section 11B of the Director's Rule for the City of Seattle Building Tune-Ups mandate (Seattle Office of Sustainability and Environment 2016). Table 4.1 reproduces the list of requirements from the Director's Rule and lists the associated EEMs that pertain to each requirement. Note that EEM15 (Minimum VAV Terminal Box Damper Flow Reductions) was included as a response to requirement "g" because its implementation can correct simultaneous heating and cooling issues in VAV systems. It is also considered a necessary measure in order to also implement the required boiler and chiller lockouts. Without reducing minimum VAV airflow setpoints, many zones can become overcooled beyond the thermal comfort range.

Table 4.1. Requirements for Seattle Building Tune-Ups Mandate and Associated EEMs

	Requirements for Tune-Up Assessments	Measures Simulated for City of Seattle Package
1. Heating, Ventilation, and Air Conditioning		
a	Review HVAC equipment schedules (Including daily, weekly, seasonal, day/night, occupied/unoccupied hours).	EEM04: Shorten HVAC Schedules; EEM07: Exhaust Fan Control
b	Review HVAC setpoints (including space temperatures, supply air temperatures, CO_2, boiler temperatures, chilled water temperatures, economizer changeover temperatures, and building pressure).	EEM05: Supply Air Temperature Reset EEM11: Chilled Water Temperature Reset EEM14: Hot Water Temperature Reset EEM16: Wider Deadbands and Night Setbacks
c	Review reset schedules (including supply air temperature, supply air pressure, boiler and chiller water temp, lockouts with outside air temp, loop differential pressure).	EEM08: Static Pressure Reset EEM10: Chilled Water Differential Pressure Reset EEM13: Hot Water Differential Pressure Reset EEM38: Heating and Cooling Lockouts
d	Review optimal stop/start capabilities.	EEM27: Optimal Start EEM28: Optimal Stop
e	Verify that HVAC sensors are functioning, calibrated, and in appropriate locations. Identify where sensors should be repaired, adjusted, calibrated, and/or moved.	EEM01: Re-calibrate Faulty Sensors
f	Verify HVAC controls are functioning as intended.	
g	Review HVAC controls for unintended or inappropriate instances of simultaneous heating and cooling.	EEM15: Minimum VAV Terminal Box Damper Flow Reductions

	Requirements for Tune-Up Assessments	Measures Simulated for City of Seattle Package
h	Note any indications of significant air- balancing issues (e.g. wind-tunnel effect). Include assessment of entry doors to lobby/etc. that are standing open or difficult to open or close.	
i	Identify any indications of excessive ventilation rates that are greater than ASHRAE 62.1 standard and are not appropriate for the current facility requirements (e.g. no outside air supply or 100% outside air supply).	
j	Identify zones that are dominating multi-zone system operations. For example, corner zones or zones recently converted to server rooms.	
2. Lighting		
a	Identify any areas where lighting levels appear to be significantly higher than appropriate for the space use and occupant needs.	

There are three packages, rather than just one, as part of an effort to 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*** that has most common and some advanced EEMs already in place, no operational faults modeled, and limited opportunities remaining for Re-tuning;
- a ***typical building*** that has a few obvious or easy-to-implement Re-tuning measures and a handful of operational faults, but with a wide range of opportunities for energy savings still available; and
- an ***inefficient building*** that has no Re-tuning measures already in place and widespread operational faults.

Table 4.2 shows the full set of measures in each package, generally. 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 4.2) indicates the fraction of buildings for which each measure has been recommended for implementation among a set of 130 buildings surveyed by PNNL in the Re-tuning program over the past 10 years.[1] 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 considered 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 already present in efficient buildings, but not in typical or inefficient buildings. EEMs with less than 25% prevalence of opportunity are considered to be nearly universally applied already, and are only applicable as remaining opportunities in the inefficient buildings. For measures that are not applicable to office-type buildings, PNNL used professional judgment, based on over 200 total years of experience working with and analyzing commercial buildings, to place them into the three packages. To make the overall prevalence of each measure in the overall savings estimates like the observed prevalence from PNNL's Re-tuning experience, the packages are weighted as follows:

[1] http://buildingretuning.pnnl.gov/documents/pnnl_sa_110686.pdf

- 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 PNNL re-tuned may not have had an opportunity for a given EEM due to infrastructural limitations at the time (e.g., lack of BAS connections to devices, lack of variable-speed drives as pre-requisites for speed resets). We still want to consider these measures as ultimate possibilities in those buildings, keeping in mind that taking full advantage of the Re-tuning measures can sometimes necessitate capital improvements first.
- PNNL may have missed some opportunities in some buildings.

Energy consumption from each of the three packages is compared to the energy consumption from a modeled "ideal" building (column 3 of Table 4.2) that has all EEMs implemented. All EEMs that were not required as part of the Seattle Building Tune-Ups mandate are excluded from these packages and, for simplicity, are excluded from Table 4.2.

Table 4.2. Packages of EEMs used to Estimate Overall Savings from Re-tuning

Energy Efficiency Measure	Prevalence of Opportunity	Reference Case (Ideal Building)	Efficient Building (30%)	Typical Building (50%)	Inefficient Building (20%)
EEM01: Re-calibrate Faulty Sensors	30%	☐	☐		
EEM04: Shorten HVAC Schedules	48%	☐	☐		
EEM05: Supply Air Temperature Reset	79%	☐			
EEM07: Exhaust Fan Control	44%	☐	☐		
EEM08: Static Pressure Reset	76%	☐			
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%	☐	☐		
EEM27: Optimal Start	48%	☐	☐		
EEM28: Optimal Stop	48%	☐	☐		
EEM38: Heating and Cooling Lockouts	**Unknown**	☐	☐	☐	

Two demand response packages were developed to estimate whole-building 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 it can be implemented immediately upon 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 it can be implemented given that there is advanced warning (at least 4 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 4.3.

Table 4.3. Packages of Demand Response Measures

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

5.0 Results and Discussion

This section describes the simulation results and findings for the individual EEMs and DR control measures as well as simulation results for packages of measures. The section begins with the individual measure results for EEMs (shown in detail for each measure), illustrating the savings for different building prototypes. Next, individual measures are presented in the same manner for each building prototype, ranked by impact.

Individual results for the EEMs are followed by a summary of DR results. A summary of DR measures and packages of measures are presented. Electric demand savings are broken out by climate and building prototype for each DR measure.

This section concludes with a presentation of energy savings for packages of EEMs, organized by building prototype.

5.1 Individual Measure Results: Summaries by Measure

Individual measure results are included in this section, organized by measure. Results for each prototype simulated are included in each section. A graph is provided for each measure to demonstrate the impact of 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. For measures that are included in the Seattle Building Tune-Ups mandate, the savings graphs use solid-colored bars; for measures that are not included, hashed bars are used.

5.1.1 Measure 01: Re-calibrate Faulty Sensors

Figure 5.1 shows savings for all nine prototypes from the correction of specific temperature bias faults for outdoor and return air sensors. The savings are strongest for small buildings with single-zone air-conditioning at 0.6 to 1.3%. For larger buildings, the savings are generally negligible. This savings estimate is very sensitive to the actual prevalence, severity, and direction (positive or negative) of economizer temperature bias faults, which is unknown.

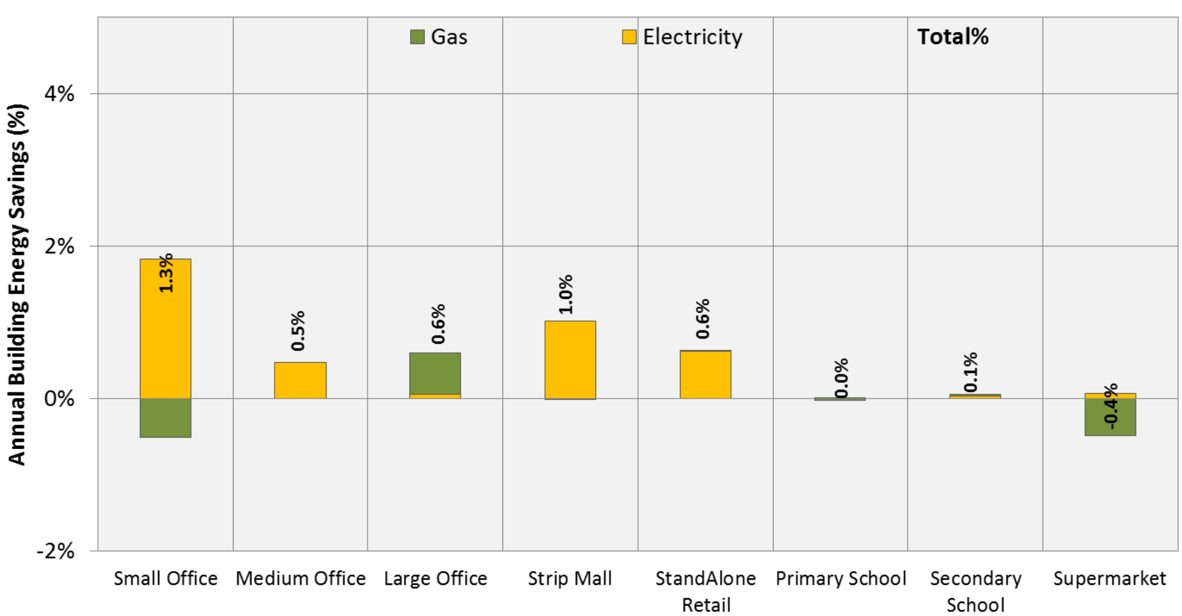

Figure 5.1. Energy Savings: Measure 01 (Re-calibrate Faulty Sensors)

5.1.2 Measure 02: Fix Low Refrigerant Charge

Figure 5.2 shows the impact of correcting RTUs that are 20% undercharged with refrigerant. Because of low cooling demands in the Seattle climate, the savings from this measure is low—generally less than 0.5% for applicable buildings (although over 1% savings was modeled in the Medium Office prototype).

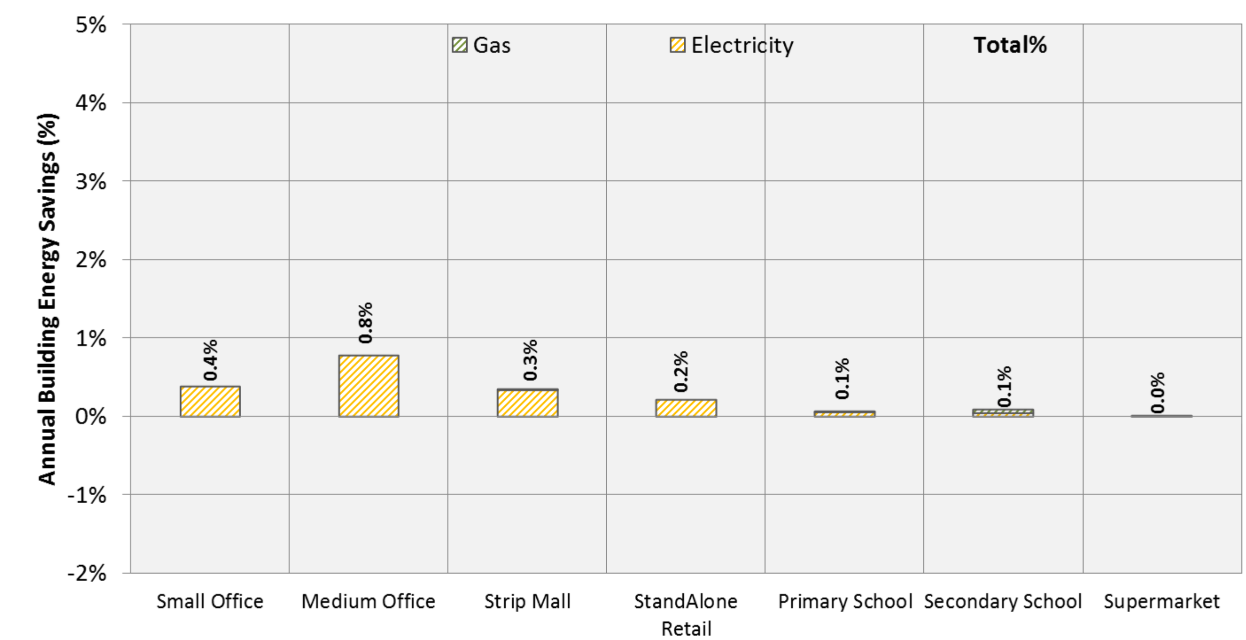

Figure 5.2. Energy Savings: Measure 02 (Fix Low Refrigerant Charge)

5.1.3 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 building type, with the strongest savings by far simulated for the Large Office and Primary School prototype. Figure 5.3 shows savings for the four building prototypes for which this measure was applicable. This savings estimate is 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); this balance may allow the savings estimate to be realistic.

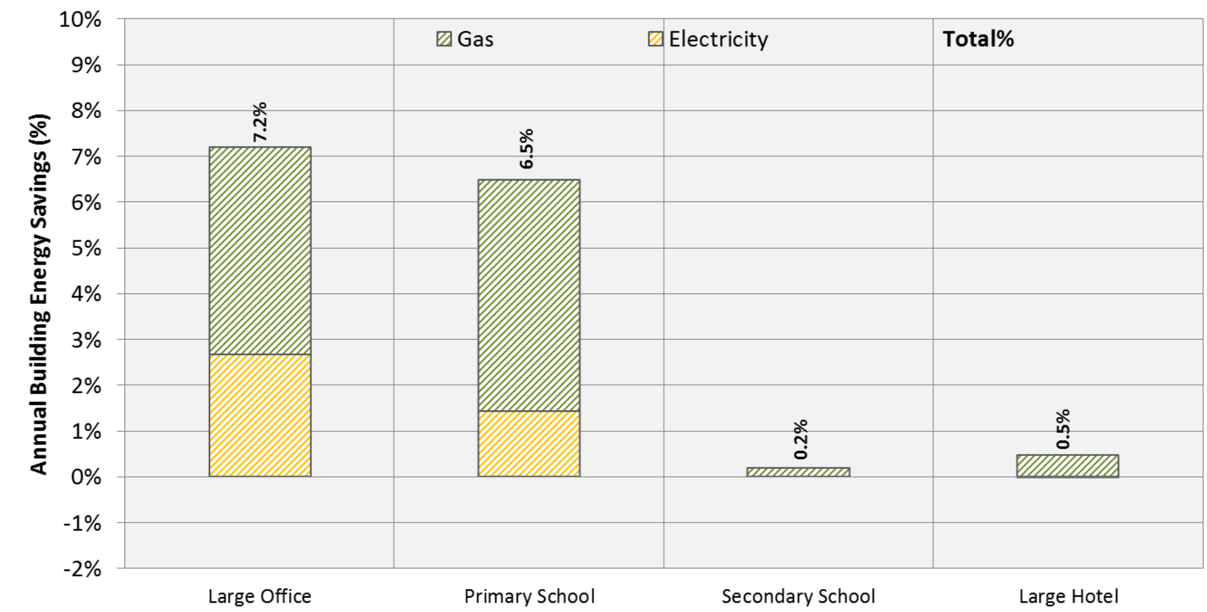

Figure 5.3. Energy Savings: Measure 03 (Fix Leaking Heating Coil Valves)

5.1.4 Measure 04: Shorten HVAC Schedules

Figure 5.4 shows the impact of shortening HVAC schedules by 4 hours in the evenings for all applicable prototypes. This reduces fan, heating, and cooling energy consumption. Savings range from 6–16% by building type.

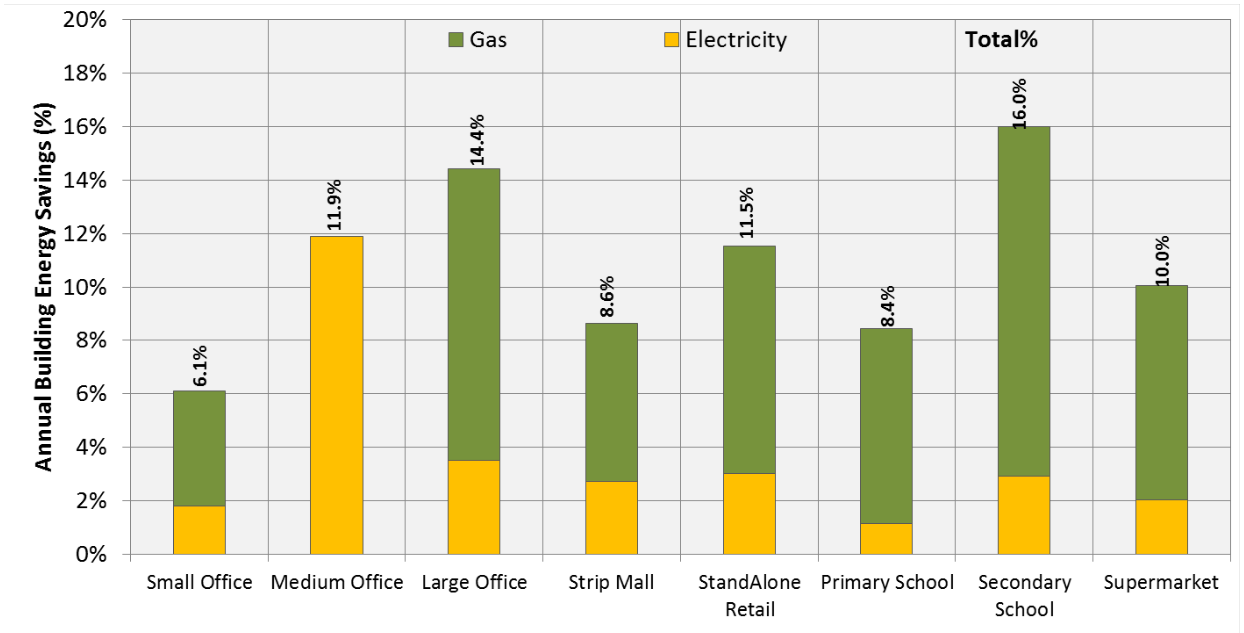

Figure 5.4. Energy Savings: Measure 04 (Shorten HVAC Schedules)

5.1.5 Measure 05: Supply Air Temperature Reset

Figure 5.5 shows the impact of an outdoor air temperature-based SAT reset and Figure 5.6 shows the impact of a seasonal adjustment to the SAT setpoint. This measure achieves savings through reduced use of heating in terminal box reheat coils. 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 highest savings from this measure are in office and hotel buildings at around 10%, while 2% to 4% savings is possible in schools.

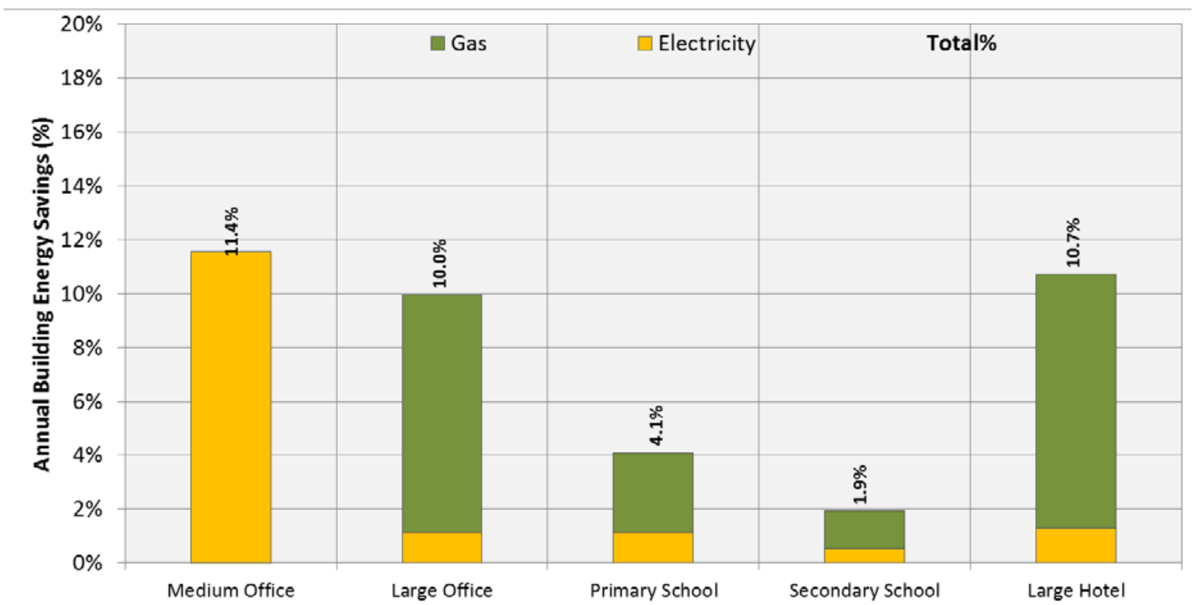

Figure 5.5. Energy Savings: Measure 05 (Supply Air Temperature Reset): Outdoor Air Reset

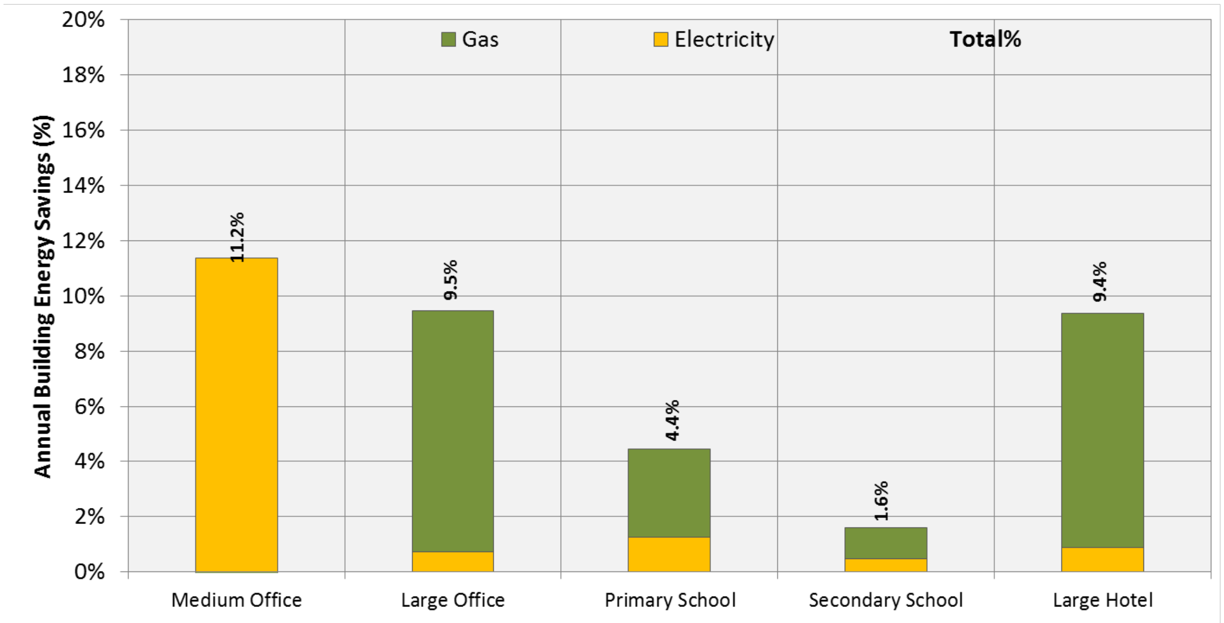

Figure 5.6. Energy Savings: Measure 05 (Supply Air Temperature Reset): Seasonal Reset

5.1.6 Measure 06: Outdoor Air Damper Faults and Control

Figure 5.7 shows the impact of fixing damper seals and using zero minimum outdoor airflow during unoccupied periods. The widely divergent savings among building types 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 buildings that use VAV systems 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. Combining this measure with SAT reset is expected to improve this measure's performance in buildings with VAV systems. 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 important for occupant health and comfort.

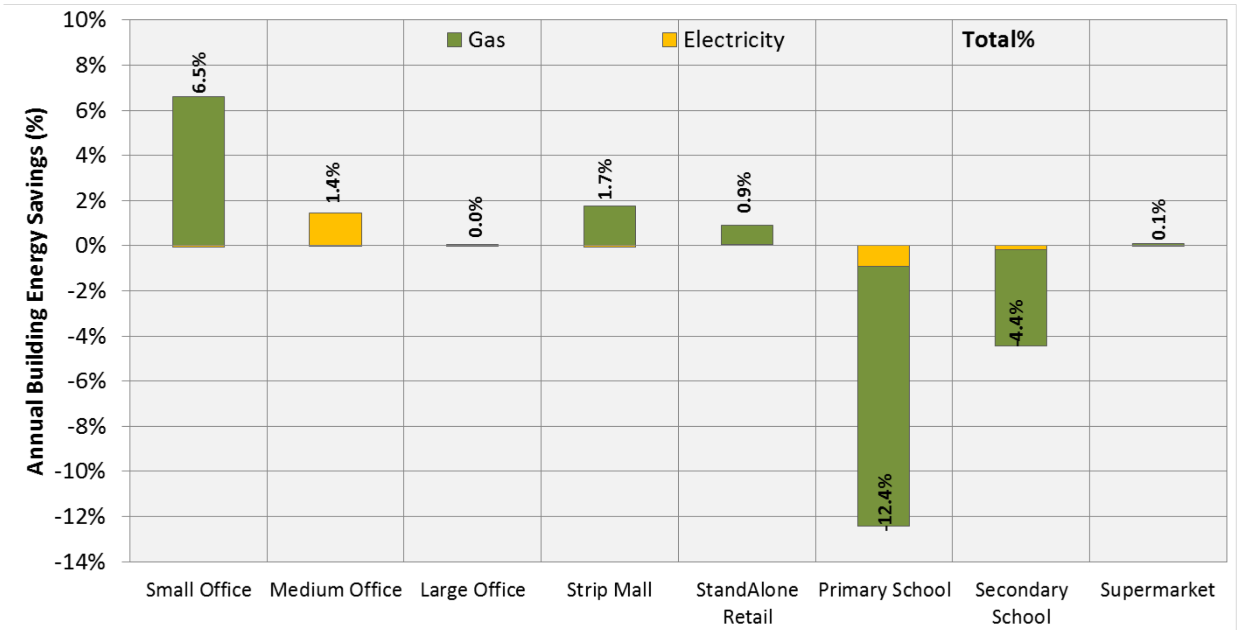

Figure 5.7. Energy Savings: Measure 06 (Outdoor air Damper Faults and Control)

5.1.7 Measure 07: Exhaust Fan Control

Figure 5.8 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 in Seattle is generally in the range of 1-2% for this measure.

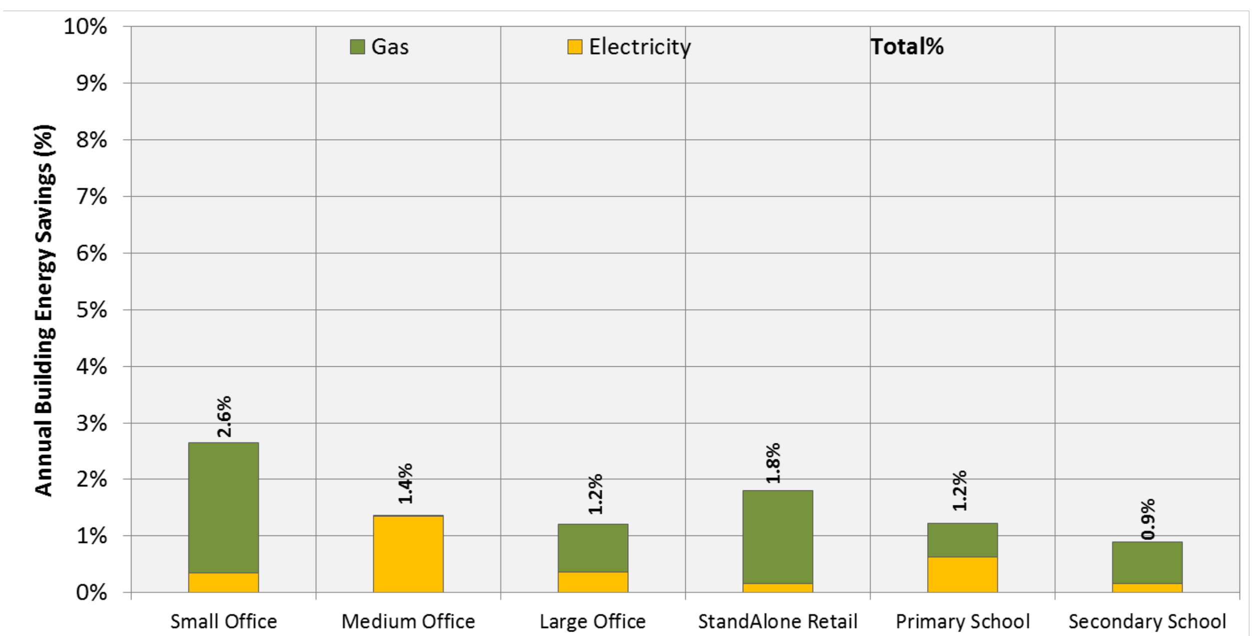

Figure 5.8. Energy Savings: Measure 07 (Exhaust Fan Control)

5.1.8 Measure 08: Static Pressure Reset

Figure 5.9 shows the impact of static pressure reset reductions based on VAV damper positions in all five applicable prototype buildings and Figure 5.10 shows the impact of static pressure reset based on the time of day for the four prototypes that can use this variation of the measure. Savings tend to be about twice as high for the VAV damper approach compared to the simpler time-of-day approach. Savings are 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.

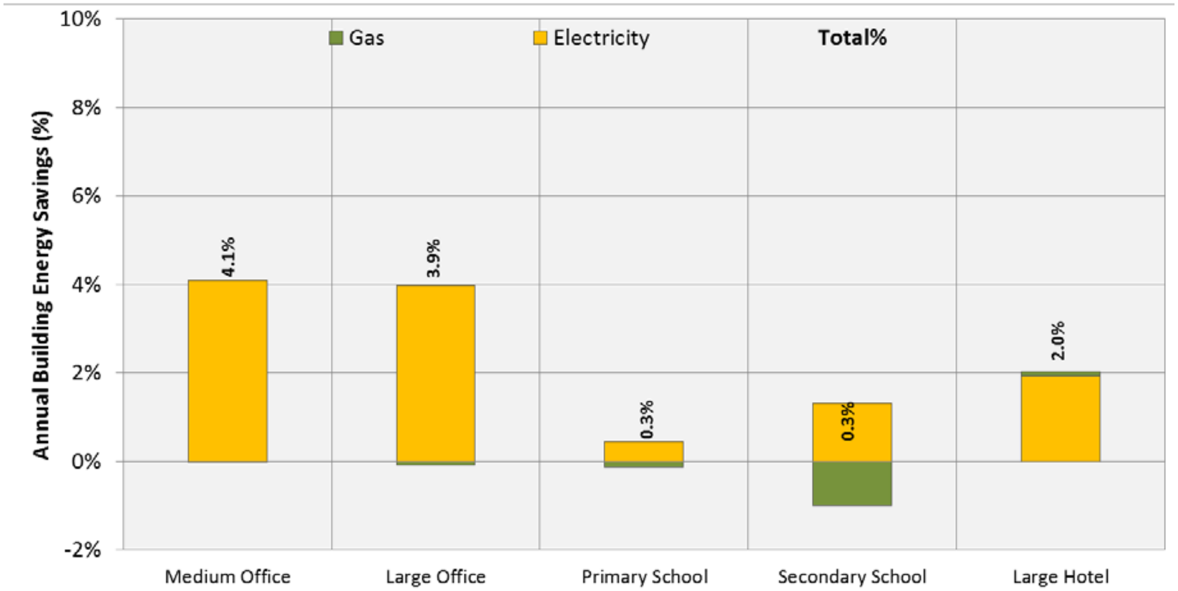

Figure 5.9. Energy Savings: Measure 08 (Static Pressure Reset): VAV Damper Position Approach

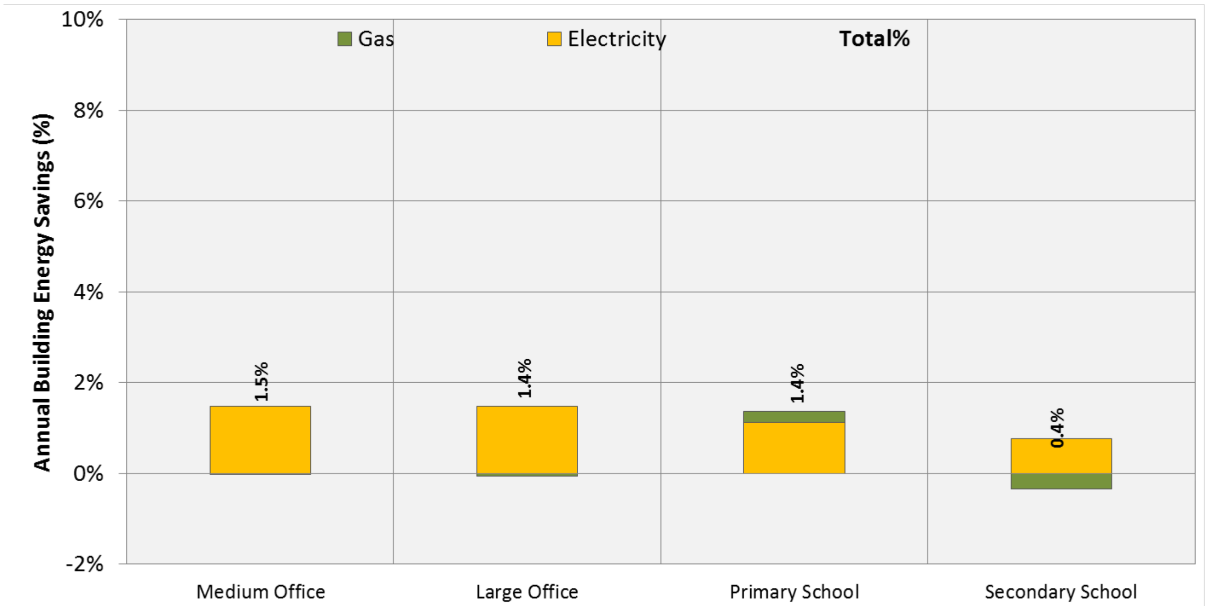

Figure 5.10. Energy Savings: Measure 08 (Static Pressure Reset): Time-of-Day Approach

5.1.9 Measure 09: Plant Shutdown When There Is No Load

Measure 09 simulates turning off secondary hot water pumps when there is no demand for hot water in the building and shutting off secondary chilled water 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 for Seattle is 0.4%, both from electricity to run the pumps and savings on natural gas from reduced circulation and standby losses (from hot water piping) of heat.

5.1.10 Measure 10: Chilled Water Differential Pressure Reset

Figure 5.11 shows the savings from chilled water DP 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).

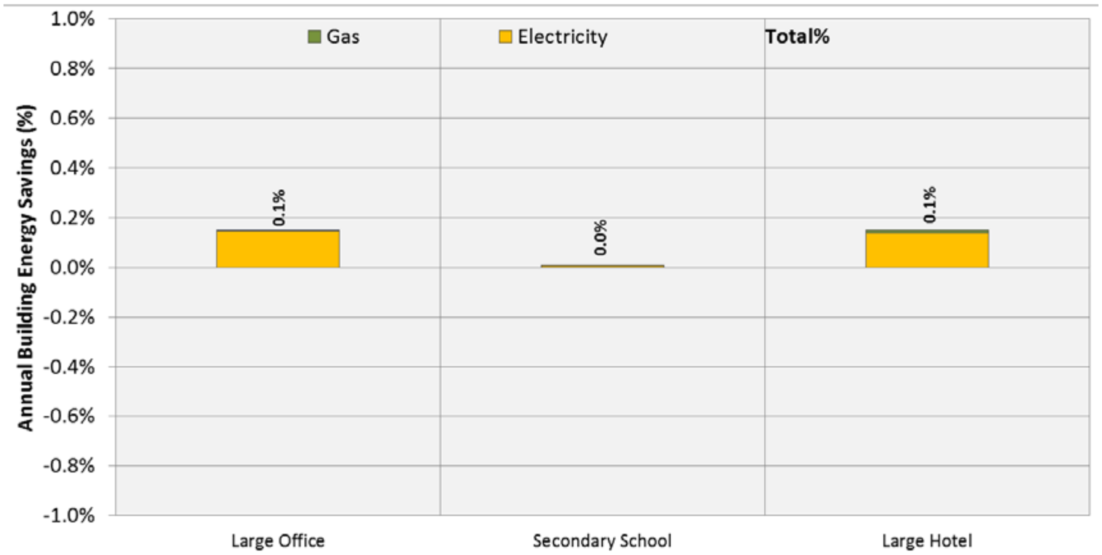

Figure 5.11. Large Office Energy Savings: Measure 10 (Chilled Water Differential Pressure Reset)

5.1.11 Measure 11: Chilled Water Temperature Reset

Energy savings results for chilled water temperature reset (based on outdoor air temperature) are shown in Figure 5.12 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. 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 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).

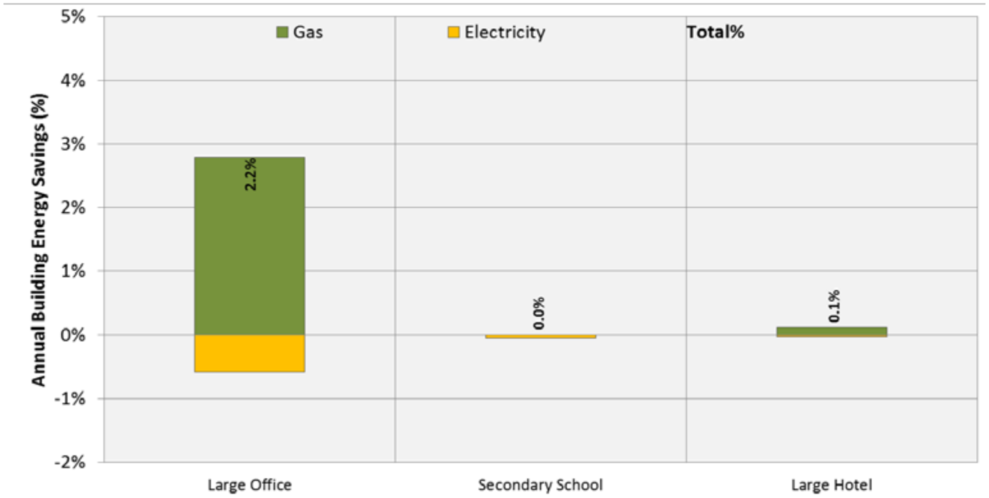

Figure 5.12. Energy Savings: Measure 11 (Chilled Water Temperature Reset Based on Outdoor Air Temperature)

5.1.12 Measure 12: Condenser Water Temperature Reset

This measure was applicable for only the Large Office prototype because it is the only one with water-cooled chillers. The savings from condenser water reset in Seattle is 0.4% (electricity) for the Large Office prototype.

5.1.13 Measure 13: Hot Water Differential Pressure Reset

Figure 5.13 shows the savings from hot water DP reset in the four prototype buildings that use variable-speed 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 increased 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 are very minor because hot water pumps are much smaller in size than chilled water pumps and the savings are proportionally less.

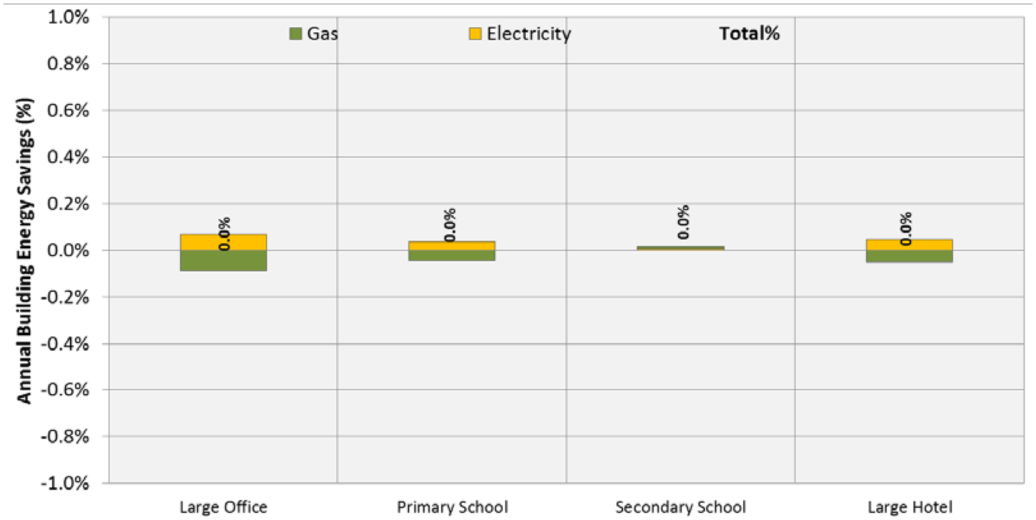

Figure 5.13. Energy Savings: Measure 13 (Hot Water Differential Pressure Reset)

5.1.14 Measure 14: Hot Water Temperature Reset

Figure 5.14 shows the savings from hot water temperature reset in the four prototype buildings with hot water loops. Modeled savings in all three cases are based on reduced standby losses in building hot water piping. Buildings with condensing boilers would reap significant additional gas savings from this measure. Savings are generally under 1% in Seattle for all building types, except Primary School, which shows almost 5% savings.

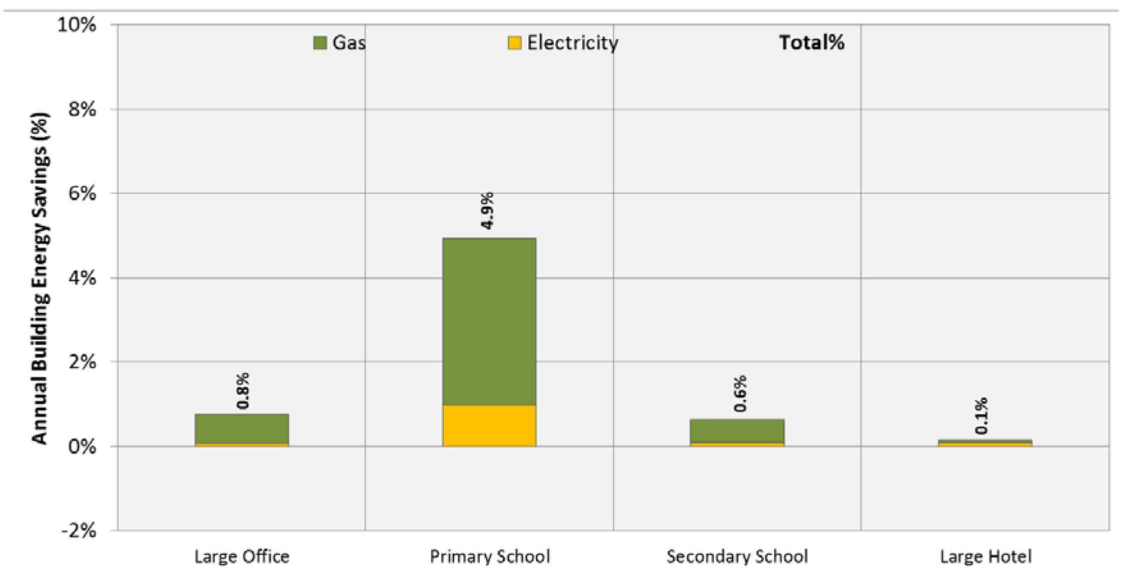

Figure 5.14. Energy Savings: Measure 14 (Hot Water Temperature Reset): Large Office, Primary School, and Large Hotel Prototypes

5.1.15 Measure 15: Minimum VAV Terminal Box Damper Flow Reductions

Figure 5.15 shows 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 air flow setpoints, especially when combined with cool SATs, 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, the savings are between 15% and 20% in the Medium Office and Large Office 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; therefore, the savings from this measure is less in those buildings, but is still substantial (2% to 6% site energy savings).

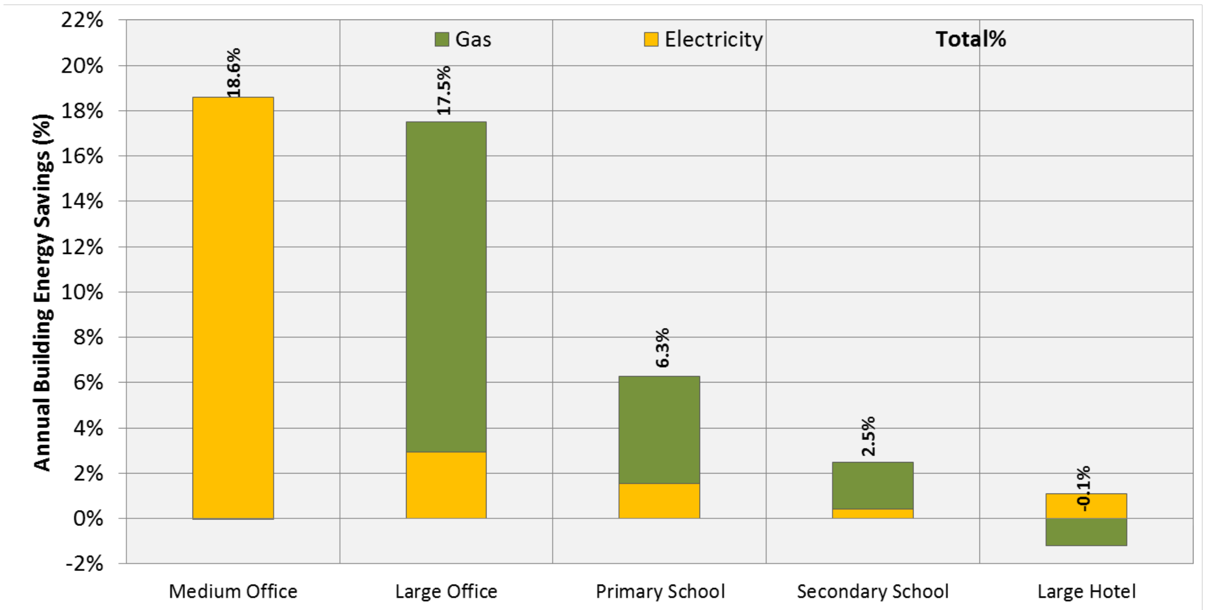

Figure 5.15. Energy Savings: Measure 15 (Minimum VAV Terminal Box Damper Flow Reductions)

5.1.16 Measure 16: Wider Deadbands and Night Setback

Figure 5.16, shows 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 a mild climate like Seattle, there is a particularly high benefit to increasing the thermostat deadband because there is a large fraction of hours in the year when the outdoor air temperature is close to a given building's balance point (typically between 55°F and 60°F). For most prototypes, the savings are around 10%. 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.

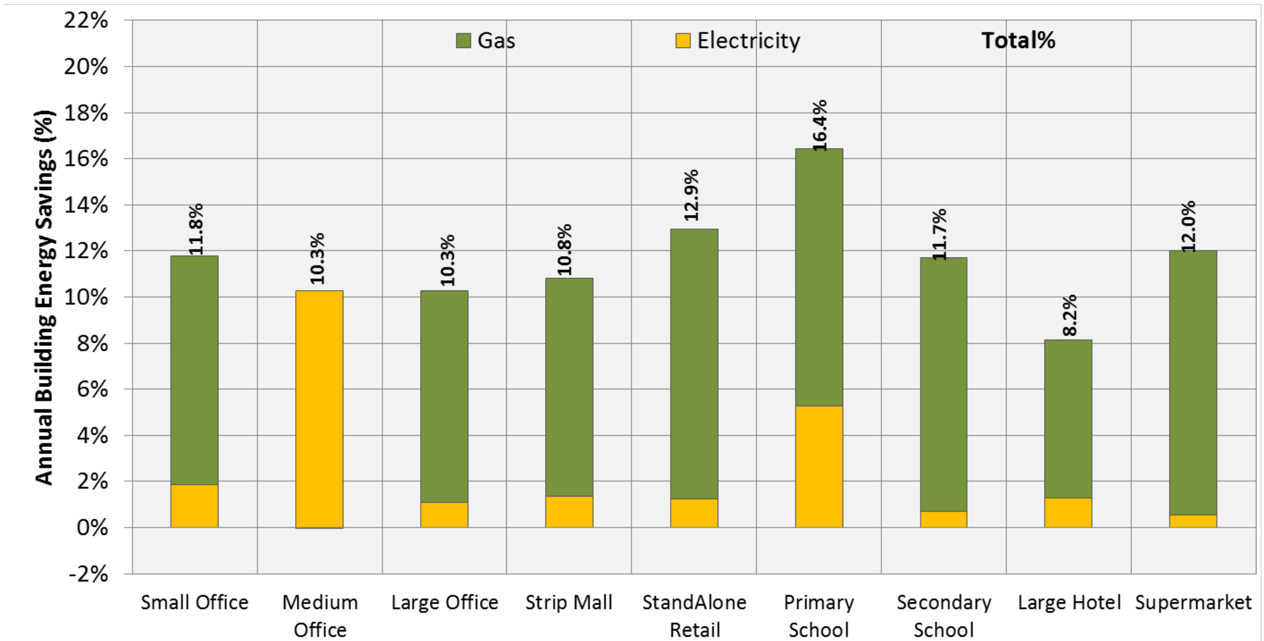

Figure 5.16. Energy Savings: Measure 16 (Wider Deadbands and Night Setback): Office Prototypes

5.1.17 Measure 17: Demand Control Ventilation

Figure 5.17 shows 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 (e.g., over 20% building energy savings in the Secondary School). In buildings that have more constant and lower occupancy rates, VAV systems for air distribution, and no zone-by-zone CO_2 sensing and control (e.g., Medium and Large Office), there may not be any savings from this measure in Seattle's climate.

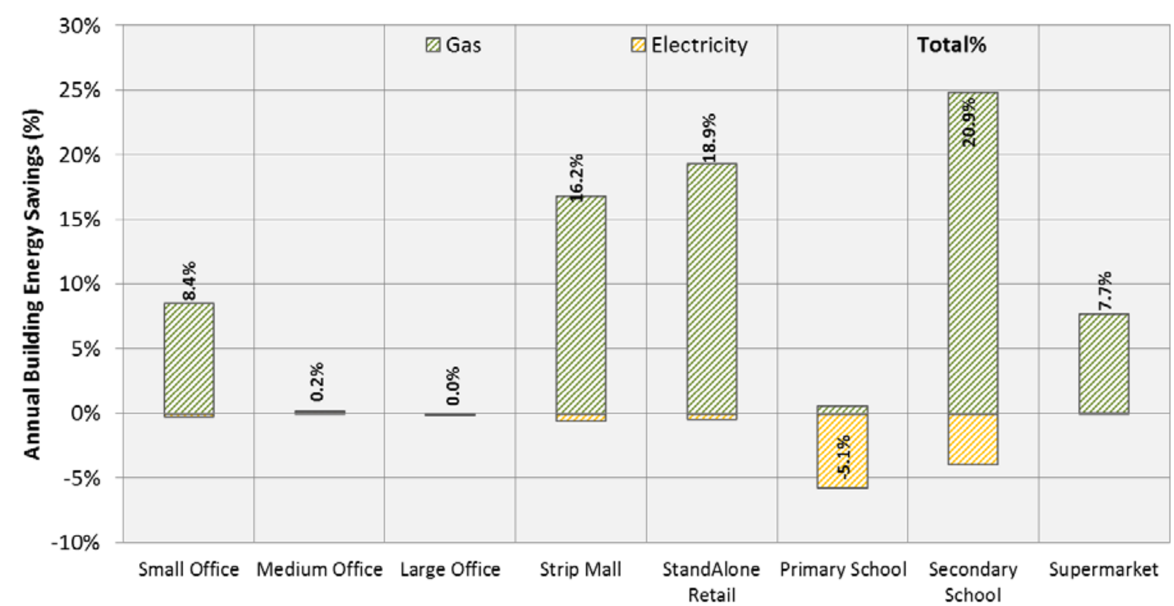

Figure 5.17. Energy Savings: Measure 17 (Demand Control Ventilation)

5.1.18 Measure 18: Occupancy Sensors

Figure 5.18 shows the impact of the use of occupancy sensors for lighting in all eight applicable prototypes. Savings are 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 take advantage of these sensors). Because this measure reduces internal heat gains, it may increase the need for heating, especially in perimeter zones. Certain building types show higher modeled increases in natural gas for heating than others. In certain cases, the net effect on site annual energy use 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.

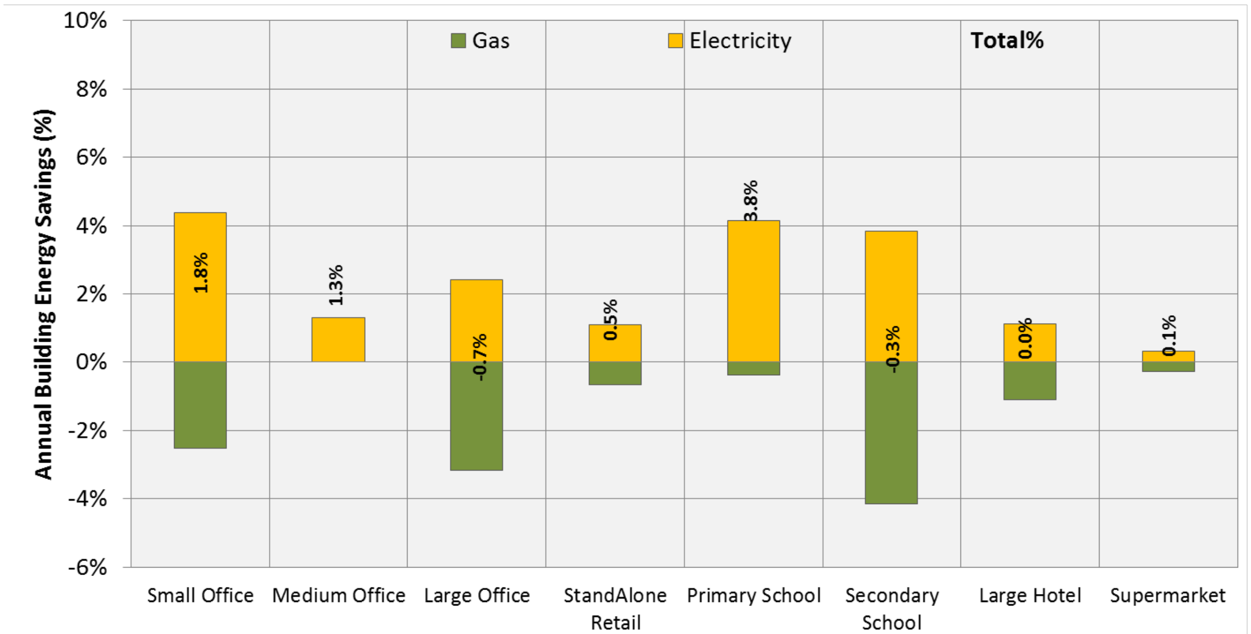

Figure 5.18. Energy Savings: Measure 18 (Occupancy Sensors)

5.1.19 Measure 19: Daylighting Controls

Figure 5.19 shows 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% and 10%), for which perimeter zones represent a higher fraction of total floor space. As was the case for occupancy sensors (Measure 18), 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 as a result.

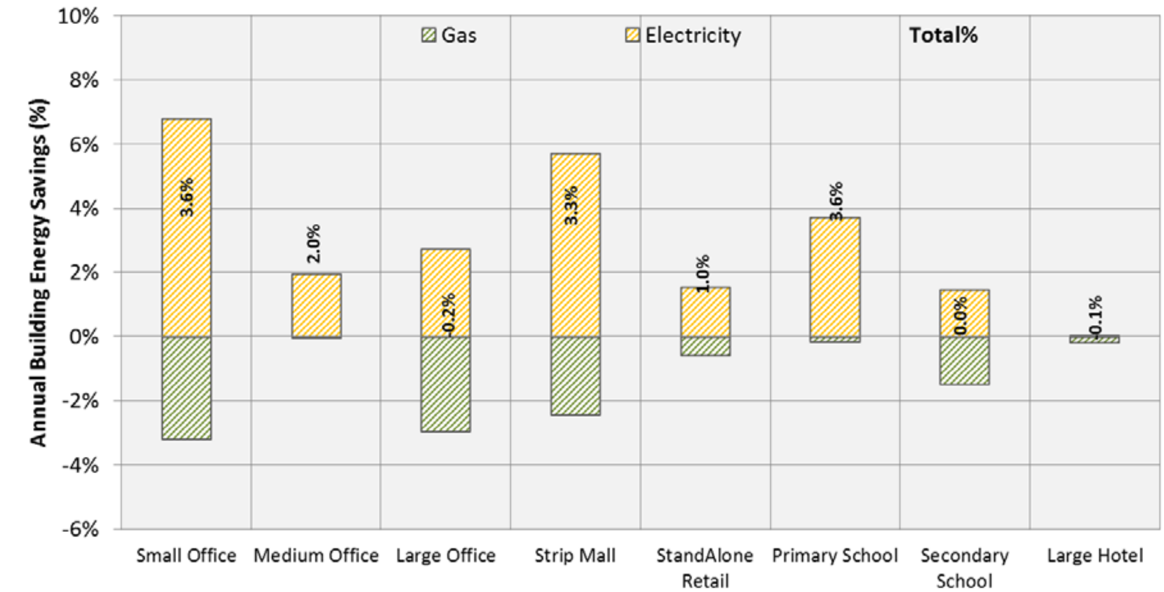

Figure 5.19. Energy Savings: Measure 19 (Daylighting Controls)

5.1.20 Measure 20: Exterior Lighting Controls

Figure 5.20 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). The savings varies significantly by building type, based on the size of the parking lot.

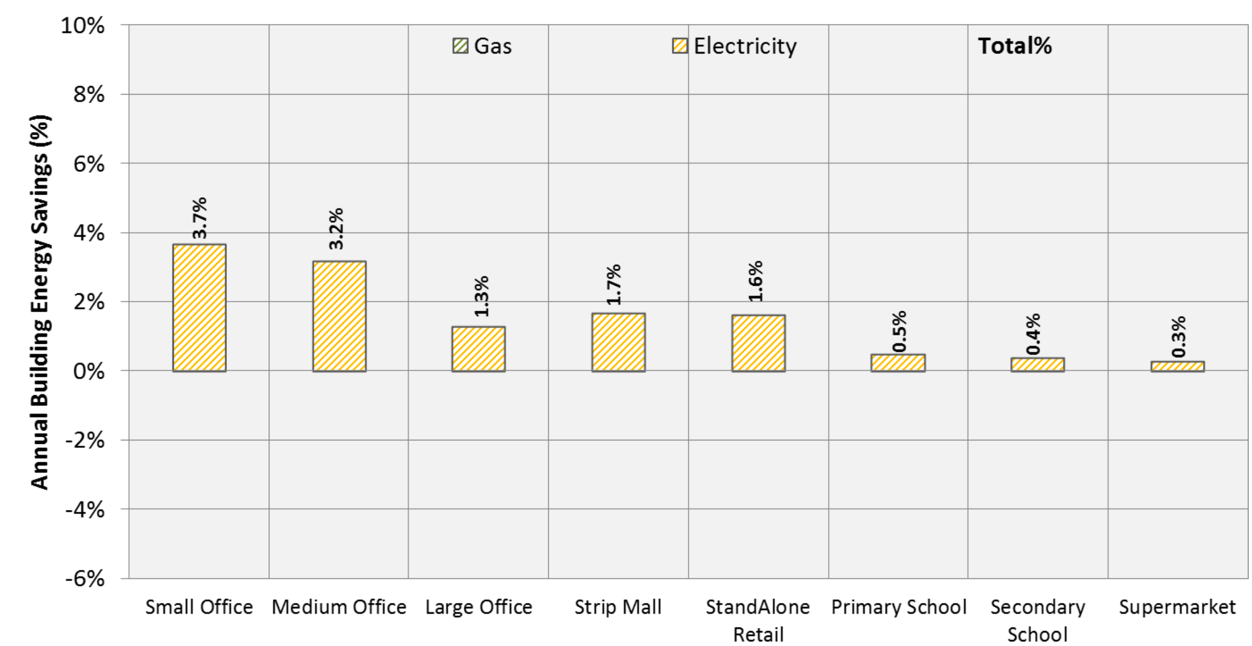

Figure 5.20. Energy Savings: Measure 20: Exterior Lighting Controls: Medium Office, StandAlone Retail, and Secondary School Prototypes

5.1.21 Measure 21: Advanced Plug Load Controls

Figure 5.21 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. Electricity is much more valuable than natural gas, so the measure should still be considered worthwhile.

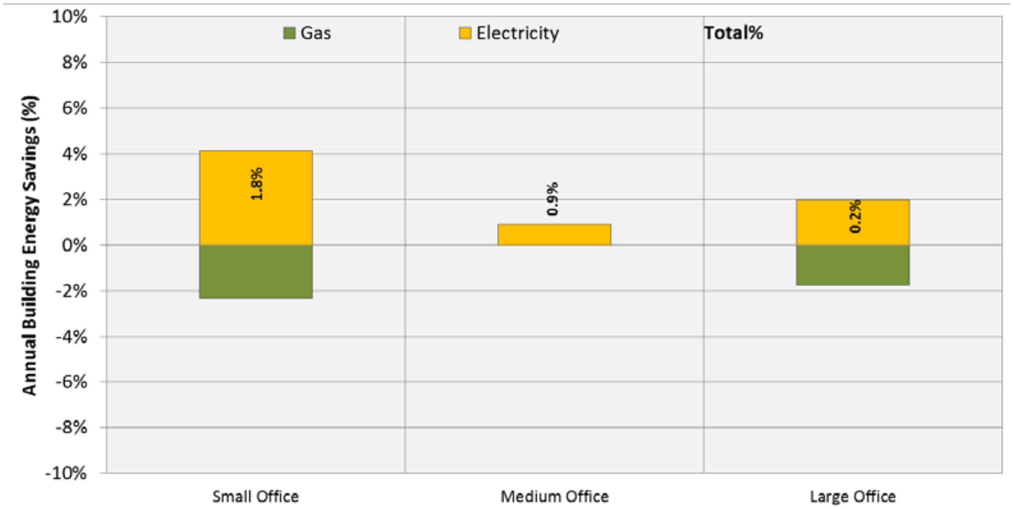

Figure 5.21. Energy Savings: Measure 21 (Advanced Plug Load Controls): Office Prototypes

5.1.22 Measure 22: Night Purge

Figure 5.22 shows the impact of night purge control strategies. Conventional wisdom dictates that this measure is usually only worth considering in dry climates with warm days and cool nights. The savings potential is fairly limited for all building types in Seattle, at up to 0.5%.

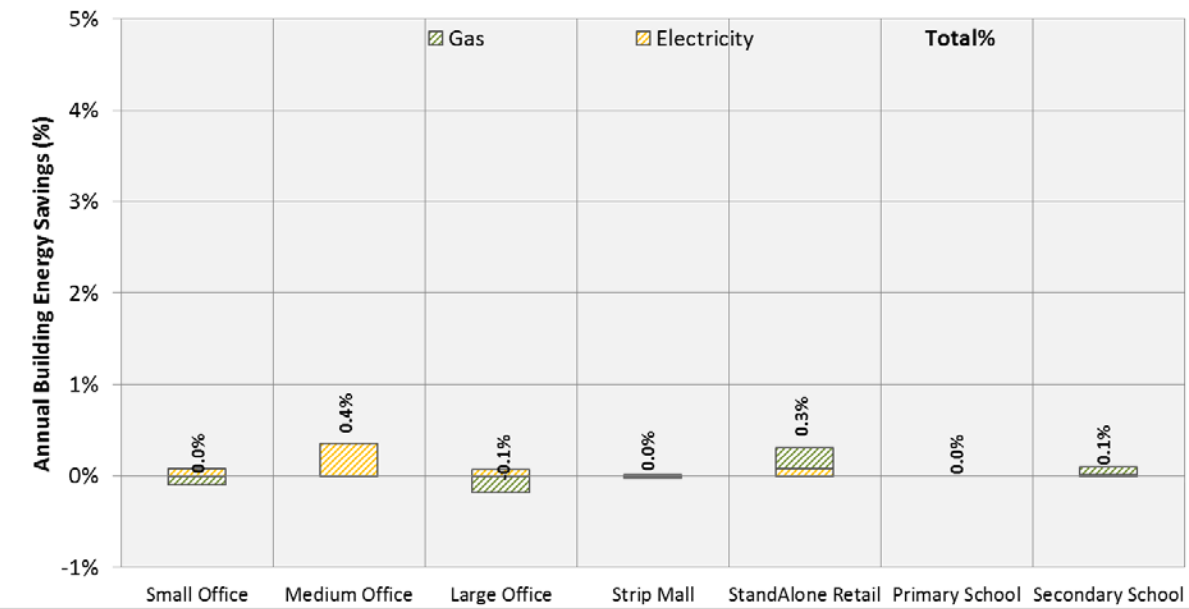

Figure 5.22. Energy Savings: Measure 22 (Night Purge)

5.1.23 Measure 23: Advanced RTU Controls

Figure 5.23 shows 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 7 to 12% in buildings with full coverage of single-zone packaged units (Small Office, Strip Mall, and StandAlone Retail) and from 3% to 6% in buildings with partial coverage. Because of the increase in heating, the overall savings is often close to 0; however, this measure is the best source of electricity savings through controls for several building types, which should make it highly desirable.

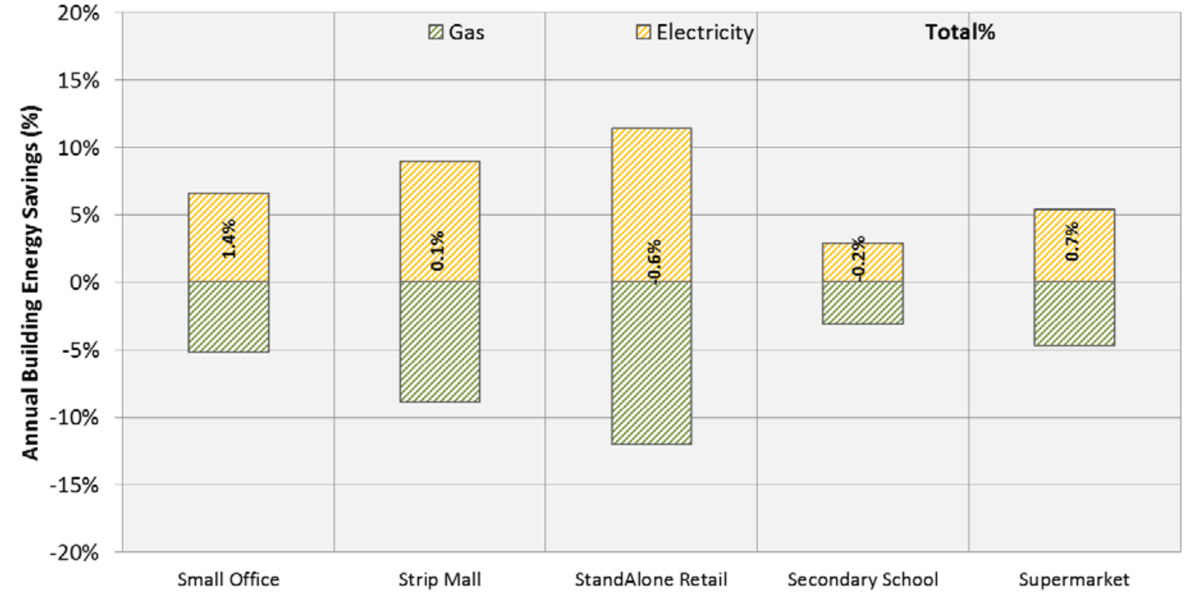

Figure 5.23. Energy Savings: Measure 23 (Advanced RTU Controls)

5.1.24 Measure 24: Elevator Lighting and Ventilation Control

Figure 5.24 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.

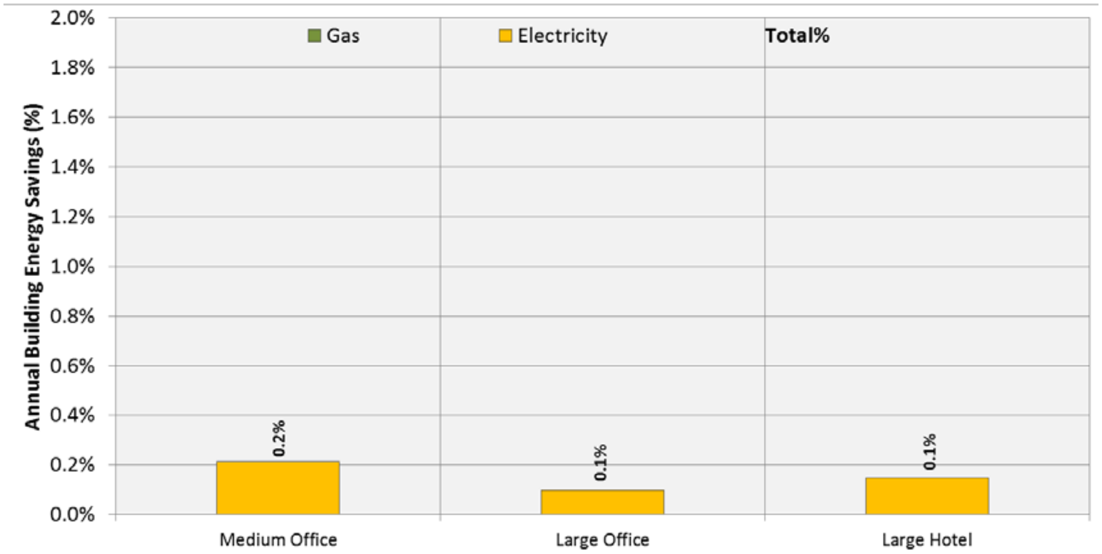

Figure 5.24. Energy Savings: Measure 24 (Elevator Lighting and Ventilation Control): Medium and Large Office and Large Hotel Prototypes

5.1.25 Measure 25: Waterside Economizer

Measure 25 simulated the enabling of 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, which is uncommon in Seattle. The Large Office prototype also has air-side economizing, so the additional benefit of a waterside economizer is small. Because of these factors, no savings were achieved in the simulation of this measure for Seattle.

5.1.26 Measure 26: Cooling Tower VFD Control

Measure 26 simulates 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 a large savings of 5.5% in Seattle; all from electricity.

5.1.27 Measure 27: Optimal Start

Figure 5.25 shows 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, between 6% and 14%, and delivers savings both in electricity and natural gas. 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 3 hours in advance of occupancy every day. Gas savings are typically higher than electricity, in part because the deferred HVAC operations often coincide with the coldest part of the day (close to sunrise).

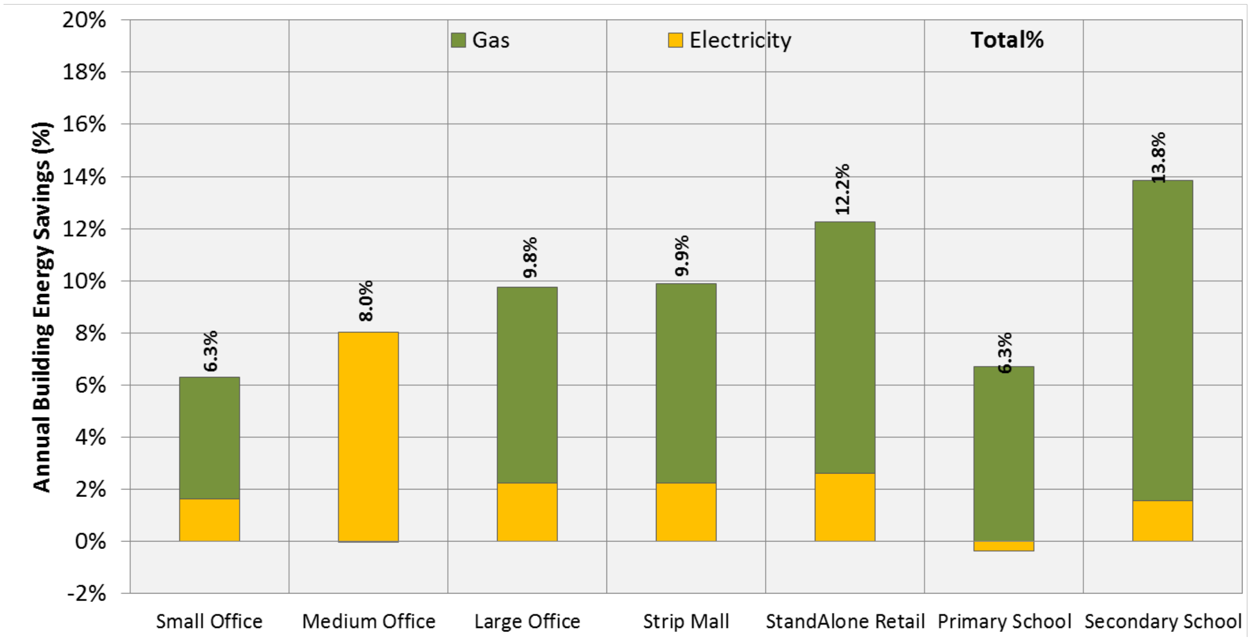

Figure 5.25. Energy Savings: Measure 28 (Optimal Start)

5.1.28 Measure 28: Optimal Stop

Figure 5.26 shows energy savings from optimal stop in three selected building prototypes (Large Office, Strip Mall, and Secondary School). Seattle is a very favorable climate for optimal stop because the cool and mild climate means that there are typically a large number of days each year that the fan systems can shut down early without significant impact on zone temperatures.

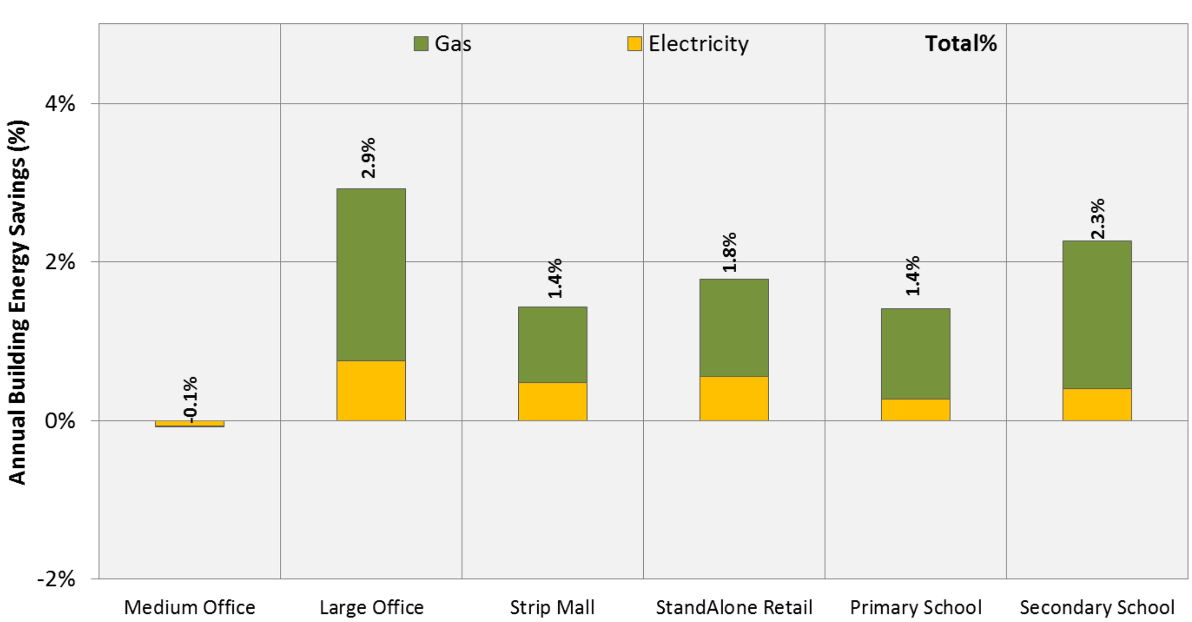

Figure 5.26. Energy Savings: Measure 28 (Optimal Stop)

5.1.29 Measures 29–37: Supermarket and Large Hotel Only Measures

Measures 29 to 35 affect only the Supermarket prototype and measures 36 and 37 affect only the Large Hotel prototype. Simulation results for each of these measures in Seattle are shown in Figure 5.27. The Supermarket measures each affect the refrigeration system. The top three measures are floating head pressure control (3.7% savings), anti-sweat heater controls (1.5% savings), and optimized defrost strategy (0.8%). Each of the two measures affecting large hotels (occupancy sensors for room thermostats and lighting and optimized use of heat recovery wheel) lead to a savings of approximately 3% in Seattle.

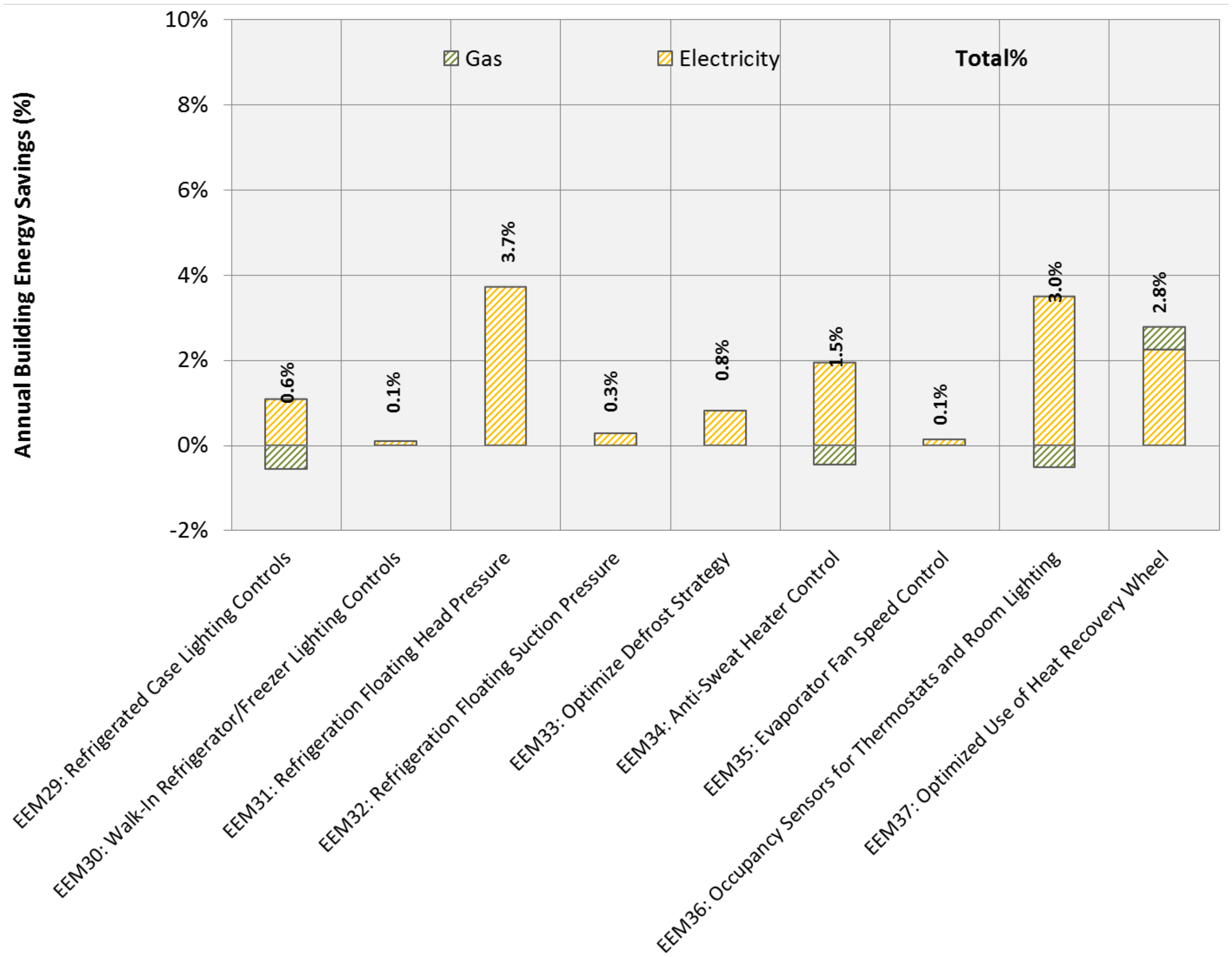

Figure 5.27. Energy Savings from Measures 29–35 (Supermarket only) and 36-37 (Large Hotel only)

5.1.30 Measure 38: Heating and Cooling Lockouts

Figure 5.28 shows the energy savings in each of the nine building types from implementation of outdoor air temperature-based heating and cooling lockouts. This measure has virtually no impact for small buildings in which each zone is well-coupled to outdoor air conditions (e.g., Small Office, Strip Mall). This measure is very effective, however, at preventing unnecessary simultaneous heating and cooling in VAV systems in larger buildings. The heating lockout generally accounts for most of the savings. Cooling lockouts for buildings with functioning air-side economizers (as modeled) have limited value unless more aggressive lockout setpoints are chosen (e.g., 60°F). These kinds of lockouts can force the building to cool only with outdoor air in relatively warmer conditions, which works for some buildings. For this study, however, a more conservative 50°F lockout was chosen. Savings for buildings with VAV systems ranged from 2% in Medium Office buildings to 6.2% in Large Office buildings.

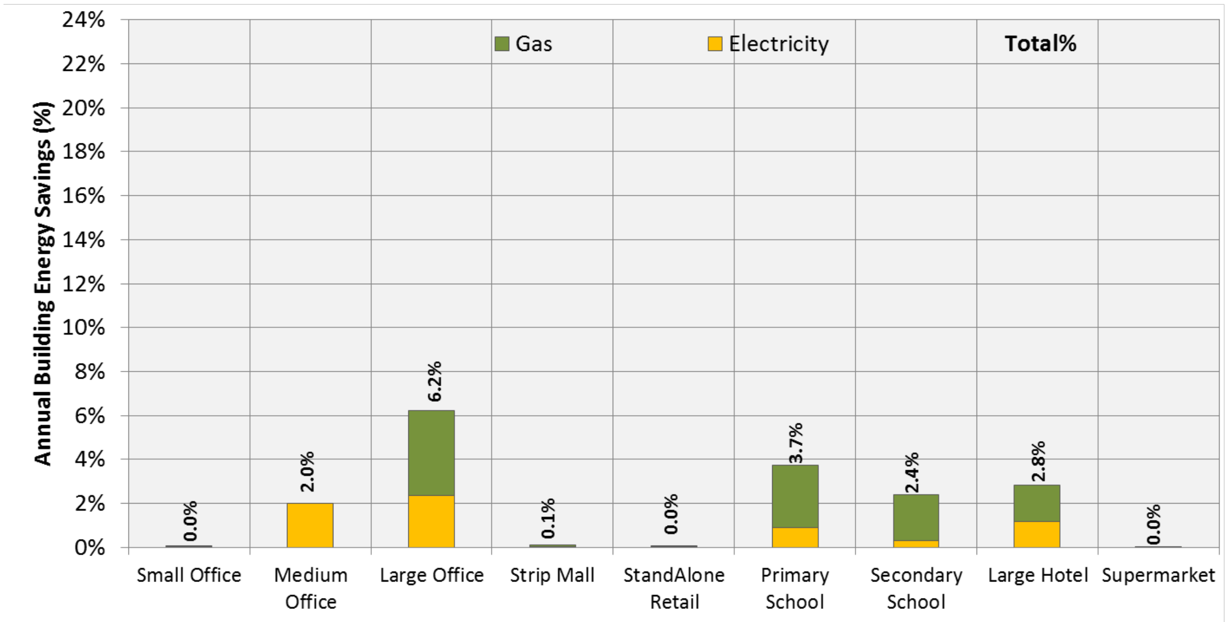

Figure 5.28. Energy Savings: Measure 38 (Heating and Cooling Lockouts)

5.2 Individual Measure Results: Summaries by Building Type

Figure 5.29 through Figure 5.37 show the individual EEMs, ranked by energy savings, for each of the nine simulated prototypes. These summaries show the impact of implementing any given EEM on each of the building prototypes in Seattle. For measures that are included in the Seattle Building Tune-Ups mandate, the bars are solid-colored, while for measures that are not included, hashed bars are used.

For small office buildings (Figure 5.29), the total site savings ranged from 0% (EEM22: night purge) to approximately 12% (EEM16: wider deadbands and night setbacks). The natural gas savings ranged from -5% (EEM23: advanced RTU controls) to almost 10% (EEM16: wider deadbands and night setbacks) and the electricity savings ranged from 0% (EEM22: night purge) to 7% (EEM23: advanced RTU controls). Note that for some EEMs, although there is always a net positive savings, there is an increase in natural gas consumption (e.g., EEM23: advanced RTU controls). The reason for this increase is that the reduction in electricity consumption results in a decrease in heat gain, which has to be compensated 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.

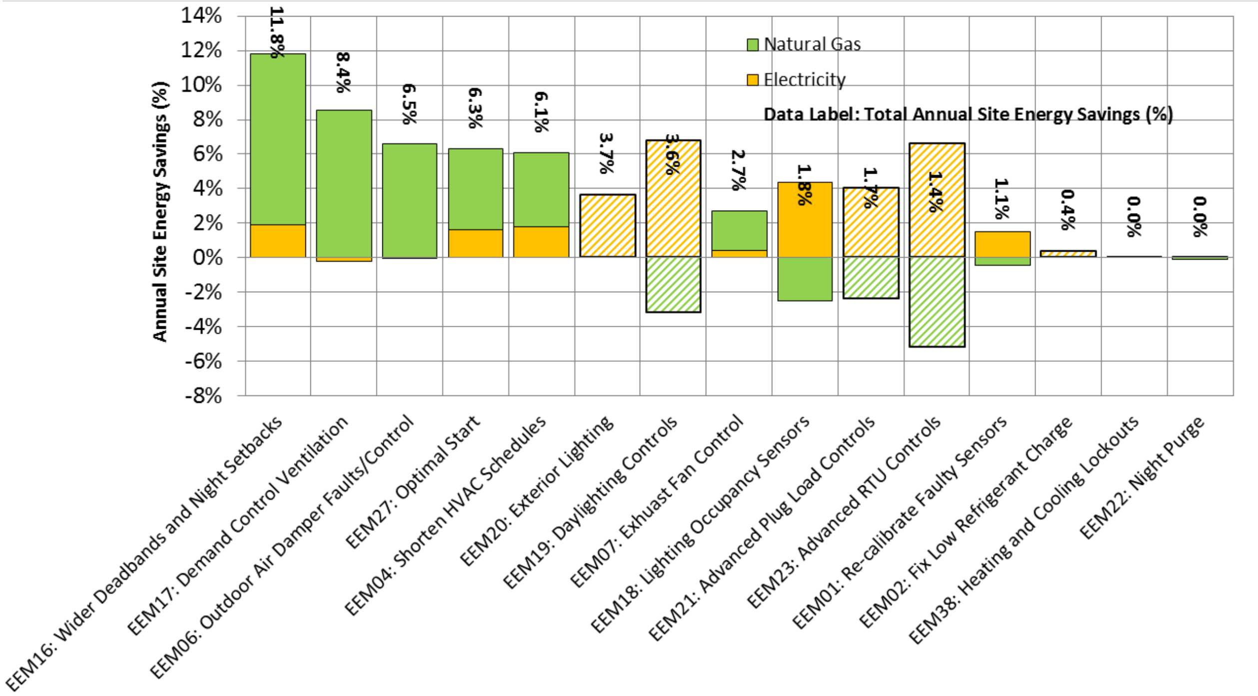

Figure 5.29. Individual EEMs Ranked by Impact for Small Office Buildings

For Medium Office and outpatient healthcare buildings (Figure 5.30), the total site savings ranged from -0.1% (EEM28: optimal stop) to almost 19% (EEM15: minimum VAV terminal box damper flow reductions). Natural gas was virtually unaffected by all measures, thus all site energy savings was from electricity.

For Large Office, college/university, and hospital (administrative portion) buildings (Figure 5.31), the total site savings ranged from -1% (EEEM06: outdoor air damper faults/controls) to over 17% (EEM15: minimum VAV terminal box damper flow reductions). The natural gas savings ranged from -3% (EEM18: lighting occupancy sensors) to 13% (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 an increase in the heating load (e.g., daylighting controls). The electricity savings ranged from -0.3% (EEM25: waterside economizer) to 4% (EEM26: cooling tower controls).

For Primary School (Figure 5.32), the total site savings ranged from -12% (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 -12% (EEM06: outdoor air damper faults/controls) to 11% (EEM16: wider deadbands and night setbacks) and the electricity savings ranged between -6% (EEM17: demand control ventilation) and 5% (EEM16: wider deadbands and night setbacks).

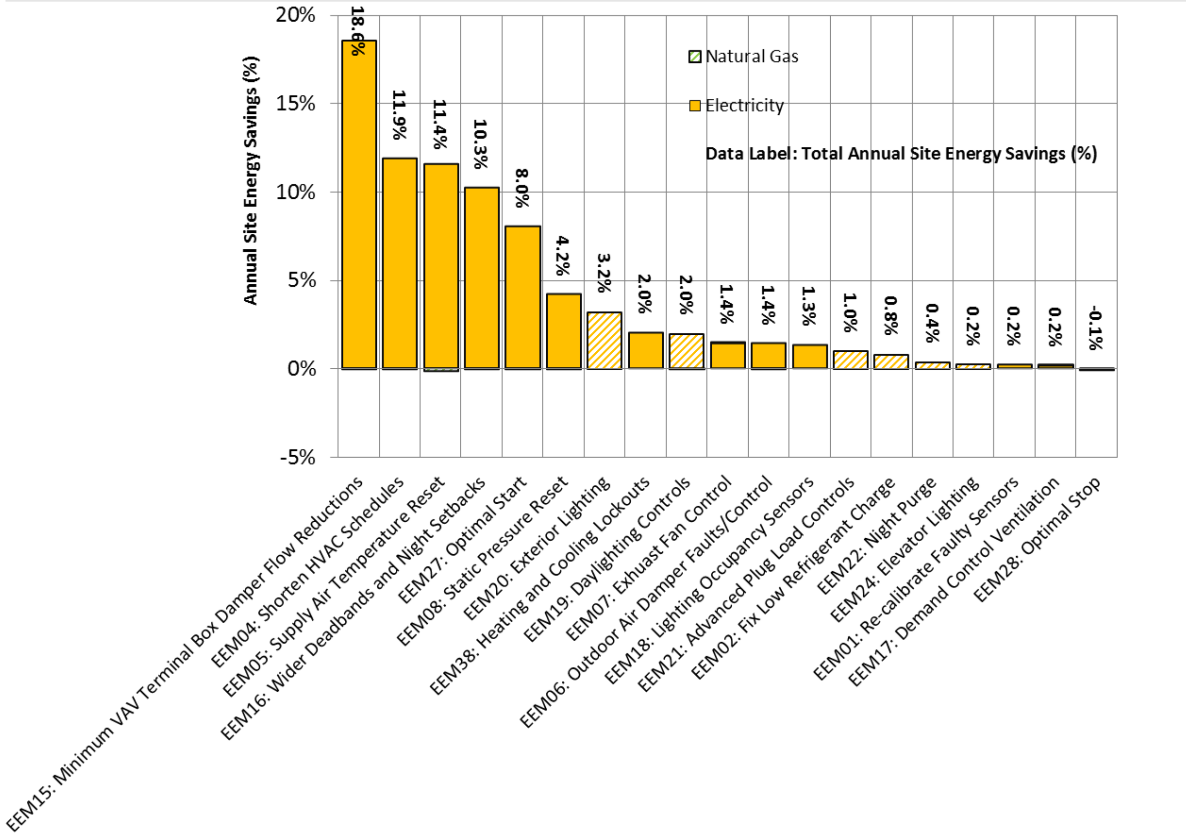

Figure 5.30. Individual EEMs Ranked by Impact for Medium Office and Outpatient Healthcare Buildings

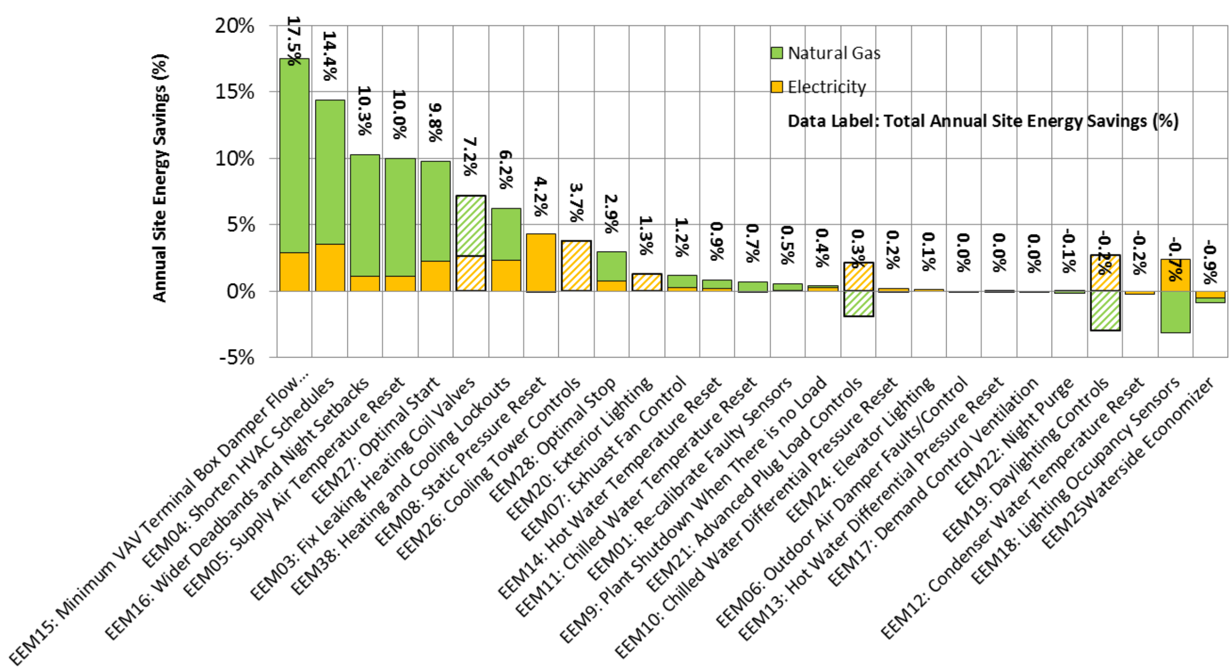

Figure 5.31. Individual EEMs Ranked by Impact for Large Office, College/University, and Hospital (Administrative)

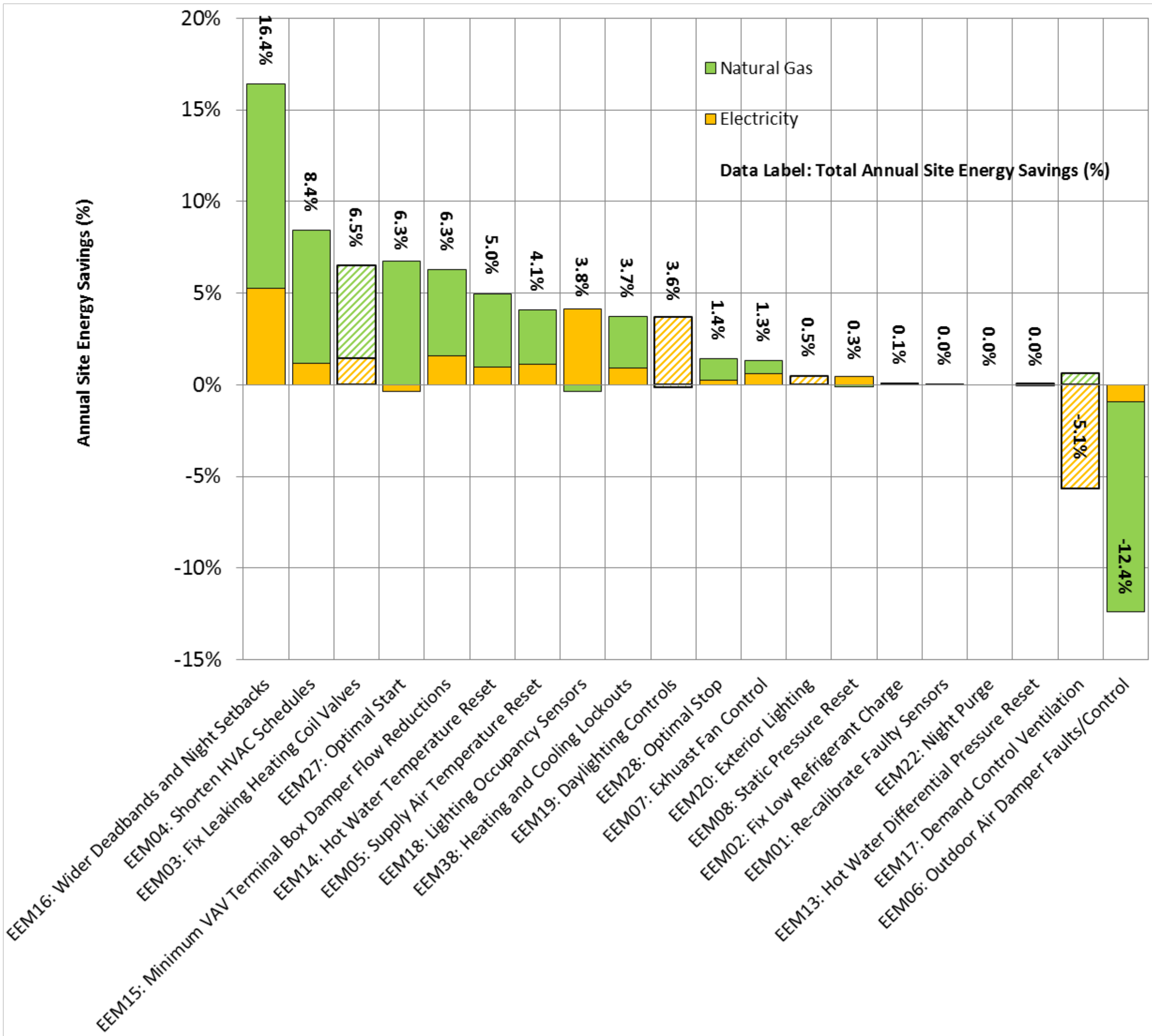

Figure 5.32. Individual EEMs Ranked by Impact for Primary School

For Secondary School buildings (Figure 5.33), the total site savings ranged from -4% (EEEM06: outdoor air damper faults/controls) to 21% (EEM17: demand control ventilation). The natural gas savings ranged from -3.7% (EEM06: outdoor air damper faulty/controls) to 25% (EEM17: demand control ventilation) and electricity savings from -4% (EEM17: demand control ventilation) to 4% (EEM18: lighting occupancy sensors).

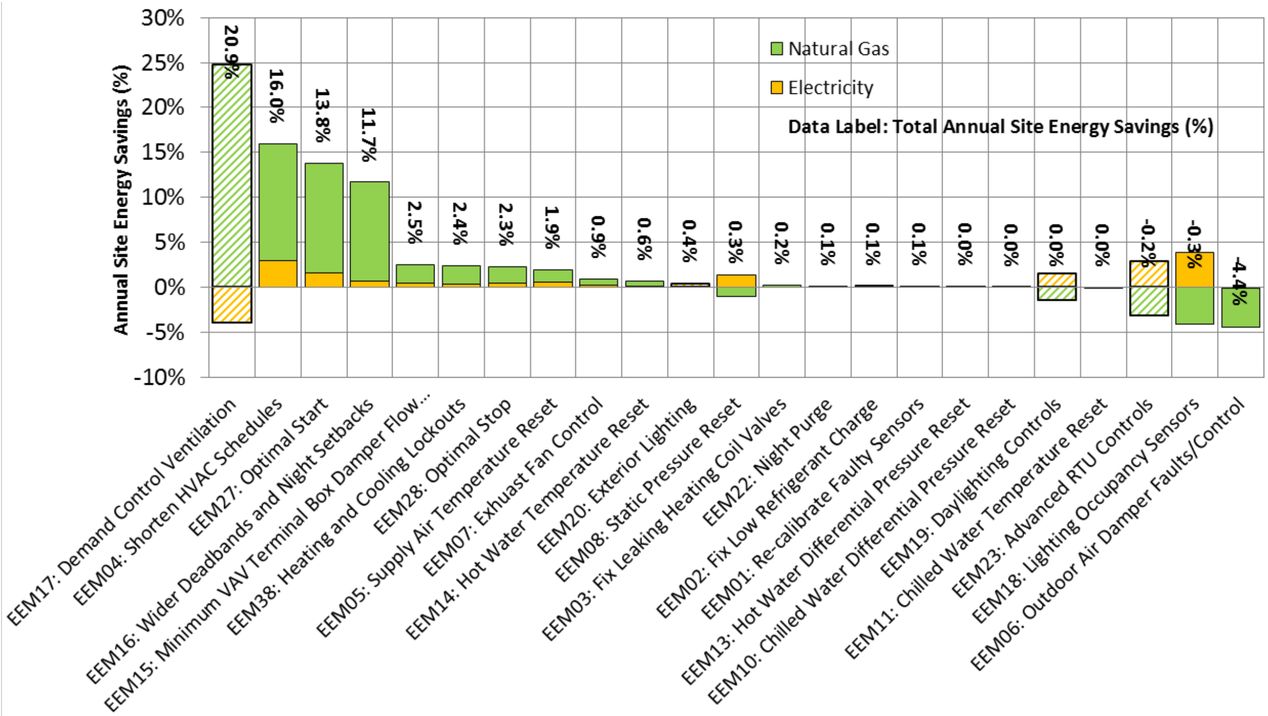

Figure 5.33. Individual EEMs Ranked by Impact for Secondary School

For Large Hotel buildings (Figure 5.34), the total site savings ranged from 0% (EEM19: daylighting controls) to 11% (EEM05: supply air temperature reset). The natural gas savings ranged from -1% (EEM18: lighting occupancy sensors) to 9% (EEM05: supply air temperature reset) and electricity savings ranged from 0% (EEM13: hot water differential pressure reset) to 4% (EEM36: occupancy sensors for thermostats and room lighting).

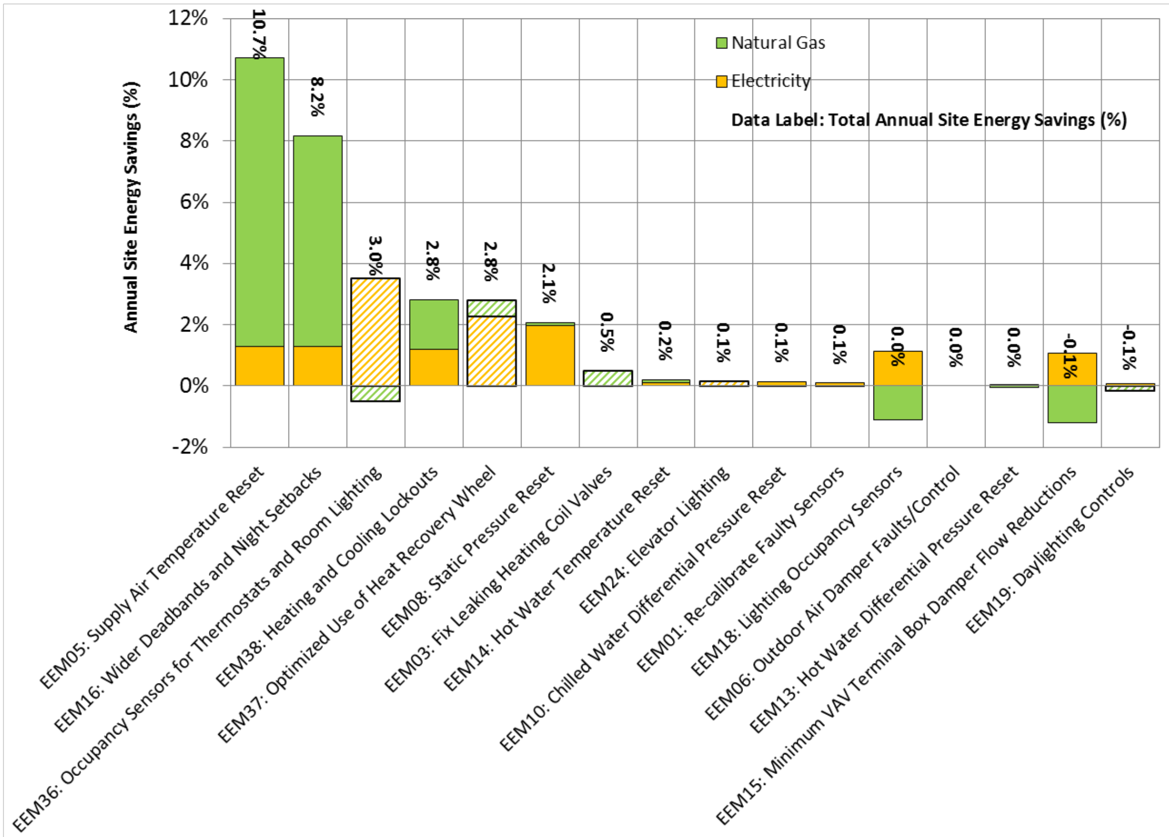

Figure 5.34. Individual EEMs Ranked by Impact for Large Hotel

For StandAlone Retail and Retail Dealership buildings (Figure 5.35), the total site savings ranged from -1% (EEM23: advanced RTU controls) to 19% (EEM17: demand control ventilation). The natural gas savings ranged between -12% (EEM23: advanced RTU controls) and 19% (EEM17: demand control ventilation) and electricity savings ranged from 0% (EEM17: demand control ventilation) to 11% (EEM23: advanced RTU controls).

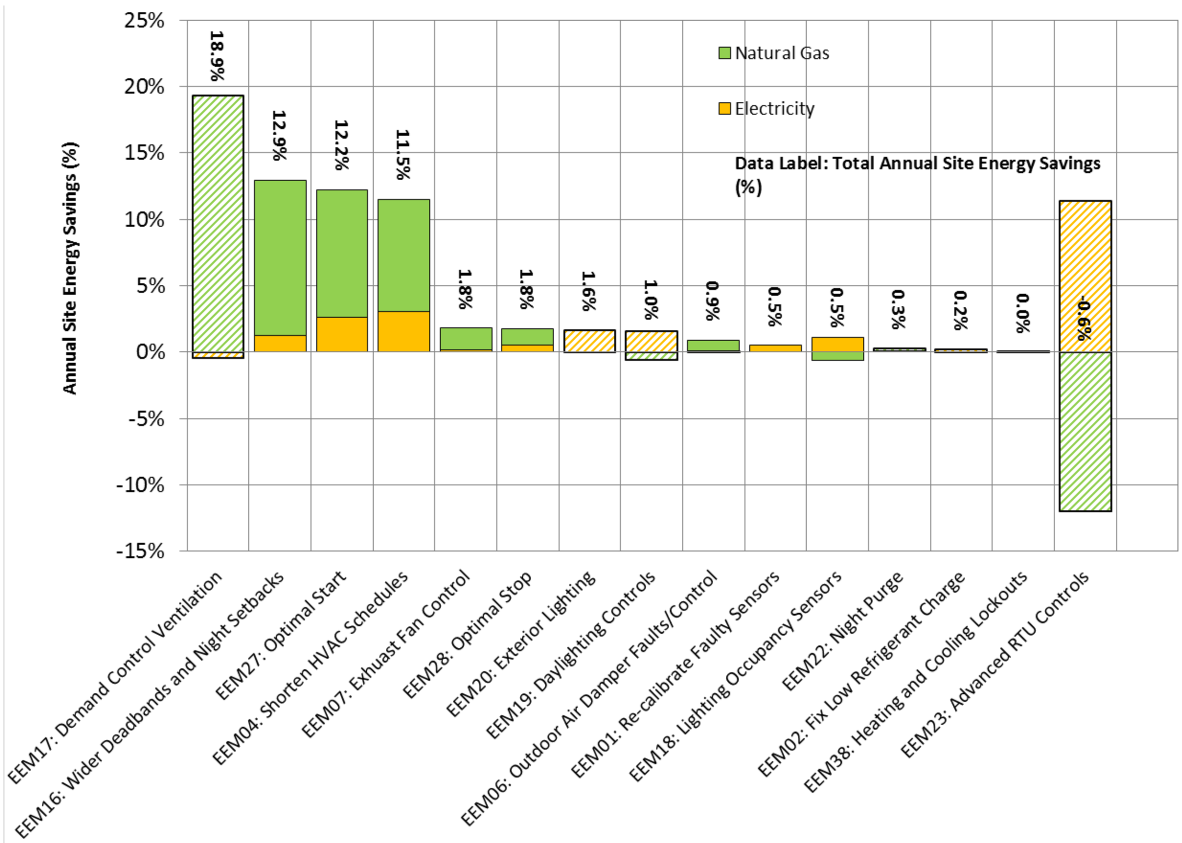

Figure 5.35. Individual EEMs Ranked by Impact for Standalone Retail and Retail Dealership

For strip malls (Figure 5.36), the total site savings ranged from 0% (EEM22: night purge) to more than 16% (EEM17: demand control ventilation). The natural gas savings ranged from -9% (EEM23: advanced RTU controls) to almost 17% (EEM17: demand control ventilation) and electricity savings ranged from 0.5% (EEM17: demand control ventilation) to almost 9% (EEM23: advanced RTU controls).

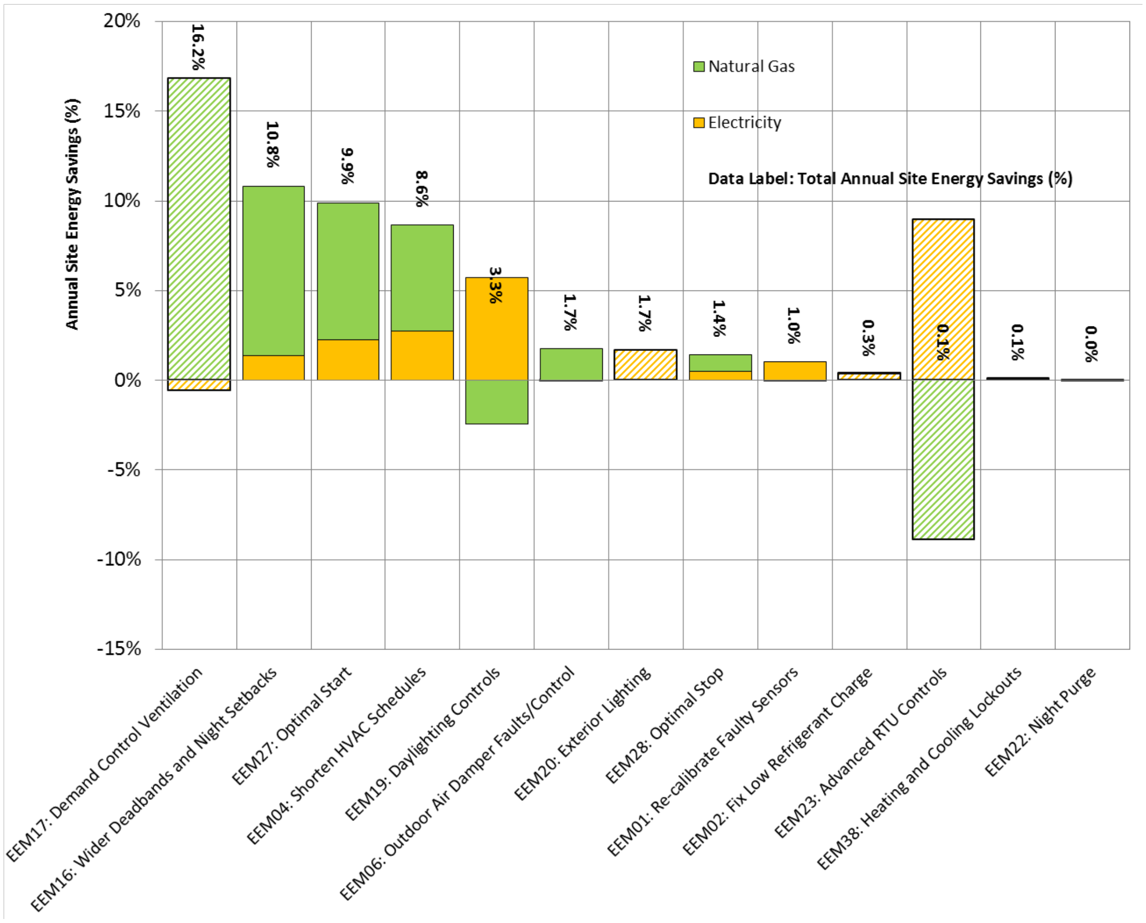

Figure 5.36. Individual EEMs Ranked by Impact for Strip Mall Retail

For Supermarket and Other Food Sales buildings (Figure 5.37), the total site savings ranged from -0.4% (EEM01: re-calibrate faulty sensors) to 12% (EEM16: wider deadbands and night setback). The natural gas savings ranged from -5% (EEM01: re-calibrate faulty sensors) to 12% (EEM16: wider deadbands and night setback) and electricity savings ranged from 0% (EEM01: re-calibrate faulty sensors) to more than 5% (EEM23: advanced RTU controls). Note that the measures ranked from #3 to #12 in terms of overall impact in Supermarkets are not covered by the requirements of the Seattle Building Tune-Ups package.

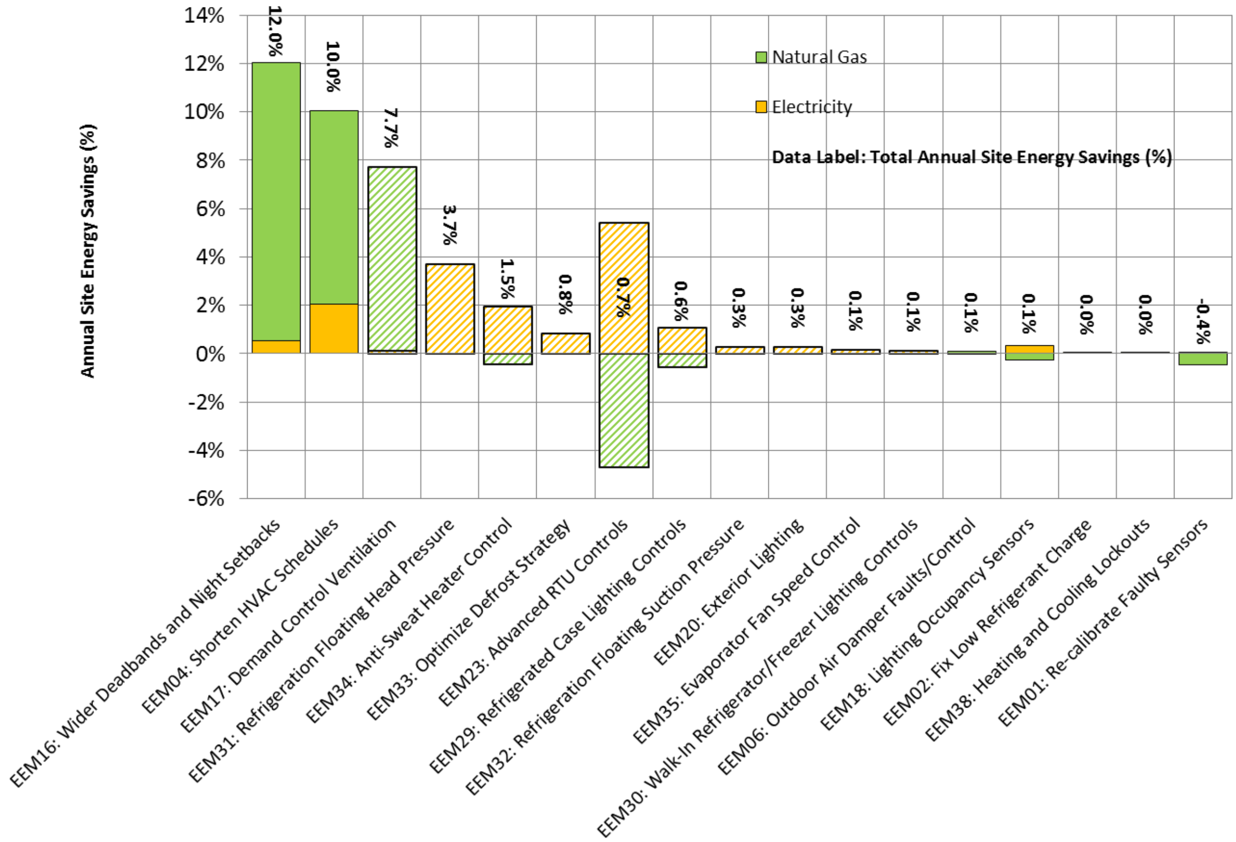

Figure 5.37. Individual EEMs Ranked by Impact for Supermarket and Other Food Sales

5.3 Demand Response: Results by Measure

Individual DR-measure results are included in this section, organized by measure. Results for each prototype simulated are included in each section. Graphs are provided for each measure to demonstrate the impact of building type on electric demand savings.

5.3.1 Measure 39: Demand Response: Setpoint Changes

Figure 5.38 shows the performance impact of cooling thermostat setpoint reductions during CPP events for all applicable prototypes. This measure showed demand reductions above 15% for four prototypes; however, Medium Office, Large Office, and Supermarket prototypes did not see much demand reduction. This measure is not particularly effective in supermarkets because higher zone temperatures can increase refrigeration electricity loads.

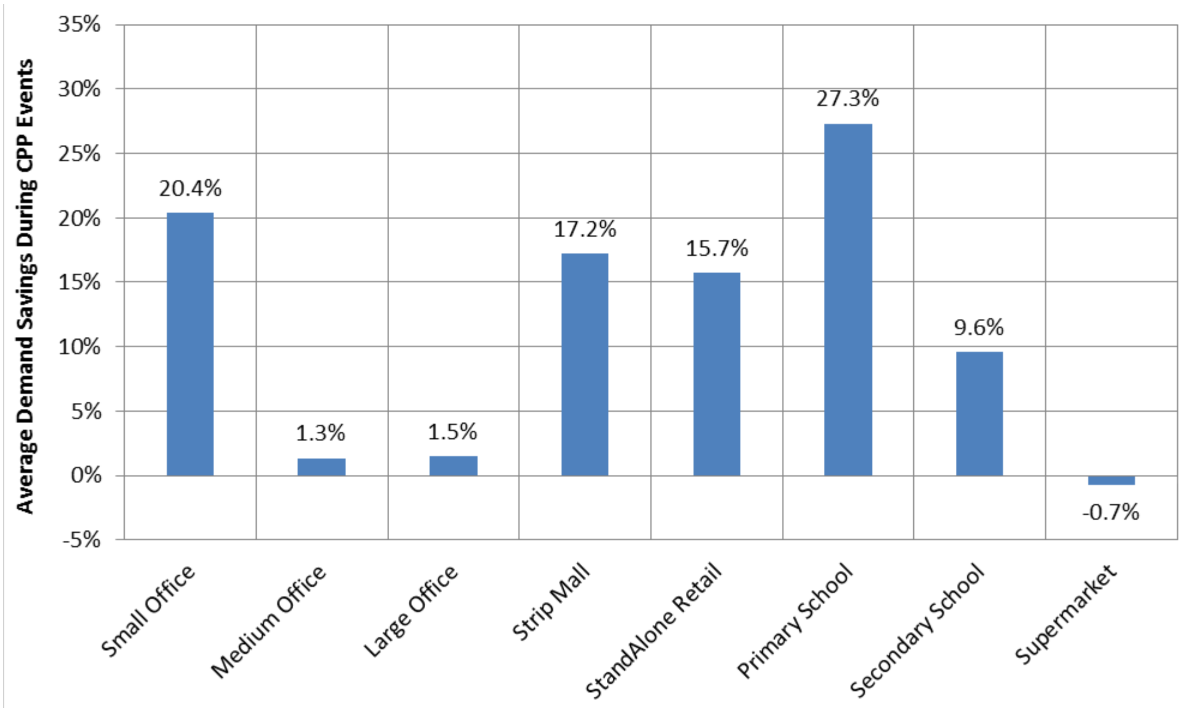

Figure 5.38. Demand Response: Electric Demand Savings: Measure 38 (Setpoint Changes)

5.3.2 Measure 40: Demand Response: Pre-cooling

Figure 5.39 illustrates modeled savings from the pre-cooling DR measure. The results are very similar to Measure 39 (Setpoint Changes), except for slightly stronger demand savings for all prototypes. As mentioned previously, the results of this measure are in question because of suspected problems with the simulation of building thermal mass in EnergyPlus.

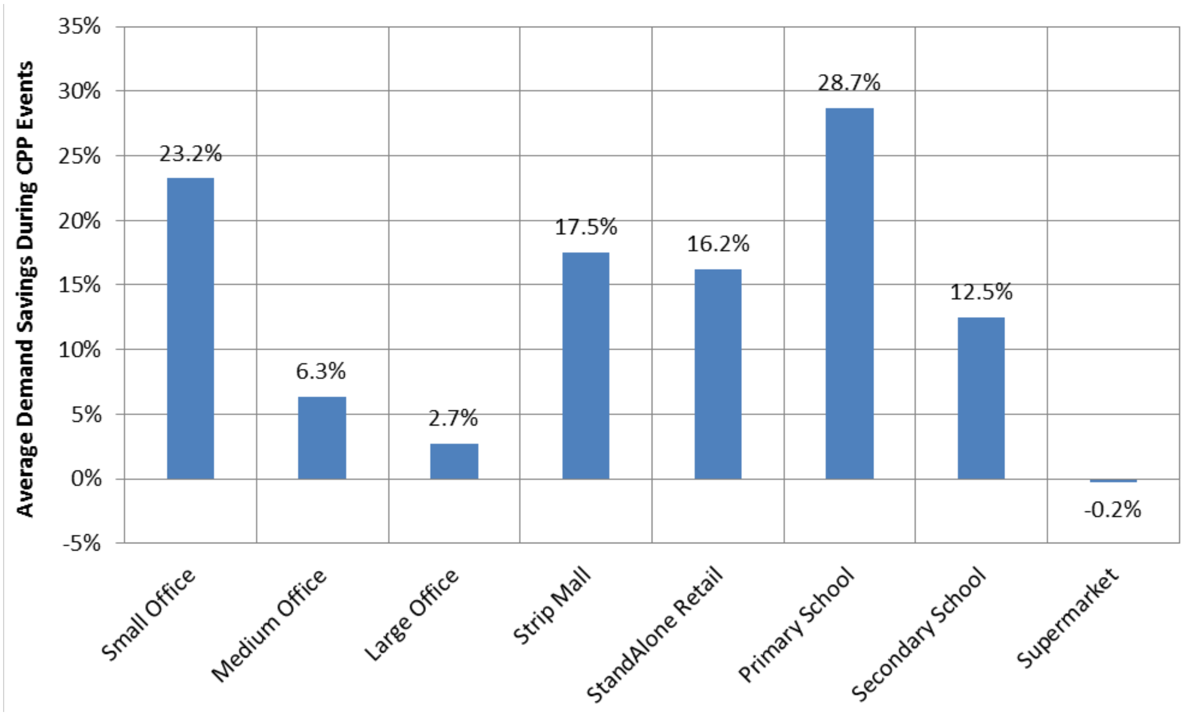

Figure 5.39. Demand Response: Electric Demand Savings: Measure 39 (Pre-Cooling)

5.3.3 Measure 41: Demand Response: Duty Cycle

Figure 5.40 shows 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 are lower than for Measures 39 or 40, it may still be considered a better option for achieving 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.

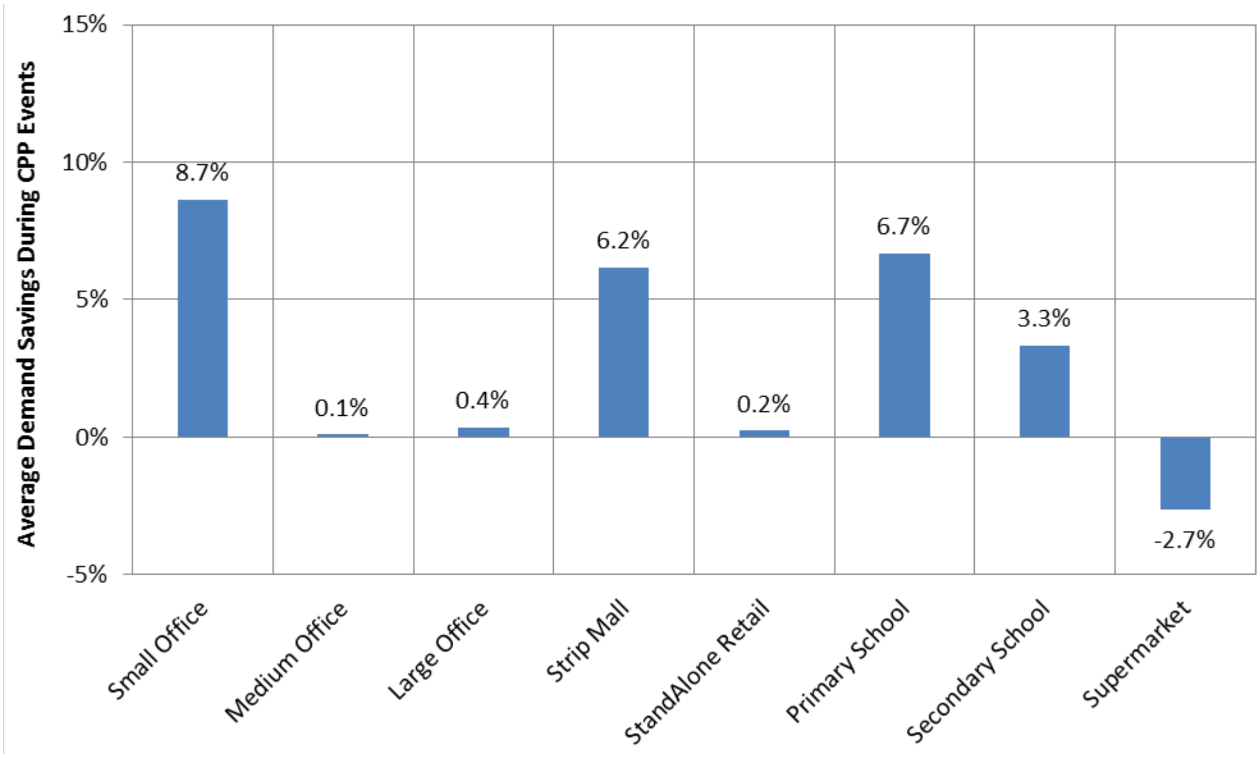

Figure 5.40. Demand Response: Electric Demand Savings: Measure 40 (Duty Cycle): Office Prototypes

5.3.4 Measure 42: Demand Response: Lighting Control

Figure 5.41 shows the performance impact of dimming lights by 10% during CPP events. Demand savings is much more consistent and predictable from this measure, and is typically between 3% and 5%.

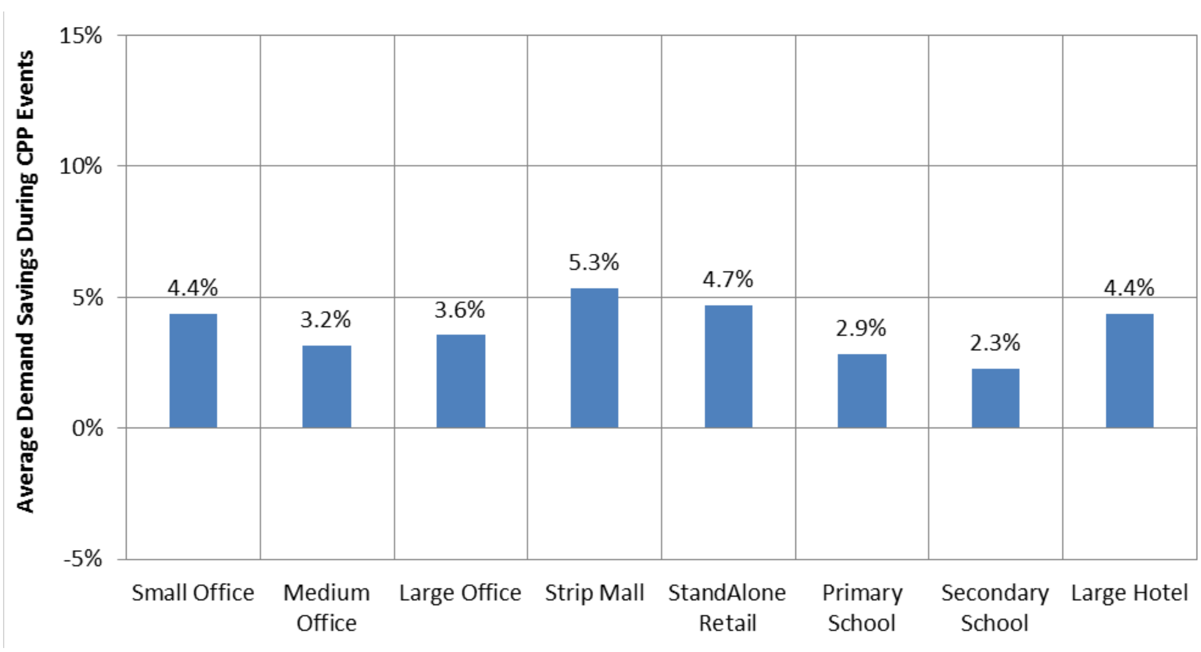

Figure 5.41. Demand Response: Electric Demand Savings: Measure 41 (Lighting): Office Prototypes

5.3.5 Measure 43: Demand Response: Chilled Water Temperature Control

Figure 5.42 shows DR savings from raising the chilled water temperature while holding fan speeds constant. Demand savings for the Large Office prototype was about 5%. Savings for the Secondary School prototype was much higher, at around 10%. No savings were modeled for the Large Hotel building in the Seattle climate.

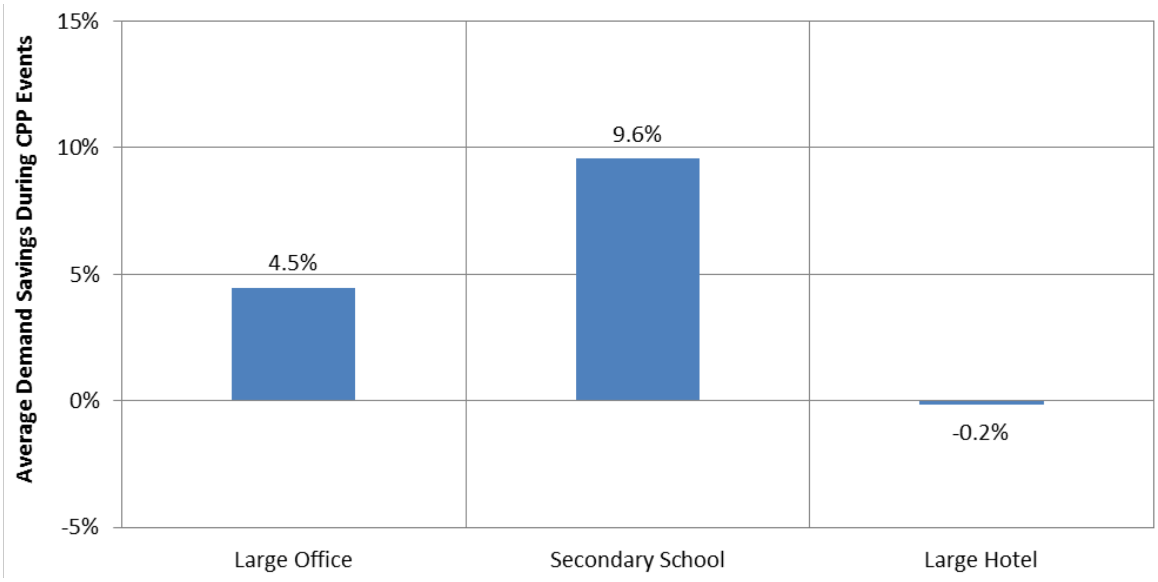

Figure 5.42. Demand Response: Electric Demand Savings: Measure 42 (Chilled Water Temperature Control): Large Office, Large Hotel, and Secondary School Prototypes

5.3.6 Measure 44: Demand Response: Refrigeration

Electric demand savings for refrigeration DR strategies in supermarkets was 7.3% during CPP events.

5.4 Demand Response: Packages

Figure 5.43 shows savings from the reactive packages of DR measures for each prototype. These packages included the setpoint change measure (Measure 39) and either the lighting DR Measure 42 (most prototypes) or the refrigeration DR Measure 44 (Supermarkets). For Seattle, the demand savings for Large and Medium Office buildings are about 5%; however, meaningful reductions in the range of 12% to 30% were achieved for 5 of the 8 prototypes where DR is applicable. Combining load reduction measures (reduced lighting) with thermostat setbacks led to greater DR savings than the savings from the sum of their independent implementation.

Figure 5.44 shows similar savings for the predictive DR package, which swaps the pre-cooling measure (Measure 40) for the setpoint change measure (Measure 39). Using this approach, DR savings were improved from under 5% to almost 10% for Medium Office. Small Office and Secondary School package savings also increased by about 3%, but for the remaining prototypes, the increased savings was less than 2%.

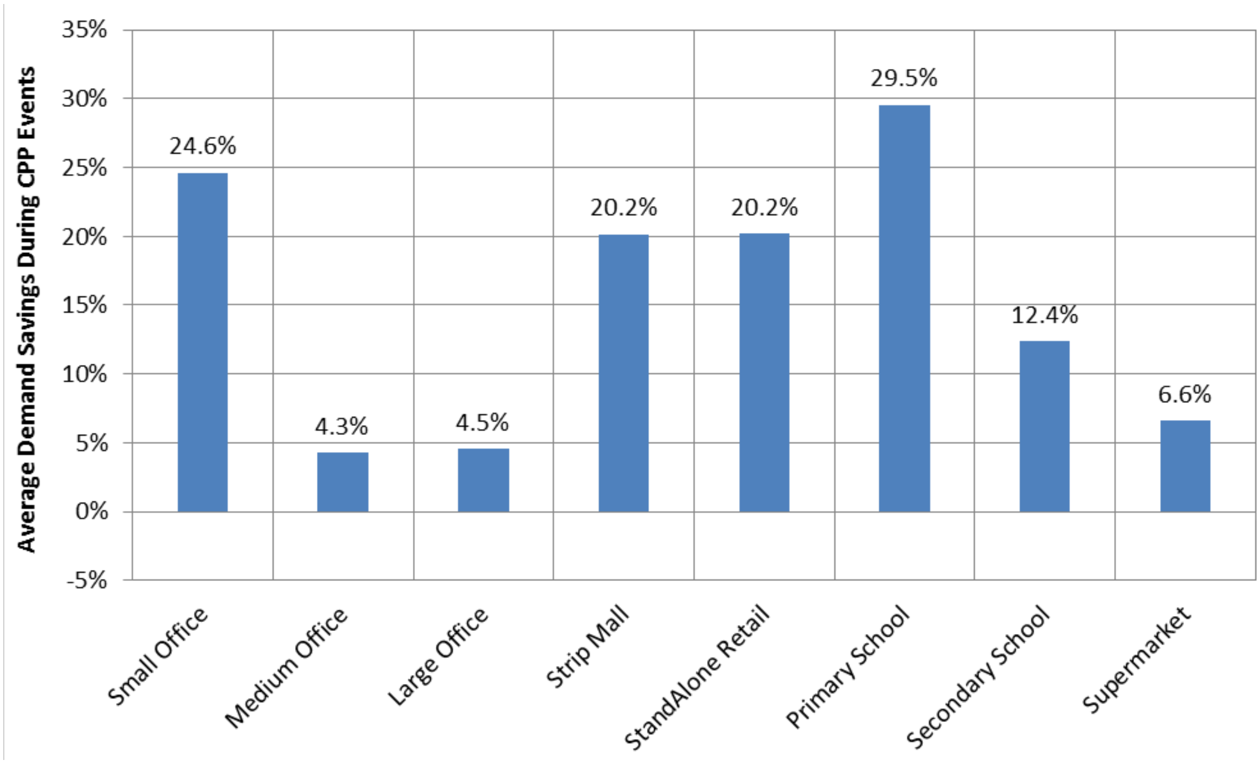

Figure 5.43. Demand Response: Electric Demand Savings for Reactive Package

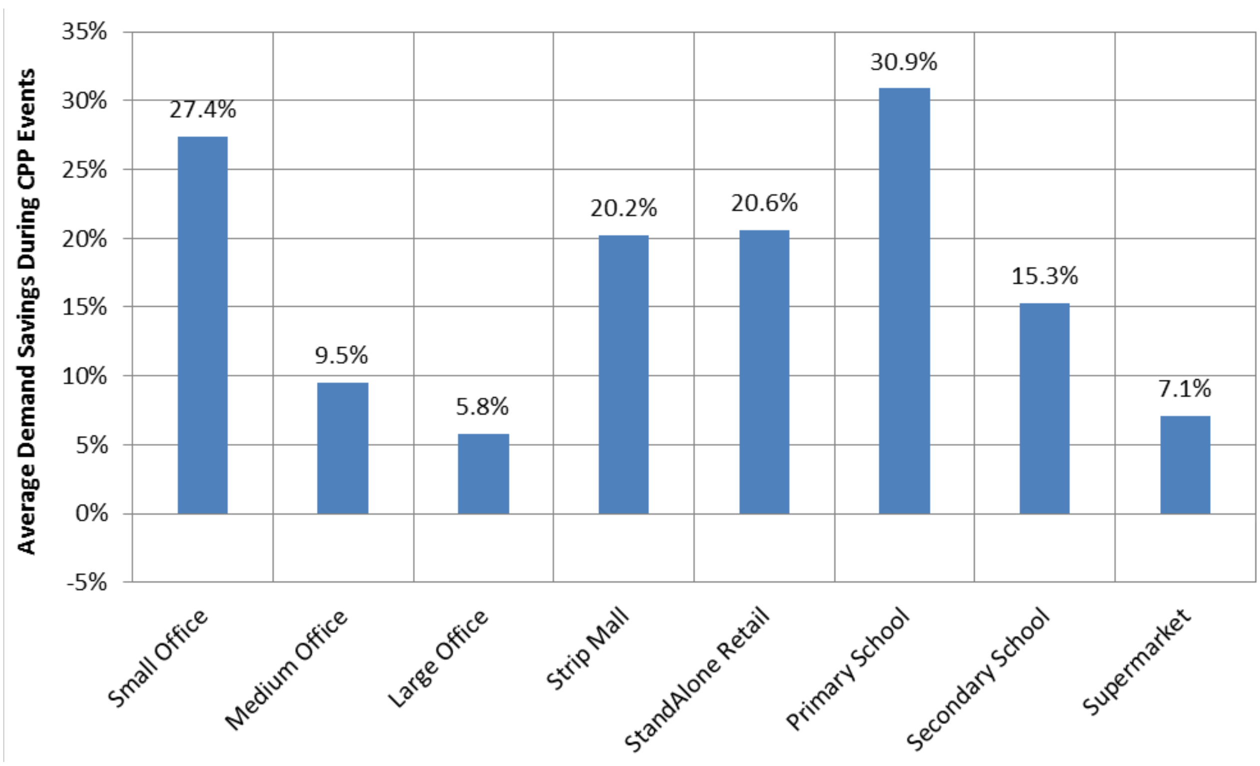

Figure 5.44. Demand Response: Electric Demand Savings for Predictive Package

5.5 Packages of Energy Efficiency Measures Results

This section describes the savings potential from full implementation of the Seattle Building Tune-Ups Required package of Re-tuning measures in the nine simulated prototype buildings. Three packages of Re-tuning measures have been created to estimate the overall savings potential from Re-tuning: 1) efficient building, 2) typical building, and 3) inefficient building. The efficient building package only includes a few EEMs because the buildings to which this package applies (approximately 30% of the building stock) are considered to be efficient with little possibility of improvement. The inefficient building package, on the other hand, is assumed to have significant savings opportunity (all EEMs) because it is considered to be inefficient (applies to 20% of the building stock). The typical building package falls in between the other two packages in both opportunity and prevalence (50% of building stock).

First, savings from each of the three packages representative of inefficient (Package A), typical (Package B), and efficient buildings (Package C) are presented with savings by prototype. Whole-building energy savings is presented first in each case, followed by savings in the individual meters (electricity and gas).

All results shown in the figures in this subsection are presented in tabular form in Appendix A.

5.5.1 Package A: Inefficient Buildings

Figure 5.45 shows whole-building energy savings by prototype for each of the inefficient building packages, broken out into site electricity savings and site natural gas savings. Overall savings ranges from 19% in Supermarket buildings to 45% in Standalone Retail. Figure 5.46 shows savings in the electricity and gas meters, independently, for inefficient buildings. For electricity, savings is highest (34%) for Medium Office, in large part because it is predominately electrically-heated. Most building types have electricity savings under 20%. Four building types have natural gas savings in the range of 60–80%, indicating that in a mild climate like Seattle, the vast majority of heating energy is wasted in poorly controlled (inefficient) buildings.

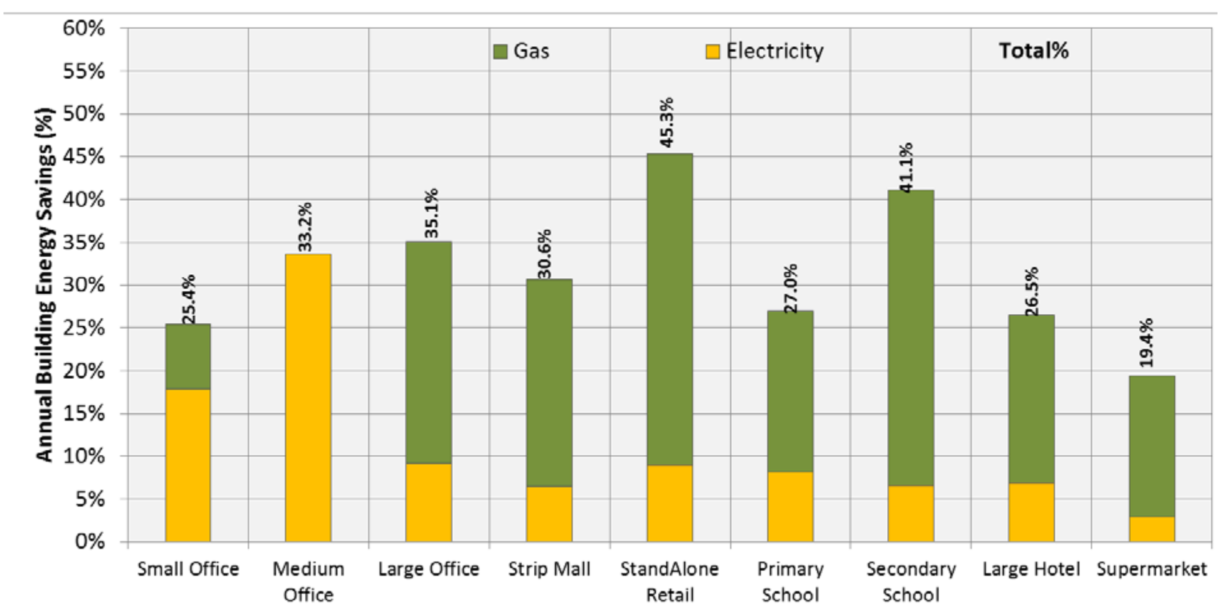

Figure 5.45. Packages of Measures: Energy Savings: Whole Building Energy Savings from Inefficient Buildings

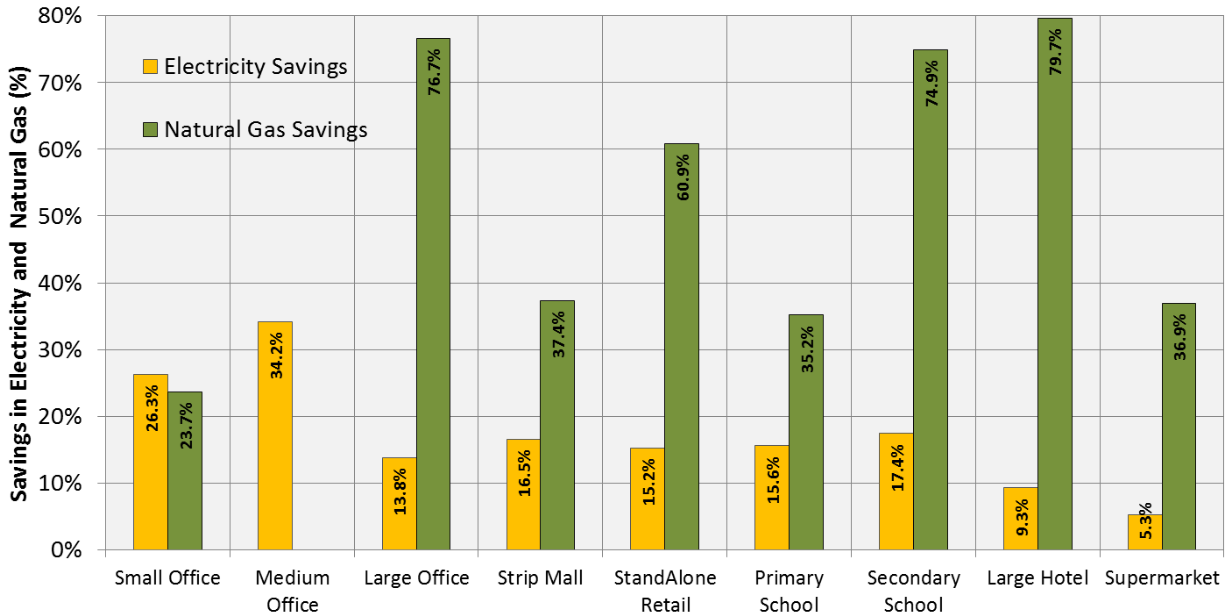

Figure 5.46. Packages of Measures: Energy Savings: Electricity and Natural Gas Energy Savings from Inefficient Buildings

5.5.2 Package B: Typical Buildings

Figure 5.47 shows whole-building energy savings by prototype for each of the typical building packages, broken out into site electricity savings and site natural gas savings. Total savings ranges from 17% to 39% by prototype. Figure 5.48 shows electricity and natural gas savings, independently, for typical buildings. Electricity savings for typical buildings ranges between 5% and 18%, while natural gas savings is typically much higher—in the range of 30% to 70%.

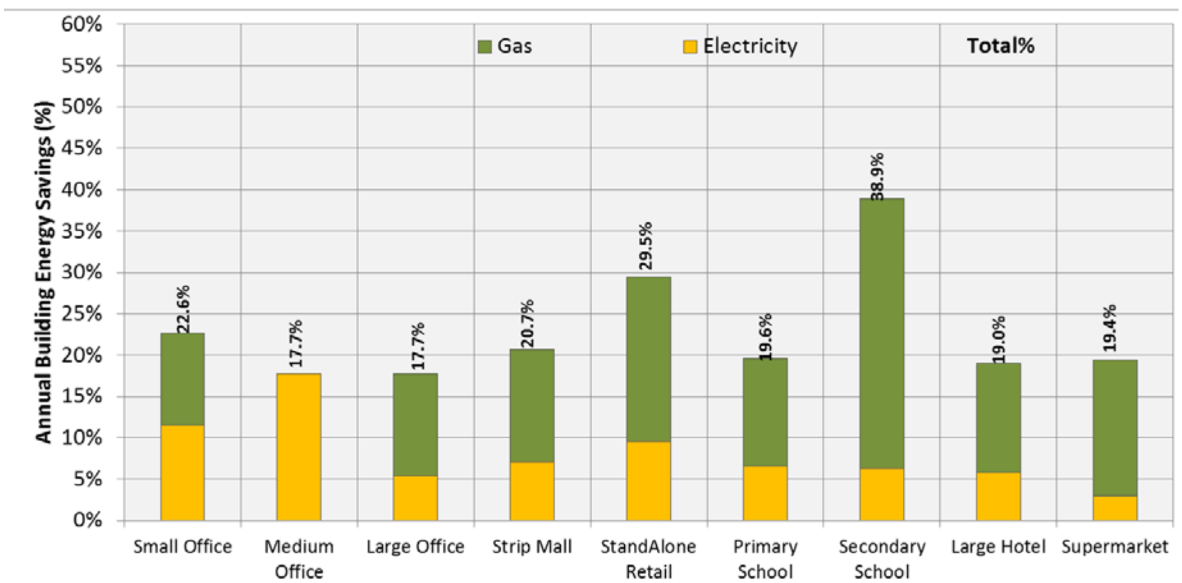

Figure 5.47. Packages of Measures: Energy Savings: Savings from Typical Buildings by Climate: Office Prototypes

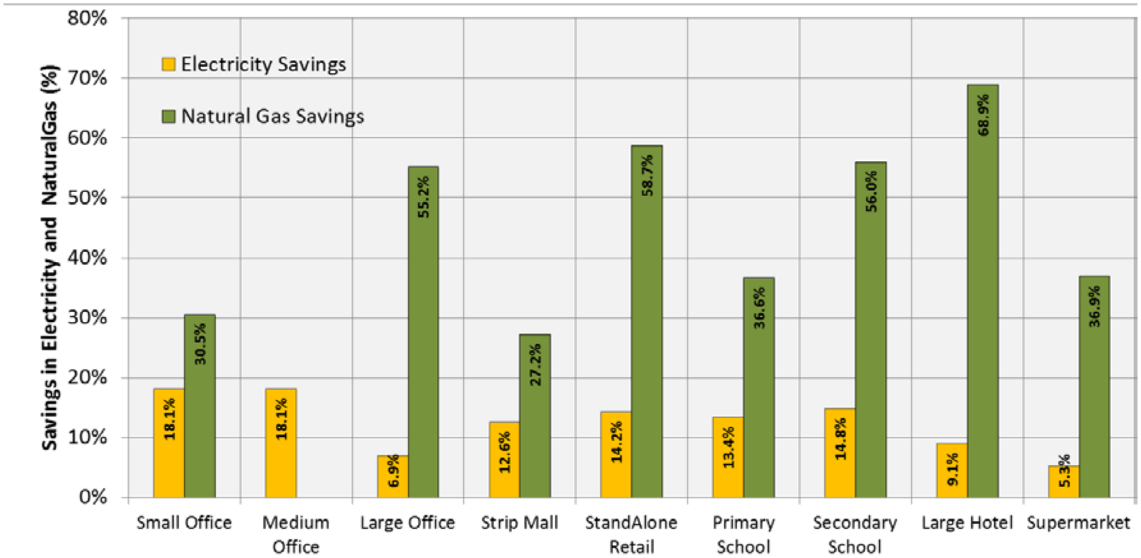

Figure 5.48. Packages of Measures: Energy Savings: Electricity and Natural Gas Energy Savings from Typical Buildings

5.5.3 Package C: Efficient Buildings

Figure 5.49 shows savings by climate for each of the typical building packages, broken out into site electricity savings and site natural gas savings. With the exception of the office and hotel buildings, there is little or no savings from the Seattle Building Tune-Ups package in efficient buildings, indicating that most efficient buildings may have already capitalized on these industry-standard Re-tuning measures. Figure 5.50 shows electricity and natural gas savings, independently, for efficient buildings.

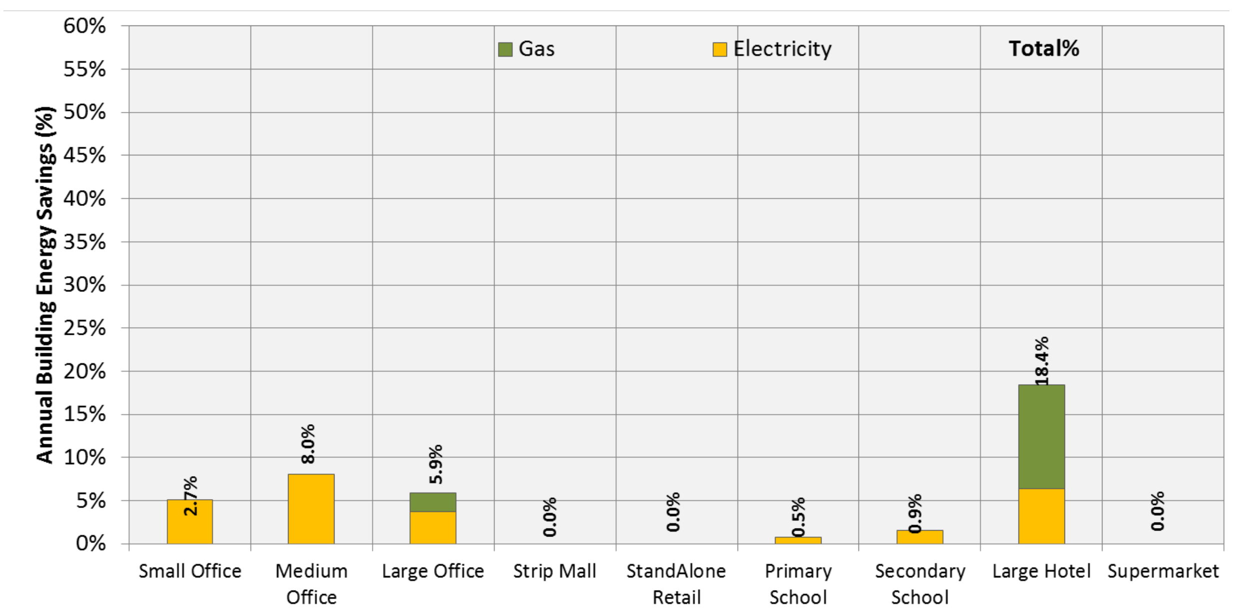

Figure 5.49. Packages of Measures: Energy Savings: Savings from Efficient Buildings by Climate: Office Prototypes

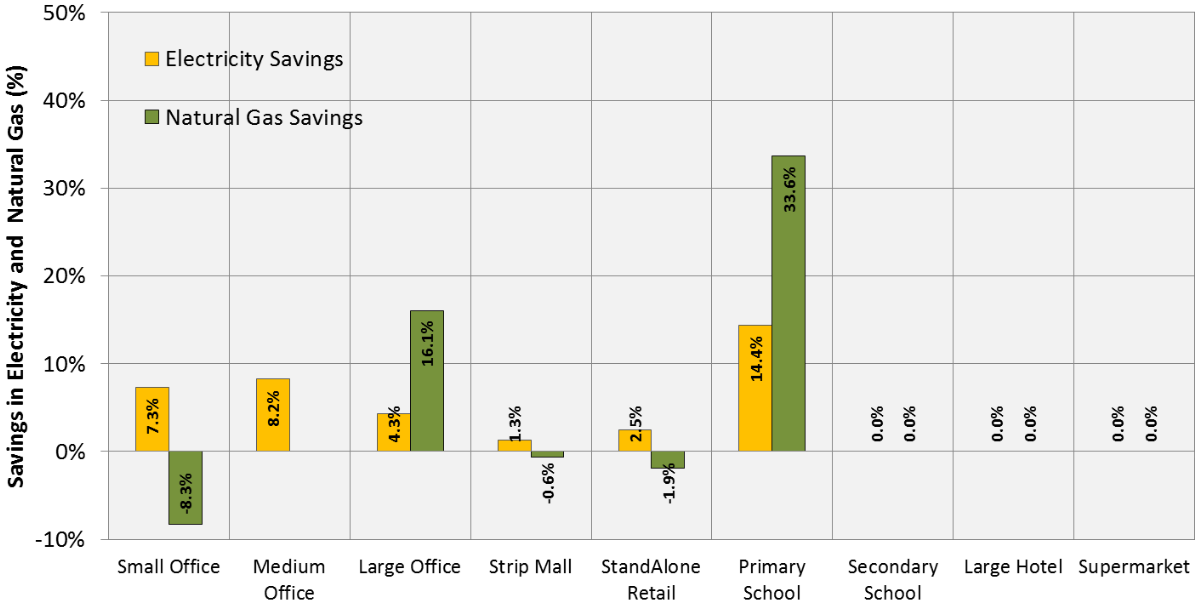

Figure 5.50. Packages of Measures: Energy Savings: Electricity and Natural Gas Energy Savings from Efficient Buildings

5.5.4 Overall Savings Summary – Seattle

The overall savings potential from the required Seattle Building Tune-Ups packages in the Seattle climate by building type is determined through an application of the weights of the different packages. Figure 5.51 shows the savings (in percentage terms) from each building efficiency level for each set of building type. Savings are 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 overall savings for each set of building types is represented by a black diamond. For most building types, the potential overall savings ranges from 14 to 19%, with the exception of Large Hotel (26%), StandAlone Retail/Dealership (27%), and Secondary School (32%).

Figure 5.52 presents this same analysis for electricity savings. Overall electricity savings from the Seattle Building Tune-Ups package ranges from 4% in Supermarkets to 20% in Medium Office buildings (with the caveat that this level of savings may only be valid for electrically-heated buildings). Figure 5.53 presents natural gas savings. All building types have overall natural gas savings above 20%, with three building types over 50%.

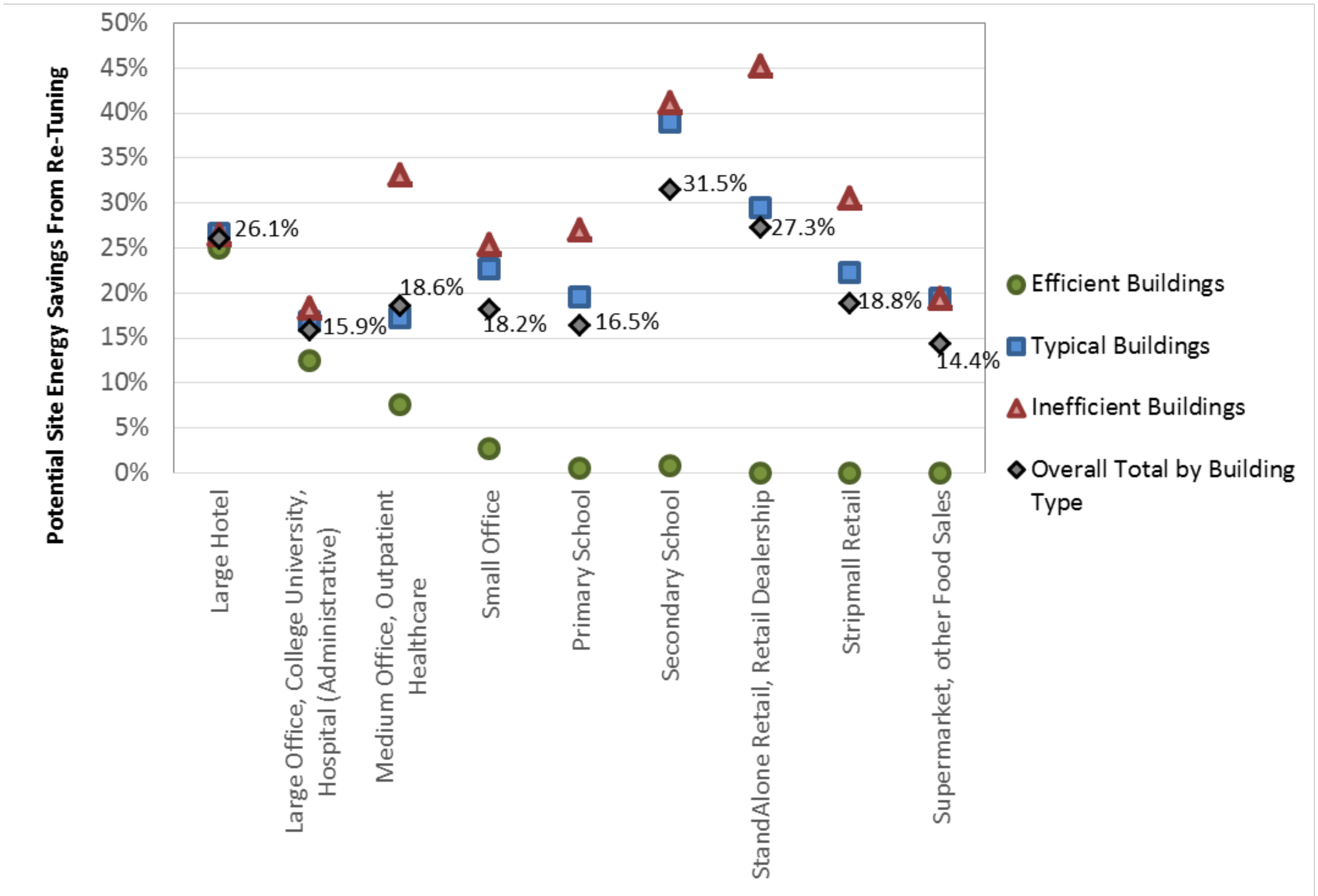

Figure 5.51. Packages of Measures: Energy Savings: Summary of Total Re-Tuning Savings by Building Type for Seattle Building Tune-Ups Required Package in Seattle, Washington

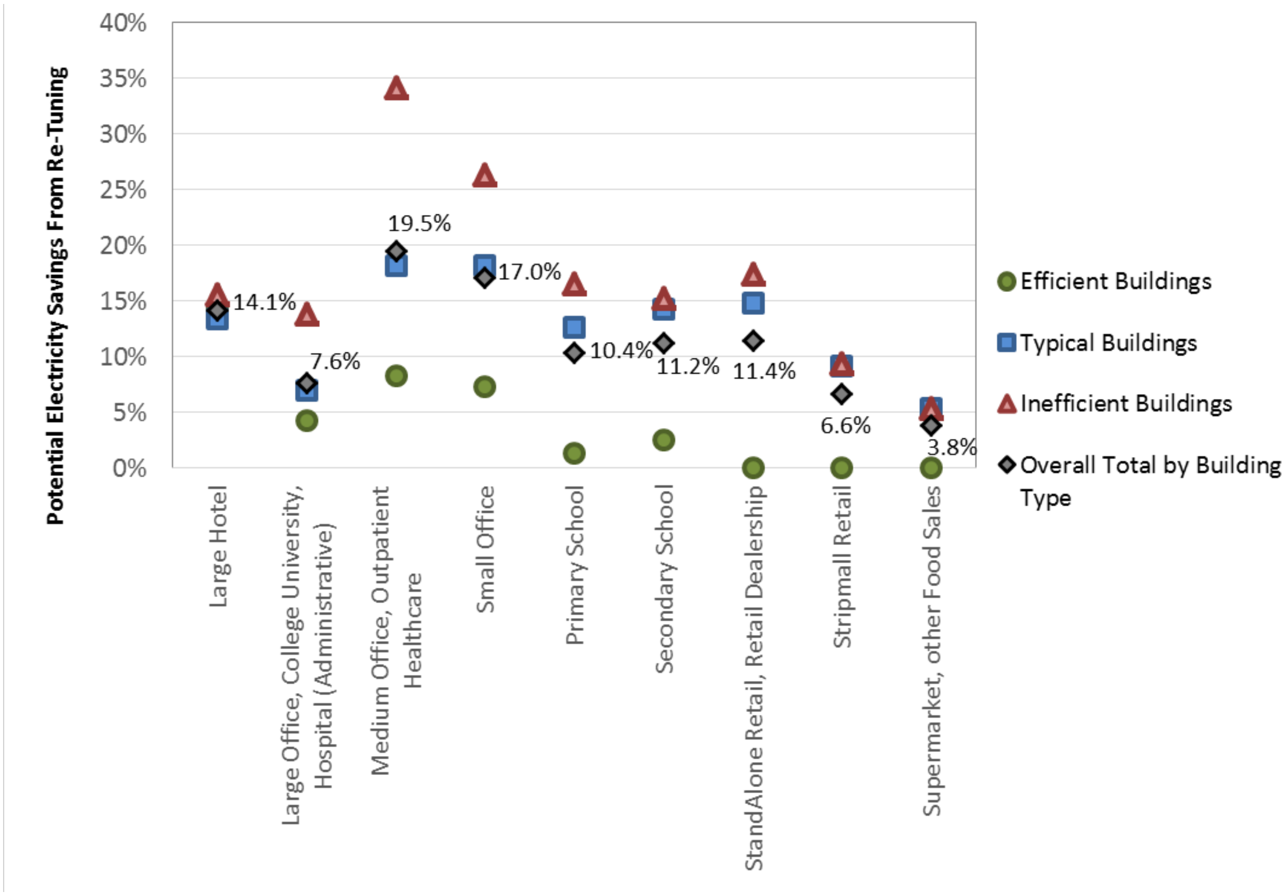

Figure 5.52. Packages of Measures: Electricity Savings: Summary of Total Re-Tuning Savings by Building Type from Seattle Building Tune-Ups Required Package in Seattle, Washington

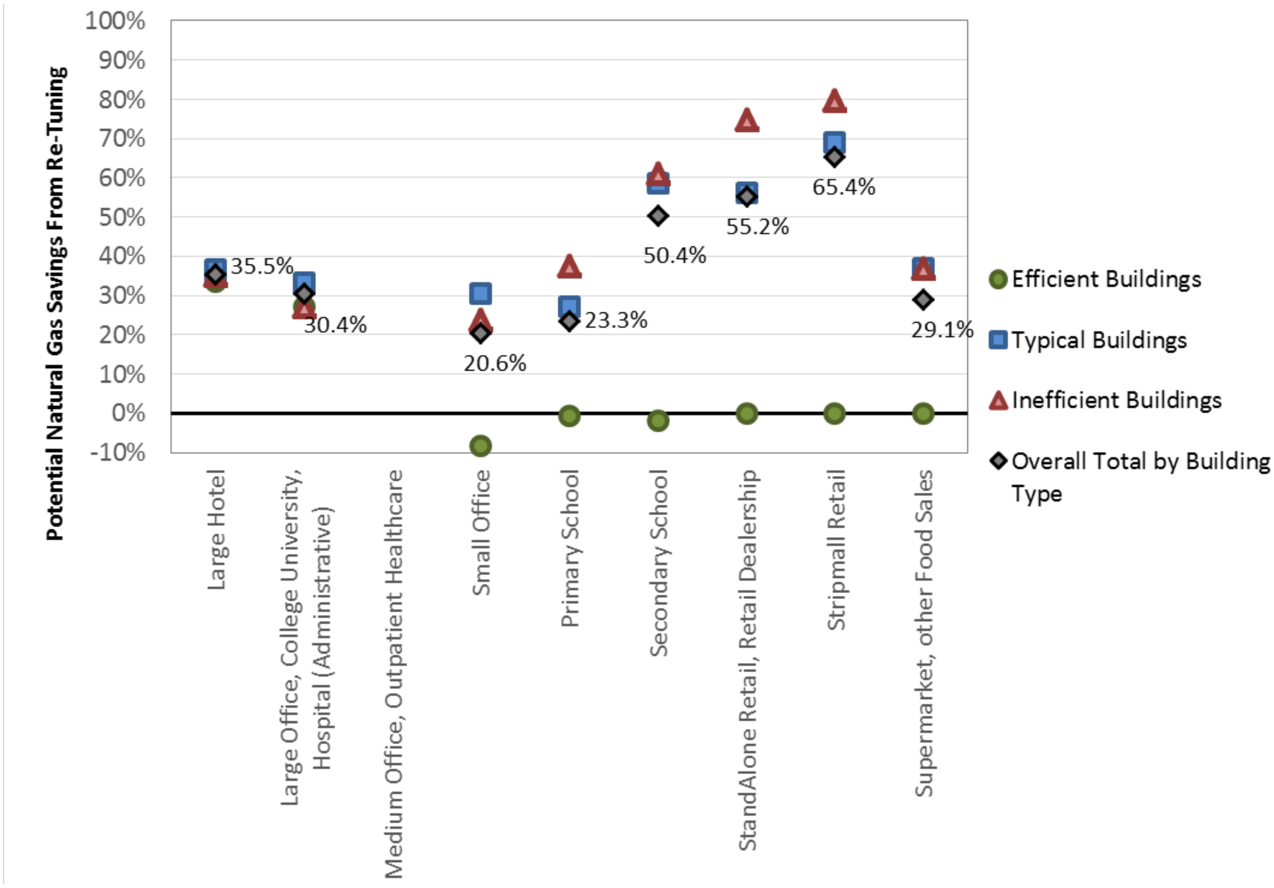

Figure 5.53. Packages of Measures: Natural Gas Savings: Summary of Total Re-Tuning Savings by Building Type from Seattle Building Tune-Ups Required Package in Seattle, Washington

6.0 Summary of Results

Commercial buildings in the United States use approximately 18 Quads (Quadrillion British thermal units) of primary energy. Many studies have shown that as much as 30% of building energy consumption can be avoided by using more accurate sensing, using existing controls better, and deploying advanced controls. In addition, many studies have shown that 10% to 20% of commercial building peak load can be temporarily managed/curtailed to provide grid services. Therefore, the main motivation for the work described in this report was to quantify the potential energy and cost savings derived from the use of more accurate sensing, better use of existing controls, deployment of more advanced controls, and deployment of grid services.

Although many studies have indicated significant potential for reducing the energy consumption in commercial buildings, very few have documented the savings. Even the studies that documented the savings provide savings at the whole-building level, which makes it difficult to assess the potential from each individual measure deployed. In the study reported herein, a detailed simulation-based approach was used to quantify the savings. Using detailed simulations, savings from individual EEMs can be isolated, but the types of EEMs that can be simulated are limited. Despite the limitation, 44 different EEMs were simulated for 9 prototypical buildings in Seattle, Washington. 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. 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 represents practical limitations such as available baseline energy models.

The savings were calculated for each individual EEM for each relevant building type. Because building owners may choose to apply a package of synergistic measures rather than an individual measure, three packages (each containing a set of measures) were also created: 1) the efficient building package, 2) the "typical" building package, and 3) the "inefficient" building package. The savings calculated for the individual measures were also calculated for the packaged measures.

6.1 Energy Savings from Individual Measure by Building Type and Climate Location

The total site savings, natural gas savings, and electricity savings were estimated for each measure by building type (Figure 5.1 through Figure 5.28). A total of 37 individual measures were simulated and the savings were estimated. Many of the EEMs only apply to a few building types; therefore, 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.

6.2 Energy Savings from Individual Measures by Building Type

A set of simulations was run to estimate the impact of implementing any given EEM on each of the building prototypes. 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 analyses.

For Small Office buildings (Figure 5.29), the total site savings ranged from 0% (EEM22: night purge) to approximately 12% (EEM16: wider deadbands and night setbacks). The natural gas savings ranged from -5% (EEM23: advanced RTU controls) to almost 10% (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 is always a net positive savings, there is an increase in natural gas consumption (e.g., EEM23: advanced RTU controls). The reason for this increase is that the reduction in electricity consumption results in a decrease in heat gain, which has to be compensated by additional heat energy. About 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 5.30), the total site savings ranged from -2% (EEM17: demand control ventilation) to almost 20% (EEM15: minimum VAV terminal box damper flow reductions). Natural gas was virtually unaffected by all measures, thus all site energy savings was from electricity.

For Large Office, college/university, and hospital (administrative portion) buildings (Figure 5.31), the total site savings ranged between -1% (EEEM06: outdoor air damper faults/controls) and almost 17% (EEM15: minimum VAV terminal box damper flow reductions). The natural gas savings ranged from -3% (EEM18: lighting occupancy sensors) to 13% (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 -1% (EEM17: demand control ventilation) to 6% (EEM26: cooling tower controls).

For Primary School buildings (Figure 5.32), the total site savings ranged from -11% (EEM06: outdoor air damper faults/controls) to 17% (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 -10% (EEM06: outdoor air damper faults/controls) to 11% (EEM16: wider deadbands and night setbacks) and the electricity savings ranged between -6% (EEM17: demand control ventilation) and 6% (EEM16: wider deadbands and night setbacks).

For Secondary School buildings (Figure 5.33), the total site savings ranged from -4% (EEEM06: outdoor air damper faults/controls) to 21% (EEM17: demand control ventilation). The natural gas savings ranged from -4% (EEM06: outdoor air damper faulty/controls) to 25% (EEM17: demand control ventilation) and electricity savings from -4% (EEM17: demand control ventilation) to 4% (EEM18: lighting occupancy sensors).

For Large Hotel buildings (Figure 5.34), the total site savings ranged from 0% (EEM19: daylighting controls) to 11% (EEM05: supply air temperature reset). The natural gas savings ranged from -1% (EEM18: lighting occupancy sensors) to 9% (EEM05: supply air temperature reset) and electricity savings ranged from 0% (EEM13: hot water differential pressure reset) to 4% (EEM36: occupancy sensors for thermostats and room lighting).

For Standalone Retail and Retail Dealership buildings (Figure 5.35), the total site savings ranged from -1% (EEM23: advanced RTU controls) to 19% (EEM17: demand control ventilation). The natural gas savings ranged between -12% (EEM23: advanced RTU controls) and 19% (EEM17: demand control ventilation) and electricity savings ranged from -1% (EEM17: demand control ventilation) to 12% (EEM23: advanced RTU controls).

For Strip Malls (Figure 5.36), the total site savings ranged from 0% (EEM22: night purge) to more than 16% (EEM17: demand control ventilation). The natural gas savings ranged from -9% (EEM23: advanced RTU controls) to almost 17% (EEM17: demand control ventilation) and electricity savings ranged from 0% (EEM22: night purge) to almost 9% (EEM23: advanced RTU controls).

For Supermarket and Other Food Sales buildings (Figure 5.37), the total site savings ranged from 0% (EEM01: re-calibrate faulty sensors) to 12% (EEM16: wider deadbands and night setback). The natural gas savings ranged from -5% (EEM01: re-calibrate faulty sensors) to 12% (EEM16: wider deadbands and night setback) and electricity savings ranged from 0% (EEM01: re-calibrate faulty sensors) to more than 5% (EEM23: advanced RTU controls).

6.3 Energy Savings from a Package of Measures

Three packages of measures were created to estimate the whole building energy savings and the electricity savings from the set of required measures in the Seattle Building Tune-Ups mandate. The three packages of Re-tuning measures created to estimate the overall savings potential from Re-tuning were described previously in Section 4.0.

The total site energy savings by building type for the efficient building package, the typical building package, and the inefficient building package ranged from 0% to 18%, 17% to 39%, and 19% to 45%, respectively. Based on the weighting of these three efficiency levels, the expected overall savings among buildings of the same type were also estimated. For most building types, the potential savings ranged from 14% to 19%, except for Large Hotel (26%), Secondary School (32%) and Standalone Retail/Dealership (27%). Likewise, electricity savings by building type for the efficient building package, the typical building package, and the inefficient building package ranged from 0% to 14%, 5% to 18%, and 5% to 19%, respectively, with overall savings ranging from 4 to 20%.

It should be noted that the building types that were represented in this study account for 52% of commercial building floor space and 57% of the commercial building sector energy consumption. Significant additional savings would be expected in the remaining set of commercial buildings that were outside the scope of this study.

6.4 Peak Reductions from Individual Demand-Response Measure by Building Type and Climate Location

The peak reductions for each of six DR measures were estimated for each of the nine primary building types for the climate in Seattle (Figure 5.38 through Figure 5.53). The reductions varied across the building types.

7.0 Conclusions, Gaps, and Recommendations

This study investigated the potential energy savings derived from implementing common and advanced controls measures in commercial buildings in Seattle, Washington. These measures focus on equipment operation and control, 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 implementing equipment or building envelope retrofits. In many cases, however, measures may require upgrades of BASs, such as enhanced communication capabilities and installation of variable-speed drives on certain fans and pumps in some buildings. This study simulated 38 control measures in 9 commercial buildings. 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.

Of the 38 measures simulated, 6 measures, when simulated individually, showed the potential for over 6% savings in at least 3 building types. These measures included wider deadbands and night setbacks (9 building types), shortened HVAC schedules (8), optimal start (7), demand control ventilation (5), SAT reset (3), and minimum VAV terminal damper flow reductions. The two most impactful measures on electricity savings—achieving over 5% whole-building energy savings in electricity in at least three building types—were not included in the previous list of six measures (which all primarily affected natural gas savings for heating). These two measures are advanced RTU controls (4 building types) and daylighting sensors (3).

Using the three packages of measures representing the commercial building stock, the potential site energy savings from Re-tuning in Seattle was estimated. For overall savings among buildings of a similar type, the potential savings ranged between 14% and 19% for six of the nine building prototypes, while the other three building prototypes (Secondary Schools [32%], StandAlone Retail [27%], and Large Hotel [26%]) achieved more than 40% savings. Several building types were not considered in this study; these building types may also benefit from many of the control measures identified in this report.

7.1 Gaps in the Study

Although this study was expansive, it had some limitations and research gaps. First, the set of modeled buildings represents just over half of the commercial buildings sector square footage. More models are needed to fully represent the current building stock.

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 many faults and the severity of the fault levels for almost all faults are 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 this 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.

Commercial buildings are supposed to be at positive pressure when the HVAC systems are running during occupied periods. However, many buildings are negatively pressurized for a number of reasons (e.g., imbalance between outdoor air intake and exhaust), which creates significant infiltration. The current study did not account for this phenomenon. Addressing building pressurization problems is among the requirements for the Seattle Building Tune-Ups mandate.

Another major research gap that needs to be addressed is benchmarking. Several questions need to be investigated. For example, it needs to be determined to what extent the 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, control parameter settings, etc. 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.

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Appendix A

Tabular Results

Appendix A

Tabular Results

This appendix contains tabular results for the package simulations presented in this report.

Table A.1. Packages: Electricity Savings as a Percent of Total Building Consumption

	Large Hotel	Large Office, College University, Hospital (Administrative)	Medium Office, Outpatient Healthcare	Small Office	Primary School	Secondary School	StandAlone Retail, Retail Dealership	Stripmall Retail	Supermarket, other Food Sales
Savings (Inefficient)	6.9%	9.1%	33.6%	17.9%	8.2%	6.6%	9.0%	6.5%	2.9%
Savings (Typical)	5.8%	4.3%	17.7%	11.5%	6.6%	6.3%	9.5%	7.1%	2.9%
Savings (Efficient)	6.4%	2.7%	8.0%	5.1%	0.7%	1.6%	0.0%	0.0%	0.0%
Savings (Percent, Overall)	6.2%	4.8%	19.0%	11.3%	5.5%	5.4%	7.3%	5.2%	2.2%

Table A.2. Packages: Electricity Savings as a Percent of Total Electricity Consumption

	Large Hotel	Large Office, College University, Hospital (Administrative)	Medium Office, Outpatient Healthcare	Small Office	Primary School	Secondary School	StandAlone Retail, Retail Dealership	Stripmall Retail	Supermarket, other Food Sales
Savings (Inefficient)	15.6%	13.8%	34.2%	26.3%	16.5%	15.2%	17.4%	9.3%	5.3%
Savings (Typical)	13.4%	6.9%	18.1%	18.1%	12.6%	14.2%	14.8%	9.1%	5.3%
Savings (Efficient)	14.4%	4.3%	8.2%	7.3%	1.3%	2.5%	0.0%	0.0%	0.0%
Savings (Percent, Overall)	14.1%	7.6%	19.5%	17.0%	10.4%	11.2%	11.4%	6.6%	3.8%

Table A.3. Packages: Natural Gas Savings as a Percent of Total Building Consumption

	Large Hotel	Large Office, College University, Hospital (Administrative)	Medium Office, Outpatient Healthcare	Small Office	Primary School	Secondary School	StandAlone Retail, Retail Dealership	Stripmall Retail	Supermarket, other Food Sales
Savings (Inefficient)	19.6%	9.2%	-0.4%	7.6%	18.8%	34.5%	36.3%	24.1%	16.4%
Savings (Typical)	20.8%	12.6%	-0.5%	11.1%	13.0%	32.6%	20.0%	15.2%	16.4%
Savings (Efficient)	18.6%	9.8%	-0.5%	-2.4%	-0.3%	-0.7%	0.0%	0.0%	0.0%
Savings (Percent, Overall)	19.9%	11.1%	-0.4%	6.9%	11.0%	26.1%	20.0%	13.6%	12.2%

Table A.4. Packages: Natural Gas Savings as a Percent of Total Natural Gas Consumption

	Large Hotel	Large Office, College University, Hospital (Administrative)	Medium Office, Outpatient Healthcare	Small Office	Primary School	Secondary School	StandAlone Retail, Retail Dealership	Stripmall Retail	Supermarket, other Food Sales
Savings (Inefficient)	35.2%	27.1%	-22.8%*	23.7%	37.4%	60.9%	74.9%	79.7%	36.9%
Savings (Typical)	36.6%	33.4%	-21.9%*	30.5%	27.2%	58.7%	56.0%	68.9%	36.9%
Savings (Efficient)	33.6%	27.1%	-18.8%*	-8.3%	-0.6%	-1.9%	0.0%	0.0%	0.0%
Savings (Percent, Overall)	35.5%	30.4%	-21.1%*	20.6%	23.3%	50.4%	55.2%	65.4%	29.1%

* *Total natural gas consumption is minimal, and these increases are small in total magnitude*

Table A.5. Packages: Total Site Energy Savings as a Percent of Total Building Consumption

	Large Hotel	Large Office, College University, Hospital (Administrative)	Medium Office, Outpatient Healthcare	Small Office	Primary School	Secondary School	StandAlone Retail, Retail Dealership	Stripmall Retail	Supermarket, other Food Sales
Savings (Inefficient)	26.5%	18.3%	33.2%	25.4%	27.0%	41.1%	45.3%	30.6%	19.4%
Savings (Typical)	26.6%	16.9%	17.3%	22.6%	19.6%	38.9%	29.5%	22.3%	19.4%
Savings (Efficient)	25.0%	12.6%	7.6%	2.7%	0.5%	0.9%	0.0%	0.0%	0.0%
Savings (National Total)	26.1%	15.9%	18.6%	18.2%	16.5%	31.5%	27.3%	18.8%	14.4%

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