U.S. DEPARTMENT OF ENERGY

PNNL- 22072

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

Energy Savings for Occupancy-Based Control (OBC) of Variable-Air-Volume (VAV) Systems

J Zhang
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January 2013

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Richland, Washington 99352

Executive Summary

Terminal boxes usually serve a single building zone, controlling the air-flow rate to the zone and reheating the air when it is too cool. Each terminal box has a minimum air-flow rate that ensures the ventilation requirements of the occupants of the zone served are met. This minimum air-flow rate is maintained at a constant value based on the design occupancy of the zone, which often corresponds to the maximum occupancy, because measurements of actual occupancy are not currently used to adjust the flow rate. Therefore, the minimum flow rate must meet the ventilation needs of the fully occupied zone. The total flow rate may be higher than the minimum to provide adequate cooling or heating, but the minimum for ventilation should always be met.

In practice, control system integrators and installers often set the cooling minimum air-flow rate for ventilation to between 30% and 50% of the maximum air-flow rate of the terminal box. Building occupancy, however, varies dynamically. Conference rooms, cafeterias, auditoriums, and other assembly spaces are often unoccupied for significant periods of time. Office occupancy varies during the course of a work day, from day to day, and over the longer term because of attendance of meetings elsewhere, business travel, changing room functions, and variations in staffing. The resulting over-ventilation, during times when the space has less than maximum occupancy or is unoccupied, wastes significant fan energy and causes discomfort for occupants in some spaces (e.g., conference rooms) from overcooling or overheating, especially in interior zones that do not have reheat in the terminal boxes.

Common occupancy sensors, which measure whether occupants are present or not, are commonly used for lighting control in conference rooms and other spaces with variable occupancy. They could be used to enable a terminal box to be switched to an occupied standby mode in which the air-flow rate is set to zero when no occupants are in the zone the box serves. If advanced occupancy sensors, which count the actual number of occupants in a room, were used to control terminal boxes, the minimum air-flow rate set point for the terminal box could be reset dynamically based on the actual occupancy sensed. This study evaluates the savings potential from use of occupancy-based control (OBC) of terminal boxes for large office buildings with variable-air-volume (VAV) heating, ventilating and air-conditioning (HVAC) systems using both common occupancy sensors and advanced occupancy sensors.

Large office buildings were selected for this study because they represent the subsector of commercial buildings with the greatest use of VAV HVAC systems in the U.S. They contribute 4.4 billion ft^2 of floor space and represent 6.1% of the total commercial floor space.

Energy savings are determined from estimates of annual energy consumption obtained from simulations of representative large office buildings with and without OBC of terminal boxes and lighting for all 15 U.S. climate zones. The building without any OBC is called the Base Case building. Three Improved Case buildings identical to the Base Case building except for the OBC details are also defined. Energy savings are determined by taking the difference in energy consumption between any two of these buildings.

The Base Case building is intended to represent a large office building with VAV HVAC constructed in 1989 and retrofitted with several energy efficiency features over its 23-year lifetime to date. Twenty-three years is the median age of U.S. large office buildings as determined by the Energy Information Administration's 2003 Commercial Building Energy Consumption Survey (CBECS). This building is represented for simulation by a U.S. Department of Energy (DOE) large office building prototype that complies with ANSI/ASHRAE/IESNA Standard 90.1-2004, which establishes energy efficiency requirements for new, except low-rise residential, buildings. Adjustments are made to this building to decrease its efficiency and make it more representative of a 1989-constructed building as retrofitted on average over its 23-year life and operated in 2012. The resulting Base Case building has an Energy Utilization Index or Energy Use Intensity (EUI, which is the annual energy consumption per unit area per year) between 40 and 50 kBtu/ft^2-y. With an EUI this low, the adjusted prototype is likely still more efficient than the actual average building it is intended to represent.

The Improved Case I building has occupancy-based lighting control using common occupancy sensors. Improved Case II has occupancy-based lighting and terminal-box control using common occupancy sensors. Improved Case III uses advanced occupancy sensors to provide OBC for both lighting and HVAC.

The results show that average site energy savings vary considerably across the climate zones. Lighting using common occupancy sensors to turn off lights when no occupants are present in rooms provide relatively small savings of less than 1.1% of total building energy use for all climate zones with the greatest savings in climate zone 1A, where Miami is located, and the smallest in climate zone 8, where Fairbanks, Alaska, is located (see Figure ES-1). The total savings from adding OBC of lighting and terminal boxes using common occupancy sensors to the large office building with no OBC (the Base Case) are considerably greater and range from 1.3 kBtu/ft^2-y for climate zone 1A (Miami) to 3.8 kBtu/ft^2-y for climate zone 8 (Fairbanks) with the greatest savings as a percentage of the Base Case energy use of 8% (which is just under 3.5 kBtu/ft^2-y) for Salem, Oregon, in climate zone 4C. The monetary savings on energy expenditures are between \$15,000/y (\$0.030/ft^2-y) for climate zone 1A (Miami) to \$44,200/y (\$0.089/ft^2-y) for climate zone 8 (Fairbanks) with 10 of the 15 climate zones having monetary savings greater than \$20,000/y (\$0.040/ft^2-y).

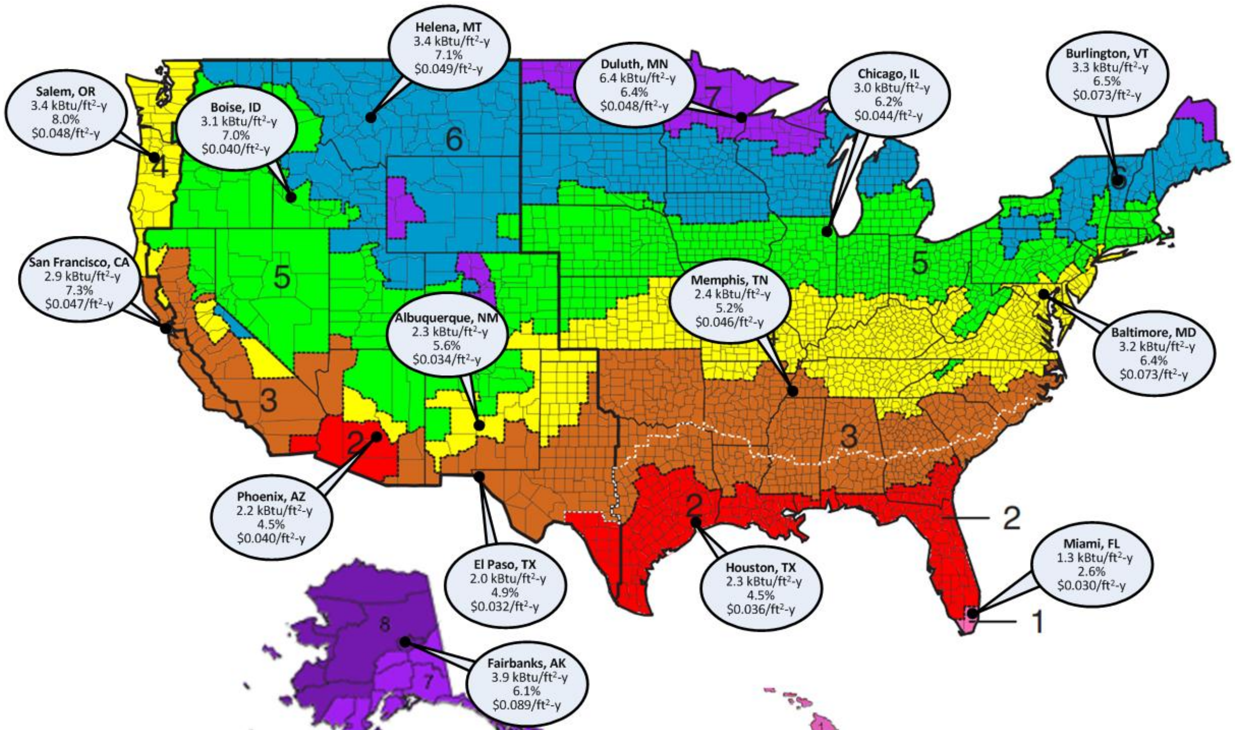

Figure ES- 1. Savings from retrofit of OBC using common occupancy sensors for lighting and terminal boxes in the large office building that initially has no OBC for locations in the 15 U.S. climate zones. The numbered climate zones are color coded. [map adapted from DOE (2010)]

Use of advanced occupancy sensors for both lighting and terminal-box control (Improved Case III) yields the largest savings by far (see Figure ES- 2). Savings range from 2.2 kBtu/ft^2-y for climate zone 1A to 12 kBtu/ft^2-y for climate zone 8, and the largest savings as a fraction of the base case energy consumption is 23% for climate zone 4C (Salem, Oregon). Monetary savings on fuel expenditures exceed \$100,000/y (\$0.201/ft^2-y) for climate zones 4A and 8 (\$100,300/y and \$110,900/y for Baltimore and Fairbanks, respectively). Thirteen of the 15 climate zones have monetary savings greater than \$40,000/y (\$0.08/ft^2-y). The marginal savings of OBC for terminal boxes and lights with advanced occupancy sensors compared to OBC based on common occupancy sensors is considerable. The absolute savings for the advanced occupancy sensors exceed the savings for common occupancy sensors by a factor of about 2 for very hot climate zones [climate zone 1A (Miami) and climate zone 3B (El Paso)], where the savings are minimum, and by about a factor of 3 for all other climate zones. At a national scale, the construction-volume-weighted average energy savings are 17.8% for OBC using advanced occupancy sensors and 5.9% using common occupancy sensors.

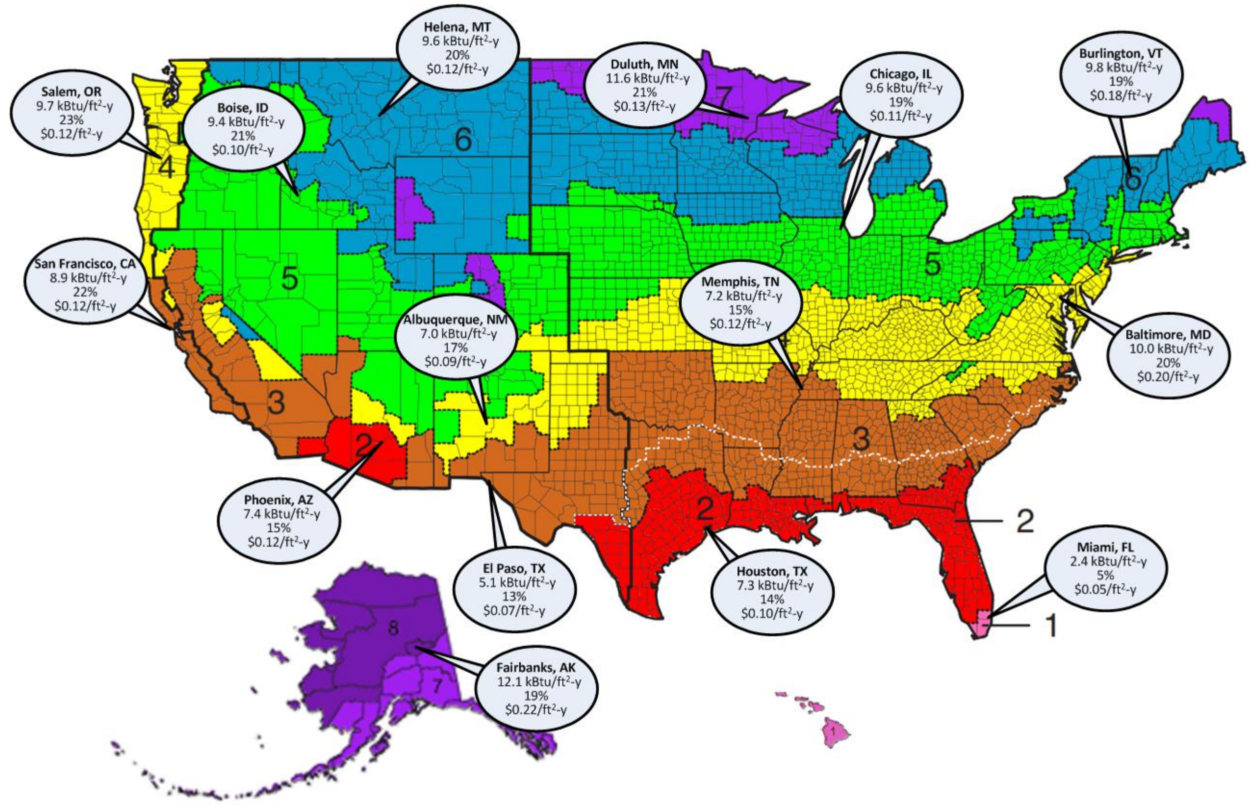

Figure ES- 2. Savings from retrofit of OBC using common occupancy sensors for lighting and terminal boxes in the large office building that initially has no OBC for locations in the 15 U.S. climate zones [map adapted from DOE (2010)]

These results show significant potential energy and associated monetary savings from deployment of occupancy-based control of VAV terminal boxes and tend to support the importance of developing the advanced occupancy sensor technology for this application. The largest savings by far are for climate zones 3C (warm, marine) through 8 (subarctic), with savings ranging from 17% to 23% for advanced occupancy sensor control for both terminal boxes and lighting compared to the building without any OBC. The simulation results also showed that these savings can be obtained with no significant increases in hours when cooling and heating loads are not met, which could lead to comfort complaints.

Acknowledgements

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1. Introduction

Outdoor air (OA) brought into buildings by heating, ventilating and air-conditioning (HVAC) systems for ventilation has a significant effect on building energy consumption, occupant health, and occupant satisfaction with the indoor environment. For many systems, especially those in larger commercial buildings with built-up systems, air is brought in through air-handling units, which supply conditioned air to many thermal zones. Air-handling units mix outdoor air in a controlled proportion with recirculated air and then cool (or sometimes heat) the air mixture before distribution to terminal boxes. Each terminal box usually serves a single thermal zone of a building, controlling the air-flow rate to the zone and reheating the air before it is discharged from the terminal box, when the zone-air temperature drops below the heating set point.

Each terminal box has a minimum set point for its air-flow rate that is sufficient to meet the design requirements for ventilation of the zone the box serves. This minimum air-flow rate set point is maintained at a constant value based on the design occupancy of the zone served, which often corresponds to the maximum occupancy of the zone. In practice, control system integrators and installers often set the cooling minimum air-flow rates for ventilation to between 30% and 50% of the terminal-box maximum air-flow rate (Cho 2009, Cho and Liu 2008, 2009). Building occupancy, however, varies dynamically. For example, conference rooms, cafeterias, break rooms, auditoriums, and other assembly spaces are often unoccupied for significant periods of time. Office occupancy also varies during the course of a work day, from day to day, and over the longer term because of meetings in the office, attendance of meetings elsewhere, business travel, changing room functions, and variations in staffing. The resulting over-ventilation, during times when the space has less than maximum occupancy or is unoccupied, wastes significant fan energy and can cause discomfort for occupants in some spaces (e.g., conference rooms) from overcooling or overheating.

Existing terminal-box designs and control methods do not solve the challenges of varying occupancy for multi-zone systems in commercial buildings (Liu and Brambley 2011, Liu 2012, Liu et al. 2012). Many spaces such as conference rooms, training rooms, and auditoriums, are not continuously fully occupied. Because the minimum air-flow rate set point for these spaces is continuously maintained for full occupancy, significant occupant discomfort and energy waste may occur when a zone is unoccupied or lightly occupied.

Occupancy-based control (OBC) strategies for variable-air-volume (VAV) terminal boxes maintain thermal comfort and meet the ventilation requirements of each zone by continuously monitoring zone temperature and zone occupancy conditions to determine the minimum required air-flow rate, thus reducing energy consumption for space conditioning. The zone occupancy condition can be identified either by common occupancy sensors (which detect whether a room is occupied or unoccupied) or advanced occupancy sensors (which count the number of people in each room).

Advanced occupancy sensors enable resetting of the minimum air-flow rate set point based on the actual measured occupancy during hours when the building is operating in the occupied mode. In contrast, common occupancy sensors enable terminal boxes to be switched to an occupied standby mode when no occupants are in the zone. Therefore, although both types of occupancy sensors provide energy savings when used for OBC, the savings should be greater when advanced occupancy sensors are used. The system schematic diagrams, control strategies, and minimum air-flow rate set point reset procedures are described in Liu (2012).

Both common and advanced occupancy sensors can also be used to ensure that lights are turned off when rooms are unoccupied. Common occupancy sensors, which are frequently installed in commercial buildings for lighting control, generally use delay times of 10 to 20 minutes after no occupants are detected until lights are switched off. This delay is intended to ensure that no occupants are present when the lights are turned off. Because advanced occupancy sensors have much greater accuracy than common occupancy sensors in detecting the presence of occupants, delay times can be nearly eliminated when they are used to control lights, increasing the energy savings for lighting compared to control of lights using common occupancy sensors. Because measures to increase lighting efficiency are often among the first implemented to increase the efficiency of buildings, total lighting energy use has decreased as a fraction of total building energy consumption over the last decade or longer. As a result, the potential energy savings from OBC for lighting are likely much less than the savings from OBC for HVAC.

Control of ventilation rates to zones based on occupancy determined with either advanced occupancy sensors or common occupancy sensors should decrease the energy use by air-handler fans, for cooling air to appropriate supply-air conditions in air handlers, and to reheat air in terminal boxes. The study documented by this report quantifies the energy savings and the corresponding monetary savings on energy purchases resulting from retrofit of VAV terminal boxes and lighting in existing buildings with occupancy-based control systems. Section 2 of the report describes the methodologies used to estimate the energy savings from retrofit of OBC, Section 3 presents the results, Section 4 describes conclusions, and Section 5 identifies needs for additional research and development.

2. Analytic Methodology

Energy savings are determined as the difference between the annual energy use of a prototypical building with common terminal-box control without OBC and the same building with OBC. In both control cases, the energy use is estimated by simulation using the U.S. Department of Energy's (DOE's) EnergyPlus building energy simulation program (DOE 2012a). Savings are determined for the 15 U.S. climate zones, which are characterized in Table 1 and shown geographically in Figure 1.

Table 1. U.S. climate zones

Climate Zone	Climate Type	Representative City	Thermal Criteria*
1A	Very hot, humid	Miami, FL	5000 < CDD 50°F
2A	Hot, humid	Houston, TX	3500 < CDD 50°F ≤ 5000
2B	Hot, dry	Phoenix, AZ	3500 < CDD 50°F ≤ 5000
3A	Warm, humid	Memphis, TN	2500 < CDD 50°F ≤ 3500
3B	Warm, dry	El Paso, TX	2500 < CDD 50°F ≤ 3500
3C	Warm, marine	San Francisco, CA	HDD 65°F ≤ 2000
4A	Mixed, humid	Baltimore, MD	CDD 50°F ≤ 2500 HDD 65°F ≤ 3000
4B	Mixed, dry	Albuquerque, NM	CDD 50°F ≤ 2500 HDD 65°F ≤ 3000
4C	Mixed, marine	Salem, OR	2000 < HDD 65°F ≤ 3000
5A	Cool, humid	Chicago, IL	3000 < HDD 65°F ≤ 4000
5B	Cool, dry	Boise, ID	3000 < HDD 65°F ≤ 4000
6A	Cold, Humid	Burlington, VT	4000 < HDD 65°F ≤ 5000
6B	Cold, Dry	Helena, MT	4000 < HDD 65°F ≤ 5000
7	Very Cold	Duluth, MN	5000 < HDD 65°F ≤ 7000
8	Subarctic	Fairbanks, AK	7000 <HDD 65°F

*CDD 50°F: Cooling-degree-days for base temperature 50°F;
HDD 65°F: Heating-degree-days for base temperature 65°F.

Two primary types of OBC are considered in this study: 1) OBC based on common occupancy sensors that are frequently used for lighting control, which detect when a room has any occupants and when it is completely vacant and 2) OBC based on advanced occupancy sensors, which count the number of occupants in a room.

2.1 Prototype buildings

Buildings suitable for retrofit of OBC already have VAV HVAC systems with terminal boxes. Therefore, the types of commercial buildings with VAV currently in place are candidates for retrofit of OBC. The data in Table 2 show that large office buildings, colleges and hospitals built after 1980 (as of 2003, the last year in which a Commercial Buildings Energy Consumption Survey was completed; EIA 2003) have fractions of the total floor space served by VAV systems equaling or exceeding 84%. Medium office buildings have the next largest fraction at 65%. Furthermore, large office buildings and hospitals built before 1980 have fractions of the total floor space served by VAV systems of 72% and 67%, respectively,

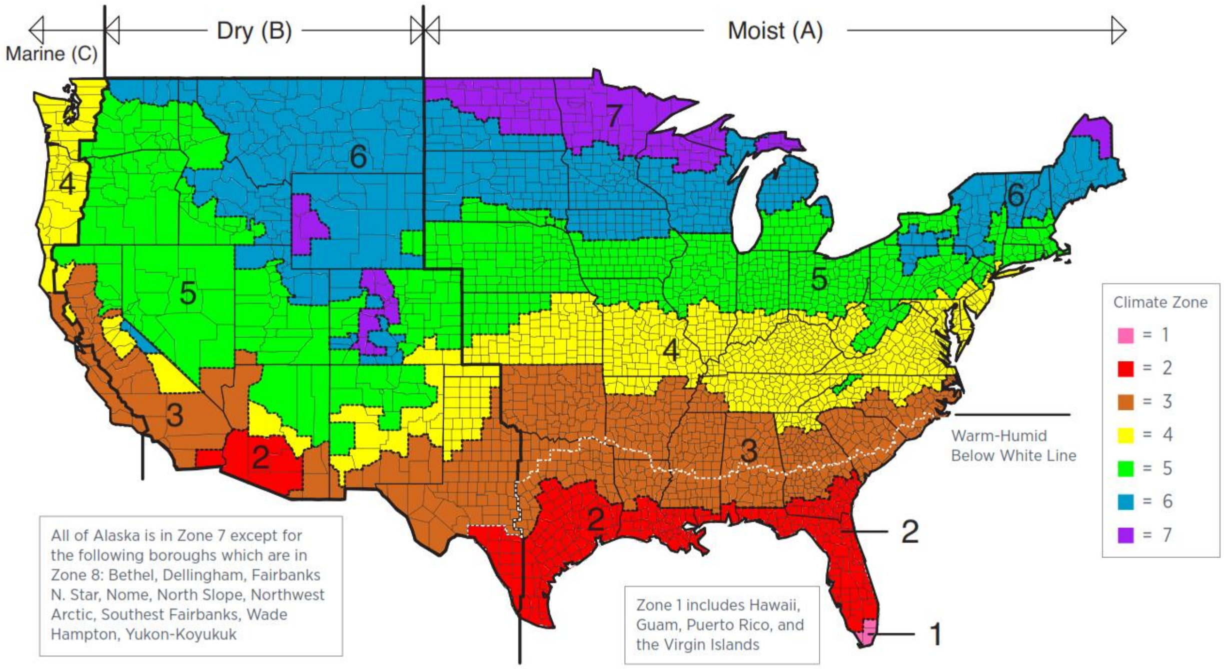

Figure 1. U.S. climate zone map [reproduced from DOE (2010)]

Table 2. Total floor space, fraction of total U.S. commercial floor space, total annual energy consumption, and fractions of floor space having VAV systems for the primary commercial building types in the U.S. All values shown are based on data from EIA (2003).

Building Type	Total Floor Space (Million Square Feet)	Fraction of Total Commercial Floor Space (%)	Total Annual Energy Consumption (Trillion Btu/y)	Floor Space of Buildings Constructed in 1980 and Later Having VAV Systems (% of Total Floor Space for the Buliding Type)	Floor Space of Buildings Constructed Prior to 1980 Having VAV Systems (% of Total Floor Space for the Building Type)
Large Office*	4,354	6.1%	455	84%	72%
Medium Office*	3,647	5.1%	342	65%	40%
Small Office*	4,207	5.9%	336	18%	13%
Warehouse	10,078	14.1%	456	22%	12%
Retail	4,317	6.0%	319	12%	10%
Schools (K-12)	7,265	10.1%	525	53%	33%
Colleges	1,421	2.0%	221	88%	49%
Hospitals/Impatient Health Care	1,905	2.7%	475	95%	67%
Food Sales	1,255	1.8%	251	17%	10%
Grocery Stores	715	1.0%	153	31%	8%
Restaurants/Cafeterias	1,062	1.5%	245	31%	23%
Fast Food	262	0.4%	118	12%	40%
Hotels and Motels	2,952	4.1%	288	42%	23%

*Office buildings are categorized as follows: Small: floor space ≤ 25,000 ft^2; medium: floor space ≥ 25,001 ft^2 and ≤ 150,000 ft^2; large: floor space ≥ 150,000 ft^2.

Colleges have the next highest fraction with 49%. Therefore, the commercial building types with the greatest potential for application of OBC are large office buildings and hospitals, which represent 4.4 billion ft^2 and 1.9 billion square feet of floor space in the U.S., respectively (6.1% and 2.7% of total U.S. commercial floor space in 2003; see Table 1). Hospitals have special ventilation requirements and represent less than 50% of the floor area attributable to large office buildings; therefore, large office buildings were selected as the initial target for application of OBC.

The median age of large office buildings in the U.S. was approximately 23 years in 2003 (EIA 2003). Assuming that this median age has not changed appreciably between 2003 and 2012, the median year in which currently-standing large office buildings were built is 1989. Ideally, the building modeled to estimate likely energy savings from retrofit with OBC would be the average large office building built in 1989 but in its present 2012 condition. Buildings that are 23 years old have likely been retrofit many times already, which may include changes to lamps and lighting fixtures, controls, some HVAC upgrades, and many cosmetic changes. Replacements of chillers, air handlers and all terminal boxes are much less likely, although they will have occurred in some cases. Sufficient data are not available to identify the median set of retrofit upgrades implemented in large office buildings over the last 23 years. If the data were available, a large office building conforming to codes or standards in effect in 1989 could be assumed upgraded with the median package of retrofits to estimate its condition in 2012. Not having sufficient information for that, however, an alternate procedure is used for defining a representative large office building for this study.

Starting with the large office building prototype model from the U.S. Department of Energy Commercial Prototype Building Models (DOE 2012b) that conforms with ASHRAE Standard 90.1-2004 (ANSI/ASHRAE/IESNA 2004), adjustments were made to bring the model closer to the characteristics that might be expected for a building constructed in 1989 that has been upgraded over the last 23 years. The changes implemented to the DOE prototype and the rationales for them are provided in Table 3, and the primary characteristics of the adjusted prototype model used to estimate energy savings in this study are given in Table 4. Figure 2 and Table 5 provide supporting information, Appendix Section A-1 provides a more complete description of the adjusted building model, Appendix Section A-2 gives the building operation schedule, Appendix Section A-3 provides the lighting power schedules, Appendix Section A-4 provides weekend occupancy schedules for private offices, open office space, and conference rooms, and Appendix Section A-5 provides equipment power use schedules for all spaces.

The DOE prototype buildings (DOE 2012b) were developed for use in simulations for the purpose of determining the impacts of successive version Standard 90.1, an example of which is Standard 90.1-2004 (ANSI/ASHRAE/IESNA 2004). Models for prototypes of 16 types of buildings were developed, which are intended to represent realistic building characteristics and construction practices. The prototypes were derived from the U.S. DOE Commercial Reference Building Models (Deru et al. 2011) in an effort led by Pacific Northwest National Laboratory with extensive input from members of the ASHRAE Standing Standards Project Committee 90.1 and other building industry experts.

The large office building prototype model represents a newly-constructed building compliant with Standard 90.1-2004 (ANSI/ASHRAE/IESNA 2004), which is not representative of an average new building until a few years after 2004 when state and local authorities have incorporated the new requirements into building energy codes. The adjustments made to create the large office building model for this study are intended to change this Standard 90.1-2004-compliant building model into a model that approximately represents a median building constructed in 1989 that is still in service and has been upgraded with retrofits of various sorts over the last 23 years. The changes (see Table 3) were selected based on the professional judgment of the authors of this report; no data sufficient to support specification of such changes were found to be available.

This resulting model has a gross floor area of just under 500,000 ft^2 on 12 above-grade floors and a basement. Windows comprise 37.5% of total exterior wall area. The exterior walls are constructed of pre-cast concrete panels having 8-inch thick heavy-weight concrete, wall insulation and 0.5-inch gypsum board as the interior layer. The wall insulation and window thermal resistance satisfy the climate-

Table 3. Changes to the DOE large office building prototype to create a building model that approximates a large office building constructed in 1989 as it would exist in 2012 and the rationale for each change.

Category	Change	Rationale
Zone Description	Specific space types (conference room, private office, and open office) are assigned to the thermal zones.	Actual buildings have distinct space types with varying functions and schedules. The use of distinct space types i.e., conference rooms, private offices and open-plan offices, enables evaluation of the savings associated with OBC based on the unique occupancy patterns of the different spaces.
	Maximum occupancy density is changed from 7 people/1000 ft^2 to 5 people/1000 ft^2 for offices and 50 people/1000 ft^2 for conference rooms.	Based on work by Persily et al. (2004, 2005) documenting occupancy densities in existing buildings. The values of occupant density correspond to values in ASHRAE 62.1 2007 (ANSI/ASHRAE 2007).
	The occupancy profiles associated with the prototype building were modified for private offices, open offices, and conference rooms.	More realistically model occupancy of offices and conference rooms. Based on research by Wang et al. (2005) and Hart (2012).
HVAC Sizing	Terminal-box size (flow rate and reheat) sizing factor is increased from 1.0 to 1.2.	The larger size for the terminal boxes more realistically represents a late 1980s office building, which would be less efficient than buildings constructed to meet Standard 90.1-2004.
	Lighting peak load power density (LPD) is scaled to 133% of the LPD required by Standard 90.1-2004 for HVAC sizing. The LPD for calculating lighting energy consumption is unchanged from the 90.1-2004 prototype building.	A late 1980s building's HVAC system would have been sized for the less efficient lighting of the era. Lamps and lighting fixtures are assumed to have been replaced with more efficient ones since building construction in 1989, but retrofit of HVAC components, primarily the terminal box, is assumed to have been considered too expensive to have been replaced in most buildings.
	Peak plug load density is scaled to 140% of the Standards 90.1-2004 prototype plug load density for HVAC sizing. Plug load density for modeling energy consumption is unchanged from the Standard 90.1-2004 prototype.	A late 1980s building's HVAC system would have been sized for the larger plug load densities of the era. Expensive HVAC system replacement, such as for terminal boxes, are less likely to have been done.
Outdoor Air-Flow Rate	Outdoor air-flow rate is set to 6 cfm/person for conference rooms and 17 cfm/person for office spaces from the constant value of 20 cfm/person used for all zones in the DOE prototype.	Different space types, with different occupant densities, require different outdoor-air ventilation rates. The DOE prototype building does not distinguish between the ventilation requirements of different space types and, therefore, has one ventilation rate for all zones.
	Determination of the rate at which outdoor is brought into the air handling units is changed from the multiple-zone ventilation rate procedure (VRP) required by ASHRAE 62.1-2004 to the sum of the zone outdoor air requirements.	The multiple-zone VRP is rarely used for existing buildings. In practice, two basic outdoor-air control strategies are widely used for existing buildings (EPA 2000): fixed outdoor-air fraction (FOAF) and constant outdoor air (COA) flow rate, which is used in this study. For COA for a VAV system, the outdoor-air damper opens wider as the total supply-air flow rate is decreased in response to decreased thermal demands.
Terminal-Box Settings	The minimum air-flow rate for conference rooms is changed from 30% to 50% of the design peak flow rate.	Implementation of this procedure is based common practices with for conference room minimum damper positions presented by Yu et al. (2007) and Stein (2005).
	Minimum fan flow fraction is changed from 25% to 0%, enabling the VAV supply fan to match the needs of the terminal boxes served.	This minimum enables the supply-fan flow rate to decrease to the total flow rate required by all terminal boxes it serves (which at the lower limit is 0 when no zones are occupied). This saves fan energy when spaces are not occupied without reducing indoor air quality. .
	In reheat mode, damper position is changed from a fixed value of 30% to a modulating value between 30% and 50% with a maximum reheat air temperature of 104 °F	Implementation of OBC has the potential to increase the number of hours during which the temperature set point is not met. By enabling the ventilation rate to vary up to 50% rather than remain constant at 30%, thermal-comfort conditions are maintained more consistently.

Table 4. Base Case building characteristics

Characteristic	Description
Energy Sources	
Electricity	Used for cooling, chilled- and hot-water distribution, ventilation and air distribution, lighting, plug loads
Natural Gas	Used for space heating, domestic hot-water heating
Form	
Total Floor Area (ft^2)	498,588
Floor Dimensions	239.854 ft × 159.901 ft rectangle (38,352.9 ft^2)
Number of Floors	12 above grade plus one basement
Window-to-Wall ratio	37.5% of total exterior wall area
Window Locations	Even distribution among above-grade exterior walls
Thermal zoning	See Figure 2
Floor-to-Floor height (feet)	13
Floor-to-Ceiling height (feet)	9
Glazing Sill Height (feet)	3
Architecture	
Exterior walls	
Construction	Pre-cast concrete panels: 8-inch heavy-weight concrete + wall insulation + 0.5-inch gypsum board
U Factor	See Table 5
Windows	
U Factor	See Table 5
HVAC	
System Type	
Heating Plant	Natural gas boiler
Cooling Plant	Two water-cooled centrifugal chillers
Air Distribution System	VAV air handlers with cooling coils; VAV terminal boxes with hot-water reheating coils; minimum supply air-flow rate equal to 30% of the design peak supply air-flow rate
HVAC Control	
Zone Set Point in Occupied Building Mode	75°F cooling/70°F heating
Zone Set Point in Unoccupied Building Mode	85°F cooling/60°F heating (setback)
Economizers	In climate zones 2B, 3B, 3C, 4B, 4C, 5A, 5B, 6A, 6B, 7, 8
Internal Loads and Schedules	
Lighting	
Average Power Density of Installed Lighting	1.0 W/ft^2
Occupancy Sensors	No
Lighting Power Schedule	See Appendix Section A-2
Plug Loads	
Average Power Density	0.75 W/ft^2 for all floors except basement 0.45 W/ft^2 for basement

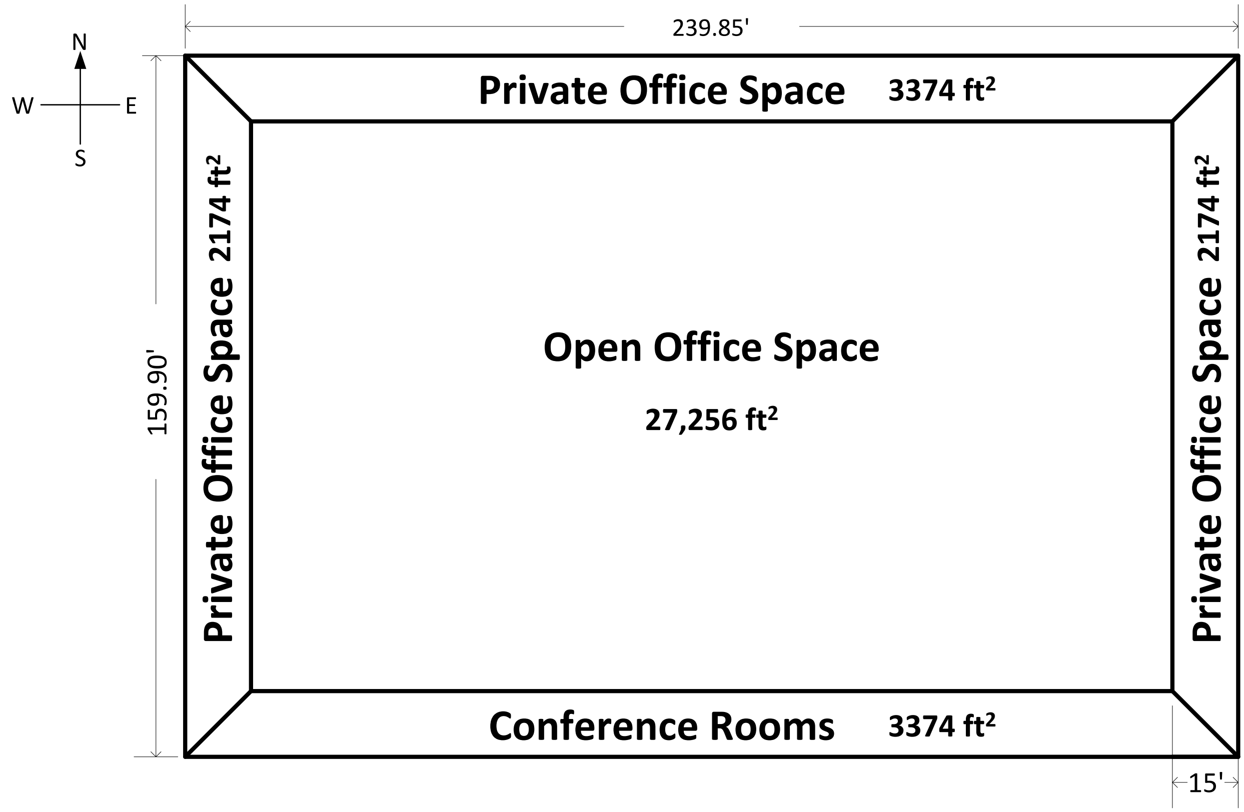

Figure 2. Dimensions, thermal zoning and orientation of a floor

Table 5. U-values for the windows and exterior above-grade walls of the Base Case building, including insulation.

Location	Climate Zone	U (Btu/ h-ft^2-ºF)	
		Walls	Windows
Miami, FL	1A	0.580	1.22
Houston, TX	2A	0.580	1.22
Phoenix, AZ	2B	0.580	1.22
Memphis, TN	3A	0.151	0.57
El Paso, TX	3B	0.151	0.57
Las Vegas, NV	3B	0.580	0.57
San Francisco, CA	3C	0.151	1.22
Baltimore, MD	4A	0.151	0.57
Albuquerque, NM	4B	0.151	0.57
Salem, OR	4C	0.151	0.57
Chicago, IL	5A	0.123	0.57
Boise, ID	5B	0.123	0.57
Burlington, VT	6A	0.104	0.57
Helena, MT	6B	0.104	0.57
Duluth, MN	7	0.090	0.57
Fairbanks, AK	8	0.080	0.46

dependent requirements of Standard 90.1-2004 (ANSI/ASHRAE/IESNA 2004). Cooling is provided by a variable-air-volume system with 12 built-up VAV air-handling units (1 per floor) and one built-up constant-air-volume air-handling unit for the basement, all served by two centrifugal chillers. Air is distributed to VAV terminal boxes that have hot-water reheating coils served by a natural-gas boiler. The minimum supply air-flow rate for each VAV box equals 30% of its design peak supply air-flow rate. The zone set points for occupied hours are 75°F and 70°F for cooling and heating, respectively, and are set back by 10°F during scheduled unoccupied hours. This building is designated the Base Case model, and occupancy-based control retrofits are made to it to estimate their energy savings benefits.

A few of the building characteristics deserve special mention because they relate more directly to OBC than many of the other building characteristics, although all characteristics have some impact on the savings associated with use of OBC, even if only through their impact on the building heating and cooling loads or HVAC system efficiencies.

For the Base Case building, the total ventilation requirement is set to 17 cfm per person for office spaces and 6 cfm per person for conference rooms per ASHRAE Standard 62.1 (ANSI/ASHRAE 2007). These ventilation rates are used for cases without OBC for terminal boxes. When OBC is used for terminal boxes, the ventilation rate is modulated based on whether a space is occupied or not when common occupancy sensors are used and based on the actual number of occupants when advanced occupant-counting sensors are used.

The occupancy of the zones is critical to the evaluation of the impacts of OBC. For this study an occupant density of 5 people per 100 m^2 (4.6 per 1000 ft^2) is used for the maximum design occupancy for both private and open-plan office spaces. Persily et al. (2004, 2005) analyzed ventilation data from the U.S. Environmental Protection Agency Building Assessment Survey and Evaluation (BASE) Study (EPA 2012) and found a mean value for the design occupant density of 5.5 people per 100 m^2 (5.1 per 1000 ft^2) and a median value is 3.9 per 100 m^2 (3.6 per 1000 ft^2). These ventilation rates for individual air handlers are less than the default value of 7 people per 100 m^2 (6.6 per 1000 ft^2) specified in ASHRAE Standard 62.1-2004 (ANSI/ASHRAE 2004), but close to the default value of 5 people per 100 m^2 (4.6 per 1000 ft^2) for office spaces in Addendum n to the Standard (ASHRAE 2003). For conference rooms, the maximum design occupancy density is 50 people per 1000 ft^2 according to Standard 62.1-2004 (ANSI/ASHRAE 2004). The occupancy densities and ventilation requirements for the Base Case building are summarized in Table 6.

Table 6. Occupancy density and ventilation rates

Space Type	90.1-2004 Occupant Density (occupants/1000 ft^2)	90.1-2004 Total Outdoor Air Requirement
Offices	5	17 cfm/person
Conference rooms	50	6 cfm/person

The values for the outdoor-air requirements in Table 6 are design flow rates at which outdoor air must be provided to zones to meet the ventilation needs of each occupant, which must always be satisfied by each terminal box for zones without OBC. In the proposed implementation of OBC examined in this study, the minimum ventilation rate is adjusted based on the presence or absence of occupants when using common occupancy sensors and on actual measured occupancy of the zone when using advanced occupancy sensors that count the number of occupants. To analyze the impact of varying occupancy on ventilation needs and, therefore, energy use, schedules or the zones are required, which are developed based on studies of occupancy reported in the literature.

Wang et al. (2005) propose that occupancy in a private office follows a non-homogenous Poisson model with two different exponential distributions. The Poisson model is a probabilistic stochastic process using data on occupancy of private offices to develop a model to predict future occupancy. The model is then simplified and used in simulations to describe the occupancy in each private office throughout the day. Figure 3 shows the probability of occupancy for private offices for each hour of weekdays, adapted from the simulated occupied rate of Wang et al. (2005).

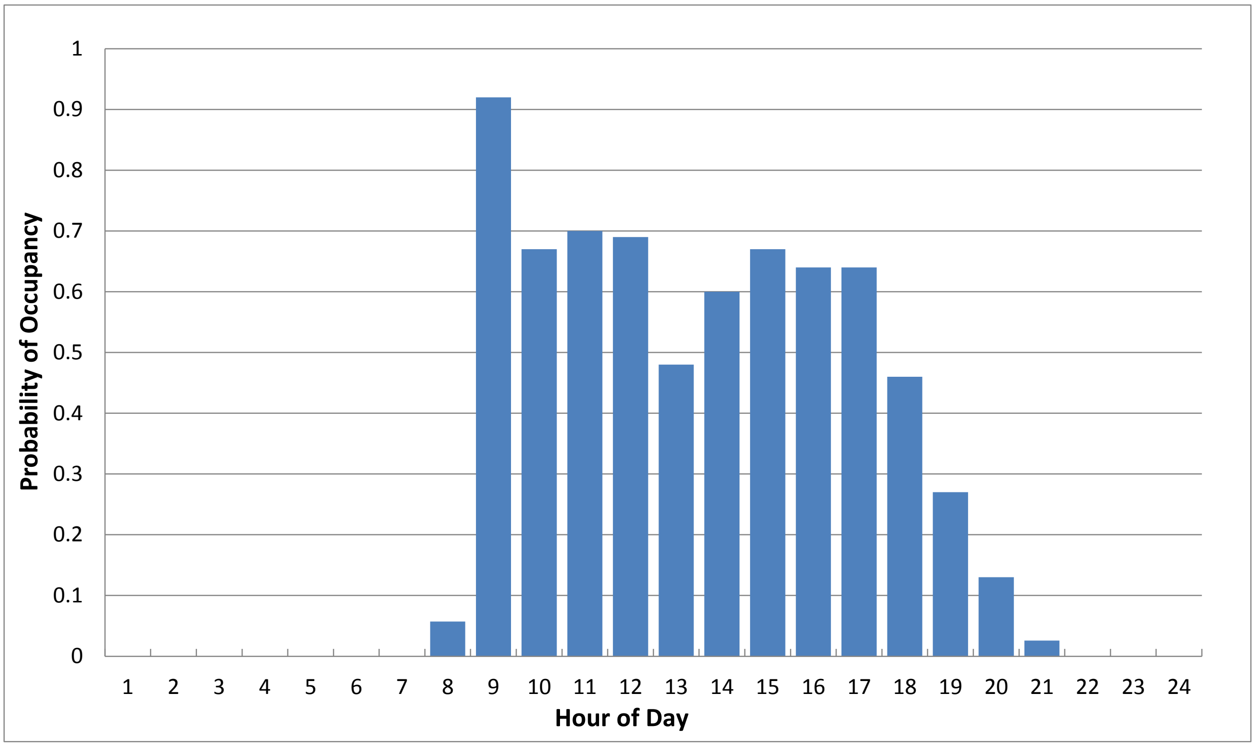

Figure 3. Probability of occupancy versus hour of day during weekdays for private offices.

Private offices are grouped into zones of three offices for the Base Case building. The probability ($P_{i,zone}$) of all three offices being unoccupied in a three-office zone at any hour i is given by

$$P_{\text{private-office zone},i} = (1 - P_{\text{private-office},i})^3 \quad \text{for I} = 1, 2, \ldots, 24, \tag{1}$$

where $P_{\text{private-office},i}$ is the probability of an individual office in the zone being occupied during hour i, the occupancies of the three offices are independent of one another, and all private offices are assumed to have the same distribution of $P_{\text{private-office},i}$ for the hours of the day (Figure 3). The resulting probability profile for all three offices in a zone being unoccupied during the hours of a weekday is shown in Figure 4. These probabilities are important for simulating when a zone is entirely unoccupied, which is required for the terminal box serving a private-office zone with common occupancy sensors to change to unoccupied operating mode.

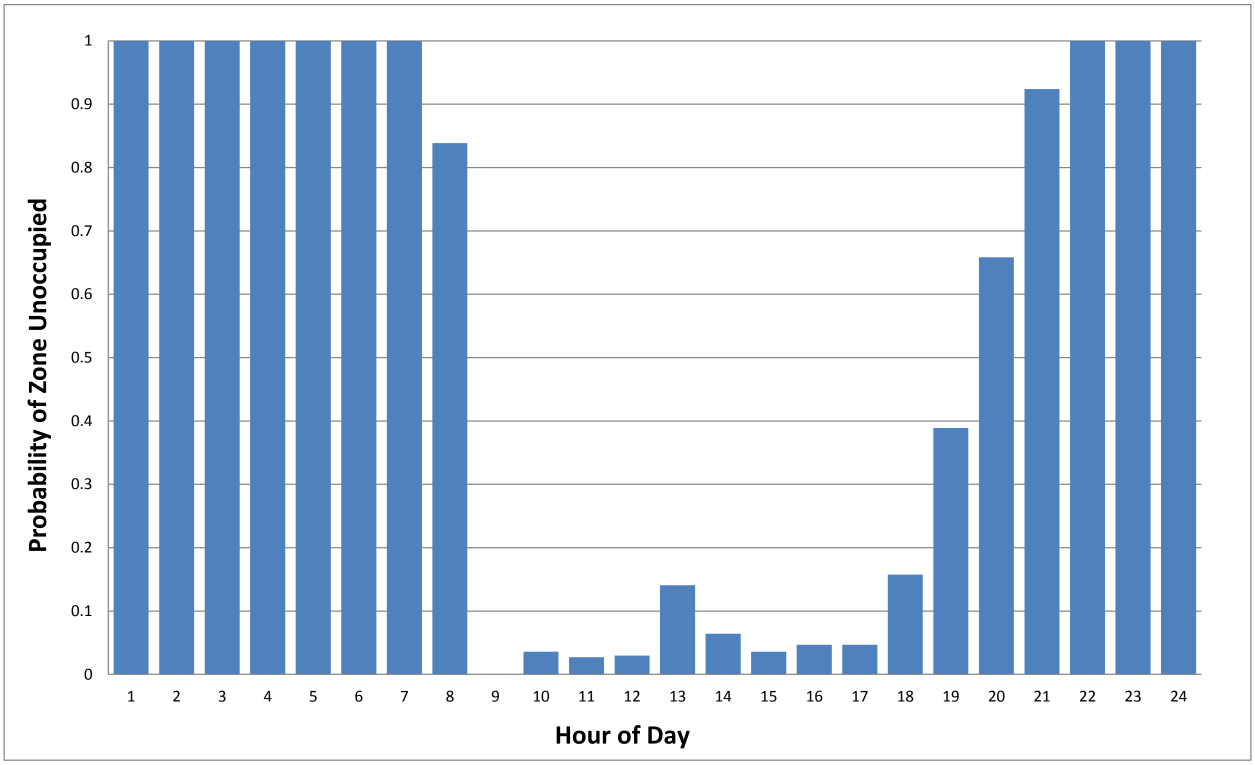

Figure 4. Probability of a zone of three private offices being unoccupied for each hour of a weekday

The open-plan office area on each floor has a maximum occupancy of 136 people [(5 persons/1000 ft^2) x 27.2 x 10^3 ft^2]. Assuming that the occupancy probability profile for private offices (Figure 3) applies to the open office space (i.e., $P_{open\text{-}office,i} = P_{private\text{-}office,i}$ for i = 1, 2,..., 24), the occupancy for any hour i during the weekday is given by the relation

$$Occupancy_{open\text{-}office,i} = \text{Open-Office Design Occupancy} \times P_{open\text{-}office,i} = 136 \times P_{open\text{-}office,i}\,, \tag{2}$$

where $P_{open\text{-}office,i}$ represents the probability of the open office space being occupied during hour i, which over the approximate 250 non-holiday weekdays of the year, is a good estimate of the average occupancy rate for each weekday hour. The resulting daily occupancy profile for the open-office zone on each floor is shown in Figure 5.

The occupancy profile for conference rooms of Hart (2012) was used for conference rooms. Hart examined various demand control ventilation techniques, e.g. , monitored CO_2 concentrations and the buildup of volatile organic compounds (VOCs) and their relationships to the ventilation technique and occupancy to infer occupancies. The weekday profile for conference rooms is shown in Figure 6.

The occupancy profiles for all zones, private offices, open-plan offices and conference rooms, are given in tables in Appendix Section A-4 for Saturdays and Sundays/holidays.

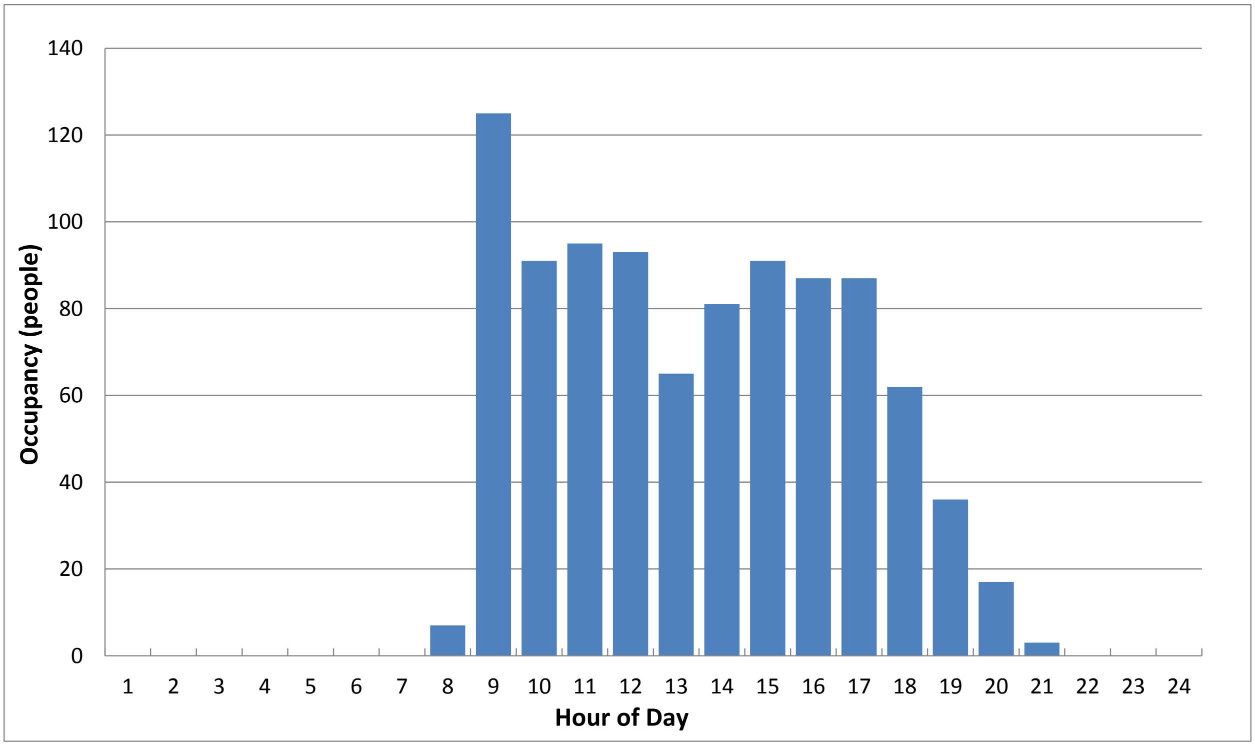

Figure 5. Average weekday occupancy profile for open-office zones

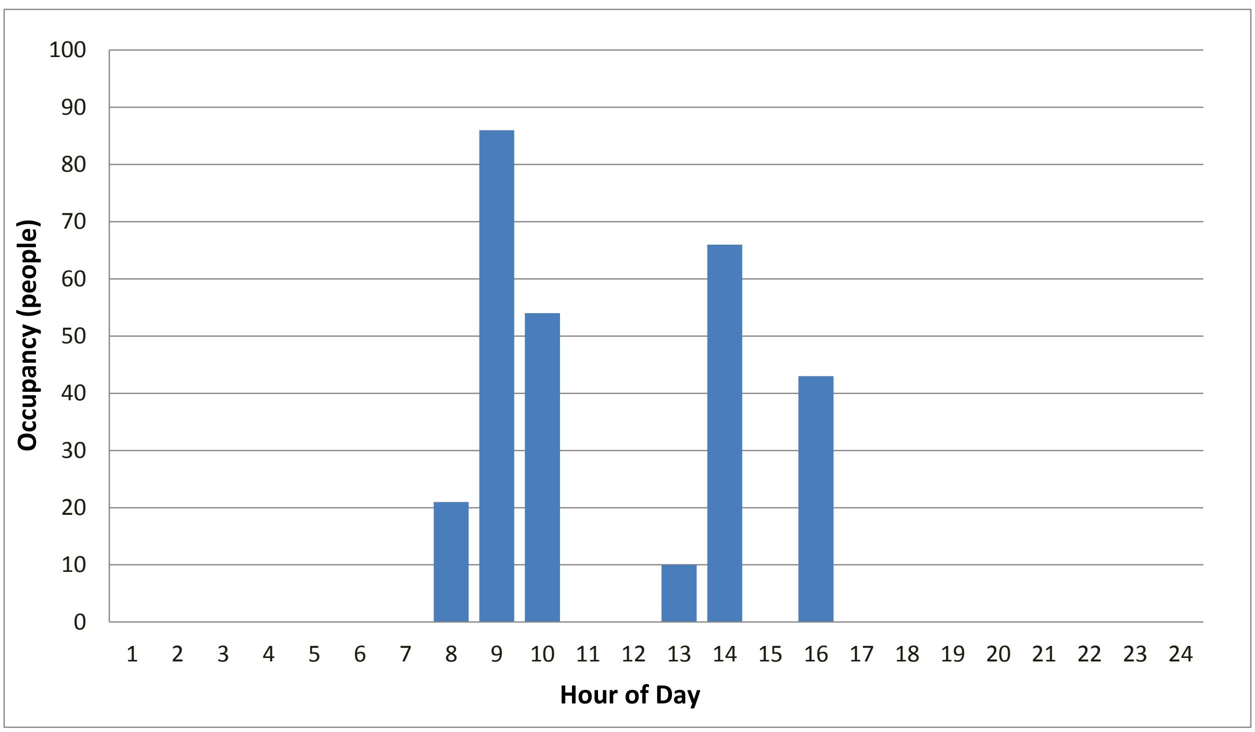

Figure 6. Average weekday occupancy profile for conference rooms [adapted from Hart (2012)]

The size of the terminal boxes in the DOE prototype large office building also requires adjustment so that it better represents the sizes of terminal boxes installed in 1989. The terminal boxes in the DOE prototype are smaller than terminal boxes as commonly sized in 1989, because they are sized for a more efficient building with smaller loads. These smaller loads result from more stringent requirements on the envelope overall coefficient of heat transfer (U), lower values that must be met for the lighting power density (LPD), and other requirements that lead to more efficient buildings. The terminal boxes for the Base Case building are sized by EnergyPlus to meet heating and cooling loads of this less efficient building described in Table 4.

The adjusted building model is likely to be more efficient than the actual median large office building built in 1989 that is still operating today than it is to be less efficient. The package of adjustments made to create this model are few, resulting in a model building that corresponds to one built in 1989 that has been extensively retrofit and is closer in efficiency to a post-2004 building. The estimated EUIs of the Base Case building, based on EnergyPlus simulations for all 15 U.S. climate zones, are shown graphically in Figure 7. All of the EUIs lie between 40.2 kBtu/ft^2-y for San Francisco and 63.7 kBtu/ft^2-y for Fairbanks, Alaska. The median EUIs for office buildings and large office buildings in the U.S. from the 2003 CBECS (EIA 2003) are 67.4 and 90.3 kBtu/ft^2-y, respectively, exceeding the values for the Base Case building for all climate zones. The Base Case building has EUIs between 40.2 and 51.3 kBtu/ft^2-y for all climate zones, except the most severe, for which the representative cities are Duluth, Minnesota, and Fairbanks, Alaska. These data show that the Base Case building (described in Table 4) is considerably more efficient than the median 2003 large office building, even though it is less efficient than the DOE large office prototype that satisfies ASHRAE Standard 90.1-2004 (DOE 2012b).

A less efficient building generally yields larger energy savings than a more efficient one to which the same energy efficiency improvements are made. Therefore, based on this characteristic, the savings estimates in this study for implementation of OBC are likely to be conservatively low rather than high, to the extent they deviate from the median.

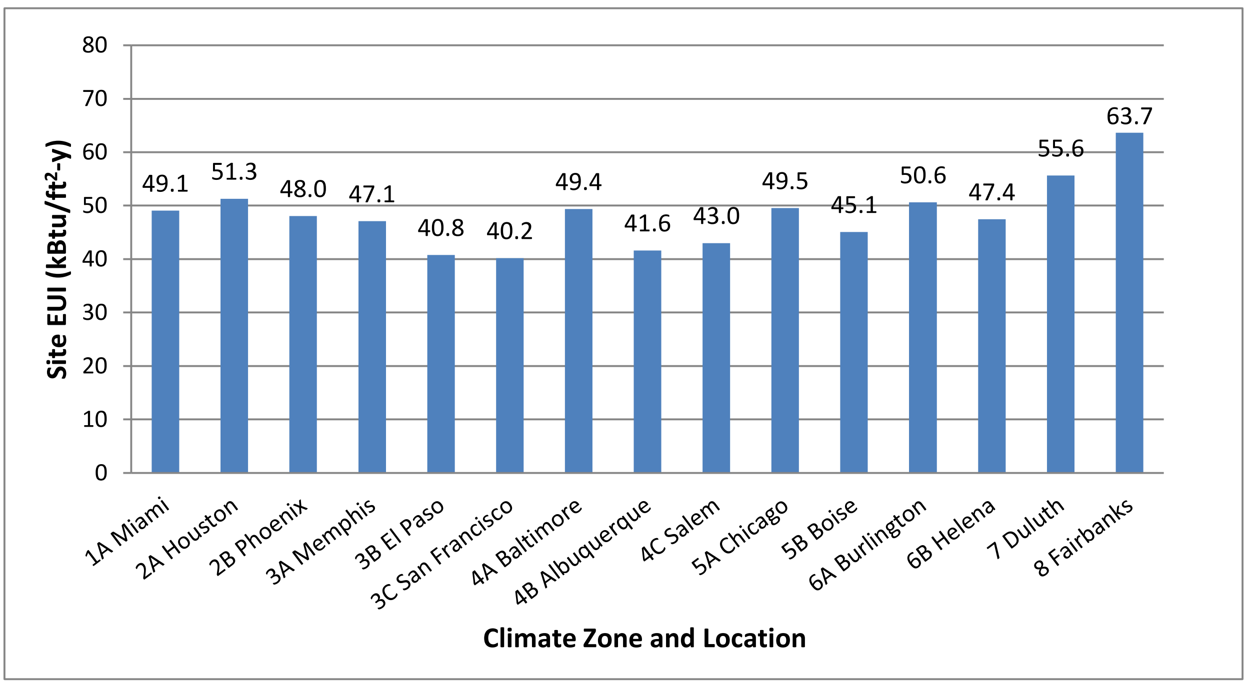

Figure 7. EUIs for the Base Case building for all 15 U.S. climate zones

2.2 Energy savings

The EnergyPlus building energy simulation software (DOE 2012a) was used to simulate the thermal behavior of the representative office building in all 15 U.S. climate zone. EnergyPlus models heating, cooling, lighting, ventilation, other energy flows, and water use with many innovative simulation capabilities: time-steps less than 1 hour, modular systems and plants integrated with heat balance-based zone simulation, multi-zone air flow, thermal comfort, water use, natural ventilation, and photovoltaic systems.

Key primary energy-savings results from this analysis are: 1) the savings associated with adding OBC for terminal boxes and lighting using advanced occupancy sensors (AOS) to buildings with no OBC ($ES_{\text{NoOBC to AOS-TB\&Light}}$), 2) the savings from adding OBC for terminal boxes and lighting using common occupancy sensors (COS) to buildings with no OBC ($ES_{\text{NoOBC to COS-TB\&Light}}$), 3) the savings from adding OBC of terminal boxes using COS to buildings already having COS-based lighting control ($ES_{\text{COS-Light to COS-TB\&Light}}$), and 4) the incremental savings associated with using AOS-based control for terminal boxes and lighting compared to using COS-based control of terminal boxes and lighting ($ES_{\text{COS-TB\&Light to AOS-TB\&Light}}$).

Four cases of control, described by Liu (2012), are defined for analysis of the energy savings associated with use of OBC (see Table 7). All are implemented in the Base Case building, described in Section 2.1, to create Improved Cases that differ from the Base Case by the OBC added. The Base Case has conventional terminal-box control with no use of occupancy sensors. Improved Case I is the Base Case building with common occupancy sensors added for lighting control; Improved Case II is the Base Case building with common occupancy sensors used for both lighting and terminal-box control; Improved Case III is the Base Case Building with advanced occupancy sensors used for both lighting and terminal-box control. Simulation is used to determine the annual energy use for each case, and the energy savings are then estimated using the relations

Table 7. Definitions of the four control cases analyzed.

Case	Common Occupancy Sensors (COS) for lighting	Common Occupancy Sensors (COS) for HVAC	Advanced Occupancy Sensors (AOS) for lighting	Advanced Occupancy Sensors (AOS) for HVAC
Base Case: No occupancy sensors				
Improved Case I: Common occupancy sensors for lighting control only	X			
Improved Case II: Common occupancy sensors for lighting and terminal-box control	X	X		
Improved Case III: Advanced occupancy sensors for lighting and terminal-box control			X	X

$$ES_{\text{NoOBC to AOS-TB\&Light}} = E_{\text{Improved III}} - E_{\text{Base}} \,, \tag{3}$$

$$ES_{\text{NoOBC to COS-TB\&Light}} = E_{\text{Improved II}} - E_{\text{Base}} \,, \tag{4}$$

$$ES_{\text{COS-Light to COS-TB\&Light}} = E_{\text{Improved I}} - E_{\text{Improved II}} \text{, and} \tag{5}$$

$$ES_{\text{COS-TB\&Light to AOS-TB\&Light}} = E_{\text{Improved III}} - E_{\text{Improved II}} \;. \tag{6}$$

Here, E_{Base} (e.g., in kBtu/y or kBtu/ft^2-y) represents the estimated annual energy use of the Base Case building, and $E_{Improved\ I}$, $E_{Improved\ II}$ and $E_{Improved\ III}$ represent the estimated annual energy use of the Improved Case I, II and III buildings, respectively. The energy savings associated with retrofitting OBC for lighting only using common occupancy sensors on a large office building ($ES_{\text{NoOBC to COS- LightOnly}}$) are given for purposes of comparing the savings from using OBC for terminal-box control to OBC for lighting only by

$$ES_{\text{NoOBC to COS- LightOnly}} = E_{\text{Improved I}} - E_{\text{Base}} \;. \tag{7}$$

Detailed descriptions of the terminal–box ventilation and space temperature controls are provided in Table 8 [also see the control strategies described by Liu (2012)]. Four characteristics differentiate the four control cases: the type of lighting control, control of the minimum air-flow rates from the terminal boxes, and the zone cooling and heating set points for the occupied building operation mode.

Lighting control is either occupancy-based or not occupancy-based. Occupancy-based control for lighting can be based on common occupancy sensors that turn lights on when occupants enter a room and off following a delay (usually 15 or 20 minutes) after all occupants leave the room. With advanced occupancy sensors that count occupants and have spatial resolution, lighting could, in principle, be controlled based on the positions of occupants in a room. In this study, however, advanced occupancy sensors are used only to turn lights on and off, except that the delay time between when all occupants leave a room and the lights turn off is essentially eliminated (set equal to 5 seconds). Common occupancy sensors usually located at light switches often have limitations on successfully detecting when all occupants vacate a room. Delay times of approximately 15 minutes are used to help ensure that lights do not turn off while occupants are still in the room. Advanced occupancy sensors under development have the ability to precisely identify when a room is vacated, some sensors even being able to distinguish between the only occupant of a room crawling under a desk and leaving the room. This refined ability to detect occupants so that delay times can be reduced substantially leads to fewer total hours of lights operating and, therefore, greater energy savings.

Occupancy-based control of the minimum air-flow rate to meet the ventilation needs of the occupants of the zone served by a terminal box presents another opportunity for energy savings. Common occupancy sensors can be used to identify when occupants are present in the rooms of a zone. When occupants are present, the air-flow rate to the zone must at least meet the total rate required to satisfy the outdoor-air requirements for ventilation specified by standards. When heating or cooling of the zone requires a greater air-flow rate, the rate is increased above this value, but the flow rate should not be allowed to decrease below the minimum flow rate required for ventilation when occupants are present.

Table 8. Key control characteristics and parameters.

Category	Control Characteristic or Parameter	Base Case	Improved Case I	Improved Case II	Improved Case III
Lighting	Lighting for Private Offices and Conference Rooms	No OBC	OBC with 15-minute delay time	OBC with 15-minute delay time	OBC with 5-second delay time
	Lighting for Open-Plan Offices	No OBC	No OBC	No OBC	No OBC
Ventilation Air-Flow Rate (% of peak design primary air-flow rate)	Private Office Terminal-Box Control Minimum Air-flow Rate for Occupied Building Mode	30% (constant)	30% (constant)	30% when occupied 0 when unoccupied	Varied between 0 and 30% based on occupancy
	Open-Plan Office Terminal-Box Control Minimum Air-flow Rate For Occupied Building Mode	30% (constant)	30% (constant)	30% (constant)	Varied between 0 and 30% based on occupancy
	Conference Room Terminal Box Control Minimum Air-flow Rate For Occupied Building Mode	50% (constant)	50% (constant)	50% when occupied 0 when unoccupied	Varied between 0 and 50% based on occupancy
	Terminal-Box Control Minimum Air-flow Rate for All Zones for Unoccupied Building Mode	30% (constant) Supply fan cycles on with need for heating or cooling	30% (constant) Supply fan cycles on with need for heating or cooling	30% (constant) Supply fan cycles on with need for heating or cooling	0% (constant) Supply fan cycles on with need for heating or cooling
Cooling Temperature Set Points	Zone Temperature Cooling Set Point for Occupied Building Mode	75°F	75°F	75°F	75°F
	Zone Temperature Cooling Set Point for Unoccupied Zone During Normal Occupied Building Mode	75°F (no setback)	75°F (no setback)	79°F Conference Rooms Only	79°F Conference Rooms and Private Offices*
	Zone Temperature Cooling Set Point for Unoccupied Building Mode	80°F	80°F	80°F	80°F
Heating Temperature Set Points	Zone Temperature Heating Set Point for Occupied Building Mode	70°F	70°F	70°F	70°F
	Zone Temperature Heating Set Point for Unoccupied Zone During Normal Occupied Building Mode	70°F (no setback)	70°F (no setback)	66°F Conference Rooms Only	66°F Conference Rooms and Private Offices*
	Zone Temperature Heating Set Point for Unoccupied Building Mode	60°F	60°F	60°F	60°F

*Temperature setback is used in simulation for private-office zones only when the probability that all three offices in a zone are empty is 50% or greater.

In this exploratory study of the impacts of OBC, the air-flow rate from the terminal box is, however, set to zero when all rooms served by the terminal box are vacant. No occupants are present so, in principle, no ventilation is required. This control practice may violate a requirement of Standard 62 -2007 (ANSI/ASHRAE 2007), which apparently requires the flow rate not be set below the area-only component of ventilation, but is used in this study to explore the potential savings from OBC of terminal boxes with common occupancy sensors. The authors believe this potential control practice is worth examining because any non-occupant-originating indoor pollutants that build up while the ventilation is off in conference rooms and private offices (the only spaces for which OBC for terminal boxes is considered in this study) will decrease relatively quickly as soon as an occupant enters and the terminal box begins to provide air flow for ventilation. Ventilation standards committees may decide to reconsider this constraint on ventilation control for some spaces if the potential energy savings are significant and the risk of exposure to unhealthy pollutant concentrations can be shown to be low.

Advanced occupancy sensors with their occupant counting capability can be used to modulate the ventilation air-flow rate to meet the needs of the actual number of occupants in a zone as a function of time. Common occupancy sensors cannot support this capability. Only Improved Case III includes this type of control of terminal-box air-flow rates based on advanced occupancy sensors with the flow rate modulated between zero when no occupants are present to 50% of the peak design primary air-flow rate (V_{max}) when the zone is fully occupied for conference rooms and from zero to 30% of V_{max} for private offices. Liu (2012) provides background information and the rationale for the selection of these ranges. As with OBC using common occupancy sensors, the air-flow rate is set to zero when there are no occupants in the zone served by the terminal box. As a result, advanced occupancy sensors provide incremental savings associated with modulating air-flow rates based on the variation in the number of occupants in each zone with time, resulting in additional energy savings.

Conference rooms, because of their variable occupancy and high design occupant densities, present a design challenge. Minimum ventilation rates at the design occupancy represent a high percentage of the overall supply air-flow rate, particularly, for interior conference rooms. At low occupancies and low loads, design minimum ventilation rates may exceed the supply air-flow rate required to maintain a comfortable room temperature, potentially causing the room to be overcooled, especially for interior conference rooms served by terminal boxes without reheat. Hydeman et al. (2005) state that the minimum air-flow rate is frequently set to 75% to 100% of V_{max} for interior conference rooms. Yu et al. (2007) proposed dynamic reset control logic for minimum and maximum air-flow rate set points based on the outdoor-air temperature, occupancy status, and outdoor-air intake ratio. They claim that a minimum air-flow rate set point of 50% of V_{max} is common practice. In an example for a series of terminal boxes used for an interior conference room, Stein (2005) uses a minimum ventilation air-flow rate set point greater than 50% of V_{max}. Based on this information, modulation of conference-room air-flow rates based on actual occupancy should, in addition to yielding energy savings, increase the comfort of occupants when much fewer than the design number of occupants are present.

The zone temperature set points for heating and cooling during scheduled occupied hours of the building are 70°F and 75°F, respectively, for all cases (see Table 8). These set points apply to all zones during all occupied hours for the Base Case and Improved Case I. The set points for conference rooms are reset to 66°F and 79°F, respectively for heating and cooling, for Improved Cases II and III (OBC for terminal boxes), when not occupied during occupied hours for the building. The set points for private-office zones are also reset to 66°F and 79°F for heating and cooling, respectively, when the probability of all three offices in the zone being unoccupied is 50% or less. All cases use reset of set points of 60°F for heating and 80°F for cooling during scheduled building unoccupied hours. Therefore, the differences in temperature control among the cases are: 1) that Improved Case II, which uses common occupancy sensors for OBC of terminal boxes, resets the heating and cooling set points for conference rooms when they are unoccupied, as indicated by the common occupancy sensors, and 2) Improved Case III, which uses advanced occupancy sensors for OBC of terminal boxes, resets the heating and cooling set points for conference rooms when they are unoccupied, as indicated by the advanced occupancy sensors, and for private-office zones when the probability of the entire zone being unoccupied is 50% or less.

2.3 Monetary Savings on Energy Purchases

The monetary value of the energy savings is given by the relation

$$CS_i = ES_{elec,i} \times P_{elec} + ES_{gas,i} \times P_{gas} , \qquad (8)$$

where CS_i is the monetary savings on site energy purchases for savings case i (e.g., "NoOBC to COS-LightOnly" or "COS-Light to COS-TB&Light"), $ES_{elec,i}$ and $ES_{gas,I}$ are respectively the energy savings for gas and electricity for savings case i, P_{gas} is the price of gas, and P_{elec} is the blended price of electricity combining the price per unit (kWh) of electricity used and an average demand charge expressed per unit of electricity used. The energy use by source (gas or electricity) for each building case at each location is obtained from simulations. The savings for each energy source for each savings case can be determined using Equations (3) through (7), evaluating the equations separately for electricity and gas. The applicable prices for electricity and gas by location are shown in Table 9. Each price shown is an average for the state in which the representative city is located.

Table 9. Average 2011 prices for electricity and natural gas for states in which the representative city in each climate zone is located (EIA 2012a, 2012b).

Climate Zone	City	State	Electricity ($/kWh)	Natural Gas ($/therm)
1A	Miami	FL	0.099	1.102
2A	Houston	TX	0.083	0.709
2B	Phoenix	AZ	0.095	0.999
3A	Memphis	TN	0.103	0.909
3B	El Paso	TX	0.083	0.709
3C	San Francisco	CA	0.113	0.827
4A	Baltimore	MD	0.138	1.034
4B	Albuquerque	NM	0.091	0.719
4C	Salem	OR	0.082	1.010
5A	Chicago	IL	0.086	0.814
5B	Boise	ID	0.064	0.820
6A	Burlington	VT	0.140	1.190
6B	Helena	MT	0.091	0.854
7	Duluth	MN	0.086	0.743
8	Fairbanks	AK	0.151	1.240

3. Energy and Monetary Savings

Energy savings are determined for each of the 15 U.S. climate zones using annual energy use estimates for the four control models defined in Table 7 and Table 8 and Equations (3) through (7). The values of annual energy use are obtained by simulating the annual performance of the buildings using EnergyPlus (DOE 2012a). National average impacts are determined by applying national weighting factors (see Figure 8) to the results for the individual climate zones and summing the results. The weighting factors for large office buildings used in this study are from weighting factors originally developed by Jarnagin and Bandyopadhyay (2010) from disaggregated construction volume data providing the floor area of new construction in the U.S. for the years 2003 through 2007.

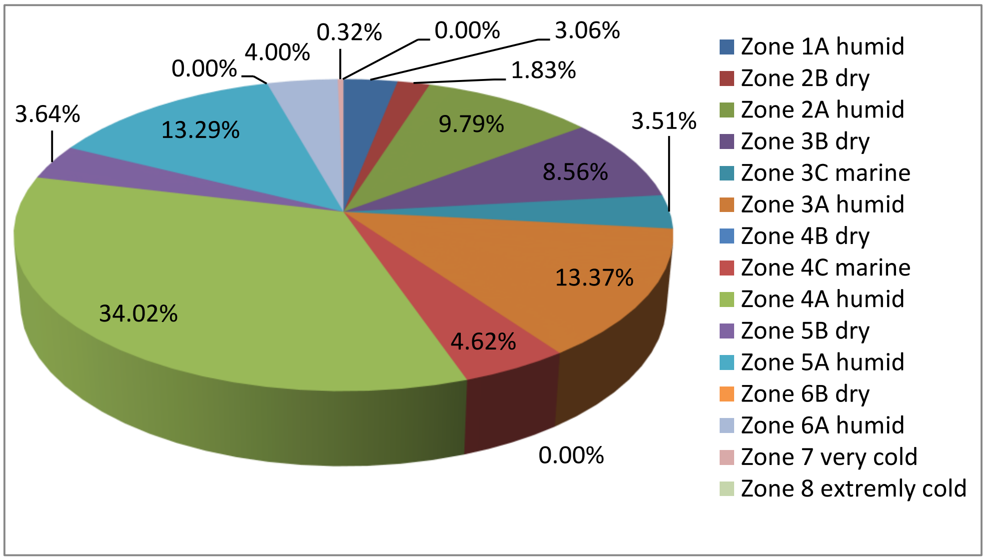

Figure 8. Climate-zone weighting factors based on fraction of national construction for large office buildings as defined by Jarnagin and Bandyopadhyay (2010)

3.1 Savings from Occupancy-Based Lighting Control

In this section, results are presented for the annual savings resulting from retrofit the Base Case building with occupancy-based control of lighting, using common occupancy sensors. Common occupancy sensors have been installed for selected rooms (e.g., conference rooms) in commercial buildings in the U.S. for many years. Although advanced occupancy sensors could be used for this purpose, their higher cost would likely require that they provide control for systems in addition to lighting to be cost effective.

The energy savings are determined using Equation (7) as the difference between the annual energy consumption for the Base Case and for Improved Case I. Improved Case I represents occupancy-based control for lighting only, using common occupancy sensors. Occupancy-based control of terminal boxes is not included. Lighting for private offices and conference rooms is turned off based on a signal from the occupancy sensor, which is often integrated into light switches, when rooms are not occupied. Occupancy sensors are not installed in other kinds of rooms. The core (interior) zone, which represents 71% of the total space on the above-ground floors (and 66% of the total building floor area), is an open-plan office with no occupancy control for lighting.

Figure 9 compares the average annual site energy use per unit area of the building (commonly known as the energy utilization index, EUI) for Improved Case I and the Base Case for the 15 U.S. climate zones. The numerical results are provided in Appendix A-4. Figure 10 shows the magnitude of the energy savings ($ES_{NoOBC\ to\ COS\text{-}\ LightOnly}$) from Equation (7) for retrofit of lighting control with common occupancy sensors and as a percentage of the base case energy consumption for 15 climate zones. The energy savings as a percentage of the total building energy use are 1.1% or less across all climate zones, with absolute savings ranging from 0.08 kBtu/ft^2-y for Fairbanks to 0.55 kBtu/ft^2-y for Miami, with savings between 40 and 50 kBtu/ft^2-y for 11 of the 15 climate zones. The energy savings generally decrease for colder climates because the amount of heat rejected to the indoor spaces decreases with the use of occupancy sensors for lighting control because less lighting is used. Heat rejected from lights contributes to meeting the heating load. With less heat rejected, more heating must be provided by the heating system, thus lowering the net energy savings.

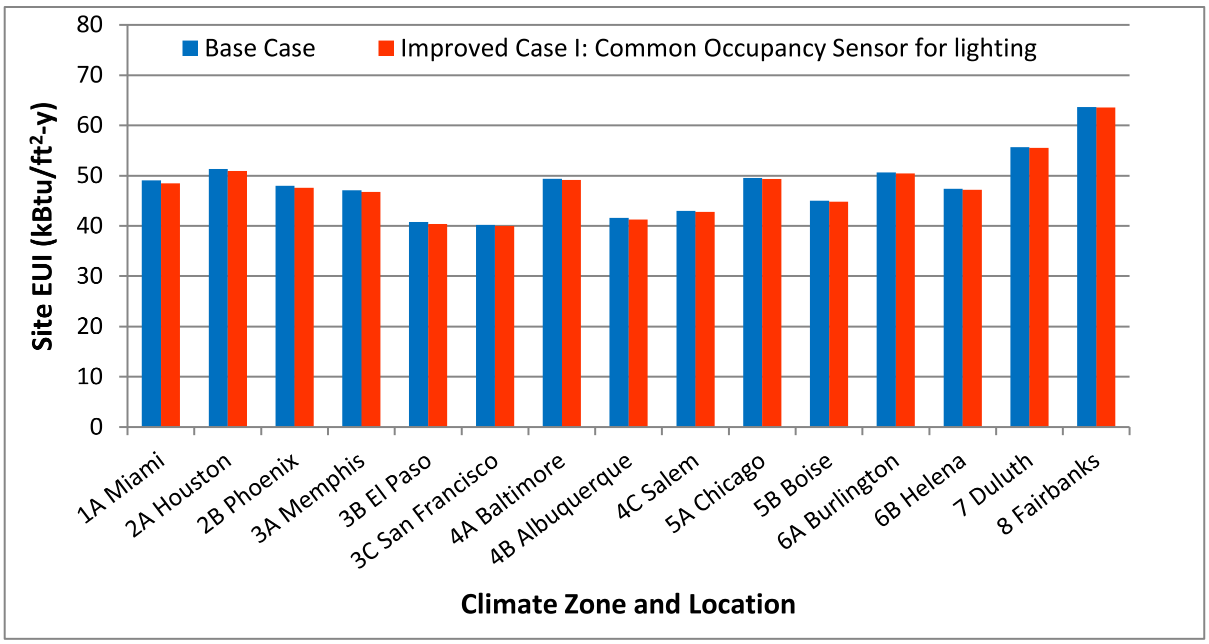

Figure 9. Values of the annual site EUI for Improved Case I and the Base Case for large office buildings at representative locations in the 15 U.S. climate zones.

The monetary savings on energy expenditures corresponding to the energy savings for electricity and natural gas given in Appendix Section A-6 (which sum to the totals shown in Figure 10) and the average energy prices given in Table 9 are shown in Figure 11. Because energy prices vary with the location, the cities with the largest and smallest monetary savings differ from those with the largest and smallest energy savings. Monetary savings range between \$3800/y (\$0.008/ft^2-y) for Boise, Idaho, which has the lowest electricity price, to \$10,000/y (\$0.020/ft^2-y) for Baltimore, which has the highest electricity price.

Table 10 shows the national (weighted) average site EUIs for the primary building end uses/sub-components and the whole building based on the zonal weighting factors in Figure 8. The interior lighting savings are the same for all locations. There are some savings for cooling and fan operation from decreased heat rejection from lighting; however, the building with occupancy-based lighting control consumes more heating energy than the Base Case building as noted previously, decreasing the net savings.

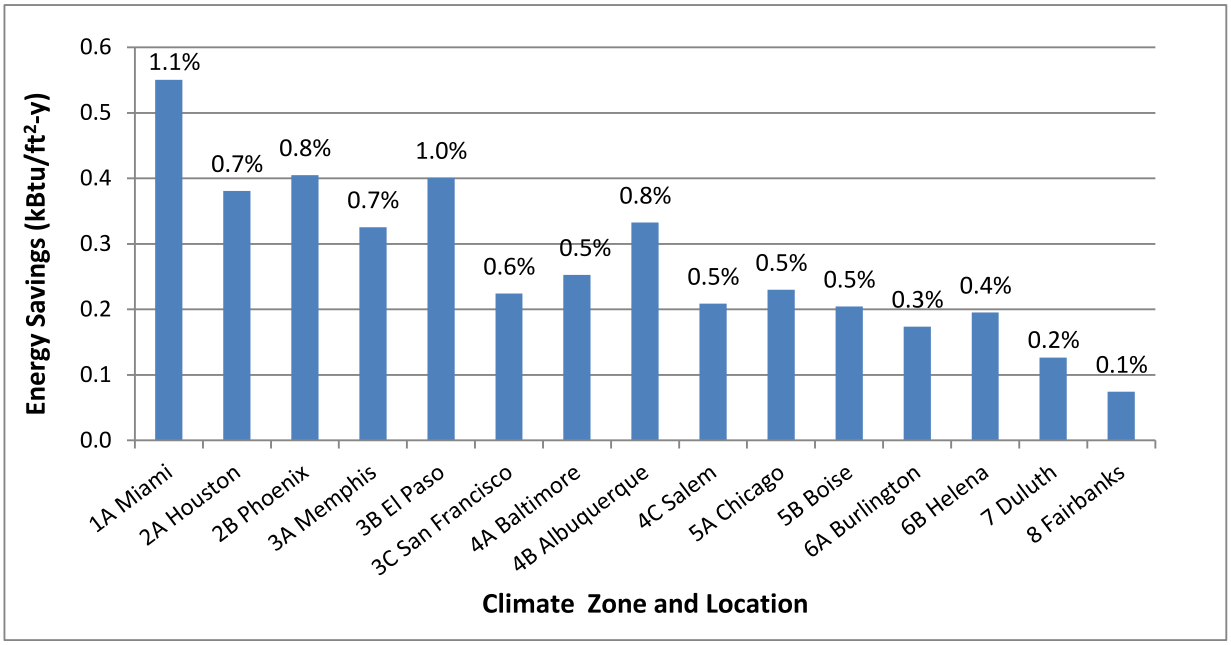

Figure 10. Annual site energy savings in kBtu/ft^2-y attributable to adding lighting control that uses common occupancy sensors in private offices and conference rooms to the Base Case large office building. Also shown above each bar is the corresponding savings as a percentage of the Base Case annual energy consumption of the building.

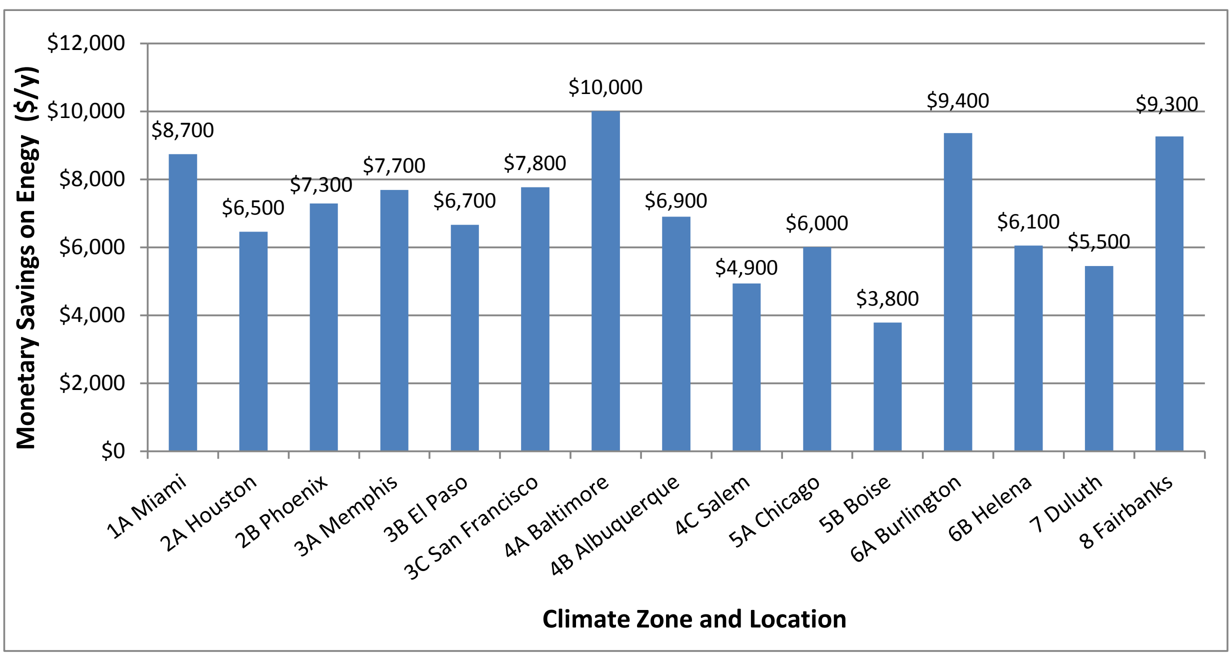

Figure 11. Annual monetary savings on energy expenditures resulting from retrofit of common occupancy sensor-based control of lighting for private offices and conference rooms in the Base Case large office building.

Table 10. National-average site EUIs for the Base Case and Improved Case I by affected end use and for the whole building and energy savings in kBtu/ft^2-y and as a percentage of the base case total building energy use for retrofit of the Base Case building with OBC for lighting and terminal boxes using common occupancy sensors .

Case	National Average Annual Site Energy Use (kBtu/ft^2-y)						Energy Savings	
	Interior Lights	Fans	Pumps	Cooling	Heating	Whole-Building	kBtu/ft^2-y	% of Base Case Energy Use
Base Case	9.77	2.14	2.27	6.88	9.00	47.8	0.3	0.6%
Improved Case I	9.22	2.13	2.27	6.85	9.30	47.5		

3.2 Savings from Occupancy-Based Control Using Common Occupancy Sensors

In this section, the annual savings for two retrofits of OBC using common occupancy sensors are presented: 1) retrofit of the Base Case building with OBC for lighting and terminal boxes and 2) retrofit of the Improved Case I building, which has OBC for lighting only, with OBC for terminal boxes. In both cases, common occupancy sensors provide the sensed data for OBC. The savings for the first retrofit ($ES_{NoOBC\ to\ COS\text{-}TB\&Light}$) are determined using Equation (4) as the difference between the annual energy consumption for the Base Case and Improved Case II. The Base Case has no OBC, and Improved Case II has OBC for both lighting and terminal-box control using common occupancy sensors. The savings for the second retrofit ($ES_{COS\text{-}Light\ to\ COS\text{-}TB\&Light}$) are determined using Equation (5) as the difference in annual energy consumption between Improved Case I and Improved Case II. Improved Case I uses common occupancy sensors to provide OBC for lighting only; therefore, the difference in annual energy savings between Improved Cases I and II represents the incremental savings associated with adding OBC for terminal boxes using common occupancy sensor to a building with common occupancy sensors used for lighting control only.

When controlled with common occupancy sensors, lighting is automatically turned off when all occupants vacate a room. The terminal box serving a zone is set into occupied standby mode when all rooms in the zone become unoccupied during scheduled building occupied hours. The standby mode is not triggered if even one occupant remains in the zone. Common occupancy-sensor-based control of lighting and HVAC is implemented for all private offices and conference rooms. There is no lighting occupancy control for the open office space (which represents 66% of the total building floor area).

Figure 12 compares the annual site energy use per unit area of the building with no OBC (E_{Base}) and with OBC for lighting and terminal boxes using common occupancy sensors ($E_{Improved\ II}$) for all 15 U.S. climate zones. The numerical results are tabulated in Appendix A-4. Figure 13 shows the magnitude of the energy savings magnitude and the savings as a percentage of E_{Base} for all climate zones.

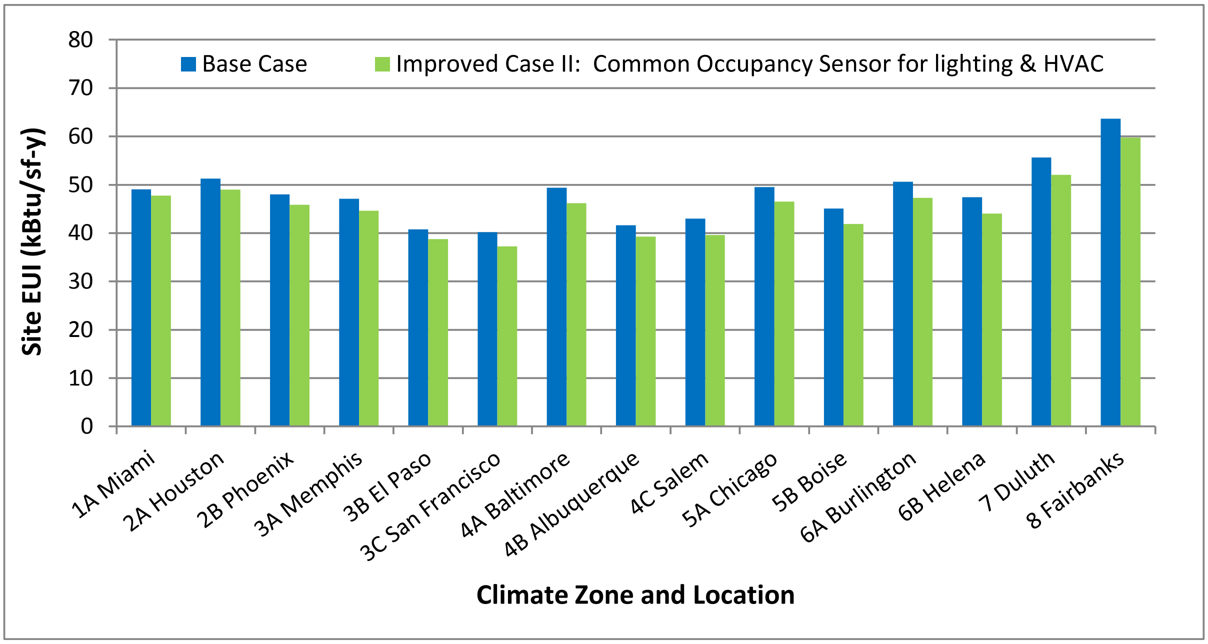

Figure 12. Values of the annual site EUI for the Base Case and Improved Case II for large office buildings in the 15 U.S. climate zones

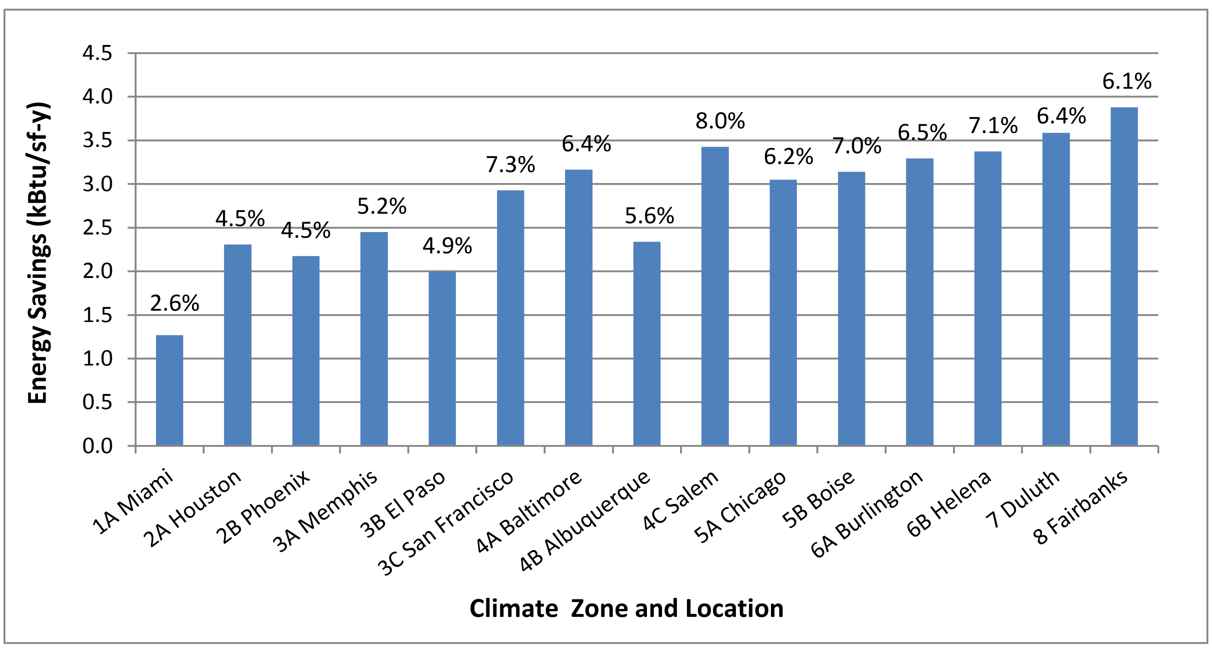

Figure 13. Annual site energy savings in kBtu/ft^2-year attributable to adding OBC that uses common occupancy sensors to control lighting and terminal boxes to the Base Case large office building for private offices and conference rooms. Also shown above each bar is the corresponding savings as a percentage of the Base Case annual energy consumption of the building.

The total site energy savings are between 1.3 kBtu/ft^2-y for Miami, the warmest climate, and 3.9 kBtu/ft^2-y for Fairbanks, the coldest climate. The savings as a percentage of the annual Base Case energy consumption for the locations lie between 2.6% for Miami and 8.0% for Salem, Oregon, in climate zone 4C for which total annual 65°F heating degree days (HDD) are between 2000 and 3000, much less than the minimum annual HDD of 7000 for climate zone 8, where Fairbanks is located. In general, site energy savings increase from warmer climates to colder climates.

The monetary savings on energy expenditures, which are shown in Figure 14, range from $15,000/y ($0.030/ft^2-y) for Miami to $44,200/y ($0.089/ft^2-y) for Fairbanks. Baltimore and Burlington, Vermont, have the next largest monetary savings at $36,400/y ($0.073/ft^2-y) after Fairbanks. The next largest savings is considerably lower at $24,500 ($0.049/ft^2-y) for Duluth, 33% less than the savings for Baltimore and Burlington. Fairbanks has the largest site energy savings at about 3.9 kBtu/ft^2-y and the highest prices for both electricity and natural gas, leading to the largest monetary savings. Although Burlington and Baltimore have only the fifth and sixth largest energy savings, their relatively high energy prices (see Table 9) result in their second highest monetary savings after Fairbanks. Burlington has the second highest prices for both electricity at $0.140/kWh and natural gas at $1.190/therm, while Baltimore has the second highest price of $0.138/kWh for electricity and the third highest gas price at $1.034/therm. Twelve of the 15 locations have annual monetary savings between $15,000/y ($0.030/ft^2-y) and $24,000/y ($0.048/ft^2-y). Numerical results for all cases are tabulated in Appendix A-4.

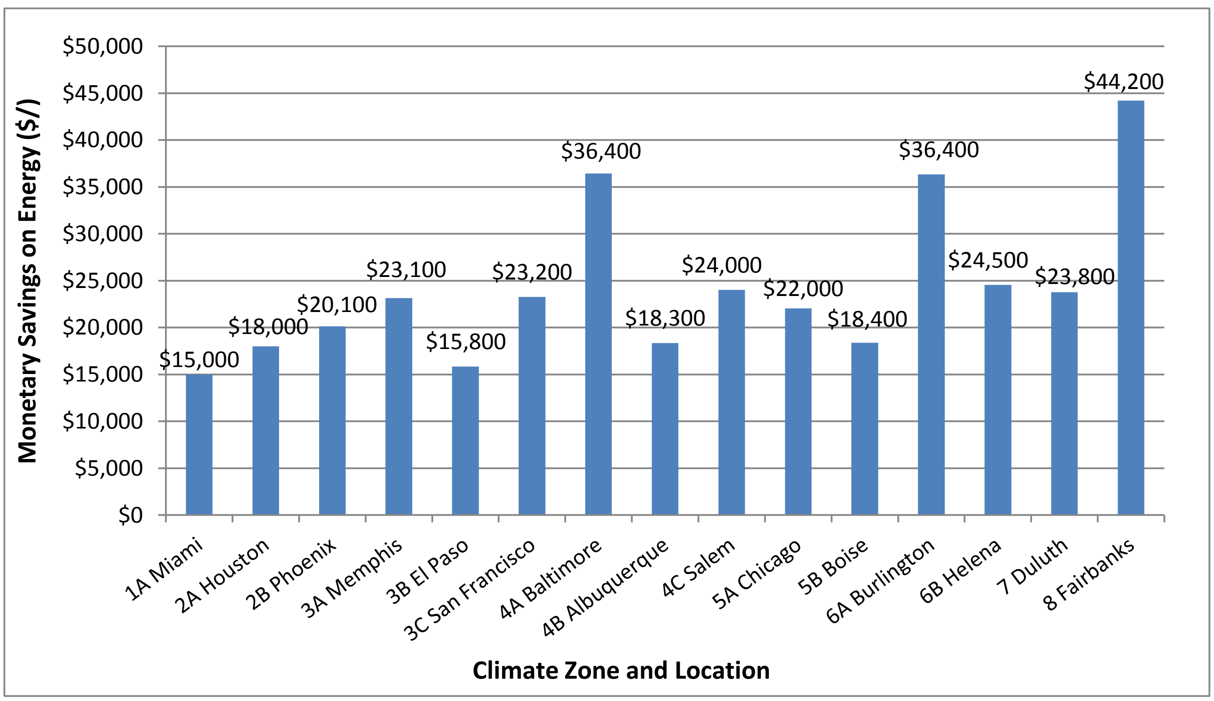

Figure 14. Annual monetary savings on energy expenditures from retrofit of common occupancy sensors for lighting and terminal-box control for private offices and conference rooms in the Base Case.

Figure 15 compares the annual site energy use per unit area of the large office building with OBC using common occupancy sensors for lighting only ($E_{Improved\ I}$) to the EUI for the building with OBC for both lighting and terminal-box control ($E_{Improved\ II}$). The corresponding site energy savings ($ES_{COS\text{-}Light\ to\ COS\text{-}}$

$_{TB\&Light}$) are shown for all climate zones in Figure 16. These are the incremental savings from adding OBC for terminal-box control to a building that already has OBC for lighting using common occupancy sensors. The incremental energy savings from adding terminal-box control with common occupancy sensors lie between 0.7 kBtu/ft^2-y for Miami to 3.81 kBtu/ft^2-y for Fairbanks; the savings as a fraction of the Improved Case I energy consumption (i.e., the building with OBC only for lighting) based on common occupancy sensors ranges between 1.4% for Miami to 6.7% for San Francisco.

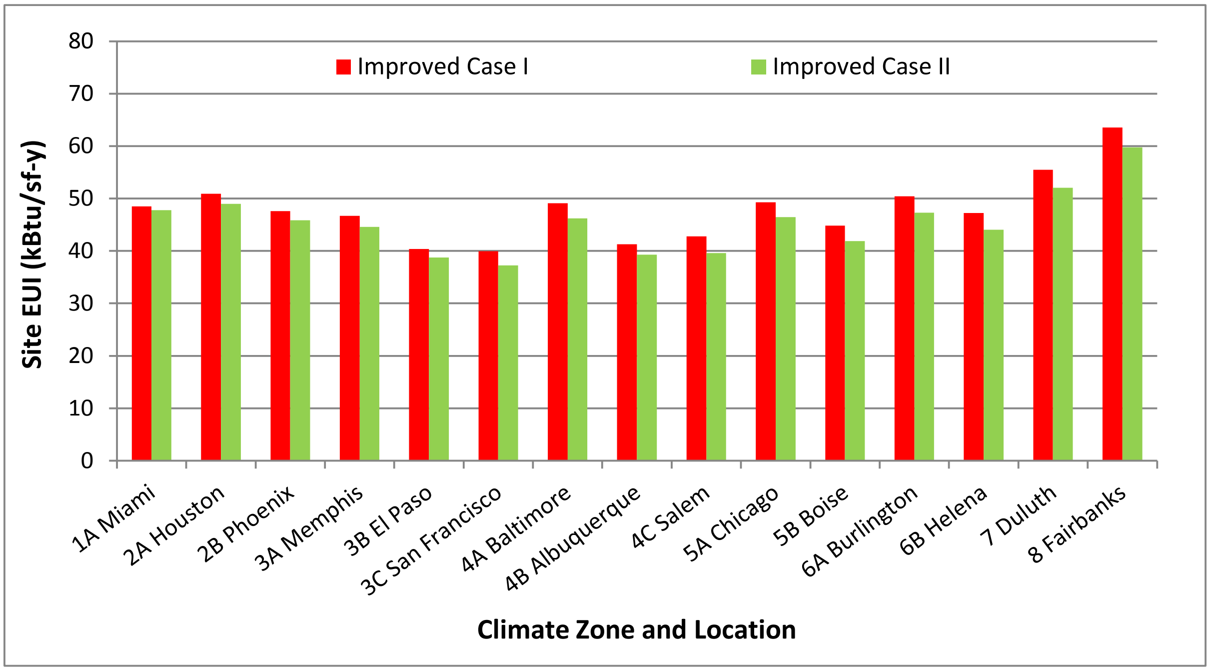

Figure 15. Values of the annual EUI for Improved Case II and Improved Case I for large office buildings in the 15 U.S. climate zones

The monetary savings on energy expenditures, which are shown in Figure 17, range from \$6000/y (\$0.012/ft^2-y) for Miami to \$34,900/y (\$0.070/ft^2-y) for Fairbanks. The second and third highest monetary savings are \$26, 900/y (\$0.054/ft^2-y) for Burlington, Vermont, and \$26,200/y (\$0.053/ft^2-y) for Baltimore. The next highest after Baltimore is \$18,400/y (\$0.037/ft^2-y) for Helena, Montana. Eleven of the 15 climate zones have monetary savings between \$9100/y (\$0.018/ft^2-y) and \$18,400/y (\$0.037/ft^2-y).

The national (weighted) average site EUIs for the primary building end uses/sub-components and the whole building based on the zonal weighting factors in Figure 8 are shown in Table 11 for the Base Case and the two cases that use common occupancy sensors for OBC (Improved Case I and Improved Case II). Improved Case I uses OBC for lighting only, while Improved Case II uses OBC for lighting and terminal boxes. Table 12 provides the national-average site energy savings for the large office building with OBC for lighting and terminal boxes compared to the same building without any OBC and with OBC for lighting only. Because the magnitude of the savings for occupancy-based lighting control are small compared to the savings from OBC used for HVAC, the savings differ by only 0.3 kBtu/ft^2-y, which is 11% of the larger savings estimate.

Comparing the savings for OBC using common occupancy sensors in Table 12 to the savings for lighting alone (see Table 10), savings for terminal-box control are more than a factor of 8 greater.

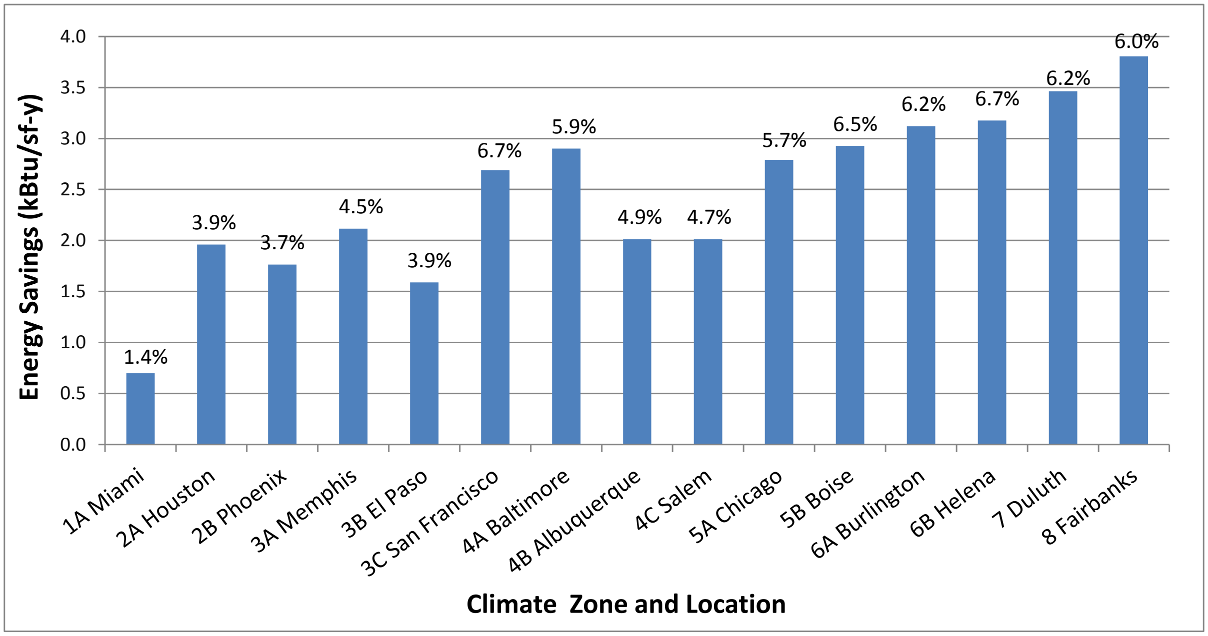

Figure 16. Annual site energy savings in kBtu/ft^2-y attributable to adding OBC based on common occupancy sensors for controlling terminal boxes for zones of private offices and conference rooms to a large office building that already has occupancy-based lighting control using common occupancy sensors (Improved Case I). Also shown above each bar is the corresponding savings as a percentage of the Improved Case I annual energy consumption of the building.

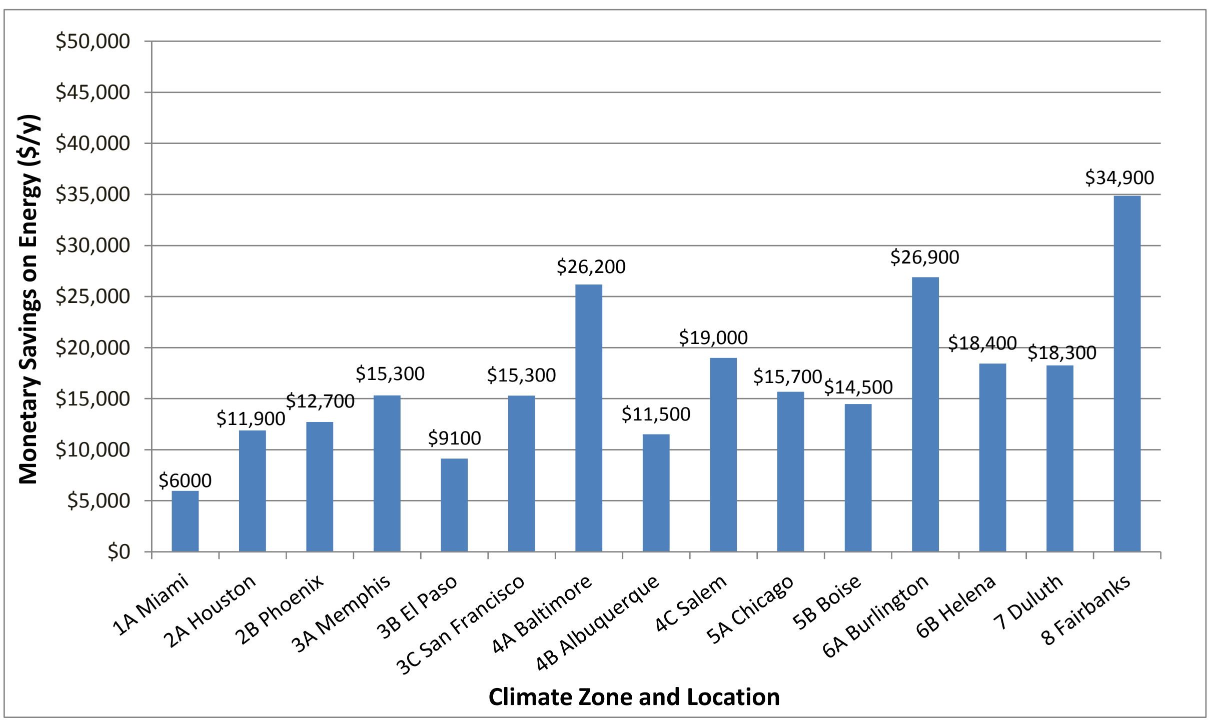

Figure 17. Annual monetary savings on energy expenditures from retrofit of OBC for terminal boxes using common occupancy sensors to private offices and conference rooms in a large office building that already has OBC for lighting.

Table 11. National average site EUIs for the Base Case, Improved Case I and Improved Case II by major end use and the whole building

Building Case	National Average Annual Site Energy Use (kBtu/ft^2-y)					
	Interior Lights	Fans	Pumps	Cooling	Heating	Whole-Building
Base Case	9.77	2.14	2.27	6.88	9.00	47.8
Improved Case I	9.22	2.13	2.27	6.85	9.30	47.5
Improved Case II	9.22	1.90	2.22	6.54	7.37	45.0

Table 12. Energy savings for OBC using common occupancy sensors

Savings Variable	Description	Cases Compared		National Average Site Energy Savings	
		Initial Case	Final Retrofitted Case	kBtu/ft^2-y	% of Initial Case Energy Use
$ES_{\text{NoOBC to COS-TB\&Light}}$ [see Equation (4)]	Retrofit of large office building having no OBC with OBC for lighting and terminal boxes using common occupancy sensors	Base Case	Improved Case II	2.8	5.9%
$ES_{\text{COS-Light to COS-TB\&Light}}$ [see Equation (5)]	Retrofit of large office building having common occupancy sensor for OBC of lighting with OBC for terminal boxes that also uses common occupancy sensors	Improved Case I	Improved Case II	2.5	5.3%

3.3 Savings from Occupancy-Based Control Using Advanced Occupancy Sensors

Advanced occupancy sensors count the number of occupants in rooms in which they are installed. As a result, for lighting control, the delay time after all occupants are initially detected to have left a room until lights are turned off can be decreased from 15 or 20 minutes, which is typical for lighting control with common occupancy sensors, to 5 seconds. Advanced occupancy sensors can also be used to reset the minimum terminal-box damper position, which determines the minimum air-flow rate set point, based on the measured zone occupancy. For this study, the changes in the occupancy of conference rooms and private offices are modeled as described in Section 2.1.

The savings from retrofit of advanced occupancy sensors for OBC are evaluated for two different initial circumstances: 1) retrofit of the Base Case large office building, which has no OBC, with OBC for lighting and terminal boxes for which results are presented in Section 3.3.1, and 2) comparison of the building having advanced sensors for OBC for lighting and terminal boxes with the building using common occupancy sensors for OBC for lighting and terminal boxes for which results are presented in Section 3.3.2. The second case provides estimates of the incremental value of advanced occupancy sensors for OBC compared to using common occupancy sensors. This is particularly important because advanced occupancy sensors, although under development, do not yet exist, and their cost is likely to significantly exceed the cost of common occupancy sensors, which are widely used for lighting control today. The savings for the first situation ($ES_{\text{NoOBC to AOS-TB\&Light}}$) are determined using Equation (3) as the difference in annual site energy consumption between the Base Case and Improved Case III. The savings for the second situation ($ES_{\text{COS-TB\&Light to AOS-TB\&Light}}$) are determined using Equation (6) as the difference between the annual site energy consumption for the Improved Case II building and the Improved Case III building, providing the incremental benefit of using advanced occupancy sensors rather than common occupancy sensors.

3.3.1 Savings from Using Advanced Occupancy Sensors for OBC

Figure 18 compares the average annual site energy EUI for Improved Case III and the base case for all 15 climate zones. The numerical results on which this and subsequent figures are based are given in Appendix A-4. Figure 19 shows the energy savings from retrofit of occupancy-based control of lighting and terminal boxes using advanced occupancy sensors, expressed in kBtu/ft^2-y and as a percentage of the Base Case energy consumption for all U.S. climate zones. The total building energy savings range from 2.4 kBtu/ft^2-y in Miami to 12.1 kBtu/ft^2-y for Fairbanks. The percentage savings are between 5% for Miami to 23% for Salem, Oregon, with 9 of the 15 climate zones (mostly cooler) having values greater than 19% and 12 of the 15 having savings of 15% and greater. Only the warm, humid climate of Miami has savings less than 13% of the energy consumption of the Base Case building.

The monetary savings on energy expenditures corresponding to the energy savings shown in Figure 19 and the average energy prices given in Table 9 are shown in Figure 20. The annual monetary savings on energy range between $23,500 ($0.047/ft^2-y) for Miami and $110,900 ($0.222/ft^2-y) for Fairbanks. The second highest savings of $100,300/y ($0.201/ft^2-y) are for Baltimore. Thirteen of the 15 locations (87%) have savings greater than $40,000/y ($0.080/ft^2-y). Only Miami and El Paso ($33,400/y) have lower monetary savings.

National-average EUIs and energy savings for retrofit of the Base Case building with OBC using advanced occupancy sensors based on the weighting factors in Figure 8 are shown in Table 13. The heating savings dominate the total, representing 71% of the total savings. Comparison of the results in Table 12 and Table 13 shows that OBC using advanced occupancy sensors increases the nationally weighted average energy savings from 5.9% to 17.9% compared to OBC using common occupancy sensors (an increase of more than 200% in national-average energy savings). The simulation results also show that there is no significant increase in the occurrence of hours during which acceptable zone temperatures are not met associated with use of advanced occupancy sensors for OBC.

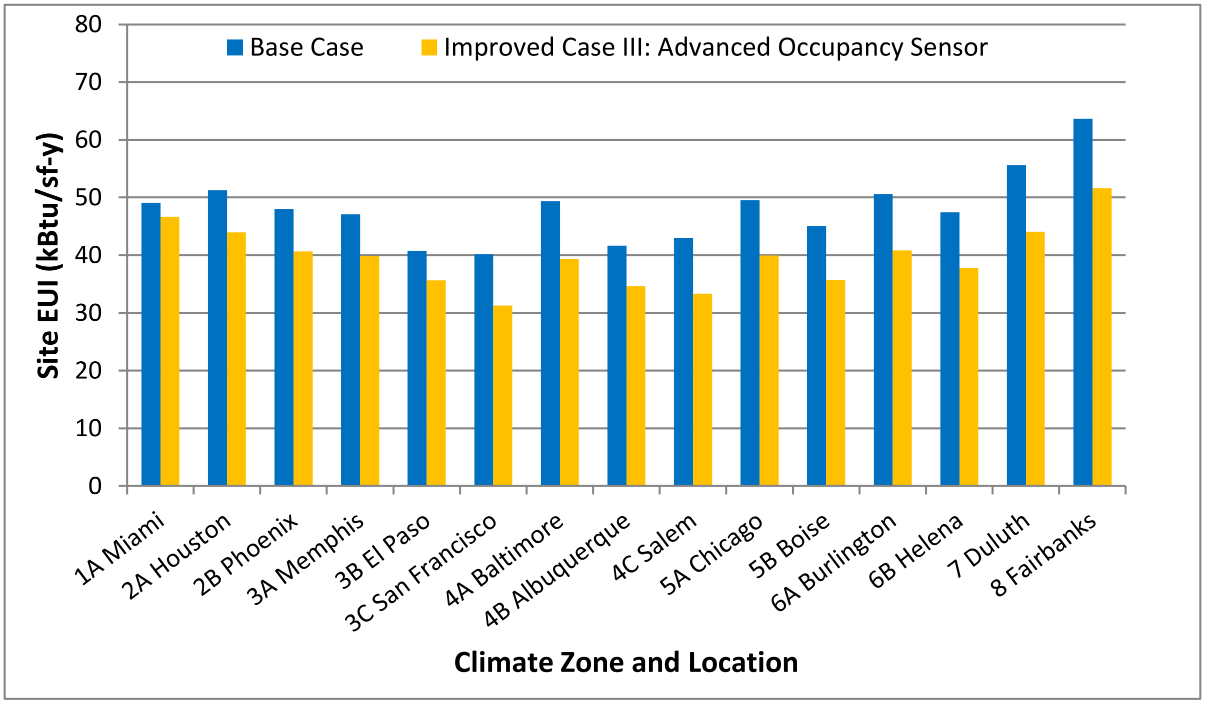

Figure 18. Annual site energy EUIs for Improved Case III and the Base Case for large office buildings in the 15 climate zones of the U.S.

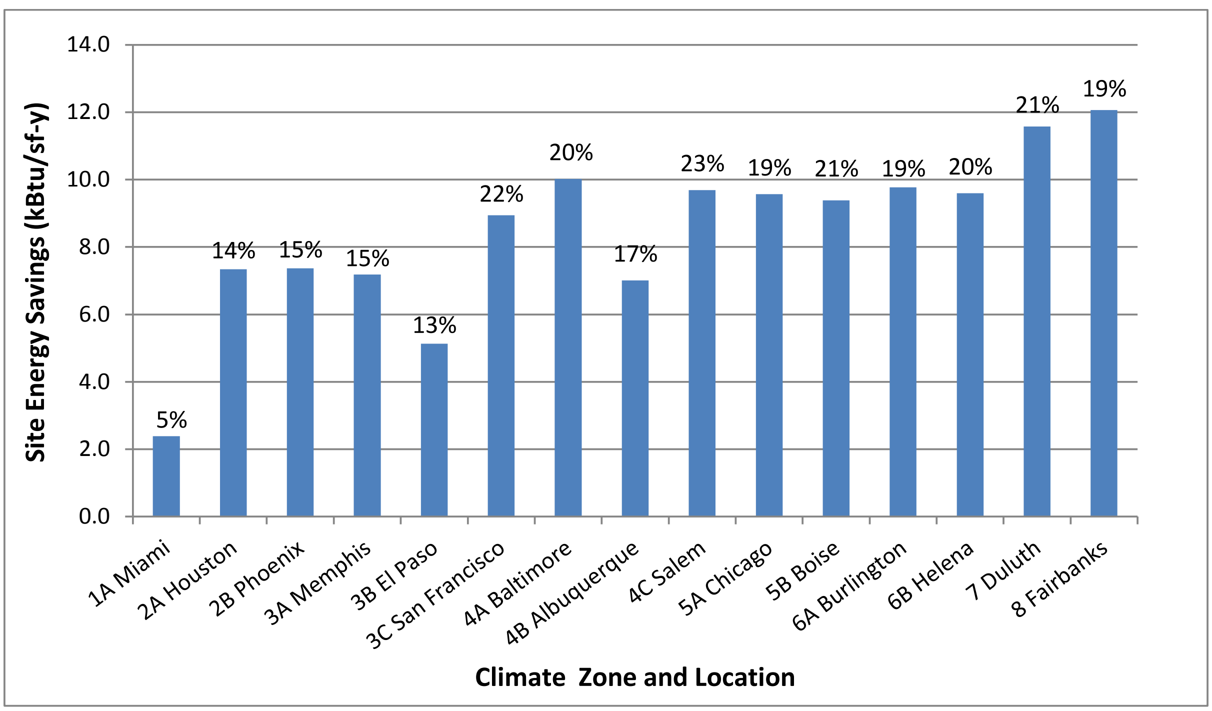

Figure 19. Annual site energy savings in kBtu/ ft^2-year attributable to adding OBC that uses advanced occupancy sensors to control lighting and terminal boxes for private offices and conference rooms to the Base Case large office building. Also shown above each bar is the corresponding savings as a percentage of the Base Case annual energy consumption of the building.

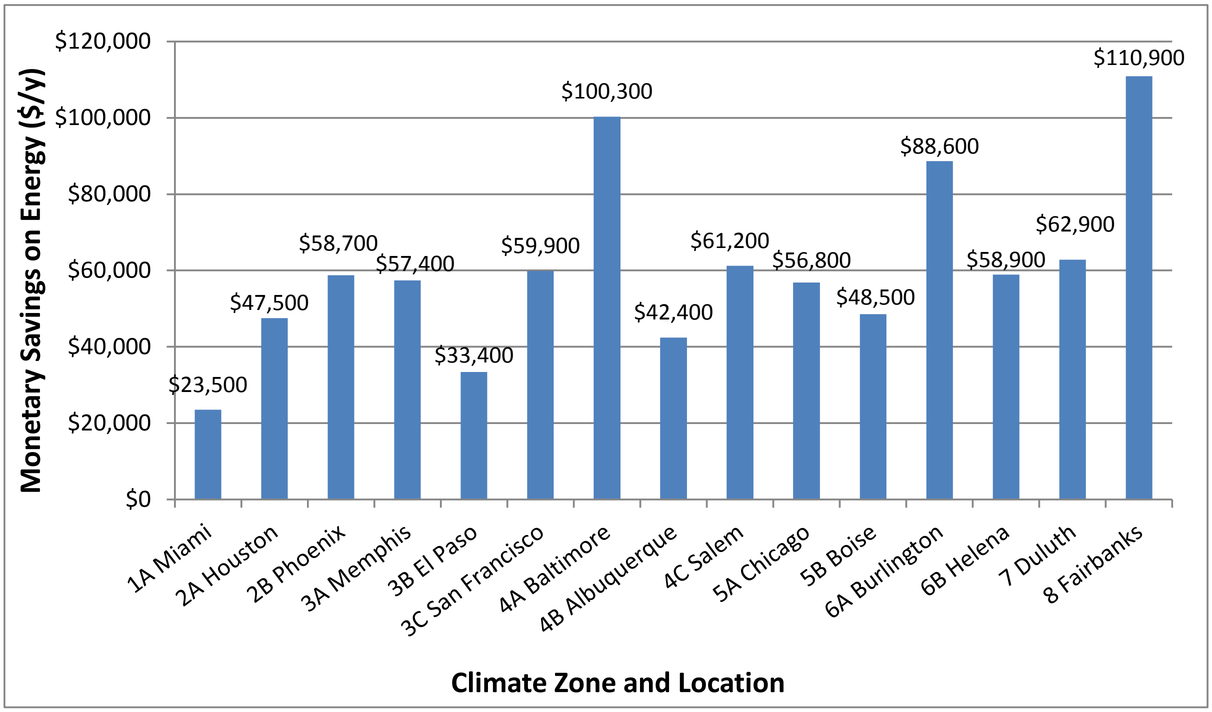

Figure 20. Annual monetary savings on energy expenditures from retrofit of advanced occupancy sensors for lighting and terminal-box control for private offices and conference rooms in the base case large office building.

Table 13. National-average site EUIs for the Base Case and Improved Case III by major end use and for the whole building and energy savings in kBtu/ft^2-y and as a percentage of the base case total building energy use for retrofit of the Base Case building with OBC for lighting and terminal boxes using common advanced sensors.

Case	National Average Annual Site Energy Use (kBtu/ft^2-y)						Energy Savings	
	Interior Lights	Fans	Pumps	Cooling	Heating	Whole-Building	kBtu/ft^2-y	% of Base Case Energy Use
Base Case	9.77	2.14	2.27	6.88	9.00	47.8	8.5	17.8%
Improved Case III	8.86	1.53	2.22	5.95	2.95	39.3		

3.3.2 Incremental Savings from Using Advanced Occupancy Sensors for OBC

Figure 21 compares the site energy consumption of the Base Case, Improved Case II and Improved Case III. Figure 22 explicitly shows the savings resulting from retrofitting the Base Case large office building with OBC for terminal boxes and lighting based on common occupancy sensors (Improved Case II) and advanced occupancy sensors (Improved Case III). These figures show that the energy savings for OBC using advanced occupancy sensors exceeds the savings attained with common occupancy sensors by a factor of about 2 for very hot climate zones (Miami and El Paso), where the savings are minimum, and by about a factor of 3 for other climate zones.

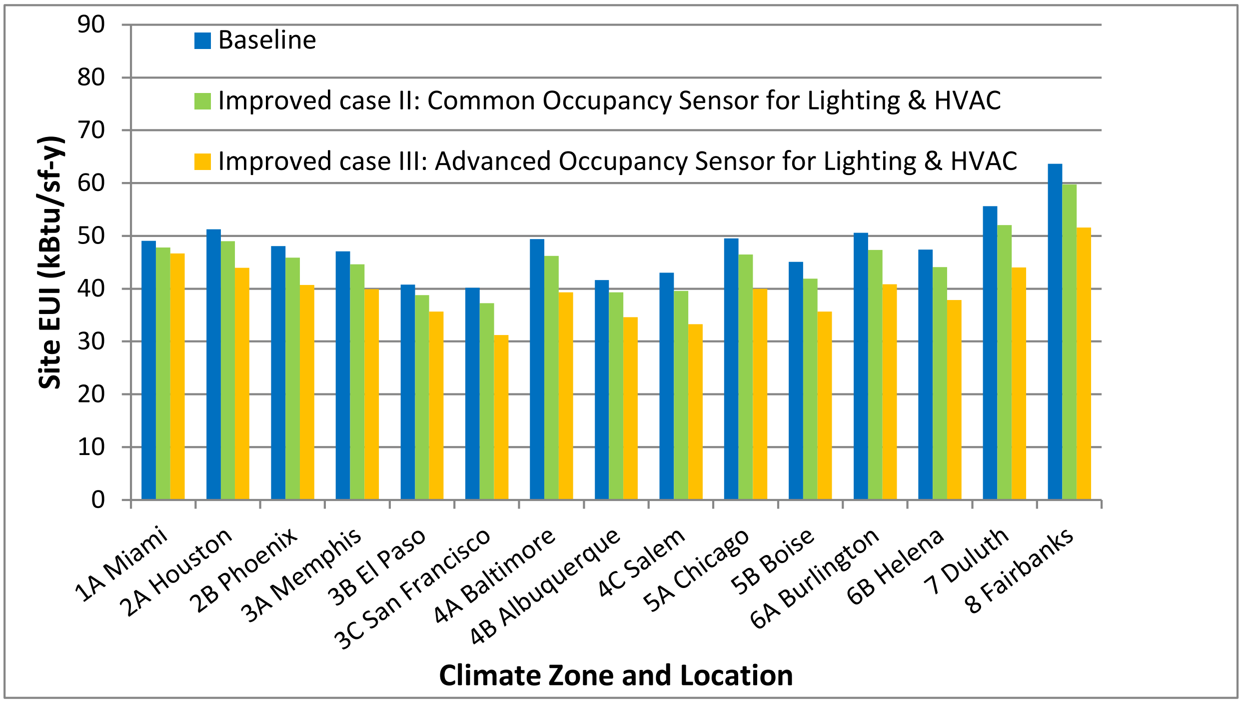

Figure 21. Comparison of annual site energy consumption for the Base Case, Improved Case II and Improved Case III

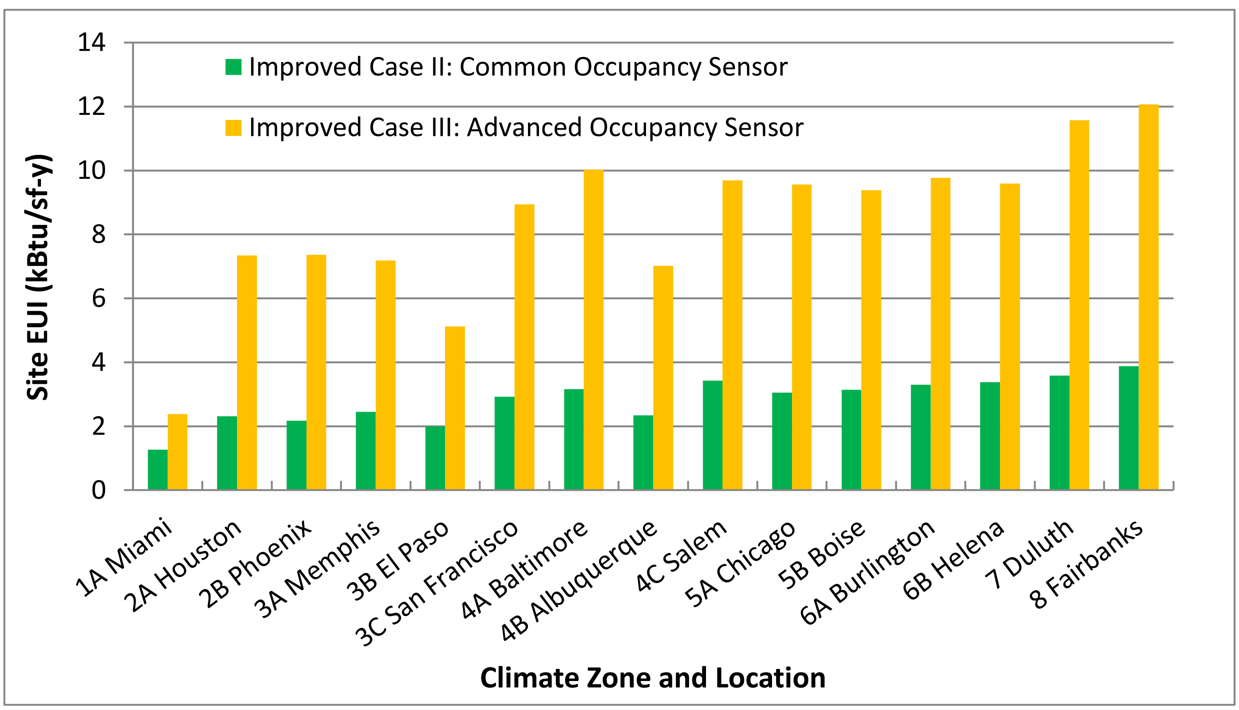

Figure 22. Site energy savings for OBC for lighting and terminal boxes using common occupancy sensors and advanced occupancy sensors

The incremental site energy savings associated with using OBC based on advanced occupancy sensors over using common occupancy sensors are shown in Figure 23 for the 15 U.S. climate zones. Miami (climate zone 1A) has the smallest incremental savings of 1.1 kBtu/ft^2-y, followed by El Paso (climate zone 3B) with incremental savings of 3.1 kBtu/ft^2-y. The incremental energy savings for all other climate zones exceed 4.5 kBtu/ft^2-y, with Fairbanks (climate zone 8) having the largest savings of 8.1 kBtu/ft^2-y.

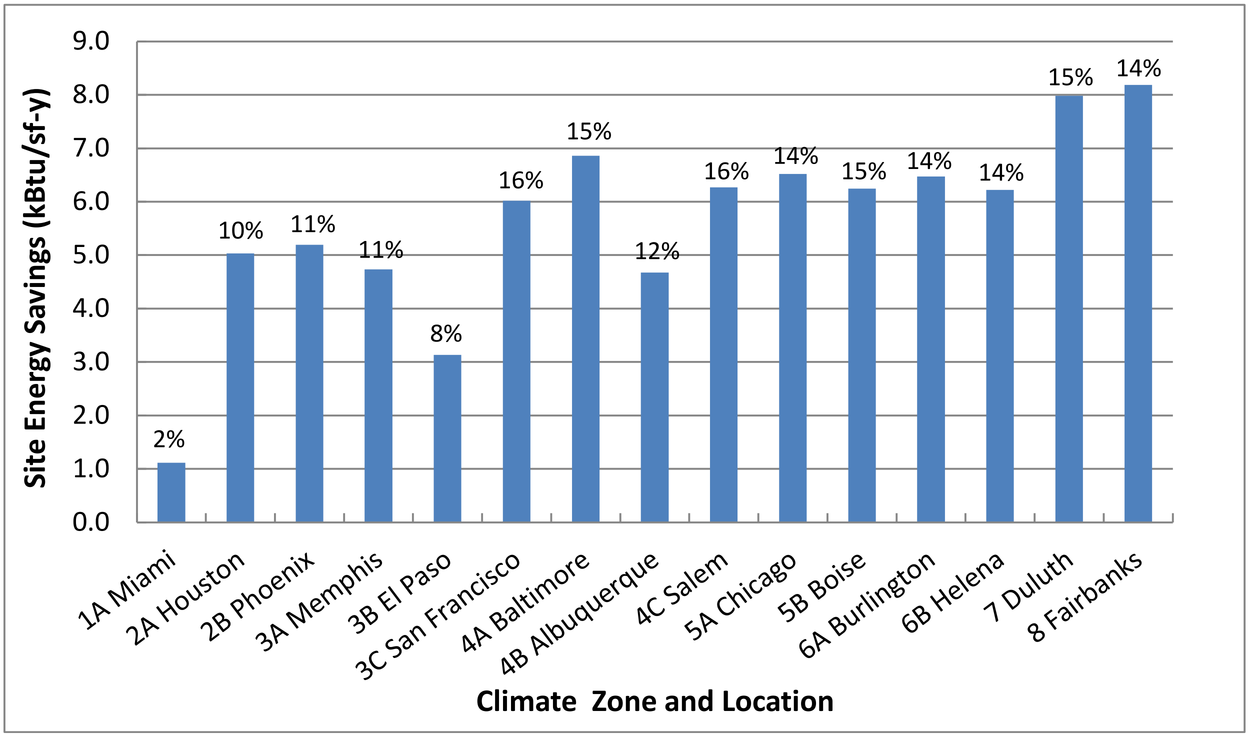

Figure 23. Incremental site energy savings associated with using advanced occupancy sensors compared to using common occupancy sensors for OBC of lighting and terminal boxes in large office buildings

4. Research and Development Needs

This study evaluates the potential savings from deployment of OBC of terminal boxes and lighting based on both common occupancy sensors and advanced occupancy sensors for large office buildings.

To realize the savings potential for different building types, ages, and system types will require additional information and further investigation. Some key needs include the following.

- Other commercial building types should be examined to evaluate the potential for benefits from use of OBC. Some types should be excluded readily because of relatively constant occupancy. Others showing potential should be analyzed.

- This study used one prototype building to analyze the energy savings potential of OBC. To better understand the effect of building vintage on the savings potential, the range of building ages should be subdivided into smaller age ranges and the savings evaluated for each range to better understand the types and ages of buildings for which OBC will be most economic and yield the greatest savings.

- Relatively recent requirements for ventilation air-flow rates were used in this study. Actual rates in existing buildings are potentially much higher than the values used. Data should be collected to better understand the distribution of actual ventilation rates in the existing commercial building stock.

- A market analysis is needed to project the cost of OBC systems and their installation to better understand the likely costs of the technology, which with the savings (e.g., from this study) can then be used to estimate the life-cycle costs and payback periods for OBC.

- The advanced occupancy sensing hardware and the control algorithms required for terminal-box OBC does not yet exist. Therefore, development is required before it can be deployed across the commercial buildings sector. Although advanced occupancy sensors are under development, adaptation to building control and integration with building control systems remains a barrier to the emergence of solutions for occupancy-based control. Brambley et al. (2012) provide a proposed plan for development and commercialization of the necessary technology.

- Research and development should include field testing of OBC using both common and advanced occupancy sensors to validate the potential savings indicated by building-energy simulations.

5. Conclusions

Several key conclusions can be reached based on the analysis of OBC for HVAC terminal boxes and lighting in large office buildings presented in this report. Large office buildings account for about 4.4 billion ft^2 of floor area in the U.S., representing about 6.1% of total commercial floor space and a comparable fraction of total commercial building energy consumption. Because of the prevalence of VAV HVAC systems in large office buildings, they are compatible with OBC for control of VAV terminal boxes are a likely promising target for deployment of this control strategy. They were thus selected for analysis in this study. Key conclusions from the study follow.

- Site energy savings as large as 12 kBtu/ft^2-y (about 20% of pre-retrofit annual energy consumption) can be achieved from retrofit of OBC based on advanced occupancy sensors in large office buildings in the cold climate zones of Duluth and Fairbanks (climate zones 7 and 8).

- Site energy savings from about 9 to 10 kBtu/ft^2-y (19% to 23% of pre-retrofit annual energy consumption) result from use of OBC based on advanced occupancy sensors in the moderate climates of Helena (zone 6B), Burlington (zone 6A), Boise (zone 5B), Chicago (zone 5A), Salem (zone 4C), Baltimore (zone 4A) and San Francisco (zone 3C).

- Site energy savings range around 7 kBtu/ft^2-y (14% to 17% of pre-retrofit annual energy consumption) result from use of OBC based on advanced occupancy sensors for the warm to hot climates of Albuquerque (zone 4B), Memphis (zone 3A), Phoenix (zone 2B), and Houston (zone 2A).

- Miami (zone 1A) and El Paso (zone 3B) have much lower site energy savings of 1 and 5 kBtu/ft^2-y (13% and 6% of pre-retrofit annual energy consumption), respectively, from using OBC based on advanced occupancy sensors.

- HVAC energy savings from use of advanced occupancy sensors represent a minimum of 62% of the total savings for Miami and a maximum of 92% for Duluth and Fairbanks (with 13 of the 15 locations having values between 87% and 92%). Lighting, which represents the remainder, is therefore a small fraction of the total savings (13% or less for all locations except Miami and El Paso).

- HVAC energy savings represent somewhat smaller fractions of the total savings attributable to OBC when common occupancy sensors are used, ranging from 56% to 86% of total savings (with 9 of the 15 locations having values of more than 80%).

- Substantially lower site energy savings result for OBC for HVAC terminal boxes and lighting based on common occupancy sensors, 30% of the savings possible using advanced occupancy sensors for most climate zones, except for zones 1A (Miami) and 3B (El Paso).

- Monetary savings on energy purchases from use of OBC in large office buildings vary considerably, partly because energy savings differ, but at least as significantly because of variations in energy prices. For example, although Burlington and Baltimore have site energy savings approximately the same as the savings for Salem, Chicago, Boise, and Helena, the monetary savings for Burlington and Baltimore are greater than the savings for the other locations by more than 44% (and as much as 107% higher for Baltimore compared to Boise).

- The energy and monetary savings estimated in this study are likely conservatively low. The median existing large office building age is about 23 years, corresponding to a year of construction of 1989. The building simulated in this study was one complying with Standard 90.1-2004 with some adjustments to lower its efficiency to align it better with a building built in 1989 but retrofit with a number of energy-efficiency measures over its life. Still, the building has a relatively low EUI (e.g., equal to or less than 50 kBtu/ft^2-y for 13 of the 15 U.S climate zones; excluding Duluth and Fairbanks, zones 7 and 8). Savings would likely be greater for a base case building with a higher initial EUI.

- Use of OBC for terminal boxes results in no significant increase in the number of heating and cooling hours when comfort conditions were not met, compared to the large office building without OBC.

These findings tend to indicate that development and deployment of OBC using advanced occupancy sensors could yield substantial energy saving in the large office building sector but also in other buildings for which space occupancy is highly variable. To achieve these savings, research should address development of low-cost advanced occupancy sensor systems and algorithms for controlling terminal boxes using the data they provided, determining the energy and cost savings from use of OBC for buildings other than large office buildings, investigating the relationship between building age and the potential savings from OBC, a market analysis to quantify the cost of the OBC technology and its return on investment, and field testing to verify that OBC yields the savings indicated by simulations.

Occupancy-based control using common occupancy sensors could be deployed sooner than OBC based on advanced occupancy sensors. The much smaller energy and monetary savings, however, would likely result in the need to replace OBC systems based on common occupancy sensors with systems using advanced occupancy sensors as soon as the advanced technology becomes commercially available. Because savings using advanced occupancy sensors exceed savings using common occupancy sensors by a factor of two to three, accelerating development of the advanced occupancy sensor technology and foregoing earlier savings using common occupancy sensors may represent the better approach.

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Appendix

A-1: Description of Base Case Building Model

Characteristic	Description
Energy Sources	
Electricity	Used for cooling, chilled- and hot-water distribution, ventilation and air distribution, lighting, plug loads
Natural Gas	Used for space heating, domestic hot-water heating
Form	
Total Floor Area (ft^2)	498,600
Floor Dimensions	240 ft × 160 ft rectangle (38,400 ft^2)
Number of Floors	12 above grade plus one basement
Window-to-Wall Ratio	37.5% of total exterior wall area
Window Locations	Even distribution among all four above-grade exterior walls
Thermal Zoning	See Figure 2
Floor-to-Floor Height (feet)	13
Floor-to-Ceiling Height (feet)	9
Glazing Sill height (feet)	3
Architecture	
Exterior walls	
Construction	Pre-cast concrete panels: 8-inch heavy-weight concrete + wall insulation + 0.5-inch gypsum board
U factor	See Table 5
Roof	
Construction	Built-up roof: Roof membrane + roof insulation + metal decking
U factor	0.048 Btu/h-ft^2- °F for climate zone 8 (Alaska) 0.063 Btu/h-ft^2- °F for all other climate zones
Windows	
U Factor	See Table 5
Foundation	
Foundation Type	Basement (unconditioned)
Construction	8-inch concrete wall; 6-inch concrete slab, 140-lb heavy-weight aggregate; no insulation
Interior Partitions	
Construction	2 x 4 un-insulated stud walls
Internal Mass	Wood (33.2 lbs/ft^3)

HVAC	
System Type	
Heating Plant	Natural gas boiler
Cooling Plant	Two water-cooled centrifugal chillers
Air Distribution System	VAV air handlers with cooling coils VAV terminal boxes with dampers and hot-water reheating coils Zone control type: minimum supply air-flow rate equal to 30% of the zone design peak supply air-flow rate
HVAC Control	
Thermostat Set Point in Occupied Building Mode	75°F Cooling/70°F Heating
Thermostat Set Point in Unoccupied Building Mode (Setback)	85°F Cooling/60°F Heating
Supply Air Temperature	Maximum 110°F, Minimum 52°F
Chilled-Water Supply Temperature	44°F
Hot-Water Supply Temperature	180°F
Economizers	In climate zones 2B, 3B, 3C, 4B, 4C, 5A, 5B, 6A, 6B, 7, 8
Supply Fan	
Minimum Fan Flow-Rate Fraction	0% (changed from 25% in 90.1-2004 Prototype)
Internal Loads and Schedules	
Lighting	
Average Power Density of Lighting Installed	1.0 W/ft^2 (For HVAC sizing see Table 3 for design LPD value)
Occupancy Sensors	No
Lighting Power Schedule	See Appendix Section A-3
Plug Loads	
Average Power Density	0.75 W/ft^2 for all floors except basement 0.45 W/ft^2 for basement (For power density for HVAC sizing see Table 3 for design plug load values)
Exterior Lighting	
Peak Power	60,216 Watts
Schedule	Sunset to sunrise based on astronomical clock

A-2: Building Operation Schedule

Table 14 provides the building operation (occupancy) schedule. The building is in occupied operation mode between 6:00 am and 10:00 pm and in unoccupied operation mode from 10:00 pm to 6:00 am on weekdays. The building is in occupied mode only from 6:00 am until 6:00 pm on Saturdays and is unoccupied for 24 hours on Sundays and holidays. During the unoccupied building mode, the HVAC system is reset to a higher cooling temperature set point and a lower heating temperature set point (see Table 8), and the supply fans operate only when heating and cooling, not for ventilation only.

Table 14. Building operation schedule

Time Period	Building Operation Mode
Weekday Time Period	
00:00 – 06:00	Unoccupied Building Mode
06:00 – 22:00	Occupied Building Mode
22:00 – 00:00	Unoccupied Building Mode
Saturday Time Period	
00:00 – 06:00	Unoccupied Building Mode
06:00 – 18:00	Occupied Building Mode
18:00 – 00:00	Unoccupied Building Mode
Sundays and Holidays	
00:00 – 24:00	Unoccupied Building Mode

A-3: Lighting Savings Estimation and Lighting Schedules

Savings on electricity for lighting associated with using common and advanced occupancy sensors were estimated using results from the occupancy monitoring study reported by VonNeida et al. (2000) and Maniccia et al. (1999). VonNeida et al. (2000) used measurements with occupancy sensors and lighting status data to determine occupancy patterns in workplaces and the impacts of lighting control using common occupancy sensors. Data from buildings in 24 states that participated in the U.S. Environmental Protection Agency's Green Lights Program were used for the study. The buildings were occupied by profit, non-profit, service, manufacturing, healthcare, primary schools, secondary schools, and local, state, and federal government offices, and represented a range of building types, ownership, efficiency, and age.

Data from 158 rooms (42 restrooms, 37 private offices, 35 classrooms, 33 conference rooms, and 11 break rooms) collected for 14-day periods from February through September 1997 were analyzed to determine the occupancy patterns, average daily energy, and annual energy costs for each room type. Each actual room had no lighting controls installed, except for manual on/off switches. Occupancy sensors were installed to detect when each room was unoccupied. At the time of installation, room area, lighting load, and light logger location were documented. The measured data established baselines. Models were then used to estimate the annual lighting energy use of the rooms if occupancy sensors were used to control the lighting. Moreover, lighting energy use was determined for four different time-delay settings between when all occupants were detected to have left the room and when lights were switched off—5 minutes, 10 minutes, 15 minutes and 20 minutes. Energy savings from use of lighting control with (common) occupancy sensors was determined as the difference between the annual baseline energy use for each room and the annual energy use for lighting with occupancy sensors having each specific delay time. The fractional savings for a specific room type were determined as the ratio of the sum of the lighting energy savings for all rooms of the selected type to the sum of the baseline annual lighting energy usages of the same rooms.

Significant savings were found for all space types (see Table 15), and they were consistent with the ranges of savings found in previous studies of the energy impacts of lighting control using occupancy sensors [e.g., Floyd, et al. 1995, Rundquist 1996, Jennings et al. 1999; Maniccia et al. 1999; Seattle City Light 1992, Richman et al. (1996)]. The results demonstrate that both the specific room use and the delay time associated with switching lights off significantly impact the magnitude of the savings.

When advanced occupancy sensors are used for lighting control, the improved detection of occupants compared to common occupancy sensors enable decreases in the delay time (e.g., to 5 seconds). For the present study, the data for energy savings for selected delay times reported by VonNeida et al. (2000) were extrapolated to estimate the energy savings for a shorter delay time. Figure 24 shows an example extrapolation for private offices.

Table 15, in addition to showing the savings from Von Neida et al. (2000), also provides the energy savings for a delay time of 5 seconds obtained for break rooms, conference rooms, private offices and rest rooms, obtained by extrapolation.

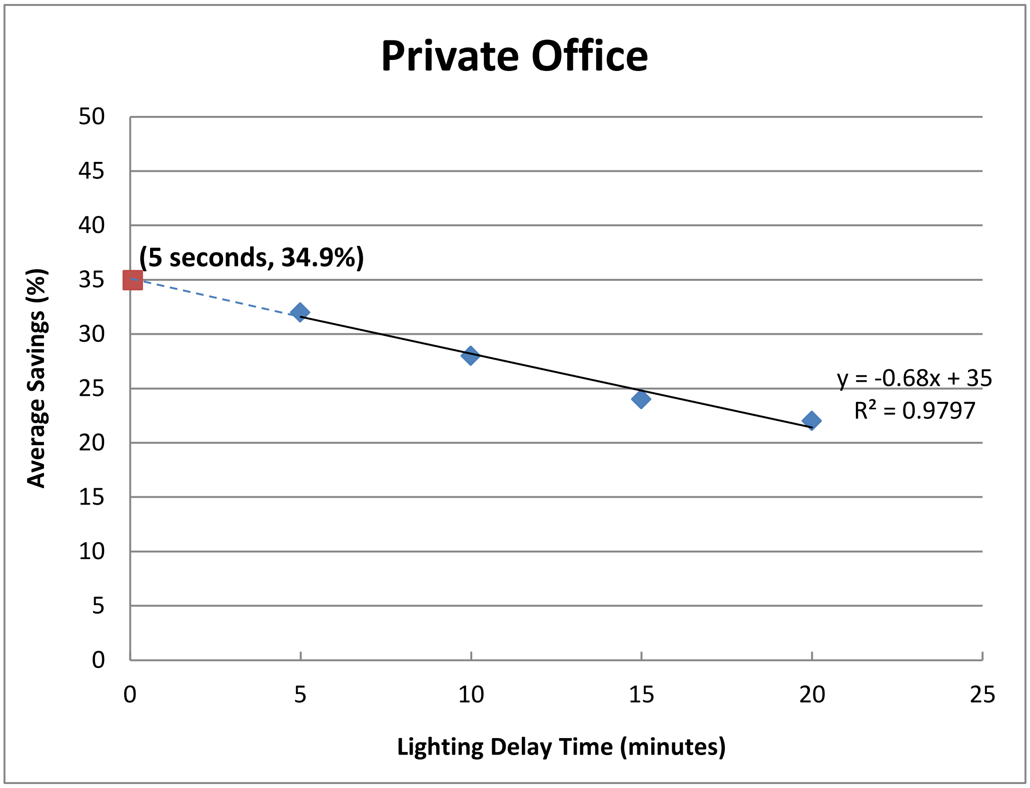

Figure 24. Lighting savings potential for private offices as a function of the time delay between detection of all occupants vacating the room and the lights turning off. Data from Von Neida et al. (2000) are shown by blue diamonds. A line fit by least-squares regression to those points (solid line) is extrapolated (dashed line) to a lighting delay time of 5 seconds (red square) for which the energy savings are 34.9% of the installed lighting power density.

Table 15. Lighting savings for different space types and delay times from VonNeida et al. (2000) are shown along with savings for a 5-second delay time obtained by extrapolating a straight line fit to the data reported by VonNeida et al. to shorter delay times. All savings are expressed as percentages of the total energy use for lighting for rooms with no use of occupancy sensors for lighting control.

Delay Time	Break Room (% Savings)	Conference Room (% Savings)	Private Office (% Savings)	Restroom (% Savings)
5 seconds	**24.9**	**50.9**	**34.9**	**49.9**
5 minutes	22	43	32	41
10 minutes	16	38	28	34
15 minutes	13	24	24	29
20 minutes	10	22	22	26

The schedule of actual lighting power density in use at each hour of each type of day (weekday, Saturday, and Sunday/holidays) is shown in Table 16 for the Base Case building, which does not use OBC for lighting.

Table 16. Base Case lighting schedule for all spaces, private offices, open office space, conference rooms, and the basement.

Weekday Time Period	**Lighting Power Density (W/ft^2)**
00:00 – 05:00	0.050
05:00 – 07:00	0.100
07:00 – 08:00	0.300
08:00 – 17:00	0.900
17:00 – 18:00	0.500
18:00 – 20:00	0.300
20:00 – 22:00	0.200
22:00 – 23:00	0.100
23:00 – 00:00	0.050
Saturday Time Period	
00:00 – 06:00	0.050
06:00 – 08:00	0.100
08:00 – 12:00	0.300
12:00 – 17:00	0.150
17:00 – 00:00	0.050
Sundays and Holidays	
00:00 – 24:00	0.050

Improved Cases I and II use common occupancy sensors with 15-minute time delays for lighting control in private office zones and conference rooms. Improved Case III uses advanced occupancy sensors with a 5-second delay time to control lighting in private office zones and conference rooms.

The lighting energy savings are input to the EnergyPlus simulations as revised schedules of lighting power density based on the fractional savings given by VanNeida et al. (2000). For each hour in the schedule, the actual lighting power density for the Base Case (with not OBC) is adjusted for the savings using the relation

$$\mathrm{LPD_{OBC}} = \mathrm{LPD_{BaseCase}} \times (1 - \text{Fractional Savings})\ , \qquad \text{(A-1)}$$

Where LPD is the actual lighting power density, the subscripts OBC and Base Case identify the LPD for cases with OBC and the Base Case, which does not use OBC, and Fractional Savings represents the lighting savings given in Table 15 for the specific room type and associated delay time. Improved Cases I and II use common occupancy sensors with a delay time of 15 minutes, and Improved Case III uses advanced occupancy sensors with a delay time of 5 seconds.

As an example, consider the LPD for private offices for Improved Cases I and II for the time interval 08:00 to 17:00 on a weekday. The actual lighting power density for the Base Case for those hours is 0.900 W/ft^2 from Table 16, and the fractional savings from Table 15 equal 24%. Therefore, LPD(Private Offices, Improved Case I or II) = 0.900 x (1 - 0.24) = 0.684.

The actual LPD schedules for private offices for Improved Cases I and II from application of Equation (A-1) to all hours of each of the day types are shown in Table 17. The value of the LPD of 0.684 for weekday hours 08:00 through 17:00 can be confirmed in this table. The lighting schedules for all other cases are shown in Table 18 – Table **22**.

Table 17. Lighting schedule for private office zones with common occupancy sensors for OBC using a 15-minute delay time for switching lights off (Improved Cases I and II)

Weekday Time Period	**Lighting Power Density (W/ft^2)**
00:00 – 05:00	0.050
05:00 – 07:00	0.100
07:00 – 08:00	0.228
08:00 – 17:00	0.684
17:00 – 18:00	0.380
18:00 – 20:00	0.228
20:00 – 22:00	0.200
22:00 – 23:00	0.100
23:00 – 00:00	0.050
Saturday Time Period	
00:00 – 06:00	0.050
06:00 – 08:00	0.076
08:00 – 12:00	0.228
12:00 – 17:00	0.114
17:00 – 00:00	0.050
Sundays and Holidays	
00:00 – 24:00	0.050

Table 18. Lighting schedule for private office zones with advanced occupancy sensors for OBC using a 5-second delay time for switching lights off (Improved Case III)

Weekday Time Period	Lighting Power Density (W/ft^2)
00:00 – 05:00	0.050
05:00 – 07:00	0.100
07:00 – 08:00	0.195
08:00 – 17:00	0.586
17:00 – 18:00	0.326
18:00 – 20:00	0.195
20:00 – 22:00	0.200
22:00 – 23:00	0.100
23:00 – 00:00	0.050
Saturday Time Period	
00:00 – 06:00	0.050
06:00 – 08:00	0.065
08:00 – 12:00	0.195
12:00 – 17:00	0.098
17:00 – 00:00	0.050
Sundays and Holidays	
00:00 – 24:00	0.050

Table 19. Lighting schedule for conference rooms with common occupancy sensors for OBC using a 15-minute delay time for switching lights off (Improved Case I and II)

Weekday Time Period	Lighting Power Density (W/ft^2)
00:00 – 05:00	0.050
05:00 – 07:00	0.100
07:00 – 08:00	0.228
08:00 – 17:00	0.684
17:00 – 18:00	0.380
18:00 – 20:00	0.228
20:00 – 22:00	0.200
22:00 – 23:00	0.100
23:00 – 00:00	0.050
Saturday Time Period	
00:00 – 06:00	0.050
06:00 – 08:00	0.076
08:00 – 12:00	0.228
12:00 – 17:00	0.114
17:00 – 00:00	0.050
Sundays and Holidays	
00:00 – 24:00	0.050

Table 20. Lighting schedules for conference rooms with advanced occupancy sensors for OBC using a 5-second delay time for switching lights off (Improved Case III)

Weekday Time Period	Lighting Power Density (W/ft^2)
00:00 – 05:00	0.050
05:00 – 07:00	0.100
07:00 – 08:00	0.147
08:00 – 17:00	0.442
17:00 – 18:00	0.246
18:00 – 20:00	0.147
20:00 – 22:00	0.200
22:00 – 23:00	0.100
23:00 – 00:00	0.050
Saturday Time Period	
00:00 – 06:00	0.050
06:00 – 08:00	0.049
08:00 – 12:00	0.147
12:00 – 17:00	0.074
17:00 – 00:00	0.050
Sundays and Holidays	
00:00 – 24:00	0.050

Table 21. Lighting schedule for open offices for the Base Case and Improved Cases I, II and III

Weekday Time Period	Lighting Power Density (W/ft^2)
00:00 – 05:00	0.050
05:00 – 07:00	0.100
07:00 – 08:00	0.300
08:00 – 17:00	0.900
17:00 – 18:00	0.500
18:00 – 20:00	0.300
20:00 – 22:00	0.200
22:00 – 23:00	0.100
23:00 – 00:00	0.050
Saturday Time Period	
00:00 – 06:00	0.050
06:00 – 08:00	0.100
08:00 – 12:00	0.300
12:00 – 17:00	0.150
17:00 – 00:00	0.050
Sundays and Holidays	
00:00 – 24:00	0.050

Table 22. Basement lighting schedule for all cases (Base Case and Improved Cases I, II and III.

Weekday Time Period	**Lighting Power Density (W/ft^2)**
00:00 – 05:00	0.050
05:00 – 07:00	0.100
07:00 – 08:00	0.300
08:00 – 17:00	0.900
17:00 – 18:00	0.500
18:00 – 20:00	0.300
20:00 – 22:00	0.200
22:00 – 23:00	0.100
23:00 – 00:00	0.050
Saturday Time Period	
00:00 – 06:00	0.050
06:00 – 08:00	0.100
08:00 – 12:00	0.300
12:00 – 17:00	0.150
17:00 – 00:00	0.050
Sundays and Holidays	
00:00 – 24:00	0.050

A-4: Weekend Occupancy Schedules

Table 23. Weekend Occupancy schedule for private offices used in simulations

Weekend Occupancy Schedule for Private Offices	
Saturday Time Period	**Fraction of Full Occupancy**
00:00 – 07:00	0.00
07:00 – 08:00	0.02
08:00 – 09:00	0.31
09:00 – 10:00	0.22
10:00 – 11:00	0.23
11:00 – 12:00	0.23
12:00 – 13:00	0.16
13:00 – 14:00	0.20
14:00 – 15:00	0.22
15:00 – 00:00	0.00
Sunday and Holiday	
0:00 – 24:00	0.00

Table 24. Weekend Occupancy schedule for open offices used in simulations

Weekend Occupancy Schedule for Open Offices	
Saturday Time Period	**Fraction of Full Occupancy**
00:00 – 07:00	0.00
07:00 – 08:00	0.27
08:00 – 09:00	0.42
09:00 – 10:00	0.29
10:00 – 11:00	0.31
11:00 – 12:00	0.31
12:00 – 13:00	0.21
13:00 – 14:00	0.27
14:00 – 15:00	0.30
15:00 – 00:00	0.00
Sunday and Holidays	
0:00 – 24:00	0.00

Table 25. Weekend Occupancy schedule for conference rooms used in simulations

Weekend Occupancy Schedule for Conference Rooms	
Saturday Time Period	**Fraction of Full Occupancy**
00:00:01 – 07:00:00	0.00
07:00:01 – 11:00:00	0.21
11:00:01 – 12:00:00	0.16
12:00:01 – 00:00:00	0.00
Sunday and Holidays	
0:00 – 24:00	0.00

A-5: Equipment Power Consumption Schedule

Table 26. Power consumption schedules for private offices, open offices, and conference rooms for the Base Case and Improved Cases I, II and II

Weekday Time Period	Equipment Power Density (W/ft^2)
00:00 – 08:00	0.300
08:00 – 12:00	0.675
12:00 – 13:00	0.600
13:00 – 17:00	0.675
17:00 – 18:00	0.375
18:00 – 00:00	0.300
Saturday Time Period	
00:00 – 06:00	0.225
06:00 – 08:00	0.300
08:00 – 12:00	0.375
12:00 – 17:00	0.263
17:00 – 00:00	0.225
Sunday and Holidays All Day	
0:00 – 24:00	0.225

Table 27. Power consumption schedules for the basement for the Base Case and Improved Cases I, II and III

Weekday Time Period	Equipment Power Density (W/ft^2)
00:00:01 – 08:00:00	0.180
08:00:01 – 12:00:00	0.405
12:00:01 – 13:00:00	0.360
13:00:01 – 17:00:00	0.405
17:00:01 – 18:00:00	0.225
18:00:01 – 00:00:00	0.180
Saturday Time Period	
00:00:01 – 06:00:00	0.135
06:00:01 – 08:00:00	0.180
08:00:01 – 12:00:00	0.225
12:00:01 – 17:00:00	0.158
17:00:01 – 00:00:00	0.300
Sunday and Holidays All Day	
0:00 – 24:00	0.300

A-6: Site Annual Energy Use and Savings

The results from all EnergyPlus simulations are given in Table 28 for all four building control cases and 15 geographic locations in kWh/ft^2-y. Table 29 provides the same results but with thermal energy uses and the total energy use of the buildings in kBtu/ft^2-y and electrical energy uses in kWh/ft^2-y. Table 30 provides the annual energy savings of Improved Cases I, II and III compared to the Base Case for electricity, natural gas and total (combined) energy use.

Table 28. Building site energy consumption in kBtu/ft^2-y by end use and the entire building for all 15 locations

Location	Control Case	Interior Lights (kBtu/ft^2-y)	Plug Loads (kBtu/ft^2-y)	Fans (kBtu/ft^2-y)	Pumps (kBtu/ft^2-y)	Cooling (kBtu/ft^2-y)	Heating (kBtu/ft^2-y)	Entire Building (kBtu/ft^2-y)
Miami	Base Case	9.77	15.22	2.16	2.96	15.41	1.24	49.03
	Improved 1	9.22	15.22	2.14	2.95	15.34	1.34	48.49
	Improved 2	9.22	15.22	2.02	2.98	15.19	0.88	47.79
	Improved 3	8.86	15.22	1.89	3.24	15.14	0.04	46.67
Houston	Base Case	9.77	15.22	2.17	2.91	12.25	6.59	51.28
	Improved 1	9.22	15.22	2.16	2.90	12.22	6.80	50.92
	Improved 2	9.22	15.22	1.97	2.86	11.90	5.43	48.96
	Improved 3	8.86	15.22	1.66	2.90	11.17	1.76	43.93
Phoenix	Base Case	9.77	15.22	2.65	2.70	9.81	5.58	48.02
	Improved 1	9.22	15.22	2.63	2.70	9.78	5.76	47.63
	Improved 2	9.22	15.22	2.42	2.74	9.51	4.45	45.87
	Improved 3	8.86	15.22	2.13	2.90	8.55	0.69	40.68
Memphis	Base Case	9.77	15.22	1.98	2.65	8.90	6.09	47.07
	Improved 1	9.22	15.22	1.97	2.65	8.86	6.35	46.73
	Improved 2	9.22	15.22	1.79	2.58	8.56	4.79	44.61
	Improved 3	8.86	15.22	1.52	2.57	7.97	1.28	39.87
El Paso	Base Case	9.77	15.22	2.29	1.81	5.54	3.69	40.76
	Improved 1	9.22	15.22	2.28	1.81	5.50	3.90	40.36
	Improved 2	9.22	15.22	2.10	1.82	5.26	2.72	38.77
	Improved 3	8.86	15.22	1.87	1.99	4.92	0.34	35.64
San Francisco	Base Case	9.77	15.22	1.92	1.33	1.85	7.56	40.18
	Improved 1	9.22	15.22	1.92	1.33	1.84	7.89	39.96
	Improved 2	9.22	15.22	1.68	1.32	1.73	5.55	37.27
	Improved 3	8.86	15.22	1.25	1.43	1.46	0.48	31.26
Baltimore	Base Case	9.77	15.22	2.10	2.68	6.92	10.11	49.36
	Improved 1	9.22	15.22	2.09	2.68	6.89	10.44	49.11
	Improved 2	9.22	15.22	1.85	2.61	6.45	8.29	46.21
	Improved 3	8.86	15.22	1.46	2.42	5.49	3.34	39.34

Albuquerque	Base Case	9.77	15.22	2.54	1.44	3.66	6.45	41.62
	Improved 1	9.22	15.22	2.53	1.44	3.63	6.71	41.30
	Improved 2	9.22	15.22	2.29	1.45	3.42	5.14	39.28
	Improved 3	8.86	15.22	1.91	1.63	3.22	1.23	34.62
Salem	Base Case	9.77	15.22	2.02	1.21	2.24	9.94	42.98
	Improved 1	9.22	15.22	2.02	1.21	2.22	10.3	42.80
	Improved 2	9.22	15.22	1.75	1.21	2.07	7.50	39.58
	Improved 3	8.86	15.22	1.33	1.35	1.89	2.06	33.29
Chicago	Base Case	9.77	15.22	2.19	1.62	4.47	13.63	49.54
	Improved 1	9.22	15.22	2.19	1.62	4.43	14.00	49.28
	Improved 2	9.22	15.22	1.91	1.57	4.22	11.71	46.49
	Improved 3	8.86	15.22	1.44	1.68	3.96	6.17	39.96
Boise	Base Case	9.77	15.22	2.38	1.26	2.96	10.85	45.06
	Improved 1	9.22	15.22	2.38	1.26	2.95	11.21	44.84
	Improved 2	9.22	15.22	2.07	1.26	2.76	8.76	41.92
	Improved 3	8.86	15.22	1.60	1.42	2.55	3.40	35.67
Burlington	Base Case	9.77	15.22	2.17	1.33	3.39	16.04	50.61
	Improved 1	9.22	15.22	2.17	1.33	3.37	16.44	50.43
	Improved 2	9.22	15.22	1.86	1.29	3.13	13.90	47.31
	Improved 3	8.86	15.22	1.39	1.39	2.91	8.39	40.83
Helena	Base Case	9.77	15.22	2.45	1.09	2.31	13.89	47.44
	Improved 1	9.22	15.22	2.44	1.09	2.29	14.27	47.24
	Improved 2	9.22	15.22	2.10	1.09	2.09	11.64	44.07
	Improved 3	8.86	15.22	1.57	1.24	1.95	6.29	37.83
Duluth	Base Case	9.77	15.22	2.54	1.08	2.27	21.97	55.64
	Improved 1	9.22	15.22	2.54	1.08	2.26	22.40	55.50
	Improved 2	9.22	15.22	2.12	1.06	2.08	19.56	52.03
	Improved 3	8.86	15.22	1.46	1.16	1.93	12.64	44.05
Fairbanks	Base Case	9.77	15.22	2.63	0.82	1.40	30.91	63.65
	Improved 1	9.22	15.22	2.63	0.82	1.39	31.39	63.58
	Improved 2	9.22	15.22	2.11	0.80	1.21	28.30	59.78
	Improved 3	8.86	15.22	1.44	0.93	1.10	21.13	51.58

Table 29. Building site energy consumption in kBtu/ft^2-y for natural gas and whole-building energy use and by in kWh/ft^2-y for electricity for all 15 locations

Location	Control Case	Interior Lights (kWh/ft^2-y)	Plug Loads (kWh/ft^2-y)	Fans (kWh/ft^2-y)	Pumps (kWh/ft^2-y)	Cooling (kWh/ft^2-y)	Heating (kBtu/ft^2-y)	Entire Building (kBtu/ft^2-y)
Miami	Base Case	2.86	4.46	0.63	0.87	4.52	1.24	49.03
	Improved 1	2.70	4.46	0.63	0.86	4.50	1.34	48.49
	Improved 2	2.70	4.46	0.59	0.87	4.45	0.88	47.79
	Improved 3	2.60	4.46	0.55	0.95	4.44	0.04	46.67
Houston	Base Case	2.86	4.46	0.64	0.85	3.59	6.59	51.28
	Improved 1	2.70	4.46	0.63	0.85	3.58	6.80	50.92
	Improved 2	2.70	4.46	0.58	0.84	3.49	5.43	48.96
	Improved 3	2.60	4.46	0.49	0.85	3.27	1.76	43.93
Phoenix	Base Case	2.86	4.46	0.78	0.79	2.88	5.58	48.02
	Improved 1	2.70	4.46	0.77	0.79	2.87	5.76	47.63
	Improved 2	2.70	4.46	0.71	0.80	2.79	4.45	45.87
	Improved 3	2.60	4.46	0.62	0.85	2.51	0.69	40.68
Memphis	Base Case	2.86	4.46	0.58	0.78	2.61	6.09	47.07
	Improved 1	2.70	4.46	0.58	0.78	2.60	6.35	46.73
	Improved 2	2.70	4.46	0.52	0.76	2.51	4.79	44.61
	Improved 3	2.60	4.46	0.45	0.75	2.34	1.28	39.87
El Paso	Base Case	2.86	4.46	0.67	0.53	1.62	3.69	40.76
	Improved 1	2.70	4.46	0.67	0.53	1.61	3.90	40.36
	Improved 2	2.70	4.46	0.62	0.53	1.54	2.72	38.77
	Improved 3	2.60	4.46	0.55	0.58	1.44	0.34	35.64
San Francisco	Base Case	2.86	4.46	0.56	0.39	0.54	7.56	40.18
	Improved 1	2.70	4.46	0.56	0.39	0.54	7.89	39.96
	Improved 2	2.70	4.46	0.49	0.39	0.51	5.55	37.27
	Improved 3	2.60	4.46	0.37	0.42	0.43	0.48	31.26
Baltimore	Base Case	2.86	4.46	0.62	0.79	2.03	10.11	49.36
	Improved 1	2.70	4.46	0.61	0.79	2.02	10.44	49.11
	Improved 2	2.70	4.46	0.54	0.76	1.89	8.29	46.21
	Improved 3	2.60	4.46	0.43	0.71	1.61	3.34	39.34

Albuquerque	Base Case	2.86	4.46	0.74	0.42	1.07	6.45	41.62
	Improved 1	2.70	4.46	0.74	0.42	1.06	6.71	41.30
	Improved 2	2.70	4.46	0.67	0.42	1.00	5.14	39.28
	Improved 3	2.60	4.46	0.56	0.48	0.94	1.23	34.62
Salem	Base Case	2.86	4.46	0.59	0.35	0.66	9.94	42.98
	Improved 1	2.70	4.46	0.59	0.35	0.65	10.30	42.80
	Improved 2	2.70	4.46	0.51	0.35	0.61	7.50	39.58
	Improved 3	2.60	4.46	0.39	0.40	0.55	2.06	33.29
Chicago	Base Case	2.86	4.46	0.64	0.47	1.31	13.63	49.54
	Improved 1	2.70	4.46	0.64	0.47	1.30	14.00	49.28
	Improved 2	2.70	4.46	0.56	0.46	1.24	11.71	46.49
	Improved 3	2.60	4.46	0.42	0.49	1.16	6.17	39.96
Boise	Base Case	2.86	4.46	0.70	0.37	0.87	10.85	45.06
	Improved 1	2.70	4.46	0.70	0.37	0.86	11.21	44.84
	Improved 2	2.70	4.46	0.61	0.37	0.81	8.76	41.92
	Improved 3	2.60	4.46	0.47	0.42	0.75	3.40	35.67
Burlington	Base Case	2.86	4.46	0.64	0.39	0.99	16.04	50.61
	Improved 1	2.70	4.46	0.64	0.39	0.99	16.44	50.43
	Improved 2	2.70	4.46	0.55	0.38	0.92	13.90	47.31
	Improved 3	2.60	4.46	0.41	0.41	0.85	8.39	40.83
Helena	Base Case	2.86	4.46	0.72	0.32	0.68	13.89	47.44
	Improved 1	2.70	4.46	0.72	0.32	0.67	14.27	47.24
	Improved 2	2.70	4.46	0.62	0.32	0.61	11.64	44.07
	Improved 3	2.60	4.46	0.46	0.36	0.57	6.29	37.83
Duluth	Base Case	2.86	4.46	0.74	0.32	0.67	21.97	55.64
	Improved 1	2.70	4.46	0.74	0.32	0.66	22.40	55.50
	Improved 2	2.70	4.46	0.62	0.31	0.61	19.56	52.03
	Improved 3	2.60	4.46	0.43	0.34	0.57	12.64	44.05
Fairbanks	Base Case	2.86	4.46	0.77	0.24	0.41	30.91	63.65
	Improved 1	2.70	4.46	0.77	0.24	0.41	31.39	63.58
	Improved 2	2.70	4.46	0.62	0.23	0.35	28.30	59.78
	Improved 3	2.60	4.46	0.42	0.27	0.32	21.13	51.58

Table 30. Site savings of electricity (in kWh/ft^2-y), natural gas (in kBtu/ ft^2-y) and total building energy use (in kBtu/ft^2-y) for Improved Cases I, II and III relative to the Base Case site energy use for 15 U.S. locations.

Location	Control Case	Electrical Energy Savings (kWh/ft^2-y)	Natural Gas Energy Savings (kBtu/ft^2-y)	Total Building Energy Savings (kBtu/ft^2-y)
Miami	Improved 1	0.19	-0.10	0.55
	Improved 2	0.26	0.36	1.25
	Improved 3	0.34	1.20	2.37
Houston	Improved 1	0.18	-0.21	0.39
	Improved 2	0.34	1.16	2.31
	Improved 3	0.74	4.83	7.34
Phoenix	Improved 1	0.18	-0.18	0.42
	Improved 2	0.30	1.13	2.17
	Improved 3	0.73	4.89	7.38
Memphis	Improved 1	0.18	-0.26	0.34
	Improved 2	0.34	1.30	2.45
	Improved 3	0.70	4.81	7.19
El Paso	Improved 1	0.18	-0.21	0.39
	Improved 2	0.30	0.97	1.98
	Improved 3	0.52	3.35	5.12
San Francisco	Improved 1	0.16	-0.33	0.23
	Improved 2	0.27	2.01	2.93
	Improved 3	0.55	7.08	8.95
Baltimore	Improved 1	0.17	-0.33	0.26
	Improved 2	0.39	1.82	3.16
	Improved 3	0.95	6.77	10.01
Albuquerque	Improved 1	0.17	-0.26	0.33
	Improved 2	0.30	1.31	2.34
	Improved 3	0.52	5.22	7.01
Salem	Improved 1	0.17	-0.36	0.21
	Improved 2	0.29	2.44	3.43
	Improved 3	0.53	7.88	9.69

Chicago	Improved 1	0.17	-0.37	0.22
	Improved 2	0.33	1.92	3.05
	Improved 3	0.62	7.46	9.57
Boise	Improved 1	0.16	-0.36	0.20
	Improved 2	0.31	2.09	3.15
	Improved 3	0.57	7.45	9.39
Burlington	Improved 1	0.17	-0.40	0.17
	Improved 2	0.34	2.14	3.30
	Improved 3	0.62	7.65	9.76
Helena	Improved 1	0.17	-0.38	0.20
	Improved 2	0.33	2.25	3.37
	Improved 3	0.59	7.60	9.60
Duluth	Improved 1	0.16	-0.43	0.13
	Improved 2	0.35	2.41	3.59
	Improved 3	0.66	9.33	11.58
Fairbanks	Improved 1	0.16	-0.48	0.08
	Improved 2	0.38	2.61	3.89
	Improved 3	0.67	9.78	12.07

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