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City Reach Code Technical Support Document

October 2017

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U.S. DEPARTMENT OF ENERGY

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

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[1] New Buildings Institute, Portland, Oregon.

Executive Summary

The Architecture 2030 organization gathered a coalition of U.S. cities together with other stakeholders to facilitate the development of voluntary guidelines and standards that could be implemented in stages at the city level to improve building energy efficiency. This coalition sought technical support from the U.S. Department of Energy (DOE) for the development of these guidelines. Pacific Northwest National Laboratory (PNNL), funded under DOE's Building Energy Codes Program (BECP), provided this technical support to the coalition in collaboration with New Buildings Institute (NBI). These guidelines will be formed around a set of increasingly stringent performance metrics, starting from a 20% improvement over existing model energy codes to a policy that delivers net-zero energy performance. The focus of this project is the 20% improvement over existing commercial model energy codes.

NBI and PNNL assembled a set of energy-efficiency measures (EEMs) that would have the potential to deliver 20% energy savings over ASHRAE Standard 90.1-2013, which was chosen as the baseline model energy code for this project. The EEMs were developed using several sources including national model codes and standards, high-performance building codes and standards, regional energy codes, and measures that are being proposed as part of the on-going code development process. The EEMs improved all aspects of building design that are traditionally defined to be within the scope of energy codes, including, opaque envelope and fenestration, air leakage, interior and exterior lighting power, occupancy sensors, fan power, HVAC equipment efficiency, HVAC controls, service hot water waste heat recovery, plug load control, daylighting, and others.

Energy savings from the chosen EEMs were estimated using PNNL-developed prototype building models, which are whole building energy models built using DOE's EnergyPlus software. Five prototypes were selected for this analysis based on the typical proportion of building types in U.S. cities: High-rise Apartment, Large Hotel, Large Office, Secondary School, and Stand-alone Retail. These prototypes were simulated in six climate zones: 2B (hot, dry), 3A (warm, humid), 3C (warm, marine), 4A (mixed, humid), 4C (mixed, marine), and 5A (cool, humid). Individual EEMs were applied separately to the selected prototypes and climate zones to determine energy savings. EEMs were then combined into bundles to incorporate interactive effects and to determine the total impact of all EEMs.

The results show that with the group of EEMs described in this report, it is possible to achieve 20% energy savings over Standard 90.1-2013 in nearly all building types and climate zones analyzed in this study.

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The authors would like to thank David Cohan and Jeremy Williams at the U.S. Department of Energy for their review and guidance during this work. The authors would also like to thank Michael Rosenberg at PNNL for his insightful technical guidance and review of the report. The authors also acknowledge the support from Todd Taylor and Dr. Yulong Xie at PNNL who set up the simulation infrastructure that makes large-scale simulation analysis, such as this one, possible. This project was a true team effort and the authors would like to express their deep appreciation to everyone who contributed to the completion of this work.

Acronyms and Abbreviations

ACEEE	American Council for an Energy-Efficient Economy
AEDG	Advanced Energy Design Guide
AIA	American Institute of Architects
BBA	Better Buildings Alliance
BECP	Building Energy Codes Program
CAV	constant air volume
CEE	Consortium for Energy Efficiency
DOAS	dedicated outdoor air system
DOE	U.S. Department of Energy
DX	direct expansion
EEM	energy-efficiency measure
EPA	Environmental Protection Agency
ERV	energy recovery ventilator
HVAC	heating, ventilating, and air conditioning
IECC	International Energy Conservation Code
LEEP	Lighting Energy Efficiency in Parking
LPD	lighting power density
NBI	New Buildings Institute
NCG	New Construction Guide
PNNL	Pacific Northwest National Laboratory
SRR	skylight-to-roof ratio
SHGC	solar heat gain coefficient
SWH	service water heating
VAV	variable air volume
VLT	visible light transmittance
WMO	World Meteorological Organization
WSHP	water source heat pump
WWR	window-to-wall ratio

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1.0 Introduction

As cities adopt aggressive policies to address efficiency and carbon emissions, new policy strategies are needed to encourage the building sector transition toward more energy-efficient design and operations. To that end, the Architecture 2030 organization gathered a coalition of U.S. cities (through the Urban Sustainability Directors Network) joined with the American Institute of Architects (AIA), American Council for an Energy-Efficient Economy (ACEEE), and the New Buildings Institute (NBI) to facilitate the development of voluntary guidelines and standards that could be implemented in stages at the city level to improve building energy efficiency. A set of increasingly stringent performance metrics is envisioned, starting from a 20% improvement over baseline code performance to a policy that delivers net-zero energy performance in buildings. This coalition sought technical support from the U.S. Department of Energy (DOE) for the development of the first of these guidelines. Pacific Northwest National Laboratory (PNNL), funded under DOE's Building Energy Codes Program (BECP), provided this support in collaboration with NBI.

The focus of this project is the 20% improvement over existing commercial model energy codes. A key requirement of this initial 20% City Reach Code is that it be 'adoptable' as an energy code, meaning that it must align with current code scope and limitations, and primarily impact building components that are currently regulated by city building departments. It is largely limited to prescriptive measures, which are what most building departments and design projects are most familiar with.

This report describes a set of energy-efficiency measures (EEMs) that demonstrate 20% energy savings over ANSI/ASHRAE/IES Standard 90.1-2013 (ASHRAE 2013) across a broad range of commercial building types and climate zones. The EEMs were developed from national model codes and standards, high-performance building codes and standards, regional energy codes, and measures being proposed as part of the on-going code development process. PNNL analyzed these measures using whole building energy models. Cities which have the legal authority to adopt energy codes can use part or all of the measures in this City Reach Code to increase code stringency or adopt a reach code strategy with incentives. For jurisdictions that are not able to adopt codes outside of a state process, this code could be used in conjunction with utility or other incentives.

Section 2.0 of this report describes the analysis methodology, including the building types and climate zones selected for the analysis, the baseline, and the basis for the measure selection. Section 3.0 provides detailed specifications of the EEMs and bundles. Section 4.0 provides the results of individual EEMs and EEM bundles by building type and climate zone and summarizes the analytical findings.

2.0 Methodology

Analysis of the EEMs was conducted using DOE's Commercial Prototype Building Models[1] (Thornton et al. 2011) that were developed using DOE's EnergyPlus software (DOE 2013). These are whole building energy models representing the national building stock in the United States. This section describes the prototypes and climate zones selected for the study, the simulation infrastructure used to conduct the large-scale simulation, how EEMs were chosen, and how they were combined to achieve the targeted 20% energy reduction.

2.1 Building Types

A large set of prototype models has been created over time to analyze various Standard 90.1 editions, from 2004 through 2016. The prototype models complying with Standard 90.-2013 were used as the starting point for this analysis. EEMs were applied to these models to estimate their energy savings.

PNNL has also developed detailed construction weights by building type, climate zones and subzones at the national level (Jarnagin and Bandyopadhyay 2010). Cities have a distribution of building types that differs from the national average. Based on discussions between NBI and PNNL, the following prototypes were chosen for the analysis because they were deemed to represent the highest proportion of new construction in typical cities within the United States: Large Office, High-rise Apartment, Large Hotel, Secondary School, and Stand-alone Retail. These five prototypes represent 43% of the national building stock.

Table 1 summarizes some of the major features of the prototype models selected for the study. For more detailed information on the prototype models, please refer to Thornton et al. (2011).

Table 1. Features of prototype models selected for the study

Building Prototype	Floor Area (ft^2)	Number of Floors	Window-to-Wall Ratio (WWR)	Heating	Cooling	Primary System
Large Office	498,640	12	40%	Boiler	Chiller, cooling tower	VAV w/reheat
Stand-alone Retail	24,690	1	7%	Gas Furnace	Unitary DX	Packaged CAV
Secondary School	210,910	2	33%	Boiler	Air-cooled chiller	VAV w/reheat
Large Hotel	122,120	6	27%	Boiler	Air-cooled chiller	CV Fan-coil units
High-rise Apartment	84,360	10	15%	Boiler	Fluid Cooler	CV WSHP

2.2 Climate Zones

ASHRAE Standard 90.1 and the International Energy Conservation Code (IECC) define eight climate zones covering the entire country: very hot (climate zone 1), hot (2), warm (3), mixed (4), cool (5), cold (6), very cold (7), and subarctic (8). They are further subdivided into three moisture regimes: dry, humid, and marine, which leads to a total of 15 climate subzones that are found in the United States. The majority of the new construction within the United States occurs in the hot, warm, and mixed climate zones (Jarnagin and Bandyopadhyay 2010), which also include major U.S. cities and large population centers.

[1] https://www.energycodes.gov/development/commercial/prototype_models

These considerations led to the selection of six climate subzones for this analysis as well as the selection of a weather file to represent each climate zone. Table 2 shows the climate zones and representative weather files selected for this study.

Table 2. Climate zones and representative weather files selected for the study

Climate Zone	Climate Zone Type	Representative Weather File[(a)]
2B	Hot, dry	Davis-Monthan AFB (Tucson), Arizona (WMO id 722745)
3A	Warm, humid	Atlanta Hartsfield Int'l Airport, Georgia (WMO id 722190)
3C	Warm, marine	San Diego/Brown Field, California (WMO id 722904)
4A	Mixed, humid	New York J F Kennedy Intl Airport, New York (WMO id 744860)
4C	Mixed, marine	Seattle-Tacoma Int'l Airport, Washington (WMO id 727930)
5A	Cool, humid	Buffalo Niagara Int'l Airport, New York (WMO id 725280)

(a) The weather files were selected from the set of approved files used in the development of ASHRAE Standard 90.1.

2.3 Baseline

At the time the City Reach Code effort was conceived, Standard 90.1-2013 was the most recent version of the standard and it was also the official national model energy code (as determined by the U.S. Department of Energy). In addition, PNNL had conducted an analysis demonstrating it was cost-effective compared to Standard 90.1-2010 (Hart et al. 2015). Being the most advanced commercial building standard available at the time that was also determined to be cost-effective, it was chosen as the baseline against which performance improvements would be measured. The prototype models meeting the minimum requirements from Standard 90.1-2013 were used as the starting point for this analysis.

2.4 Measure Selection

NBI had previously developed an inventory of energy code measures based on requirements in national model codes and standards, high-performance building codes and standards, as well as measures that are being proposed as part of the on-going code development process. Pulling from a variety of sources, this inventory allows NBI to track and compare innovative and new code approaches to the most current iteration of base codes and standards, starting with 2015 IECC (ICC 2015) and ASHRAE 90.1-2013. The City Reach Code development process started with a review of this code inventory with a focus on sources such as ANSI/ASHRAE/USGBC/IES Standard 189.1-2014 (ASHRAE 2014), the International Green Construction Code (ICC 2012), the 2016 NY Stretch-Energy Code[2] and California's Building Energy Efficiency Standards for Residential and Nonresidential Buildings, known as Title 24 (CEC 2013), as well as the measures that appear in NBI's Advanced Buildings New Construction Guide (NBI 2015). This initial list of measures was then refined through discussions between NBI and PNNL into a final list that represented the potential to deliver the 20% energy savings target. Detailed descriptions of the measures were developed so that they could be simulated using the prototype models.

[2] https://www.nyserda.ny.gov/All-Programs/Programs/Energy-Code-Training/NYStretch-Energy

3.0 Measure and Bundle Descriptions

This section describes the individual EEMs in detail and specifies the modeling strategies used to estimate savings in the selected prototype models. Selected EEMs were then grouped into bundles to determine the total savings while accounting for interactive effects. These bundles are also described in this section.

3.1 Energy-Efficiency Measure Descriptions

EEM01 Opaque Insulation

EEM01 increases the insulation requirement for opaque envelopes (i.e., roof and above-grade wall). This measure reduces the U-factor for walls by 5% in climate zones 4 and 5, and then selects the most stringent value (in bold in Table 3 and Table 4) in each class of construction—an approach developed by PNNL for the 50% Concept Analysis[1]— in all climate zones. This assumes the design will meet the most stringent U-factor regardless of the construction types. Specific insulation values and applicable building types are given below in Table 3 and Table 4.

Affected Prototypes: All

Table 3. U-factors for exterior wall (Btu/hr-ft^2-F)

Walls, Above-Grade	Climate Zone	90.1-2013			EEM 01		
		Non-Res	Res	Semiheated	Non-Res	Res	Semiheated
Mass	Zone 2	0.151	0.123	0.580	0.151	0.123	0.580
Metal Building		0.094	0.094	0.162	0.094	0.094	0.162
Steel-Framed		0.084	0.064	0.124	**0.084**	**0.064**	0.124
Wood-Framed and Other		0.089	0.089	0.089	0.089	0.089	**0.089**
Mass	Zone 3	0.123	0.104	0.580	0.123	0.104	0.580
Metal Building		0.094	0.072	0.162	0.094	0.072	0.162
Steel-Framed		0.077	0.064	0.124	**0.077**	**0.064**	0.124
Wood-Framed and Other		0.089	0.064	0.089	0.089	0.064	**0.089**
Mass	Zone 4	0.104	0.090	0.580	0.099	0.086	0.551
Metal Building		0.060	0.050	0.162	**0.057**	**0.048**	0.154
Steel-Framed		0.064	0.064	0.124	0.061	0.061	0.118
Wood-Framed and Other		0.064	0.064	0.089	0.061	0.061	**0.085**
Mass	Zone 5	0.090	0.080	0.151	0.086	0.076	0.143
Metal Building		0.050	0.050	0.094	**0.048**	**0.048**	0.089
Steel-Framed		0.055	0.055	0.084	0.052	0.052	**0.080**
Wood-Framed and Other		0.051	0.051	0.089	0.048	0.048	0.085

[1] Presented to the ASHRAE Standard 90.1 Advanced Energy Standards Working Group, October 19, 2011, Chicago, IL.

Table 4. U-factors for roof (Btu/hr-ft^2-F)

Roofs	Climate Zone	90.1-2013			EEM 01		
		Non-Res	Res	Semiheated	Non-Res	Res	Semiheated
Insulation Entirely above Deck	Zone 2	0.039	0.039	0.173	0.039	0.039	0.173
Metal Building		0.041	0.041	0.096	0.041	0.041	0.096
Attic and Other		0.027	0.027	0.053	**0.027**	**0.027**	**0.053**
Insulation Entirely above Deck	Zone 3	0.039	0.039	0.119	0.039	0.039	0.119
Metal Building		0.041	0.041	0.096	0.041	0.041	0.096
Attic and Other		0.027	0.027	0.053	**0.027**	**0.027**	**0.053**
Insulation Entirely above Deck	Zone 4	0.032	0.032	0.093	0.030	0.030	0.088
Metal Building		0.037	0.037	0.082	0.035	0.035	0.078
Attic and Other		0.021	0.021	0.034	**0.020**	**0.020**	**0.032**
Insulation Entirely above Deck	Zone 5	0.032	0.032	0.063	0.030	0.030	0.060
Metal Building		0.037	0.037	0.082	0.035	0.035	0.078
Attic and Other		0.021	0.021	0.034	**0.020**	**0.020**	**0.032**

EEM02 Fenestration Properties

EEM02 requires more efficient and higher performance fenestration than 90.1-2013. Improved U-factors, solar heat gain coefficient (SHGC), and visible light transmittance (VLT) values are proposed for both windows and skylights. Recommendations from NBI's New Construction Guide (NCG) 2.19 (NBI 2015) are used to select the U-factor and SHGC based on the window-to-wall ratio (WWR) and the skylight-to-roof ratio (SRR) of each building type. The NCG also requires the VLT to be at least 1.5 times the SHGC. Skylight changes are only applicable to the Stand-alone Retail and Secondary School prototypes. Table 5 compares the fenestration properties (U-factor and SHGC) between Standard 90.1-2013 and NCG recommendation 2.19. Table 6 shows the same comparison as Table 5 for skylights.

Affected Prototypes: All

Table 5. Fenestration properties from 90.1-2013 and NCG 2.19

Prototype	CZ	90.1-2013				NCG 2.19			
		Non-Res		Res		Non-Res		Res	
		U	SHGC	U	SHGC	U	SHGC	U	SHGC
Large Office	2B	0.60	0.25	NA	NA	0.30	0.25	NA	NA
	3A	0.53	0.25	NA	NA	0.22	0.25	NA	NA
	3C	0.53	0.25	NA	NA	0.22	0.25	NA	NA
	4A	0.45	0.40	NA	NA	0.22	0.35	NA	NA
	4C	0.45	0.40	NA	NA	0.22	0.35	NA	NA
	5A	0.45	0.40	NA	NA	0.22	0.35	NA	NA
Stand-alone Retail	2B	0.58	0.25	NA	NA	0.40	0.25	NA	NA
	3A	0.52	0.25	NA	NA	0.37	0.25	NA	NA
	3C	0.52	0.25	NA	NA	0.37	0.25	NA	NA
	4A	0.44	0.40	NA	NA	0.29	0.35	NA	NA
	4C	0.44	0.40	NA	NA	0.29	0.35	NA	NA
	5A	0.44	0.40	NA	NA	0.29	0.35	NA	NA

Table 5. (contd)

		90.1-2013				NCG 2.19			
		Non-Res		Res		Non-Res		Res	
Prototype	CZ	U	SHGC	U	SHGC	U	SHGC	U	SHGC
Secondary School	2B	0.60	0.25	NA	NA	0.30	0.25	NA	NA
	3A	0.53	0.25	NA	NA	0.22	0.25	NA	NA
	3C	0.53	0.25	NA	NA	0.22	0.25	NA	NA
	4A	0.45	0.40	NA	NA	0.22	0.35	NA	NA
	4C	0.45	0.40	NA	NA	0.22	0.35	NA	NA
	5A	0.45	0.40	NA	NA	0.22	0.35	NA	NA
Large Hotel	2B	0.61	0.25	0.61	0.25	0.30	0.25	0.30	0.25
	3A	0.55	0.25	0.55	0.25	0.22	0.25	0.22	0.25
	3C	0.55	0.25	0.55	0.25	0.22	0.25	0.22	0.25
	4A	0.47	0.40	0.47	0.40	0.22	0.35	0.22	0.35
	4C	0.47	0.40	0.47	0.40	0.22	0.35	0.22	0.35
	5A	0.46	0.40	0.46	0.40	0.22	0.35	0.22	0.35
High-rise Apartment	2B	NA	NA	0.57	0.25	NA	NA	0.40	0.25
	3A	NA	NA	0.52	0.25	NA	NA	0.37	0.25
	3C	NA	NA	0.52	0.25	NA	NA	0.37	0.25
	4A	NA	NA	0.45	0.40	NA	NA	0.29	0.35
	4C	NA	NA	0.45	0.40	NA	NA	0.29	0.35
	5A	NA	NA	0.44	0.40	NA	NA	0.29	0.35

Table 6. Skylight properties from 90.1-2013 and NCG 2.19

		90.1-2013		NCG 2.19	
Prototype	CZ	U	SHGC	U	SHGC
Stand-alone Retail	2B	0.65	0.35	0.55	0.35
	3A	0.55	0.35	0.50	0.35
	3C	0.55	0.35	0.50	0.35
	4A	0.50	0.40	0.50	0.40
	4C	0.50	0.40	0.50	0.40
	5A	0.50	0.40	0.50	0.40
Secondary School	2B	0.65	0.35	0.55	0.35
	3A	0.55	0.35	0.50	0.35
	3C	0.55	0.35	0.50	0.35
	4A	0.50	0.40	0.50	0.40
	4C	0.50	0.40	0.50	0.40
	5A	0.50	0.40	0.50	0.40

EEM03 Air Leakage Testing

EEM03 requires envelope air leakage testing. This measure is derived from DOE/PNNL's proposal CE105 developed for the 2018 IECC[2]. This proposal requires measured air leakage to not exceed 0.40 cfm/ ft^2 of the building thermal envelope area at a pressure differential of 75 Pa. Table 7 shows the requirements for this EEM. The baseline (90.1-2013) infiltration rate has been modeled as 1.00 cfm/ft^2 and this EEM reduces the infiltration rate to 0.40 cfm/ft^2.

Affected Prototypes: Large Office, Secondary School, Large Hotel, and High-rise Apartment (Table 8).

Table 7. Air leakage requirements for EEM03

PNNL Prototype	Gross Floor Area (sf)	Occupancy Type (R-residential, O-other)	Climate zone					
			2B	3A	3C	4A	4C	5A
Residential Requirement			NR	25,000	NR	9,000	50,000	6,000
Other Requirement			NR	350,000	NR	75,000	NR	40,000
Large Hotel	122,130	R	NR	Required	NR	Required	Required	Required
Large Office	498,600	O	NR	Required	NR	Required	NR	Required
Stand-alone Retail	24,695	O	NR	NR	NR	NR	NR	NR
Secondary School	210,900	O	NR	NR	NR	Required	NR	Required
High-rise Apartment	84,360	R	NR	Required	NR	Required	Required	Required

NR = not required

Table 8. Climate zones and prototypes affected by EEM 03

PNNL Prototype	Gross Floor Area (sf)	Occupancy Type (R-residential, O-other)	Climate zone					
			2B	3A	3C	4A	4C	5A
Large Hotel	122,130	R	NR	Required	NR	Required	Required	Required
Large Office	498,600	O	NR	Required	NR	Required	NR	Required
Stand-alone Retail	24,695	O	NR	NR	NR	NR	NR	NR
Secondary School	210,900	O	NR	NR	NR	Required	NR	Required
High-rise Apartment	84,360	R	NR	Required	NR	Required	Required	Required

NR = not required

EEM04 Interior Lighting Power Density

EEM04 reduces the interior lighting power density (LPD). Reduced LPD values for this EEM are based on a California Energy Codes & Standards Statewide Utility Program proposal, which in turn was based on updates to the Standard 90.1-2016 interior lighting models, and modified in response to comments during the standards development process[3]. Specific interior LPD values are listed in Table 9. Changes to the retail area display allowance are also captured and are shown in Table 10.

[2] Available at: https://www.energycodes.gov/doe-proposals-2018-iecc
[3] Email correspondence: Jon McHugh, McHugh Energy Consultants.

Affected Prototypes: All

Table 9. Interior LPD values comparison between 90.1-2013 and EEM04

Type	Method	90.1-2013 (W/ft^2)	EEM04 (W/ft^2)
Office – enclosed	Common Space Type	1.11	0.85
Corridor – all other corridors	Common Space Type	0.79	0.58
Retail	Building Area Method	1.26	0.91
Electrical/Mechanical Room	Common Space Type	0.95	0.89
Storage Room – all other storage rooms	Common Space Type	0.63	0.43
Laundry/Washing Area	Common Space Type	0.60	0.43
Dining area – in family dining	Common Space Type	0.89	0.62
Lobby – in a hotel	Common Space Type	1.06	0.68
Guest Room	Common Space Type	0.91	0.75
Corridor – all other corridor	Common Space Type	0.66	0.58
Corridor – all other corridor	Common Space Type	0.66	0.58
Food Preparation Area	Common Space Type	1.21	0.92
Office	Building Area Method	0.82	0.69
Sales Area	Common Space Type	1.44	1.06
Sales Area	Common Space Type	1.44	1.06
Sales Area	Common Space Type	1.44	1.06
Lobby – all other lobbies	Common Space Type	0.90	0.86
Classroom/Lecture Hall/ Training Room – all other	Common Space Type	1.24	0.74
Corridor – all other corridors	Common Space Type	0.66	0.58
Lobby – all other lobbies	Common Space Type	0.90	0.86
Electrical/Mechanical Room	Common Space Type	0.95	0.89
Restroom – all other restrooms	Common Space Type	0.98	0.75
Office – enclosed	Common Space Type	1.11	0.85
Gymnasium/Fitness Center – in an exercise room	Building Specific Space Type	0.72	0.50
Food Preparation	Common Space Type	1.21	0.92
Dining area – in cafeteria or fast food dining	Common Space Type	0.65	0.53
Library	Building Area Method	1.19	0.72
Audience Seating Area – in an auditorium	Common Space Type	0.63	0.63[a]

(a) LPD for auditorium in EEM04 is 0.67. The 90.1-2013 value is used since it is more efficient.

Table 10. Display lighting allowance comparison between 90.1-2013 and EEM04

Retail Area[a]	90.1-2013 (W/ft^2)	EEM04 (W/ft^2)
Retail Area 1	0.6	0.4
Retail Area 2	0.6	0.4
Retail Area 3	1.4	1.0
Retail Area 4	2.5	1.5

(a) Retail area is defined in 90.1-2013 Section 9.6.2.

EEM05-06 Occupancy Sensors

EEM05 and EEM06 were initially separate but because they both aim to reduce lighting energy usage by implementing occupancy sensors in all spaces (EEM06 captures open offices only) they were combined in the analysis phase and therefore are presented here as one measure. Standard 90.1-2013 covers many spaces under the occupancy sensor requirements. The remaining spaces are captured in this EEM, including:

- Office-open plan
- Corridor/transition
- Stairway
- Lobby
- Electrical/mechanical room
- Dining area
- Kitchen
- Storage >50 sf and <1000 sf
- Workshop
- Locker room
- Repair shop
- Pharmacy
- Banking Area
- Playing Area
- Auditorium Seating Area

Data from PNNL's 50% Concept Analysis[4] is used to determine occupancy sensor savings for various space types. The occupied hour savings fraction is determined using an area fraction derived from the NC^3 database[5] (Richman et al. 2008) and the savings fraction for the space type. The saving fraction is applied to lighting schedules.

Affected Prototypes: All

EEM07 Exterior Lighting Power Density

EEM07 reduces the exterior LPD. The measure is based on internal research performed by PNNL on currently available technologies for exterior lighting as part of the Lighting Energy Efficiency in Parking (LEEP) campaign under DOE's Better Buildings Alliance (BBA) program.

Table 11 shows the exterior LPDs for parking lots, building facades, and doors in various lighting zones from 90.1-2013 and EEM07.

Affected Prototypes: All

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[4] Presented to the ASHRAE Standard 90.1 Advanced Energy Standards Working Group, October 19, 2011, Chicago, IL.

[5] National Commercial Construction Characteristics (NC^3) Database, an internal database developed by PNNL to represent nationwide commercial construction energy-related characteristics.

Table 11. Exterior lighting power density requirements

Lighting Zone[a]	Parking Lots (W/ft²)		Building Façade (W/ft²)		Doors (W/linear foot of door opening)			
					90.1-2013		EEM07	
	90.1-2013	EEM07	90.1-2013	EEM07	Main Doors	Other Doors	Main Doors	Other Doors
0	0.00	0.00	0.00	0.0000	0	0	0.00	0.00
1	0.04	0.03	0.00	0.0000	20	20	12.60	12.60
2	0.06	0.03	0.10	0.0950	20	20	12.60	12.60
3	0.10	0.05	0.15	0.1425	30	20	19.95	19.95
4	0.13	0.05	0.20	0.1900	30	20	19.95	19.95

(a) Lighting zone is defined in 90.1-2013 Table 9.4.2-1.

EEM08 Exterior Lighting Control

EEM08 reduces exterior lighting energy usage by turning off parking lot lighting when there is no activity in the parking lot. This measure is based on ASHRAE Standard 90.1-2016 (ASHRAE 2016). Specifically, this measure requires luminaires

- serving outdoor parking areas,
- having a rated input wattage of greater than 78 Watts, and,
- a mounting height of 24 feet or less,

to be controlled automatically to reduce the power by a minimum of 50% when no activity has been detected for at least 15 minutes.

Affected Prototypes: All

EEM09 Fan Power Reduction

EEM09 limits the fan energy use from HVAC equipment and is based on NBI's NCG (NCG 2.12). It requires that variable air volume systems use no more than 0.80 W/cfm and constant air volume systems use no more than 0.65 W/cfm for fan power. These limits are used to compute the new static pressure for fans based on the fan power limitation rules established previously in the development of the prototype models. The baseline fan power is approximately 0.92 W/cfm for variable air volume fans, and 0.68 W/cfm for constant volume fans.

Affected Prototypes: All

EEM10 Direct Expansion Cooling Equipment Efficiency

EEM10 improves the efficiency of direct expansion (DX) equipment by specifying at least Tier 2 equipment for unitary AC units and Tier 1 or Tier 2 for unitary heat pumps from the Consortium for Energy Efficiency (CEE) specifications[6]. Tier 2 equipment is used where specified, otherwise, Tier 1 is used. Table 12 shows the CEE specifications.

Affected Prototypes: Stand-alone Retail and High-rise Apartment.

[6] Available at: https://library.cee1.org/system/files/library/7559/CEE_ComACHP_UnitarySpec2016.pdf

Table 12. CEE Tier 1 and Tier 2 equipment efficiency specifications by equipment type and capacity

Unitary AC	Capacity	<65 kBtu/h	65 <-> 135 kBtu/h	135 <-> 240 kBtu/h	240 <-> 760 kBtu/h	> 760 kBtu/h
	Specification	SEER	EER	EER	EER	EER
	90.1-2013	14	11	10.8	9.8	9.5
	CEE Tier 1	15	11.5	11.5	10.3	9.7
	CEE Tier 2	16	12	12	10.6	10.2
Heat Pump Cooling Mode	Capacity	<65 kBtu/h	65 <-> 135 kBtu/h	135 <-> 240 kBtu/h	> 240 kBtu/h	
	Specification	SEER	EER	EER	EER	
	90.1-2013	14	10.8	10.4	9.3	
	CEE Tier 1	15	11.1	10.7	10.1	
	CEE Tier 2	16	11.6	NA	NA	
Heat Pump Heating Mode	Capacity	<65 kBtu/h	65 <-> 135 kBtu/h	> 135 kBtu/h		
	Specification	HSPF	COP	COP		
	90.1-2013	8	3.3	3.2		
	CEE Tier 1	8.2	3.4	3.2		
	CEE Tier 2	8.2	NA	NA		
Water to Air HP Cooling Mode	Capacity	<17 kBtu/h	17 <-> 65 kBtu/h	65 <-> 135 kBtu/h		
	Specification	EER	EER	EER		
	90.1-2013	12.2	13	13		
	CEE Tier 1	14	14	14		
	CEE Tier 2	NA	NA	NA		
Water to Air HP Heating Mode	Capacity	<17 kBtu/h	17 <-> 65 kBtu/h	65 <-> 135 kBtu/h		
	Specification	COP	COP	COP		
	90.1-2013	4.3	4.3	4.3		
	CEE Tier 1	4.6	4.6	4.6		
	CEE Tier 2	NA	NA	NA		

EEM11 Cooling Tower and Boiler Efficiency

EEM11 is based on a proposal submitted during California's Title 24 code development[7]. It is a cooling tower efficiency of 80 gpm/hp. A boiler efficiency of 94.5% is also specified assuming the use of condensing boilers. For Standard 90.1-2013, the boiler thermal efficiency is 81.25%, and the cooling tower efficiency is 40.2 gpm/hp.

Affected Prototypes: Large Office, Secondary School, and Large Hotel.

EEM12 Hotel HVAC Vacancy Control

EEM12 reduces guest room energy usage in hotels by resetting the room temperature during the period when a guest room is unoccupied or unrented. This measure is based on Standard 90.1-2016. The measure requires the guest room thermostat setpoint to be automatically raised by at least 4°F in the cooling mode and lowered by at least 4°F in the heating mode within 30 minutes of all occupants leaving the guest room. When the guest room is unrented and unoccupied, HVAC setpoints are required to be automatically reset to 80°F or higher in the cooling mode and to 60°F or lower in the heating mode.

Affected Prototype: Large Hotel.

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[7] Proposal background can be found at: http://title24stakeholders.com/wp-content/uploads/2017/06/2019-T24-CASE-Report-_Cooling-Towers_Draft-April-2017.pdf

EEM13 Service Water Heating Waste Heat Recovery

EEM13 specifies that 40% of hot water needs are met either through drain water waste heat recovery or using a solar thermal water heating system or a combination of both. PNNL researched various methods through which drain water waste heat recovery can be accomplished and the typical returns achieved using drain water waste heat recovery.

- Using a direct heat exchanger on the drain water return provides about 30% recovery.
- Collecting greywater from the building into a single tank and using a water-source heat pump to extract heat from the greywater to provide all the service water heating (SWH) results in more than 75% recovery[8].
- Various other research papers indicate 30-60% savings from drain waste heat recovery for multi-family buildings[9].
- Up to 50% of the hot water load could be covered using solar water heating even in cold climates (Aldrich and Williamson 2016).

Thus, it was found that 40% waste heat recovery from SWH is possible and was used for this measure.

Affected Prototypes: All

EEM14 SWH Low-Flow Faucets and Showerheads

EEM14 reduces SWH energy and water usage by using low-flow faucets and showerheads. The Environmental Protection Agency's (EPA) WaterSense program (EPA 2012) showed that water use savings from low-flow faucets and showerheads is approximately 20%.

PNNL previously identified the breakdown of water usage within the High-rise Apartment prototype (from sinks, showers, dishwashing, and laundry). By weighting the faucet and showerhead savings with the fraction of usage from sinks and showers, the savings from this EEM was calculated for the High-rise Apartment. For the Secondary School and Large Hotel prototypes, usage from the commercial kitchen and laundry were modeled separately from the shower and sink usage, and thus the 20% reduction fraction was applied directly. For the Stand-alone Retail and Large Office prototypes, there is no other usage apart from sinks and showers, and thus the reduction fraction was applied directly to the peak flow as well. Table 13 shows the percent reduction in peak flow for each prototype.

Affected Prototypes: All

Table 13. Percent reduction in SWH peak flow due to low-flow faucets and showerheads

Prototype	Reduction in Peak Flow for Showers and Sinks (%)
High-rise Apartment	15.2
All Other Prototypes	20.0

[8] Source: Email correspondence with Ecotope on SWH waste heat recovery systems.
[9] Source: ACEEE Hot Water Forum 2017: http://aceee.org/conferences/2017/hwf#presentations

EEM15 Plug Load Control

EEM15 reduces plug load energy usage. This measure has two parts, 1) upgrade kitchen equipment to ENERGY STAR® equipment, and 2) turn-off computers and monitors at night. The first part of the measure is developed based on the kitchen equipment requirement from Standard 189.1-2014. The computer power management requirement is based on California's Title 24.

The kitchen cooking equipment in the Secondary School and Large Hotel sees a 28% and 23% reduction in the electricity and natural gas peak values, respectively. To capture the impact of night-time turn-off of computers, the plug load disaggregation in *Technical Support Document: 50% Advanced Energy Design Guide for Small to Medium Office Buildings* (Thornton et al. 2009) is used to determine the fraction of computer load. This load is turned off during the night (midnight to 5 am) in the Large Office prototype. Note that this measure does not affect the data center load in the Large Office.

Affected Prototypes: Large Office, Secondary School, and Large Hotel.

EEM16 Ventilation Optimization

EEM16 enables the optimization of ventilation control (i.e., dynamic ventilation reset) even in the presence of energy recovery. Previously, dynamic ventilation reset in 90.1-2013 was exempted when an energy recovery ventilator (ERV) was present. This measure is developed based on the requirement in 90.1-2106, which requires utilizing ventilation optimization regardless of ERV status.

Affected Prototype: Large Office, Secondary School.

EEM17 Off-Hour Controls

EEM 17 dealt with off-hour controls, but was later dropped because the requirements it specified already exist in Standard 90.1-2013, which is the baseline code.

EEM18 Thermal Bridging

EEM18 captures the impact of thermal bridging of wall assemblies. Using the Building Envelope Thermal Bridging Guide[10], U-factors are developed for exterior walls assuming thermal bridging from balconies for the Large Hotel and High-rise Apartment prototypes. A second set of U-factors is developed for improved assemblies that attempt to mitigate thermal bridging. NBI developed and provided PNNL the U-factors for the baseline and advanced cases.

It should be noted that this measure is simulated using a separate baseline, i.e., other measures or the EEM bundles are not affected by the base U-factors developed for this measure.

Affected Prototypes: Large Hotel and High-rise Apartment.

[10] https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/power-smart/builders-developers/building-envelope-thermal-bridging-guide-1.1.pdf

Table 14. U-factors for the exterior wall (Btu/hr-ft^2-°F)

Prototype	Condition	CZ 2	CZ 3	CZ 4	CZ 5
High-rise Apartment (Steel-framed residential)	90.1-2013	0.064	0.064	0.064	0.055
	Calculated assembly with Thermal Bridging (broken baseline)	0.174	0.174	0.141	0.132
	Calculated improved assembly (EEM18)	0.160	0.160	0.1019	0.110
Large Hotel (Mass non-residential)	90.1-2013	0.151	0.123	0.104	0.090
	Calculated assembly with Thermal Bridging (broken baseline)	0.234	0.206	0.162	0.148
	Calculated improved assembly (TEEM18)	0.194	0.166	0.145	0.131
Large Hotel (Mass residential)	90.1-2013	0.123	0.104	0.090	0.080
	Calculated assembly with Thermal Bridging (broken baseline)	0.206	0.187	0.148	0.138
	Calculated improved assembly (TEEM18)	0.166	0.147	0.131	0.121

EEM19 Window Overhangs

EEM19 adds window overhangs based on Standard 189.1-2014, which requires a projection factor of 0.5 for windows facing east, south and west.

Affected Prototypes: All

EEM20 Fenestration Area

EEM20 reduces the maximum allowable fenestration area to 30%. Currently, only the Large Office (40%) and Secondary School (34%) prototypes exceed this limit, and for these prototypes, the WWR for the advanced case is changed to 30% to capture the impact of this measure. The window sill height is increased, while keeping the width and the window head height constant so as to not change the daylighted areas.

Affected Prototypes: Large Office, Secondary School.

EEM21 Daylighting Control

EEM21 requires all daylight area to be controlled using daylighting controls. For the Large Office prototype, a maximum of 80% of the daylight area could be controlled, with the rest assumed to be in spaces where daylighting controls would not be applicable. Out of the total daylight area, 52% of the perimeter zone has daylighting dimming control based on requirements from Standard 90.1-2013. The remaining daylight area was considered to be in private offices that did not meet the power threshold for requiring daylighting controls. For the EEM, the daylighted area under sensor control in the Large Office is increased from 52% to 80%, which is the maximum possible. This measure could potentially affect the Secondary School prototype as well, however, all the daylighted area is already controlled in that prototype.

Affected Prototype: Large Office.

EEM22 Liquid Distribution and Dedicated Outdoor Air System

EEM22 requires the use of radiant heating and cooling together with a dedicated outdoor air system (DOAS) with energy recovery to replace the VAV systems in the baseline. The modeling of these two measures required significant changes to the Large Office prototype. The modeling of the radiant and DOAS system was based on the description in the *50% AEDG for Medium Office Buildings* Technical Support Document (Thornton et al. 2009). The main features of the existing system as well as the replacement radiant and DOAS system are described below.

- Existing VAV system: The Large Office prototype has a conventional VAV system with terminal reheat. The heating and cooling sources are a hot water boiler and water-cooled chiller, respectively. The water-side systems have been optimized to comply with Standard 90.1-2013. Ventilation is provided via the central air handlers, which also include air economizers that help reduce the mechanical cooling use whenever available. The load profile in Large Office prototype shows that it is dominated by cooling loads with very little reheat in all climate zones considered in the study.
- Replacement Radiant and DOAS System: The existing system is replaced with a DOAS that supplies fresh air, but does not include an air-side economizer. The heating and cooling is handled by a radiant system embedded in the floor, served by a hot water boiler and water-cooled chiller. Care is taken to ensure that the water-side configuration is identical to and performs just as efficiently as the baseline water-side system. The radiant system allows the heating and cooling setpoints to be set higher and lower than the baseline because the radiant system can provide a similar level of comfort with wider setpoints relative to the conventional air system. Intermediate floors were insulated to prevent heat loss to the zone below. Condensation is a possibility with radiant floor cooling. This was minimized by cooling the air from the DOAS and then heating it back up to meet the supply air setpoint in hot and humid climates. An enthalpy recovery wheel is used with the DOAS system. Table 15 describes properties of the baseline and radiant plus DOAS systems.
- Systems serving the data center and IT closets within the Large Office remain untouched by this measure.

Affected Prototype: Large Office.

Table 15. Properties of the VAV and radiant plus DOAS systems.

Property	VAV w/reheat (Baseline)	Radiant and DOAS (EEM 22)
Water-side system	Two water-cooled chillers and two variable-speed cooling towers. Constant primary variable secondary loop. Two condenser pumps.	Same as baseline
Air-side system	Central air handlers with energy recovery wheel, chilled water cooling coil, hot water heating coil, economizer, VAV fan	Energy recovery wheel, DX cooling coil, gas furnace heating coil, CAV fan, 100% outdoor air
Thermostat setpoints	75° F cooling/70° F heating, Setback: 80° F cooling/60° F heating	77° F cooling/67° F heating Setback: 82° F Cooling/60° F Heating
Floor slab layers	Concrete floor, expanded polystyrene insulation, screed floor covering	Same as baseline, with radiant pipes between the insulation and screed layers
Air supply temperature	Air handler: 55° F - 60° F, with supply air temperature reset	DOAS: 55° F - 60° F, with supply air temperature reset
Water supply temperature	44° F cooling/180° F heating	60° F cooling/113° F heating
ERV control	Outlet temperature control and bypass when economizer within limits	Outlet temperature control

3.2 EEM Bundle Description

After analyzing and modeling each measure individually, EEMs were combined to determine the total savings including interactive effects. For example, when improved opaque U-factors are combined with higher heating equipment efficiency, it will result in less savings than if the individual savings from improved U-factors and heating efficiency were summed. This is because the improved U-factors will reduce heating load, thereby reducing the potential for savings from the improved heating efficiency.

The following EEM bundles were created:

- **Bundle 1**: All EEMs were combined for this first bundle, except EEM 18 (thermal bridging), EEM 20 (WWR), and EEM 22 (radiant and DOAS). EEMs 20 and 22 were left out because they could be considered too restrictive for some designs. The intention was to determine the bundled energy savings without these measures and then combine them in subsequent bundles.
- **Bundle 2**: Includes all EEMs in bundle 1 and replaces the air leakage rate of 0.40 cfm/sf in EEM 03 with a tighter air leakage rate of 0.25 cfm/sf.
- **Bundle 3**: Includes all EEMs in bundle 1 and adds EEM 20 (WWR).

EEM 18 (thermal bridging) was not included in any of the bundles because it required the creation of a separate baseline as well as modified U-factors for the EEM. It would have been difficult to discern the interactive impact of adding this particular EEM with all the other EEMs. EEM 22 (radiant and DOAS) was also not included in any of the bundles because the individual savings from this EEM were negative, i.e., it increased energy consumption (see Large Office EEM savings in Table 18).

4.0 Results

4.1 Individual Measure Savings by Prototype and Climate Zone

Table 16 through Table 20 show whole building site energy savings results by prototype for each EEM in all the climate zones. If an EEM was not applicable to a given prototype or climate zone, the percent savings value is replaced with “NA”. As described in section 3.0, EEMs 05-06 were combined and are represented as EEM 05 in the tables below, and EEM 17 was dropped after the fact, and therefore, does not appear in the tables.

Table 16. High-rise apartment percent energy savings by EEM and climate zone

EEM#	1	2	3	4	5	7	8	9	10	11	12
Label	OpqIns	FenProp	AirLkge	IntLPD	OccSens	ExtLPD	ExtLTGCtrl	FanPwr	DXEff	HydrEff	VacCtrl
2B	0.2%	0.7%	NA	1.4%	0.4%	1.8%	0.7%	3.6%	2.1%	0.0%	NA
3A	0.2%	2.3%	3.4%	1.0%	0.3%	1.8%	0.6%	2.0%	1.3%	1.0%	NA
3C	0.1%	NA	NA	1.5%	0.4%	2.2%	0.8%	2.8%	0.5%	0.0%	NA
4A	1.4%	3.8%	4.7%	0.9%	0.2%	1.7%	0.6%	1.8%	1.0%	1.0%	NA
4C	1.4%	3.7%	2.6%	0.9%	0.2%	1.9%	0.7%	1.9%	0.4%	1.0%	NA
5A	1.0%	4.6%	7.0%	0.7%	0.2%	1.6%	0.6%	1.4%	0.6%	1.9%	NA
EEM#	13	14	15	16	18	19	20	21	22		
Label	SWHRec	SWHFlo	PlgCtrl	VentOpt	ThrBdg	Ovhg	WWR	DLCtrl	Rad		
2B	8.9%	3.4%	NA	NA	0.6%	1.0%	NA	NA	NA		
3A	9.9%	3.7%	NA	NA	0.8%	0.2%	NA	NA	NA		
3C	12.1%	4.7%	NA	NA	0.3%	1.3%	NA	NA	NA		
4A	10.3%	3.8%	NA	NA	2.7%	0.5%	NA	NA	NA		
4C	11.7%	4.2%	NA	NA	2.6%	1.2%	NA	NA	NA		
5A	10.5%	3.8%	NA	NA	1.9%	0.3%	NA	NA	NA		

Table 17. Large hotel percent energy savings by EEM and climate zone

EEM#	1	2	3	4	5	7	8	9	10	11	12
Label	OpqIns	FenProp	AirLkge	IntLPD	OccSens	ExtLPD	ExtLTGCtrl	FanPwr	DXEff	HydrEff	VacCtrl
2B	1.1%	1.2%	NA	2.4%	0.2%	0.9%	0.3%	0.9%	NA	0.5%	1.0%
3A	1.3%	2.2%	0.9%	2.0%	0.2%	0.8%	0.3%	0.8%	NA	1.5%	1.9%
3C	0.5%	0.5%	NA	2.5%	0.2%	0.9%	0.3%	0.7%	NA	1.4%	0.7%
4A	1.5%	2.2%	1.1%	1.7%	0.2%	0.8%	0.3%	0.7%	NA	1.6%	3.0%
4C	1.3%	2.1%	0.9%	1.9%	0.2%	0.9%	0.3%	0.8%	NA	1.6%	2.3%
5A	1.9%	3.0%	1.4%	1.5%	0.2%	0.8%	0.3%	0.6%	NA	2.4%	4.1%
EEM#	13	14	15	16	18	19	20	21	22		
Label	SWHRec	SWHFlo	PlgCtrl	VentOpt	ThrBdg	Ovhg	WWR	DLCtrl	Rad		
2B	7.2%	0.8%	4.0%	NA	0.5%	0.1%	NA	NA	NA		
3A	7.3%	0.9%	3.7%	NA	0.7%	-0.3%	NA	NA	NA		
3C	8.2%	1.1%	4.2%	NA	0.2%	0.3%	NA	NA	NA		
4A	7.9%	1.0%	3.7%	NA	0.4%	-0.2%	NA	NA	NA		
4C	8.7%	1.2%	4.1%	NA	0.4%	1.2%	NA	NA	NA		
5A	8.0%	1.1%	3.4%	NA	0.6%	-0.3%	NA	NA	NA		

Table 18. Large office percent energy savings by EEM and climate zone

EEM#	1	2	3	4	5	7	8	9	10	11	12
Label	OpqIns	FenProp	AirLkge	IntLPD	OccSens	ExtLPD	ExtLTGCtrl	FanPwr	DXEff	HydrEff	VacCtrl
2B	0.2%	0.2%	NA	1.7%	0.9%	1.0%	0.5%	0.7%	NA	0.3%	NA
3A	0.4%	1.5%	0.5%	1.5%	0.7%	1.0%	0.5%	0.5%	NA	1.1%	NA
3C	0.0%	NA	NA	1.9%	1.0%	1.1%	0.6%	0.7%	NA	0.2%	NA
4A	0.8%	2.2%	1.0%	1.2%	0.6%	0.9%	0.5%	0.5%	NA	1.7%	NA
4C	0.5%	1.1%	NA	1.4%	0.7%	1.1%	0.6%	0.5%	NA	0.5%	NA
5A	0.9%	3.0%	1.3%	1.1%	0.5%	0.9%	0.5%	0.4%	NA	2.3%	NA
EEM#	13	14	15	16	18	19	20	21	22		
Label	SWHRec	SWHFlo	PlgCtrl	VentOpt	ThrBdg	Ovhg	WWR	DLCtrl	Rad		
2B	0.5%	0.2%	0.5%	0.5%	NA	0.5%	0.4%	0.7%	-2.0%		
3A	0.6%	0.2%	0.4%	2.3%	NA	0.2%	0.5%	0.6%	0.6%		
3C	0.7%	0.3%	0.6%	NA	NA	0.0%	0.1%	0.8%	-3.3%		
4A	0.6%	0.3%	0.4%	4.5%	NA	-0.1%	0.7%	0.5%	5.2%		
4C	0.7%	0.3%	0.4%	NA	NA	-0.3%	0.3%	0.3%	-0.1%		
5A	0.6%	0.3%	0.3%	5.4%	NA	-0.2%	0.9%	0.4%	8.9%		

Table 19. Secondary school percent energy savings by EEM and climate zone

EEM#	1	2	3	4	5	7	8	9	10	11	12
Label	OpqIns	FenProp	AirLkge	IntLPD	OccSens	ExtLPD	ExtLTGCtrl	FanPwr	DXEff	HydrEff	VacCtrl
2B	0.6%	1.0%	NA	6.0%	0.8%	0.5%	0.2%	1.2%	0.5%	0.1%	NA
3A	1.1%	1.9%	NA	5.3%	0.8%	0.5%	0.2%	1.1%	0.4%	0.5%	NA
3C	0.1%	0.1%	NA	6.2%	1.0%	0.6%	0.3%	1.1%	0.3%	0.2%	NA
4A	1.2%	0.6%	0.3%	4.9%	0.8%	0.5%	0.3%	1.1%	0.3%	0.5%	NA
4C	0.6%	0.3%	NA	5.4%	0.8%	0.5%	0.3%	0.6%	0.1%	1.9%	NA
5A	1.5%	1.6%	0.8%	4.5%	0.7%	0.5%	0.3%	1.0%	0.2%	0.9%	NA
EEM#	13	14	15	16	18	19	20	21	22		
Label	SWHRec	SWHFlo	PlgCtrl	VentOpt	ThrBdg	Ovhg	WWR	DLCtrl	Rad		
2B	2.4%	0.2%	3.2%	2.1%	NA	0.9%	0.1%	NA	NA		
3A	2.6%	0.3%	3.2%	3.2%	NA	1.2%	0.2%	NA	NA		
3C	3.0%	0.3%	3.9%	NA	NA	0.7%	-0.1%	NA	NA		
4A	3.0%	0.3%	3.7%	3.4%	NA	1.4%	0.4%	NA	NA		
4C	3.0%	0.3%	3.9%	NA	NA	1.5%	0.4%	NA	NA		
5A	3.1%	0.3%	3.5%	3.9%	NA	1.2%	0.5%	NA	NA		

Table 20. Stand-alone retail percent energy savings by EEM and climate zone

EEM#	1	2	3	4	5	7	8	9	10	11	12
Label	OpqIns	FenProp	AirLkge	IntLPD	OccSens	ExtLPD	ExtLTGCtrl	FanPwr	DXEff	HydrEff	VacCtrl
2B	1.9%	0.1%	NA	12.9%	0.1%	1.7%	0.5%	1.8%	1.5%	NA	NA
3A	1.9%	0.3%	NA	12.6%	0.1%	1.8%	0.5%	1.4%	1.1%	NA	NA
3C	0.7%	0.0%	NA	14.1%	0.2%	2.0%	0.6%	1.6%	0.6%	NA	NA
4A	3.2%	0.4%	NA	11.7%	0.1%	1.8%	0.5%	1.1%	0.7%	NA	NA
4C	2.0%	0.4%	NA	9.6%	0.1%	1.8%	0.5%	1.0%	0.2%	NA	NA
5A	4.3%	0.9%	NA	10.4%	0.1%	1.8%	0.5%	0.9%	0.5%	NA	NA

EEM#	13	14	15	16	18	19	20	21	22
Label	SWHRec	SWHFlo	PlgCtrl	VentOpt	ThrBdg	Ovhg	WWR	DLCtrl	Rad
2B	2.5%	0.3%	NA	NA	NA	0.3%	NA	NA	NA
3A	2.8%	0.4%	NA	NA	NA	0.2%	NA	NA	NA
3C	3.2%	0.5%	NA	NA	NA	0.4%	NA	NA	NA
4A	3.0%	0.5%	NA	NA	NA	0.0%	NA	NA	NA
4C	3.0%	0.5%	NA	NA	NA	0.2%	NA	NA	NA
5A	3.0%	0.5%	NA	NA	NA	-0.1%	NA	NA	NA

Table 18 (Large Office) shows that for EEM 22 (radiant plus DOAS), the savings in climate zones 2B, 3C, and 4C are negative, while the savings in climate zone 3A is only 0.6%. This finding was counterintuitive to the literature on the subject of radiant and DOAS systems. The following reasons help explain this unexpected result:

1. The Large Office building requires very little heating, even in cold climates, because of its high internal gains. For example, in climate zone 3A, the total heating consumption is just 4.7% of the total energy consumed at the building. As a result, the benefit from radiant heating is not very significant.
2. The DOAS cooling coil had to be specified as a DX coil because of the nature of the system layout in EnergyPlus and therefore, could not be supplied by chilled water used in the radiant system. This is because the temperature required for cooling in the DOAS system is much lower than that for the radiant system. (Supplying the radiant system with such low temperature water could result in condensation on the floors). As a result, there is a penalty in the cooling efficiency relative to the baseline system.
3. The air handlers in the baseline are equipped with air economizers. A review of the annual economizer operating hours for climate zone 4C revealed that over 95% of the time, the system serving the first floor is able to provide at least partial free cooling. This economizing action is not available through the DOAS system. It may be possible to add a water economizer to the radiant system—this was not attempted, but may be pursued in the future.
4. The 50% Medium Office AEDG Technical Support Document (Thornton et al. 2009) specifies a radiant and DOAS system, and shows energy savings in all climate zones that were analyzed because the baseline HVAC system was a unitary DX cooling system, which is typical for small to medium-size office buildings. The cooling system in the baseline for the Large Office building in this study is a water-cooled chiller plant, a more efficient cooling system compared to DX units. Therefore, the system efficiency gain from switching to a water-cooled chiller-based system from a DX-based system is not realized in this instance.

EEM 19 (window overhangs) produces small negative savings in some climate zones for Large Hotel, Large Office, and Stand-alone Retail. This is because the addition of overhangs causes an increase in heating, and the reduction in cooling is not sufficient to make up the increase in heating.

EEM 20 (fenestration area) also produces negative savings in climate zone 3C for Secondary School. Climate zone 3C is a mild climate, with low cooling and heating consumption relative to other climate zones. The reduction in fenestration area causes an increase in lighting, and the reduction in heating and cooling is not able to make up the increase in lighting.

4.2 Bundle Savings by Prototype and Climate Zone

Table 21 shows the percent whole building site energy savings for each bundle of EEMs. Section 3.2 describes how EEMs were combined into the three bundles.

Table 21. Percent Energy Savings for Bundles of EEMs

	Bundle#	1	2	3
Prototype	Brief Description	Bundle 1[(a)]	Bundle 1 + 0.25 cfm/sf air leakage	Bundle 1 + 30% WWR
High-Rise Apartment	2B	21.9%	NA	NA
	3A	25.3%	25.9%	NA
	3C	23.6%	NA	NA
	4A	28.1%	28.5%	NA
	4C	28.5%	28.9%	NA
	5A	30.7%	31.9%	NA
Large Hotel	2B	19.4%	NA	NA
	3A	21.4%	21.5%	NA
	3C	20.3%	NA	NA
	4A	22.6%	22.7%	NA
	4C	24.3%	24.3%	NA
	5A	25.1%	25.2%	NA
Large Office	2B	7.0%	NA	7.1%
	3A	9.5%	9.6%	9.6%
	3C	6.7%	NA	6.8%
	4A	11.5%	11.7%	11.5%
	4C	7.5%	NA	7.5%
	5A	11.9%	12.2%	12.3%
Secondary School	2B	19.2%	NA	19.2%
	3A	20.2%	NA	20.2%
	3C	16.8%	NA	16.7%
	4A	20.3%	20.2%	20.2%
	4C	18.7%	18.7%	18.7%
	5A	21.6%	21.6%	21.5%
Stand-alone Retail	2B	22.9%	NA	NA
	3A	22.6%	NA	NA
	3C	23.3%	NA	NA
	4A	22.9%	NA	NA
	4C	20.5%	NA	NA
	5A	22.5%	NA	NA

(a) All EEMs except EEM 18, 20, and 22.

4.3 End-use Site Energy Comparison Between Baseline and Bundle 1 for each Prototype in Climate Zone 4A

Figure 1 through Figure 5 show the end-use breakdown and savings for bundle 1 relative to the baseline. Only one climate zone is shown as a representation of the end-use breakdown.

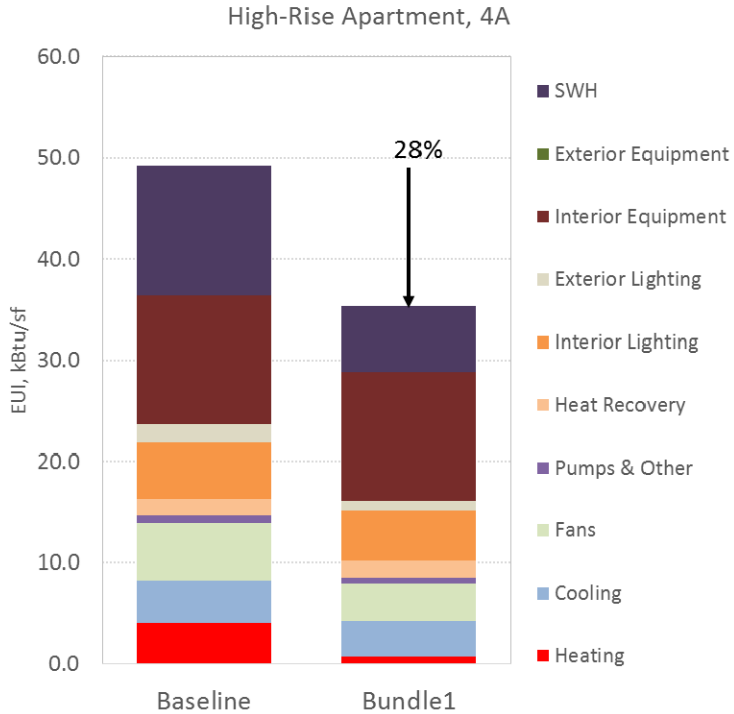

Figure 1. End-use comparison between Bundle 1 and baseline for High-rise Apartment in Climate Zone 4A

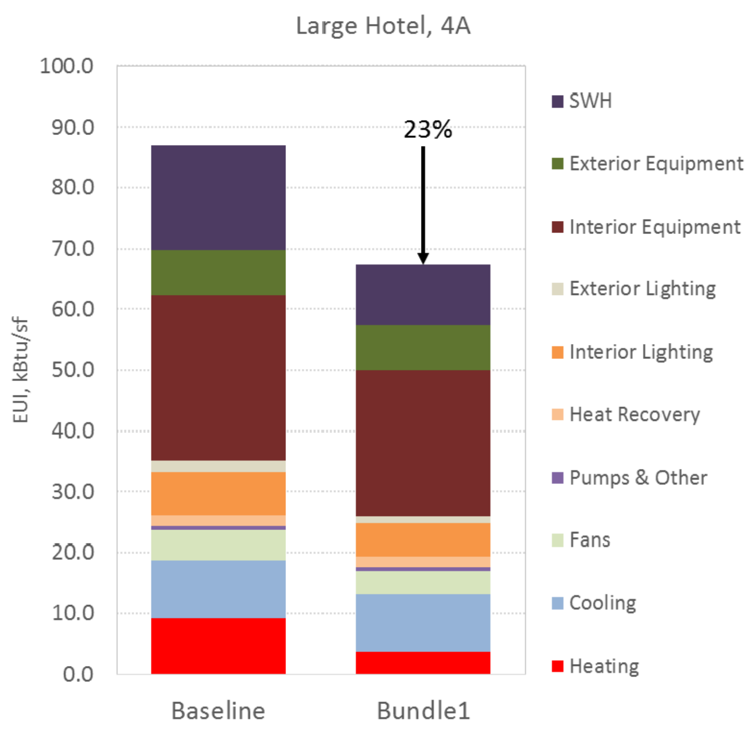

Figure 2. End-use comparison between Bundle 1 and baseline for Large Hotel in Climate Zone 4A

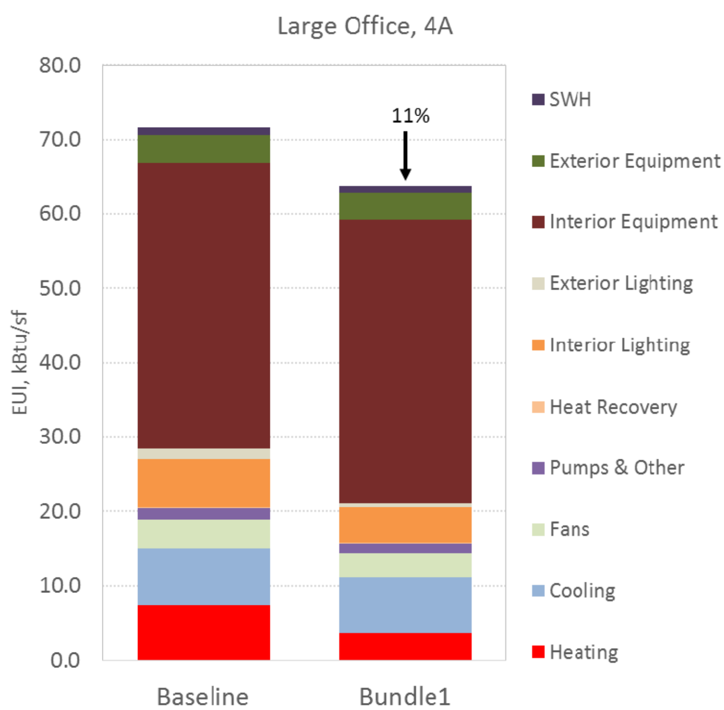

Figure 3. End-use comparison between Bundle 1 and baseline for Large Office in Climate Zone 4A

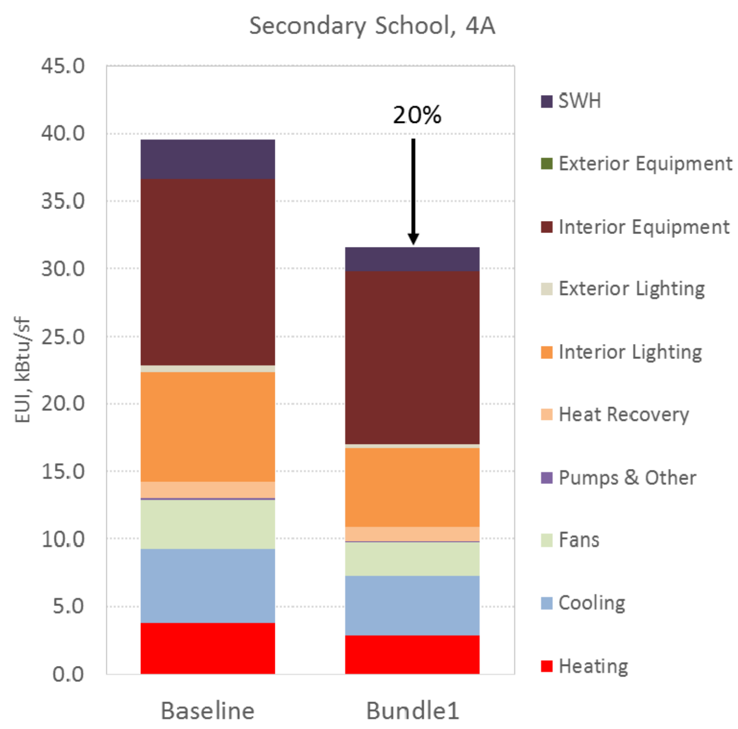

Figure 4. End-use comparison between Bundle 1 and baseline for Secondary School in Climate Zone 4A

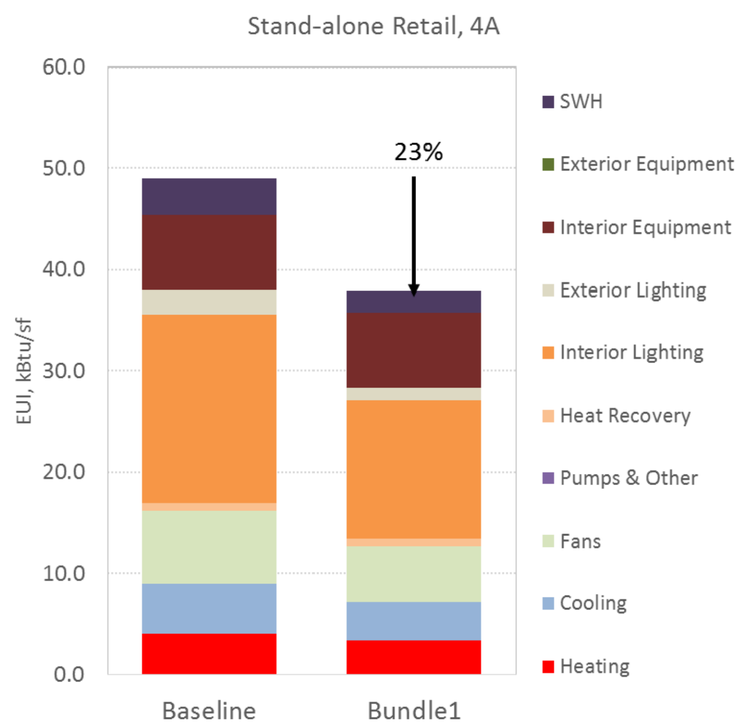

Figure 5. End-use comparison between Bundle 1 and baseline for Stand-alone Retail in Climate Zone 4A

4.4 Summary

The goal of this study was to deliver a bundle of EEMs that could achieve at least 20% energy savings relative to ASHRAE Standard 90.1-2013 across typical building types found in cities located around the United States. As shown in Table 21, the bundled EEM savings exceed the 20% reduction target for most building types in most climate zones. The savings for the Large Office building are smaller because of the substantial data center load.

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