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

Technical Support Document: 50% Energy Savings for Small Office Buildings

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April 2010

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Executive Summary

This project is conducted by Pacific Northwest National Laboratory (PNNL) for the U.S. Department of Energy's (DOE's) Building Technologies (BT) Program. Buildings account for over 40% of total energy use and over 70% of electricity use in the United States (DOE 2009b). To reduce building energy usage, DOE, through its BT Program, established a strategic goal to *"create technologies and design approaches that enable net-zero energy buildings (NZEB) at low incremental cost by 2025"*. Supporting DOE's goal directly, the project objective is to develop a package of energy efficiency measures (EEMs) that demonstrates the feasibility to achieve 50% energy savings for small office buildings with a simple payback of 5 years or less. The 50% goal is to reduce site energy usage relative to buildings that are built to just meet the minimum requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004 (ANSI/ASHRAE/IESNA 2004) before using renewable energy.

PNNL performed the research, analysis, and documentation, referred to as the Technical Support Document (TSD), with inputs from many other contributors and sources of information. An early draft version of the report was circulated to industry experts, practicioners, and another National Laboratory, for in-depth peer reviews. Appendix B documents the review comments and PNNL's responses. For use in this analysis, PNNL developed a prototypical 20,000 ft^2 (1,858 m^2) small office building model that just meets the requirements of Standard 90.1-2004. This is based on the small office prototype that PNNL developed for the 30% *Advanced Energy Design Guide for Small Office Buildings* (ASHRAE 2004). PNNL used the state-of-art energy simulation program - *EnergyPlus*- to determine the energy savings provided by the package of EEMs. The prototype building is simulated in the same eight climate zones adopted by International Energy Code Council (IECC) and ASHRAE in development of the prevailing energy codes and standards. The climate zones are further divided into moist and dry regions, represented by 16 climate locations. The TSD provides the modeling parameters used in the simulations and the energy and cost-effectiveness results.

The advanced EEMs include energy efficiency enhancements to the following building elements:

- Exterior wall and roof insulation
- Windows and glazing
- Overhangs for south windows
- Cool roof
- Interior lighting
- Occupancy sensors
- Perimeter daylighting controls
- Exterior lighting and controls
- Office and other plug load equipment
- Plug load equipment controls
- Packaged rooftop or split system heat pumps
- Dedicated outdoor air system (DOAS)
- Improved ductwork design
- Condensing gas water heaters

The TSD report shows that the recommended EEM package achieves a minimum of 50% energy savings in all 16 climate locations, and a national-weighted average energy savings of 56.6% over the United States. Cost-effectiveness analysis to implement the EEMs shows a weighted-average simple payback of 6.8 years. These results are summarized in the table below. In addition, this report provides results for an alternative EEM package substituting a variable air volume (VAV) heating, ventilation and air conditioning (HVAC) system. This alternative package achieves at least 50% energy savings in 7 of the16 climate locations, corresponding to a national-weighted average savings of 48.5%. The VAV EEM package has a national weighted-average simple payback of 8.6 years. Other packages of EEMs may also achieve 50% energy savings; this report does not consider all alternatives but rather presents at least one way to reach the 50% goal.

Results Summary for Recommended EEM Package with Heat Pumps and DOAS

Climate Zone	City	Energy Savings, (%)	Simple Payback (Years)	Climate Zone	City	Energy Savings, (%)	Simple Payback (Years)
1A	Miami	50%	6.0	4B	Albuquerque	56%	5.3
2A	Houston	56%	6.3	4C	Seattle	57%	7.2
2B	Phoenix	57%	5.4	5A	Chicago	59%	7.9
3A	Atlanta	54%	7.2	5B	Denver	58%	6.4
3B	Los Angeles	52%	8.4	6A	Minneapolis	59%	7.0
3B	Las Vegas	54%	6.5	6B	Helena	58%	6.0
3C	San Fran.	55%	9.6	7	Duluth	56%	5.8
4A	Baltimore	57%	5.9	8	Fairbanks	51%	6.8

This work is related to previous technical support documents that were used in the development of the *30% Advanced Energy Design Guide* (AEDG) series, which were published by ASHRAE and its partner organizations.[1] This TSD will be used to support development of a new *AEDG for Small to Medium Office Buildings*, targeting 50% savings. The small office TSD effort also results in a stand-alone report that may be used separately to demonstrate the feasibility of achieving 50% energy reduction for small office buildings across the full range of climate zones in the U.S..

Design teams may use this report directly to support design of energy efficient buildings. Design teams who use the report should follow an integrated design approach and utilize additional analysis to evaluate the specific conditions of a project.

This report and other sister reports developed under the 50% TSD project sponsored by DOE may also support DOE's Commercial Building Partnerships Program. This program provides technical support to large corporate building owners and managers seeking to achieve 50% energy savings in new commercial buildings, and 30% energy savings in existing commercial buildings.[2]

[1] The published AEDG guides are available for free download at http://www.ashrae.org/technology/page/938.
[2] http://www1.eere.energy.gov/buildings/commercial_initiative/building_partnerships.html

Acknowledgments

This document is prepared by Pacific Northwest National Laboratory (PNNL) for the U.S. Department of Energy's Building Technologies (BT) Program. The authors would like to thank Dr. Dru Crawley, former Team Lead of BT's Commercial Buildings Integration R&D, for his dedicated support to and thoughtful guidance on this project.

The authors would like to thank all the external peer reviewers for their tremendous volunteer efforts and insightful reviews of our energy analysis work during the development of this report. Without their expertise in reviewing the energy efficiency measures covering envelope, lighting, HVAC systems, and service water heating systems, this document would be considerably less rigorous. The following experts peer reviewed an earlier draft of this report:

Floyd Barwig, *Director, Office of Energy Efficiency and Environment, New York State Public Service Commission*

Kent Peterson, *President, P2S Engineering*

John Hogan, *Seattle Departmen of Planning & Development*

Dr. Larry Degelman, *Professor Emeritus of Architecture,Texas A&M University*

Lawrance Berkley National Laboratory

Dr. Merle McBride, *Owens Corning Science and Technology Center*

The authors would also like to specially recognize Andrew Nicholls, the program manager overseeing the Commercial Building Integration Program at PNNL, for his strong support of this particular project. The authors greatly appreciate the assistance of Todd Taylor at PNNL. Todd constructed the cluster simulation structure in *EnergyPlus*, which allowed us to evaluate the many variations of energy efficiency technologies in a timely fashion to meet the project's compressed schedule. Mike Rosenberg and Noami Miller at PNNL provided very detailed reviews on this report. Sue Arey and Rahul Athalye at PNNL provided the editial reviews on this report as well.

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.

Bing Liu, P.E.
Project Manager

Pacific Northwest National Laboratory

Acronyms and Abbreviations

AC	air conditioner
AEDG	Advanced Energy Design Guide
AFUE	annual fuel utilization efficiency
AHU	air handling unit
AIA	American Institute of Architects
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BT	Building Technologies
CAV	constant air volume
CBECS	Commercial Buildings Energy Consumption Survey
CBPP	Commercial Building Partnerships Program
CDD	cooling degree days
CEC	California Energy Commission
CFL	compact fluorescent lamp
COP	coefficient of performance
CPU	central processing unit
DCV	demand controlled ventilation
DOAS	dedicated outdoor air system
DOE	Department of Energy
DX	direct expansion
EEM	energy efficiency measures
EER	energy efficiency ratio
EIA	Energy Information Administration
EIR	energy input ratio

EPA	Environmental Protection Agency
EPDM	ethylene propylene diene terpolymer membrane
ERV	energy recovery ventilation
ESP	external static pressure
E_t	thermal efficiency
EUI	energy use index
HDD	heating degree days
HSPF	heating seasonal performance factor
HVAC	heating, ventilation, and air conditioning
IECC	International Energy Conservation Code
IES	Illuminating Engineering Society
IPLV	integrated part load value
LEED	Leadership in Energy and Environmental Design
LBNL	Lawrence Berkeley National Laboratory
LCD	liquid crystal display
LPD	lighting power density
NBI	New Buildings Institute
NC^3	National Commercial Construction Characteristics
NEA	national energy alliances
NREL	National Renewable Energy Laboratory
NZEB	net-zero energy buildings
PC	personal computer
PSZ	packaged single zone
PNNL	Pacific Northwest National Laboratory
RTU	roof top unit

SEER	seasonal energy efficiency ratio
SHGC	solar heat gain coefficient
SSPC	Standing Standard Project Committee
SL	standby loss
SWH	service water heating
TSD	technical support document
USGBC	US Green Building Council
VAV	variable air volume
VRF	variable refrigerant flow
VT	visible transmittance
WWR	window-to-wall ratio
w.c	water column
VDT	video display terminal

Contents

Figures

Tables

1.0 Introduction

Buildings account for over 40% of total energy use and over 70% of electricity use in the United States (DOE 2009b). To reduce building energy usage, the Department of Energy (DOE) has, through its Building Technologies Program, established a strategic goal to *”create technologies and design approaches that enable net-zero energy buildings (NZEB) at low incremental cost by 2025”*.

To reach NZEB by 2025, DOE BT has implemented a strategy to develop information packages and tools to support realization of 30%, 50% and 70% better buildings, relative to ANSI/ASHRAE/ IESNA Standard 90.1-2004, referred to as 90.1-2004 in the remainder of this document (ANSI/ASHRAE/IESNA 2004a). Beginning in FY2004, DOE has provided financial and technical support for the development of the *Advanced Energy Design Guides* and *Technical Support Documents* in conjunction with these partnering organizations: the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), the American Institute of Architects (AIA), the Illuminating Engineering Society (IES), and the U.S. Green Building Council (USGBC)[1].

There are two distinct but related products under this element. A *Technical Support Document* (*TSD*) is a background document describing the assumptions and methodologies used to achieve particular levels of energy performance. An *Advanced Energy Design Guide* (AEDG) is a publication targeted at architects and other practitioners that provides specific guidance on how to achieve certain levels of high energy performance in buildings.

ASHRAE and its partners have, to date, published six design guides focused on new construction in small commercial buildings. Building types covered include small office, small retail, K-12 school, small warehouse and self-storage, highway lodging, and small hospitals and healthcare facilities[2]. The purpose of these *Guides* is to provide recommendations for achieving at least 30% energy savings over the minimum code requirements of ASHRAE Standard 90.1-1999 (ASHRAE/IESNA 1999).

The 30% energy savings target was the first step toward achieving net-zero commercial buildings. Having proven the feasibility of 30% energy savings across a variety of building types, DOE has exited the 30% design guide area and focuses on the informational products to realize 50% and 70% whole-building energy savings levels across a variety of climate zones, building types, energy intensities and sizes.

The purpose of this *TSD* is to provide an energy efficiency measure package that shows a path to achieve 50% energy savings relative to Standard 90.1-2004 for small-sized office buildings. Prior to this *TSD*, the initial 30% series *Guides* were developed by a project committee administered under ASHRAE’s Special Project procedures. The AEDG project committee included membership from each of the partner organizations. Two of DOE’s national laboratories, Pacific Northwest National Laboratory (PNNL) and National Renewable Energy Laboratory (NREL), have provided leadership and energy analysis support to the various AEDG project committees in the past. Proceeding to the 50% guides,

[1] In addition, the New Buildings Institute participated in the development of the *AEDG for Small Office Buildings*.

[2] The published AEDG guides are available for free download at http://www.ashrae.org/technology/page/938.

DOE decided to develop the *TSDs* first to greatly expedite the speed at which the final guides are provided by ASHRAE to the market to impact actual design decisions in new commercial buildings.

In FY2009 PNNL started the effort for 50% energy savings with the medium office and highway lodging technical support documents and published two reports in September 2009 (Thornton et al. 2009, Jiang et al. 2009). In FY2010, PNNL focuses on two building types to analyze 50% energy savings performance: small offices (this report) and quick service restaurants (in development as a sister report). PNNL is selecting these two building types for two reasons. First, DOE has launched both National Energy Alliances (NEA) and a Commercial Building Partnerships program (CBPs) that include both quick service restaurants and small offices. Because the goal of the NEAs and CBPs is ultimately 50% energy savings, the TSDs will directly support this effort to realize energy efficiency at scale through national account building portfolio replication. Second, with regard to the office subsector, PNNL possesses technical expertise in office building areas, as evidenced by development of the *30% AEDG for Small Offices* and the *50% Design Technology Packages for Medium Offices*.

Publication and use of these two new TSDs for small office and quick service restaurants will lead to additional energy efficiency design improvements well beyond code in our nation's new office and quick service restaurants and will thus significantly contribute to BT's net-zero energy building goal in 2025. For reference, office and food services are ranked as the first and sixth largest in terms of primary energy consumption in the commercial building sector, respectively. The combination of the office and food service sectors constitutes 25% of the primary energy consumption in existing commercial buildings and represents 19% of the total square footage in the commercial building stock according to Table 3.2.2 of the 2009 Building Energy Data Book (DOE 2009b). The recommended package of EEMs will provide a sensible, hands-on approach to design through the use of "off-the-shelf" technologies and products that are practical and commercially available from major manufacturers.

DOE is also supporting the development of *50% AEDG for Small to Medium Office Buildings*. After the publication of this TSD, the 50% AEDG project committee will be convened, representing ASHRAE, USGBC, IES, AIA and DOE. The committee members will review this TSD and a sister 50% TSD for Medium Office that PNNL published in September 2009. These two TSDs will be used as a starting point to inform the development of a subsequent *50% AEDG for Small to Medium Office Buildings*.

2.0 Energy Savings Analysis Methodology

This section describes the energy savings evaluation approach, the simulation program, and the climate locations that are used to assess and quantify the 50% energy savings goal by implementing the energy efficiency measures recommended by this report and the weighting method for combining savings from 16 climate locations for a weighted national average.

The 50% goal for this work is based on the site energy usage at a small office building. Source energy and emissions at the power plant are not provided because such information is specific to the local utility and the mix of fuels and generation technologies used and is outside the scope of this project. One source for information on determining source energy and emissions is *Source Energy and Emission Factors for Energy Use in Buildings* (Deru and Torcellini 2007).

2.1 Evaluation Approach

The evaluation approach is similar to the one used for the development of the recently completed 50% TSD for Medium Offices (Thornton et al. 2009), and to the technical analysis behind the initial 30% *Advanced Energy Design Guide* series. Prototypical buildings were created, and then simulated in the eight climate zones covered in Standard 90.1-2004. The 30% AEDG series used 15 cities to represent the climate zones (Jarnagin et al. 2006, Liu et al. 2006, Liu et al. 2007, Pless et al. 2007, Jiang et al. 2008). This report uses 16 cities selected by DOE in establishing a new set of benchmark buildings. The DOE benchmark buildings are described in Section 2.4. The small office prototype model used for this analysis is based on the 20,000 ft^2 (1,858 m^2) building model developed to support the *30% AEDG for Small Office Buildings* (Jarnagin et. al. 2006).

The 50% energy savings goal is based on on-site energy savings between minimally code compliant (baseline) small offices and advanced buildings that use the recommendations in the TSD study. The baseline level energy use is modeled to match buildings that are designed in compliance with Standard 90.1-2004. The purpose of this building energy simulation analysis is to assess and quantify the energy savings potential of the TSD's final recommendations. A series of steps is taken to reach this goal.

- Develop a prototypical small office building description. Section 2.4 in this report describes the development of the prototypical building.
- Create a baseline model from the prototype that is minimally code compliant for Standard 90.1-2004. Section 3 documents the model inputs and assumptions for the baseline models.
- Identify and select energy efficiency measures to consider. The goal is to develop an integrated package of EEMs that can reach the 50% energy savings target. The integrated package should reduce loads by modifiying the envelope and lowering lighting and plug load usage, and then meet those reduced loads with more efficient HVAC strategies. EEMs are selected that are available in the market and that together provide energy cost savings and total first cost which approaches a five year simple payback. The starting point for identifying potential technologies includes the *30% AEDG for Small Office Buildings* (ASHRAE 2004) and the *Technical Support Document: 50% Energy Savings Design Technology Packages for Medium Offices* [TSD-MO], (Thornton et al. 2009). This effort is also informed by the work of the ASHRAE Standing Standard Project Committee (SSPC) 90.1 engaged in developing the next generation of Standard 90.1.

- Create an advanced model based on the identified energy efficiency measures. Section 4 documents the model inputs and assumptions for the advanced model.
- Evaluate energy savings in all 16 representative climate cities. The summary of energy simulation results for all locations and the final energy efficiency measure recommendations by climate zone are described in Section 5.
- Develop incremental first costs of the EEMs. The cost-effectiveness of the recommended energy efficiency measures is presented in Section 6.

2.2 Simulation Tool Description

EnergyPlus version 4.0 (released in October 2009) is used to assess the energy savings potential of the energy efficiency measures recommended in the TSD report. E*nergyPlus* is a complex building energy simulation program for modeling building heating, cooling, lighting, ventilation, and other energy flows in buildings. *EnergyPlus* has been under continuous development by DOE since 1996 (DOE 2010). While it is based on the most popular features and capabilities of *BLAST* and *DOE-2*, *EnergyPlus* includes many innovative simulation capabilities, such as time steps of less than 1 hour, modular systems and plants integrated with heat balance-based zone simulation, multizone air flow, thermal comfort, and renewable energy systems. *EnergyPlus* is a heavily tested program with formal validation efforts repeated for every release[1].

All energy simulations are completed within a PNNL Linux energy simulation infrastructure, which manages inputs and outputs of the *EnergyPlus* simulations. This infrastructure includes creating *EnergyPlus* input files by a PNNL-developed program known as GPARM, submitting input files to a computing cluster with 80 central processing units (CPUs) for batch simulation, and extracting energy end use results.

2.3 Climate Zones and Weighting Factors

Prior to this report, the published *30% AEDG* series to date have used standardized climate zones that have been adopted by International Energy Code Council (IECC) as well as ASHRAE for both residential and commercial applications. This results in a common set of climate zones for use in codes and standards. The common set of climate zones includes eight zones covering the entire United States, as shown in Figure 2.1 (Briggs et al. 2003). Climate zones are categorized from 1 to 8, with increasing heating degree days (HDDs) and decreasing cooling degree days (CDDs). These climate zones may be mapped to other climate locations for international use. The climate zones are further divided into moist and dry regions.

For this report, a specific climate location (city) is selected as a representative of each climate zone. The *30% AEDG* series selected 15 cities as the representative climate locations. For this project, a revised set of 16 cities is used that balances the representation of the climate zones and the number of buildings in the climate zones. Two locations are selected for climate zone 3B because these are two important locations with very different climates, which is evident from the results of the energy simulations of the

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[1] For the details of the test and validations of *EnergyPlus* program, go to http://apps1.eere.energy.gov/buildings/*EnergyPlus*/testing.cfm. Last accessed on September 26, 2008.

benchmark building models. We have designated the two 3B climate zones as “3B-CA” for the California coast in climate zone 3B and “3B-other”.

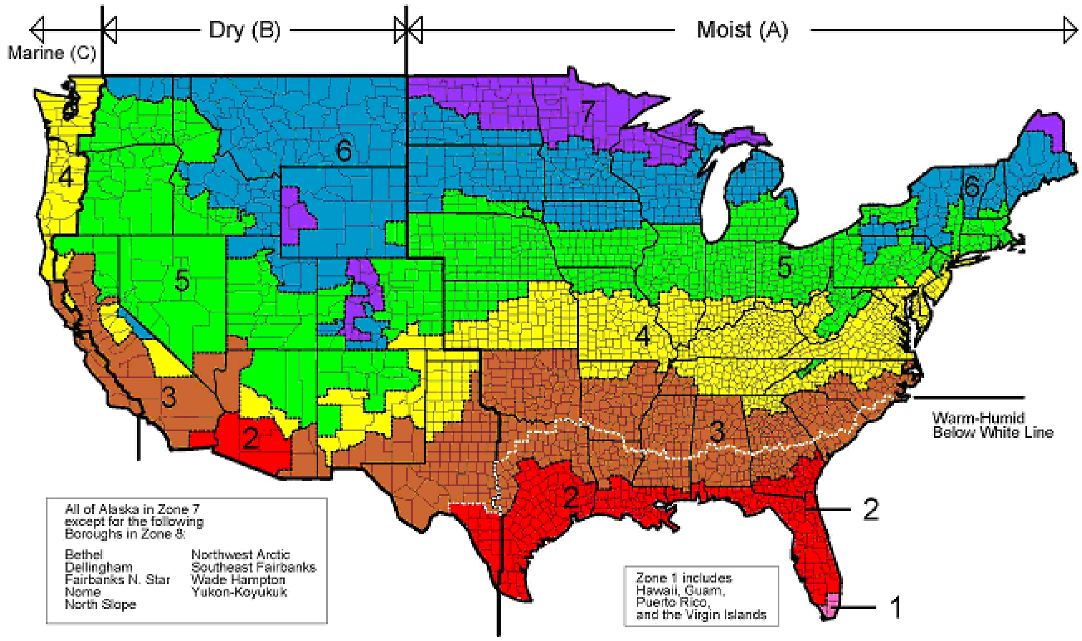

Figure 2.1. DOE-Developed Climate Zone Map

The 16 cities representing the climate zones are:

- 1A: Miami, Florida (very hot, humid)
- 2A: Houston, Texas (hot, humid)
- 2B: Phoenix, Arizona (hot, dry)
- 3A: Atlanta, Georgia (warm, humid)
- 3B-CA: Los Angeles, California (warm, coastal)
- 3B-other: Las Vegas, Nevada (warm, dry)
- 3C: San Francisco, California (marine)
- 4A: Baltimore, Maryland (mixed, humid)
- 4B: Albuquerque, New Mexico (mixed, dry)
- 4C: Seattle, Washington (mixed, marine)
- 5A: Chicago, Illinois (cool, humid)
- 5B: Denver, Colorado (cool, dry)
- 6A: Minneapolis, Minnesota (cold, humid)
- 6B: Helena, Montana (cold, dry)
- 7: Duluth, Minnesota (very cold)
- 8: Fairbanks, Alaska (subarctic)

These representative climate locations are assigned construction area weights based on the new construction floor areas from 2003 to 2007, as presented in a PNNL study that utilizes the McGraw-Hill Construction Projects Starts Database (MHC) (Jarnagin and Bandyopadhyay 2010). This study presents weighting factors for all 16 ASHRAE prototype buildings that PNNL developed to support the development of ASHRAE Stadnard 90.1-2010, as shown in Table 2.1, with small office shown in bold (see Section 2.4 for a description of the benchmark buildings). Table 2.2 shows just the small office weighting factors normalized to total 100% and labeled according to the representative cities shown above. The weights for small office by climate locations are used to calculate weighted average energy savings results for the whole country in Section 5.

Table 2.1. Construction Area Weights for All ASHRAE Building Prototypes and Climate Zones

No.	Prototype	1A moist	2A moist	2B dry	3A moist	3B-CA coastal	3B dry	3C marine	4A moist	4B dry	4C marine	5A moist	5B dry	6A moist	6B dry	7	8	National
1	Large Office	0.10%	0.33%	0.06%	0.45%	0.17%	0.11%	0.12%	1.14%	0.00%	0.15%	0.45%	0.12%	0.13%	0.00%	0.01%	0.00%	3.35%
2	Medium Office	0.13%	0.82%	0.29%	0.77%	0.30%	0.42%	0.14%	1.20%	0.04%	0.20%	1.07%	0.34%	0.30%	0.04%	0.03%	0.01%	6.09%
3	**Small Office**	**0.08%**	**1.07%**	**0.29%**	**0.97%**	**0.08%**	**0.40%**	**0.08%**	**0.94%**	**0.05%**	**0.12%**	**0.93%**	**0.32%**	**0.24%**	**0.03%**	**0.03%**	**0.00%**	**5.64%**
4	Standalone Retail	0.23%	2.23%	0.51%	2.40%	0.33%	0.93%	0.19%	2.56%	0.12%	0.43%	3.45%	0.80%	0.95%	0.09%	0.11%	0.01%	15.35%
5	Strip Mall	0.14%	1.00%	0.26%	1.03%	0.17%	0.46%	0.10%	1.01%	0.02%	0.11%	1.03%	0.20%	0.15%	0.02%	0.01%	0.00%	5.71%
6	Primary School	0.06%	0.94%	0.17%	0.95%	0.12%	0.33%	0.05%	0.90%	0.03%	0.09%	0.93%	0.23%	0.17%	0.04%	0.02%	0.00%	5.03%
7	Secondary School	0.16%	1.53%	0.23%	1.91%	0.31%	0.52%	0.11%	2.03%	0.06%	0.24%	2.30%	0.44%	0.42%	0.09%	0.08%	0.01%	10.43%
8	Hospital	0.04%	0.48%	0.10%	0.47%	0.14%	0.14%	0.04%	0.62%	0.02%	0.11%	0.82%	0.22%	0.22%	0.02%	0.03%	0.00%	3.47%
9	Outpatient Health Care	0.04%	0.57%	0.14%	0.58%	0.10%	0.18%	0.06%	0.82%	0.02%	0.18%	1.07%	0.22%	0.34%	0.03%	0.04%	0.00%	4.40%
10	Restaurant	0.01%	0.11%	0.02%	0.11%	0.01%	0.04%	0.01%	0.13%	0.01%	0.01%	0.14%	0.03%	0.03%	0.00%	0.00%	0.00%	0.66%
11	Fast Food Restaurant	0.01%	0.09%	0.02%	0.10%	0.01%	0.05%	0.01%	0.09%	0.01%	0.01%	0.13%	0.03%	0.03%	0.00%	0.00%	0.00%	0.59%
12	Large Hotel	0.11%	0.62%	0.13%	0.64%	0.18%	0.61%	0.11%	0.96%	0.04%	0.12%	0.93%	0.20%	0.23%	0.06%	0.04%	0.00%	4.98%
13	Small hotel/motel	0.01%	0.29%	0.03%	0.27%	0.02%	0.09%	0.02%	0.32%	0.02%	0.04%	0.37%	0.09%	0.11%	0.03%	0.02%	0.00%	1.73%
14	Warehouse	0.33%	2.50%	0.58%	2.91%	0.54%	1.75%	0.15%	2.36%	0.06%	0.42%	3.40%	0.66%	0.42%	0.04%	0.04%	0.00%	16.17%
15	High-rise apartment	1.53%	1.52%	0.08%	0.66%	0.37%	0.37%	0.17%	2.52%	0.00%	0.36%	1.17%	0.12%	0.13%	0.02%	0.01%	0.00%	9.02%
16	Mid-rise apartment	0.26%	1.10%	0.09%	0.83%	0.70%	0.17%	0.26%	1.70%	0.02%	0.37%	1.13%	0.32%	0.32%	0.06%	0.03%	0.00%	7.37%
	Totals	3.25%	15.21%	2.99%	15.05%	3.56%	6.56%	1.61%	19.31%	0.52%	2.99%	19.28%	4.34%	4.19%	0.56%	0.52%	0.06%	100.00%

Table 2.2. Construction Area Weights for Small Office

1A	2A	2B	3A	3B-CA	3B-other	3C	4A	4B	4C	5A	5B	6A	6B	7	8	Total
Miami	Houston	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks	
1.50%	18.97%	5.16%	17.17%	1.46%	7.01%	1.39%	16.69%	0.84%	2.18%	16.40%	5.74%	4.30%	0.54%	0.58%	0.08%	100%

3.0 Development of the Small Office Prototype and Baseline

This section presents the small office prototype and baseline building model development in terms of the following aspects: building form and orientation, operation, envelope, internal loads (people, lighting, miscellaneous equipment, and infiltration), HVAC equipment, and service water heating. Some characteristics of the small office prototype such as the shape and size of the building do not change with the baseline and the advanced models, while some characteristics such as insulation levels or HVAC system types change from the baseline to the advanced models

Baseline building components regulated by Standard 90.1-2004 are assumed to "just meet" the minimum prescriptive requirements of that standard. Components not regulated by Standard 90.1-2004 are assumed to follow typical design practice for small office buildings.

3.1 Origin of Small Office Prototype Building

The small office prototype used for this document is based on the 20,000 ft² (1,858 m^2) small office prototype developed for *30% AEDG for Small Offices* (AEDG-SO) (ASHRAE 2004). The AEDG-SO also included a 5,000 ft² (465 m^2) prototype. The smaller prototype is closely related to DOE's benchmark building series (DOE 2009a). DOE's Building Technologies Program, working with DOE's three national laboratories, including NREL, PNNL,and Lawrence Berkeley National Laboratory (LBNL), developed benchmark models for 16 commercial building types in 16 locations representing all U.S. climate zones. The 20,000 ft^2 (1,858 m^2) prototype is related to, but also differs from the smaller prototype. The prototype follows the minimum requirements of Standard 90.1. The modeling rules of the Performance Rating Method (Appendix G) of Standard 90.1-2004 provides guidance for the prototype building, but not all of those rules are strictly followed. In addition, some changes are made to allow the prototype to more closely match some available information on typical small offices.as described in this section.

3.1.1 Data Sources for Development of the Small Office Prototype

The primary data sources that are used to help form the small office prototype include the following:

- the 2003 Commercial Building Energy Consumption Survey (CBECS 2003) [1]
- the F.W. Dodge Database[2]
- New Commercial Construction Characteristics (NC^3) Database (Richman et al. 2008) [3]

The CBECS datasets are publicly available and provide statistically valid results from a periodic national survey of existing commercial buildings and their energy suppliers performed by the Energy

[1] The results of the 2003 CBECS surveys are available as downloadable reports and micro-data files from the EIA website (http://www.eia.doe.gov/emeu/cbecs/). The 2003 CBECS is the most recent dataset available.
[2] http://dodge.construction.com/analytics/MarketMeasurement/BuildingStockDatabase.asp
[3] National Commercial Construction Characteristics Database (NC^3), an internal database developed by Pacific Northwest National Laboratory with DOE Building Technologies Program support to represent nationwide commercial construction energy-related characteristics (Richman et al. 2008). The database was derived from F.W. Dodge drawings available at http://dodge.construction.com/Plans/Electronic/ViaInternet.asp (F.W. Dodge, 2002).

Information Administration (EIA). While the design package is intended for new construction, some building characteristics in new constructions are almost the same as existing construction. Furthermore, it can provide information about common characteristics of small office buildings. In the 2003 CBECS survey, 4,859 buildings were surveyed, and the sampled buildings were given base weights (CBECS variable "ADJWT8") to represent the entire stock of commercial buildings in the United States.

The F.W. Dodge database provides detailed historical and forecast databases of construction activity. It contains extensive, comprehensive coverage of existing building space throughout the United States. Up to 20 years of historical data is combined with up to 25 years of forecast data for 15 different project types. Details include floor space, number of buildings, and so on.

NC^3 is an internal PNNL database of nationwide commercial construction energy-related characteristics developed based on building characteristics taken from McGraw Hill/F.W. Dodge commercial building plans submitted for construction bids (Richman et al. 2008). The building plans used were developed in 1996 to 2007. The current database includes over 300 commercial buildings. The drawings used to create the database includes 23 small offices between 8,000 ft^2 (743 m^2) and 30,000 ft^2 (2,787 m^2). In addition to using the NC^3 database, these underlying drawings are examined, and information from them is used and the drawings are referred to as the Dodge drawings in this report.

3.2 Building Form and Orientation

The small office prototype is a 20,000 ft^2 (1,858 m^2) two-story building. The prototypical building has a square shape with dimensions of 100 ft (30.5 m) by 100 ft (30.5 m) (Figure 3.1). A square shape is chosen to be orientation neutral. Shapes and orientations for small offices vary considerably and may be constrained by site characteristics not under the control of the developer or design team. Of the surveyed 23 Dodge drawings for small office buildings, 5 buildings are described as finger-shaped, and nearly all the others have more complex shapes rather than simple rectangles, including protruding sections and surfaces at angles different than 90 degrees relative to other building faces. The average aspect ratio of all the 23 buildings is 1.6. For orientation, 13 of the buildings are elongated along the east-west axis; 6 are along the north-south axis; while the remaining 4 have other orientations.

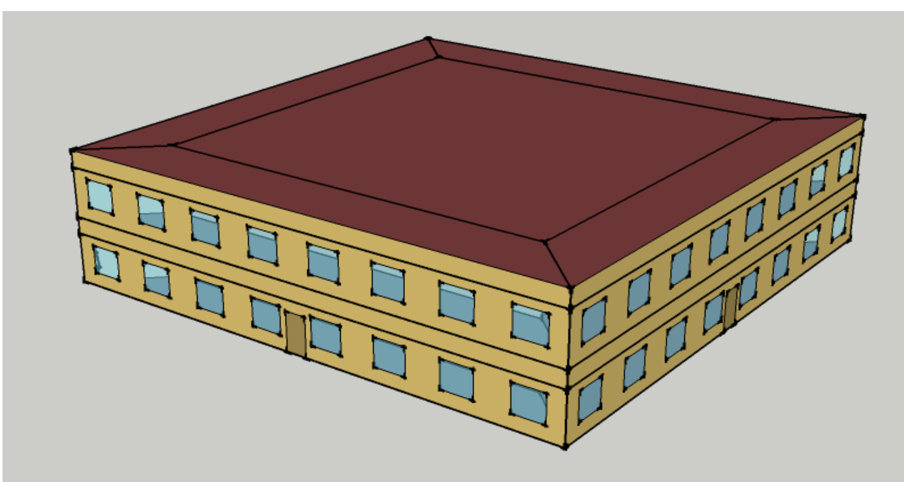

Figure 3.1. Axonometric View of Small Office Building

3.3 Building Operating Characteristics

The small office prototype operating hours are assumed to follow typical office occupancy patterns with peak occupancy occurring from 8 AM to 5 PM weekdays with limited occupancy beginning at 6 AM and extending until midnight to include janitorial functions and after-hours workers. Saturday occupancy is modeled at between 10% and 30% of the peak, and limited Sunday and holiday occupancy (approximately 5%) is assumed. Schedules for lighting and miscellaneous equipment are matched to occupancy schedules with additional limited usage during unoccupied times. HVAC system schedules allow for earlier startup times to bring the space to the desired temperature at the beginning of normal occupancy. The occupancy and HVAC schedules are from office schedules in the Standard 90.1-2004 User's Guide (ANSI/ASHRAE/IESNA 2004b). The lighting schedule is similar to that in Standard 90.1-2004 with some additional off-hours usage supported by experience in industry (Hart et al. 2004). The plug loads schedule includes 40% usage in unoccupied hours. The level of unoccupied hours usage is supported by several sources (Sanchez et. al. 2007, PNNL 2004, Hart et al. 2004). Figure 3.2 illustrates the typical weekday schedules for occupancy, lighting equipment and HVAC fans for the small office, as simulated in *EnergyPlus*. Note that there is some variation in the interior lighting, exterior lighting and plug loads schedules in the advanced case to reflect EEMs (Section 4). The principal schedules are shown in Appendix A, Tables A.2 and A.3.

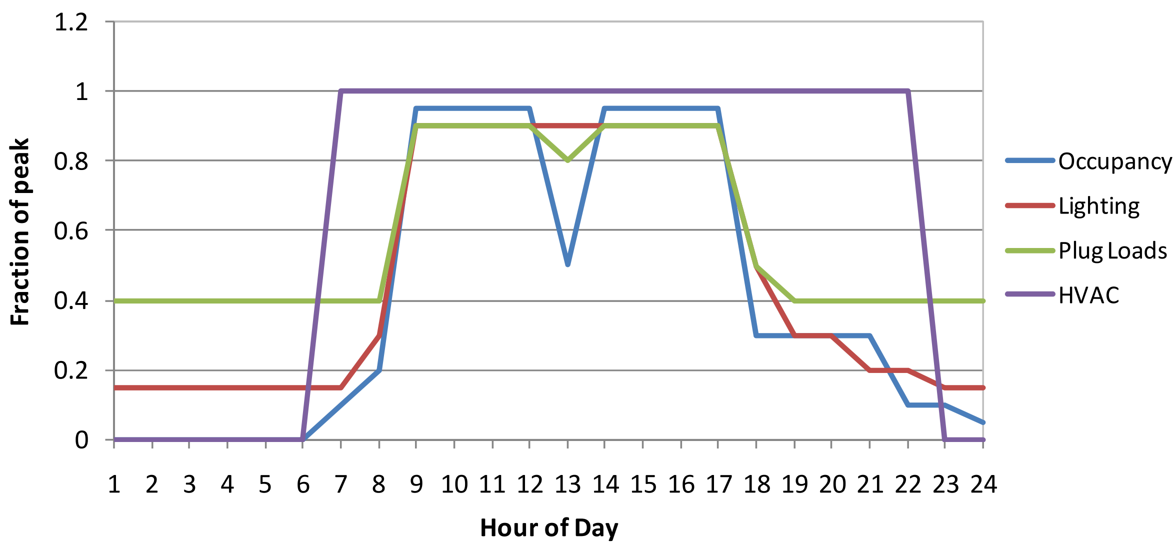

Figure 3.2. Weekday Schedule

While these schedules are applied uniformly to all areas in the building model, the analysis is based on the assumption that an office building typically has a mix of space usages. These space types are not modeled explicitly and all zones in the model assume a mix of these space types. The mix of space types is used for calculating some baseline inputs (such as lighting power density), as shown in subsequent sections.

3.4 Building Envelope Characteristics

Building opaque constructions in the small office prototype include mass walls, flat roof with insulation above the deck and slab-on-grade floors. Windows are defined as manufactured windows in punch style openings. These envelope constructions represent common practice for small office buildings in the U.S. (CBECS 2003, Richman et al. 2008).

The baseline building envelope characteristics are developed to meet the prescriptive design option requirements of Standard 90.1-2004 Section 5.3 *Prescriptive Building Envelope Option* (ANSI/ASHRAE/IESNA 2004a). The *EnergyPlus* program can calculate the U-factor of opaque assemblies by defining the material properties of each layer of the constructions. This method is used in this analysis to properly account for thermal mass impacts on the calculations of space loads. The following section describes the assumptions used for modeling the baseline building envelope components, including the exterior walls, roofs, slab-on-grade floors, fenestration, infiltration, and roof absorptance. Values shown are for the non-residential category in 90.1-2004.

3.4.1 Exterior Walls

The exterior walls of the small office prototype are mass walls with the primary structure composed of concrete block. The concrete block is modeled as 8-in. (200-mm) medium weight concrete blocks with a density of 115 lb/ft³ (1,842 kg/m^3) and solid grouted cores. Interior insulation is modeled with interior rigid insulation held in place with metal clips. Other configurations may allow a similar effective insulation value, such as a steel stud wall with batt insulation on the interior of the CMU and added rigid insulation on the interior or the exterior. The exterior wall includes the following layers:

- Exterior air film, R-0.17 h·ft^2·°F/Btu (0.03 K·m^2/W)
- 8-in. (200-mm) concrete block, 115 lb/ft³, R-0.87 h·ft^2·°F/Btu (0.15 K·m^2/W)
- Rigid insulation, held in place with metal clips. The baseline building insulation thickness varies by climate and in some warmer climate zone, there is no insulation.
- 0.5-in (13-mm) gypsum board (if baseline insulation is required), R-0.45 h·ft^2·°F/Btu (0.08 K·m^2/W)
- Interior air film R-0.68 h·ft^2·°F/Btu (0.12 K·m^2/W).

The baseline building R-values for insulated assemblies are from Standard 90.1-2004 Appendix A (*Rated R-Value of Insulation and Assembly U-Factor, C-Factor, And F-Factor Determination)* (ANSI/ASHRAE/IESNA 2004a). Insulation R-values from Table A3.1A in Appendix A of Standard 90.1-2004 are used to select a wall assembly that just meets the maximum U-factor required in Tables 5.5.1 through 5.5.8 of Standard 90.1-2004 for different climate zones. This takes into account thermal bridging from the metal clips. The baseline insulation R-values and assembly U-factors are shown in Table 3.1.

Table 3.1. Baseline Thermal Performance for Exterior Mass Wall

Climate Zone	Assembly maximum U-factor		Insulation minimum R-value (continuous insulation)	
	Btu/h·ft²·°F	*W/m²·K*	h·ft²·°F/Btu	*K·m²/W*
1	0.580	*3.29*	NR	*NR*
2	0.580	*3.29*	NR	*NR*
3A[1], 3B	0.580	*3.29*	NR	*NR*
3A[1], 3C	0.151	*0.857*	5.7	*1.0*
4	0.151	*0.857*	5.7	*1.0*
5	0.123	*0.698*	7.6	*1.3*
6	0.104	*0.591*	9.5	*1.7*
7	0.090	*0.511*	11.4	*2.0*
8	0.080	*0.454*	13.3	*2.3*

1. 3A below warm-humid line in climate zone 3 requires insulation, below warm-humid line does not. Atlanta, which represents climate zone 3A in this study, is above the warm-humid line.

3.4.2 Roofs

The small office prototype has a flat roof that consists of a roof membrane over rigid insulation, uninterrupted by framing, over a structural metal deck.

The roof construction is defined with the following layers:

- Exterior air film, R-0.17 h·ft²·°F/Btu (0.03 K·m²/W)
- Continuous rigid insulation (thickness and R-value vary by climate)
- Metal deck, R-0
- Interior air film heat flow up, R-0.61 h·ft²·°F/Btu (0.11 K·m²/W).

Roof insulation R-values are set to match the maximum roof U-factor requirements in Tables 5.5.1 through 5.5.8 of Standard 90.1-2004 for different climate zones. The baseline insulation R-values and assembly U-factors are shown in Table 3.2.

Standard 90.1-2004 does not specify either roof reflectivity or emittance. In the small office prototype, the roof exterior finish is chosen as a single-ply membrane of EPDM (ethylene-propylene-diene-terpolymer membrane. A grey EPDM is used in the baseline, and it has a solar reflectance of 0.23 and a thermal emittance of 0.87 (LBNL 2009).

Table 3.2. Baseline Thermal Performance for Roofs with Continuous Insulation Above Deck

Climate Zone	Assembly maximum U-factor		Insulation minimum R-value (continuous insulation)	
	Btu/h·ft²·°F	*W/m²·K*	h·ft²·°F /Btu	*K·m²/W*
1	0.063	*0.36*	15	*2.6*
2	0.063	*0.36*	15	*2.6*
3	0.063	*0.358*	15	*2.6*
4	0.063	*0.358*	15	*2.6*
5	0.063	*0.358*	15	*2.6*
6	0.063	*0.358*	15	*2.6*
7	0.063	*0.358*	15	*2.6*
8	0.048	*0.273*	20	*3.5*

3.4.3 Slab-On-Grade Floors

The ground floor in the small office prototype is carpet over 6-in. (150-mm) concrete slab floor poured directly on to the earth (slab-on-grade). Below the slab is 12 in. (300 mm) soil, with soil conductivity of 0.75 Btu/ h·ft^2·°F (1.3 W/m²·K).

The *EnergyPlus* conduction calculations of the ground heat-transfer (i.e., slab-on-grade floors) are two- or three-dimensional rather than one-dimensional as in other simulation programs (i.e., *DOE-2).* To use this method, the appropriate ground temperature profile is determined by the *Slab* program, a preprocessor that is one of the *Auxiliary EnergyPlus* programs. Then the calculated custom monthly average ground temperatures are manually transferred directly into *EnergyPlus* for each of 16 climate locations. The *Slab* program requires the following key inputs to calculate the ground temperatures:

- Slab material and soil density
- Building height
- Indoor average temperature setpoint
- R-value and depth of vertical insulation (if present)
- Thickness of slab-on-grade
- The floor area to perimeter length ratio for this slab
- Distance from edge of slab to the opposite edge of the area the calculation will be applied to.

For the baseline, in contrast to the U-factor for other envelope assemblies, the F-factor is set to match the minimum requirements for unheated slab-on-grade floors in Tables 5.5.1 through 5.5.8 of Standard 90.1-2004, depending on climate. F-factor is expressed as the conductance of the surface per unit length of building perimeter. Standard 90.1-2004 Chapter 5 provides the corresponding R-values of the perimeter slab edge vertical insulation when required. Only climate zone 8 has a requirement for slab edge insulation for unheated floors, as shown in Table 3.3. This continuous insulation is defined as being applied directly to the slab exterior, extending downward from the top of the slab for the distance specified in the tables. Other configurations can achieve the same required assembly F-factor.

Table 3.3. Baseline Thermal Performance for Unheated Slab-on-Grade Floor

Climate Zone	Assembly maximum F-factor		Insulation minimum R-value (24 in vertical)	
	Btu/h·ft·°F	*W/m·K*	h·ft^2·°F/Btu	*K·m^2/W*
1	0.730	*1.264*	NR	*NR*
2	0.730	*1.264*	NR	*NR*
3	0.730	*1.264*	NR	*NR*
4	0.730	*1.264*	NR	*NR*
5	0.730	*1.264*	NR	*NR*
6	0.730	*1.264*	NR	*NR*
7	0.730	*1.264*	NR	*NR*
8	0.540	*0.935*	10	*1.8*

3.4.4 Fenestration

Small office buildings generally have moderate window-to-wall ratios (WWR). According to the CBECS 2003 data (CBECS 2003), the average WWR for small offices after 1980 construction is 19%. Examination of the rough window layout (without detailed area take-offs) for small offices in the Dodge drawings supports this and shows 17 of 23 buildings with standard sized windows distributed around the building facade. The overall WWR of the entire building in the small office prototype is set at 20% including any glazing associated with entryways. This WWR is reduced from 30%, the value used in the previous small office 20,000 ft^2 (1,858 m^2) prototype developed for the *30% AEDG for Small Office Buildings*. The windows have a height of 5 ft (1.5 m) and a width of 6 ft (1.8 m) and eight such windows are distributed evenly on each face of the building.

Based on the Dodge drawings, the primary fenestration type in small office buildings is manufactured windows in punch style or similar openings (17 of 23 small office buildings). The other buildings in the database use some storefront or curtain wall, but only one has a full curtain wall with ribbons of windows across the entire building face. Thus, the small office prototype has manufactured windows in punch openings. This type of window is also chosen to provide consistency with the advanced case, which considers manufactured windows with lower U-factors than site-assembled windows can typically meet.

Although window requirements in Standard 90.1-2004 are defined by the overall properties of U-factor and solar heat gain coefficient (SHGC), *EnergyPlus* requires that the thermal/optical properties are defined layer by layer for the window assembly. It is a challenge to manually find a window construction that matches given U-factor and SHGC values exactly. To address this challenge, NREL developed a hypothetical glass library for *EnergyPlus* by creating glazing options to represent windows that match Standard 90.1-2004 performance requirements. These glazing options allow the code baseline values to fall within 0.01 of the code U-factor and SHGC for all climate zones.

Chapter 5 of Standard 90.1-2004 lists U-factor and solar heat gain coefficient (SHGC) requirements based on climate zone, window-to-wall ratio, and window operator type (fixed or operable). Based on an estimated weighting of 4.6% operable and 95.4% fixed windows[4], a baseline window U-factor and solar heat gain coefficient are determined to match the fenestration performance criteria outlined in Tables 5.5.1 through 5.5.8 of Standard 90.1-2004 for each climate zone. These performance values are shown in Table 3.4. These values are from the 10.1 to 20.0% WWR category. The same values may apply to larger or smaller WWR than this range depending on the climate zone. The effects of window frame and dividers are not modeled explicitly, rather the frames and dividers are included in the overall U-factor baseline values.

Visible transmittance (VT) is an additional quality of the fenestration. VT has no direct impact on building loads or energy consumption for the baseline. VT does impact the performance of daylighting control systems where present. The baseline does not include daylighting controls so VT has no impact on the simulation results for the baseline. There is no prescriptive requirement for VT in Standard 90.1-2004. For the baseline fenestration, VT values are from the window constructions in the theoretical glass window library that meet the desired U-factor and SHGC. The VT values are approximately the same as the SHGC values shown in Table 3.4.

Table 3.4. Baseline Fenestration Performance

Climate Zone	assembly u-factor		SHGC
	Btu/h·ft²·°F	*W/m²·K*	
1	1.220	*6.93*	0.25
2	1.220	*6.93*	0.25
3A, 3B	0.570	*3.24*	0.25
3C	1.220	*6.93*	0.39
4	0.570	*3.24*	0.39
5	0.570	*3.24*	0.39
6	0.570	*3.24*	0.39
7	0.570	*3.24*	0.49
8[1]	0.460	*2.61*	0.45

1. Baseline SHGC is not regulated for climate zone 8. The baseline SHGC shown for zone 8 is the SHGC for the modeled window with the code required U-factor for zone 8.

The baseline does not include any exterior shading elements, which are included for the advanced case (Section 4.1.4). Interior blinds are included in the baseline. The blinds are deployed when the glare from the window is too high. Daylight glare from a window depends on occupant view direction. It is highest when viewed directly at a window. The maximum allowable discomfort glare index is set at 22 in the models. When the glare index viewed directly at a window from the reference point is above 22, the interior blind will be closed; otherwise, it will be open. The glare index is the ratio of window luminance to the average surrounding surface luminance within the field of view.

[4] ASHRAE SSPC 90.1 Envelope Subcommittee provided the estimated weighting factor based on the Ducker Fenestration Market Data.

3.5 Air Infiltration

Standard 90.1-2004 does not specify a requirement for maximum air infiltration rate. Building air infiltration is addressed only indirectly in Standard 90.1-2004 through the requirements for building envelope sealing, fenestration and door air leakage, etc. For this analysis, the infiltration rate is derived from a starting point of 1.8 cfm/ft² (9.14E-3 $m^3/s{\cdot}m^2$) of above-grade envelope surface area at 0.3 in. w.c. (75 Pa) based on a study by the National Institute of Standards and Technologies (Emmerich et al. 2005). This infiltration rate is based on testing buildings at greatly increased pressure difference than in normal operating conditions. The infiltration rate used in the model for typical operating conditions is determined with the calculation steps below.

PNNL has developed the following methodology to convert the infiltration rate at 0.3 in. w.c. (75 Pa) to a corresponding wind-driven design infiltration rate input in *EnergyPlus* (Gowri et al. 2009). The *EnergyPlus* program offers three methods for addressing infiltration: the constant infiltration method (*EnergyPlus* default); the DOE-2 methodology, which accounts for wind-driven pressure differences; and the BLAST methodology which accounts for both wind-driven and stack-driven pressure differences. Based on the results of PNNL's study on infiltration modeling methodology, the DOE-2 method is utilized (Gowri et al. 2009):

Step 1: Calculate the average wind-driven building pressure on all walls of a building with a wind velocity calculated at the roof line and normal to one wall of the building using existing wind pressure formulations (Swami and Chandra 1987).

Step 2: Integrate the positive wind-driven building pressure for all angles of wind to get an average positive wind pressure across all wall surfaces as a function of wind velocity. (This step is necessary because the wind speed correlations in *EnergyPlus* are independent of direction.)

Step 3: Calculate the infiltration in the building at an average surface pressure from Step 2 and a reference wind speed at the roof line (e.g., 10 mph) by multiplying the infiltration at 0.3 in. w.c. (75 Pa) whole-building pressure difference by the ratio of the average wind pressure from Step 2 to 0.3 in. w.c. (75 Pa), as modified using a flow exponent 0.65. This provides the average infiltration rate across the wall surfaces based on the wind speed measured at the roof line.

Step 4: Adjust the calculated infiltration rate from Step 3 so that it can be correctly used as *EnergyPlus* input by multiplying it by the ratio of the wind speed at the roof line to the average wind speed impinging on a building wall with outward surface normal that is perpendicular to the wind direction. This ratio can be calculated using a power-law wind profile based on the same site terrain as in the *EnergyPlus* model. (This is necessary because the infiltration calculations in *EnergyPlus* use the wind speed at the center height of each exterior wall above ground.)

Following the above methodology, the *EnergyPlus* input design infiltration is calculated as 0.2016 cfm/ft² (1.02 E-3 $m^3/s{\cdot}m^2$) of above-grade exterior wall surface area, equivalent to the base infiltration rate of 1.8 cfm/ft^2 (9.14 E-3 $m^3/s{\cdot}m^2$) of above-grade envelope surface area at 0.3 in. w.c. (75 Pa).

In addition, an infiltration schedule is input in *EnergyPlus* to vary the peak infiltration rate calculated above with HVAC fan on/off operation, assuming that the building is positively pressurized when the

HVAC fan is on. Therefore, the schedule assumes full infiltration when the HVAC system is scheduled "off" and 25% infiltration when the HVAC system is scheduled "on".

3.6 Internal and External Loads

Internal loads include heat generated from occupants, lights, and miscellaneous equipment (plug loads such as computers, printers, and vending machines). In this study, external loads refer to the exterior lighting energy use only. Modeling the energy impacts of the building internal loads using the *EnergyPlus* simulation program requires assumptions about the building internal load intensity and operating schedules. For the occupancy loads, the load intensity refers to the peak occupancy for a typical day. For lighting and plug loads, these loads are represented by the peak power density.

The interior load schedules are from office schedules in the Standard 90.1-2004 User's Guide (ANSI/ASHRAE/IESNA 2004b). Figure 3.2 (Section 3.3) shows a graph of the typical weekday schedule profiles for each of the three internal load categories (plugs, lights and occupancy).

3.6.1 People

The value of the peak occupancy for the small office prototype is set at 88 people. This comes from the proportion of area of a typical small office building that has open and enclosed office spaces, a total of 44% (Table 3.5, Section 3.6.2) of 20,000 ft^2, i.e., 8,800 ft^2 (818 m^2). This area is divided by a work station area of 100 ft^2 (9 m^2) per person (ASHRAE 2005) to result in 88 people. Other building area occupancy is transient and does not add to total occupancy.

For the computer simulations, the total heat gain from occupants is set at 450 Btu/h (132 W) per person. This value represents the normal activity in offices, as shown in Table 1 of Chapter 18 in the ASHRAE 2009 Fundamentals Handbook (ASHRAE 2009). It is assumed that the occupant activity does not vary with the climate zones. The sensible heat fraction is automatically calculated by *EnergyPlus* as a function of the total heat gain and the room air temperature.

3.6.2 Interior Lighting

The baseline lighting is derived from the Excel spreadsheet models used by the ASHRAE SSPC 90.1 Lighting Subcommittee in development of the 90.1-2004 lighting power allowances. These spreadsheet models provide lighting fixture types, lamp types, and quantity for each building space type covered by Table 9.6.1 in 90.1-2004. The development of these values included confirming that IES recommended illumination levels are achieved with the 90.1 lighting models using AGi lighting software (http://www.agi32.com) to calculate light levels associated with models.

Table 3.5 shows how the overall lighting power is determined for the baseline applying the appropriate space type lighting power density to the small office space types. The space types represented in the small office prototype comes from the NC^3 database specifically identified for small offices (Richman et al. 2008). The mix of space is used to determine the lighting power for the whole building which is then applied evenly with the same lighting power density value.

The resulting lighting power density (LPD) for lighting is 1.0 W/ft^2 (10.8 W/m^2), as shown in Table 3.5. The 1.0 W/ft^2 (10.8 W/m^2) is applied to all zones in the baseline model. This value is also consistent with the Building Area Method of Standard 90.1- 2004, which allows a maximum 1.0 W/ft^2 (10.76 W/m^2) for the whole building.

Table 3.5. Baseline Lighting Power Density

Space Type	Percentage of Floor Area[1]	Baseline LPD (W/ft^2)	*Baseline LPD (W/m^2)*
Office – open plan	15%	1.1	*11.8*
Office – private	29%	1.1	*11.8*
Conference meeting	8%	1.3	*14*
Corridor/Transition	12%	0.5	*5.4*
Active storage	14%	0.8	*8.6*
Restrooms	4%	0.8	*8.6*
Lounge/Recreation	2%	1.2	*12.9*
Electrical/Mechanical	2%	1.5	*16.1*
Stairway	3%	0.6	*6.5*
Lobby	6%	1.3	*14*
Other	5%	1.0	*10.8*
Weighted LPD for the whole building	**100%**	**1.0**	***10.8***

1. The floor area percentage for each space type is from a National Commercial Construction Characteristics Database developed by Pacific Northwest National Laboratory (Richman et al. 2008).

Standard 90.1-2004 includes various mandatory interior lighting control requirements including building-wide automatic shutoff and occupancy sensor control in some spaces such as conference rooms, meeting rooms, and break rooms. Mandatory controls are not explicitly simulated because the lighting schedule is assumed to incorporate the effect of these mandatory controls. Figure 3.2 (Section 3.3) shows the typical weekday lighting schedule with 15% of lights energized during unoccupied hours.

3.6.3 Exterior Lighting

The building model assumes that exterior lighting is provided for parking areas, building grounds, entrances and exits, and building façade. Standard 90.1-2004 provides maximum lighting power allowances for each of these areas. The 90.1 standard allowed lighting power for exterior lighting is based on use of metal halide (MH) as the primary light source. Parking fixtures use 400 watt MH. Other grounds areas use 70 watt MH. Façade lighting uses 150 watt MH. The lighting power is based on watts per lineal foot (meter) or watts per ft² (W/m^2) depending on the area type. There is also an additional allowance of 5% of the total exterior connected load to be used anywhere on the exterior. The total baseline connected exterior lighting load is shown in Table 3.6 and includes notes to the table on how the relevant area such as parking area are determined.

Table 3.6. Baseline Exterior Lighting Power Allowances

Items	Baseline (IP units)	*(SI units)*
Parking		
parking area, ft² (m²) [1]	32,642	*3,033*
lighting power allowance for parking W/ft² (W/m²)	0.15	*1.615*
total lighting power for parking, W (W)	4,896	*4,896*
Walkways		
walkway area, ft² (m²) [2]	1632	*152*
lighting power allowance for walkway area W/ft² (W/m²)	0.2	*2.153*
total lighting power for walkway area W (W)	326	*326*
Building entrance and exits [3]		
main entries		
linear foot of door width for main entries, ft (m)	3	*0.91*
lighting power allowance for main entries W/ft (W/m)	30	*98*
canopy over entry, ft² (m²)	42	*3.90*
lighting power allowance for canopy W/ft² (W/m²)	1.25	*13.45*
total lighting power for main entries W (W)	142.5	*143*
other doors		
linear foot of door width for other doors, ft (m)	9	*2.74*
lighting power allowance for other doors W/ft (W/m)	20	*66*
canopy over entry ft² (m²)	140	*13.01*
lighting power allowance for canopy W/ft² (W/m²)	1.25	*13.45*
total lighting power for other doors W (W)	355	*355*
total lighting power for building entrance and exits W (W)	498	*498*
Building facades		
façade area lighted ft² (m²)	10,400	*966*
lighting power allowance for building facades W/ft² (W/m²)	0.2	*2.15*
total lighting power for building facades W (W)	2,080	*2,080*
Sum of lighting power for parking, building entrance and facades W (W)	7,800	*7,800*
5% additional allowance W (W)	390	*390*
Total exterior lighting power W (W)	**8,190**	***8,190***

Notes:

1. There are four parking spots per 1000 ft² (92.9 m²) of building area. Each parking spot occupies 405 ft² (37.6 m²) including associated drives.
2. Walkways are assumed to be 5% of the parking square footage. Determined from site plans used in Standard 90.1-2007 addenda *I* analysis (ANSI/ASHRAE/IESNA 2007).
3. There are four exterior doors modeled, one on each face defined for the models. All doors have a width of 3 ft (0.91 m).

Standard 90.1-2004 requires that exterior lighting shall have automatic controls capable of turning exterior lighting off when sufficient daylight is available or when lighting is not required (i.e., during unoccupied nighttime hours). Use of an astronomical time switch or a photo-sensor is required for all exterior lighting. The *EnergyPlus* model simulates the use of an astronomical time switch, which illuminates the exterior lights only when they are scheduled on and when it is expected to be dark outside.

3.6.4 Miscellaneous Equipment Loads (Plug Loads)

Office buildings have miscellaneous equipment plugged in to receptacles (plug loads), including office equipment (computers, monitors, copiers, fax machines and printers, etc.), and possibly refrigerators, coffee makers, and beverage vending machines. The plug loads not only increase the electrical energy use, but have impacts on the heating and cooling energy use as well. Plug loads increase space cooling loads and reduce space heating loads.

Previous energy analysis work by PNNL (PNNL 2004) indicates that the peak plug loads for offices range from 0.2 W/ft² (2.15 W/m²) to 0.8 W/ft² (8.61 W/m²), with most falling in the range from 0.6 to 0.8 W/ft² (6.46 to 8.61 W/m²). Unoccupied hour base plug loads are in the range from 0.0 to 0.4 W/ft² (4.31 W/m²), with many falling near 0.3 W/ft² (3.23 W/m²).

To determine the overall baseline plug load density, a breakdown of plug loads is developed for the small office building, as shown in Table 3.7. The number of computer workstations is set at 88, the same value as the number of people described in Section 3.6.1. Heat gains are developed in accordance with ASHRAE's recommended values from various office equipment and appliances (ASHRAE 2009). The values shown for As shown in Table 3.7, the peak miscellaneous load for the small office prototype is 0.75 W/ft² (8.07 W/m²), which is applied to all areas of the building. The off-hour load takes the values of 0.30 W/ft² (3.23 W/m²) as shown in the plug load operating schedule described in Section 3.3 and Table A.2 in Appendix A.

Table 3.7. Baseline Plug Load Density

Occupancy Parameter	Value	Data Source	
Gross floor area, ft^2 (m^2)	20,000 (1,858)		
Office station space ratio	0.44	Richman et al. 2008	
Office station space area , ft^2 (m^2)	8,800 (818)		
Floor area per workstation , ft^2 (m^2)	100 (9.3)	ASHRAE Handbook Fundamentals 2005	
Number of computer workstations	88		
Number of tenants	2	Assumption	
Plug Load Equipment Inventory	**Quantity**	**Plug load per unit (W/unit)**	**Plug load (W)**
Computers – servers	2	65	130
Computers – desktop	44	65	2,860
Computers – laptop	44	19	836
Monitors – server – liquid crystal display (LCD)	2	35	70
Monitors – desktop – LCD	88	35	3,080
Laser printer – network	2	215	430
Copy machine	2	1,100	2,200
Fax machine	2	35	70
Water cooler	2	350	700
Refrigerator 18 ft^3 (0.51 m^3) side mount freezer, through-door ice	2	76	152
Vending machine18 ft^3 (0.51 m^3)	2	770	1,540
Coffee maker	2	1,050	2,100
Portable HVAC (heaters, fans)	18	30	540
Other small appliances, chargers, network components etc.	88	4	352
Total plug load (W)			15,060
Plug load density, W/ft^2 (W/m^2)			0.75 **(8.1)**

Notes:
1. The office workstation space area occupies about 44% of the building area.
2. Each workstation occupies 100 ft^2 (9.3 m^2).
3. There are two tenants assumed in the entire building.
4. Each tenant has one computer server and laser printer, water cooler, fax machine, vending machine, coffee maker and refrigerator.
5. The plug load data is from a previous AEDG study (Jarnagin et al. 2006), with various data resources for the electric equipment (Rivas 2009, Sanchez et al. 2007, ASHRAE 2009)
6. The portable HVAC wattage accounts for a mix of standalone fans and heaters, and average operation over the year. Fans and heaters are expected to operate in cooling or heating season, respectively, and then operate intermittently. The 30 W value is not the instantaneous power for an individual electric resistance heater.

3.7 HVAC Systems

The small office baseline uses packaged rooftop cooling units with gas furnaces. CBECS data (Winiarski et al. 2007) indicates that for post-1980 small office buildings, 72% are heated with packaged heating units or furnaces and 76% are cooled by packaged cooling units or residential air-conditioning. Most of the remainder, 20% are heat pumps, with others of various types. The baseline model uses constant air volume (CAV) air distribution systems, supported by the CBECS data. Only 20% of the small office buildings in the CBECS survey have variable air volume HVAC systems.

3.7.1 HVAC Zoning

The small office prototype is divided into 5 thermal zones on each floor for a total of 10 zones. Zoning uses a "four and core" approach with each orientation, defining a perimeter zone that extends from the exterior wall inward for 12 ft, a common depth for enclosed offices (Figure 3.3).

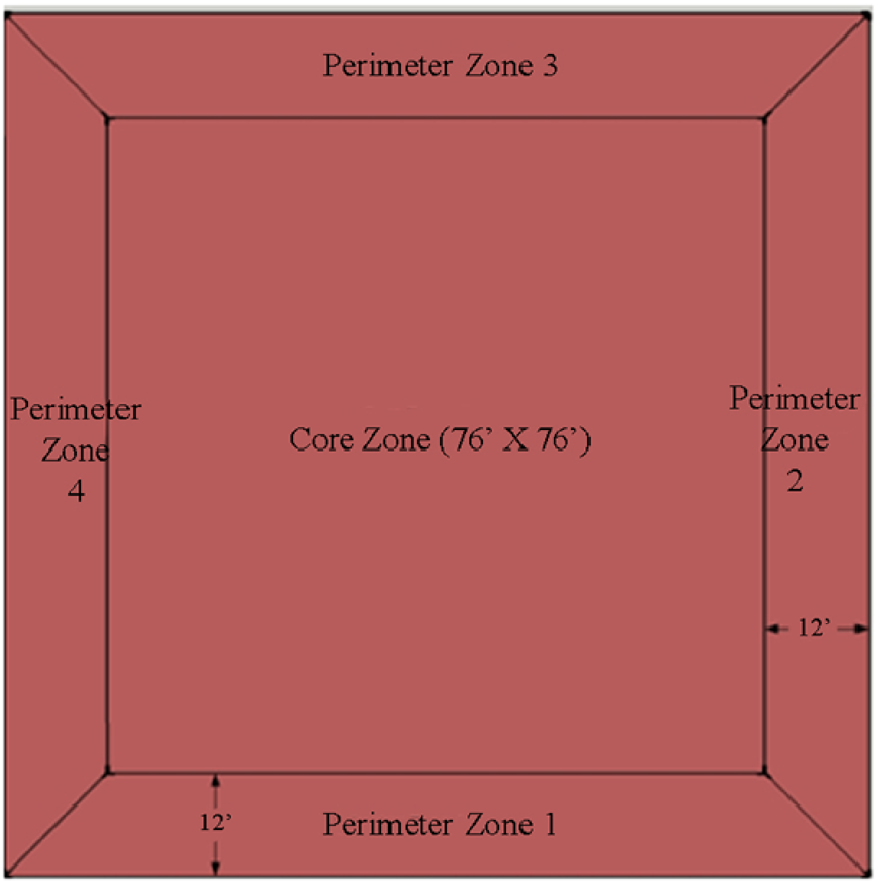

Figure 3.3. HVAC Zoning Map for the Small Office Building

The baseline building uses one system per zone for a total of 10 HVAC systems. Review of the Dodge drawings reveals that 17 of 23 small offices have CAV systems. The average number of HVAC units for the buildings with CAV systems in these drawings is about eight units per building. We considered using fewer than 10 HVAC units in the baseline model. However, but model includes simplified zoning that captures the HVAC loads by perimeter orientation and core zoning separated by building story. With this zoning, to reduce the number of units would require serving zones with significantly different thermal load profiles with a single unit such as a perimeter exposed zone with a core zone, or zones on different floors. None of the buildings in the Dodge drawings with constant volume units serve zones on different floors with a given unit, although some do serve areas on different building faces or mixed areas including core and perimeter. The 10 zones and systems used in the baseline will provide a reasonable representation of typical HVAC operation.

3.7.2 Building HVAC Operating Schedules

The prototype HVAC system operating schedule is based on serving the building occupancy including limited occupancy in the weekday evenings and on Saturdays. Each system is scheduled "on" at 6 AM during weekdays, two hours ahead of building normal opening time to pre-condition the space. The space temperature setpoint ramps from full setback to occupied setpoint over the 2-hour period prior to full occupancy. The systems are scheduled "off" at 10 PM on weekdays (see Figure 3.2, Section 3.3). On Saturdays, the HVAC systems are on 6 AM to 6 PM. When the systems are "on", the fans run continuously to supply the required ventilation air, while the compressors and furnaces cycle on and off to meet the building's cooling and heating loads. During off hours, each system will shut off, and only cycle "on" when the corresponding setback thermostat control calls for heating or cooling to maintain the setback temperature. The same HVAC system schedule is used for all the packaged units. The HVAC schedule includes longer HVAC operating hours than in the *30% AEDG for Small Office Buildings*, which limited regular HVAC system operation from 8 AM to 6 PM weekdays only.

3.7.3 Heating and Cooling Thermostat Setpoints

The HVAC systems maintain a 70°F (21°C) heating setpoint and 75°F (24°C) cooling setpoint during occupied hours. During off hours, thermostat setback control strategy is also applied in the small office prototype, assuming a 5°F (2.8°C) temperature setback to 65°F (18.3°C) for heating and 5°F (2.8°C) temperature setup to 80°F (26.7°C) for cooling.

3.7.4 HVAC Equipment Sizing

HVAC equipment sizing refers to the method used to determine the capacity of the direct expansion (DX) cooling coil, furnace, and supply fan airflow in the packaged rooftop unit. *EnergyPlus* allows users to use a "design day" simulation method for sizing equipment. When using the design day simulation method, two separate design day inputs are specified, one for heating and one for cooling. The program determines the design peak loads by simulating the buildings for a 24-hour period on each of the design days. The design peak loads are then used by the subprogram for sizing HVAC equipment. This analysis uses the design day sizing method primarily for two reasons: 1) it is common practice for designers to choose the design day method for sizing the HVAC equipment; and 2) using the design day method will prevent equipment oversizing to meet the extreme peak weather conditions occurring for a very short period of time during a year. A sizing safety factor of 15% is applied as well, consistent with typical practice.

The design day data for all 16 climate locations are developed based on the "weather data" contained in the accompanying CD-ROM of ASHRAE 2009 Handbook of Fundamentals (ASHRAE 2009). In this data, the heating design day condition is based on the 99.6% annual frequency of occurrence. The 99.6% condition means that the dry-bulb temperature occurs at or below the heating design condition for

35 hours per year in cold conditions. Similarly, annual cooling design condition is based on dry-bulb temperature corresponding to 0.4% annual frequency of occurrence in warm conditions. In *EnergyPlus* simulations, design day schedules can also be specified. To be consistent with the general design practice for HVAC equipment sizing, the internal loads (occupancy, lights, and plug loads) are scheduled as zero on the heating design day, and at maximum level on the cooling design day.

3.7.5 HVAC Equipment Efficiency

Standard 90.1-2004 specifies HVAC equipment efficiency based on heating and cooling capacities. For packaged single zone equipment with cooling capacities less than 65,000 Btu/h (19 kW), efficiency is rated by seasonal energy efficiency ratio (SEER), which represents an average efficiency throughout the year. SEER is defined as the total cooling output of an air conditioner during its normal annual usage period for cooling (in Btu) divided by the total electric energy during the same period (in Wh). Cooling equipment with capacities greater than 65,000 Btu/h (19 kW) is rated by energy efficiency ratio (EER), which represents efficiency at a particular design condition, and is defined as the ratio of net cooling capacity in Btu/h to total rate of electric input in Watts at rated conditions. Standard 90.1-2004 provides efficiency values for the baseline systems, as shown in Table 3.8. When determining efficiency requirements, Standard 90.1-2004 allows air conditioning units with a heating section other than electric resistance to take a credit of 0.2, which is subtracted from the required EER.

Table 3.8. Baseline Packaged Rooftop Unit Cooling Efficiency

Size Category	Minimum Efficiency from ASHRAE Standard 90.1- 2004	Efficiency as input in *EnergyPlus*
<65,000 Btu/h (<19 kW)	13.0 SEER	3.91 COP
65,000 ~ 135,000 Btu/h (19 ~ 40 kW)	10.1 EER	3.5 COP
135,000 ~ 240,000 Btu/h (40 ~ 70 kW)	9.5 EER	3.3 COP
240,000 ~ 760,000 Btu/h (70 ~ 223 kW)	9.5 EER	3.3 COP

In *EnergyPlus*, the efficiency of DX cooling systems is indicated by entering a coefficient of performance (COP), which is defined as the cooling power output in Watts divided by the electrical power input in watts determined at the same environmental conditions as the EER. However, unlike EER, the COP input in *EnergyPlus* does not include the rated power consumption of the supply air fan, so an adjustment to the EER is needed to remove the effect of the indoor fan energy. In addition, for equipment rated by SEER, a conversion from SEER to EER is also required (Wassmer and Brandemuehl 2006). The COP input in *EnergyPlus* is determined by the following equations.

$$EER = -0.0182 * SEER^2 + 1.1088 * SEER$$

$$COP = (EER/3.413 + R) / (1-R)$$

where R is the ratio of supply fan power to total equipment power at the rating condition.

Typical values of fan power ratio R for a commercial rooftop unit vary from about 0.05 to 0.17 depending on specific product design choices. For this analysis, we assume a ratio of about 0.12 as being representative of the broad class of products (PNNL 2004). Table 3.8 shows the cooling efficiency requirements for the HVAC equipment in the small office buildings and the calculated COP for input in the *EnergyPlus* model.

The *EnergyPlus* input for furnace efficiency is thermal efficiency (E_t). Standard 90.1-2004 allows gas furnaces less than 225,000 Btu/h (66 kW) to have a minimum efficiency of 80% thermal efficiency (E_t) or average fuel utilization efficiency (AFUE), which, like SEER, represents average annual efficiency. For furnaces less than 225,000 Btu/h, the baseline efficiency is modeled as 80% E_t. Furnaces larger than 225,000 Btu/h (66 kW) must meet an 80% combustion efficiency (E_c), and are allowed up to 0.75% jacket losses. Thermal efficiency equals the combustion efficiency minus jacket losses. So the thermal efficiency for furnaces larger than 225,000 Btu/h (66 kW) is modeled as 79.25%, which is E_c of 80% minus 0.75% jacket losses. .

3.7.6 HVAC System Fan Power

Each HVAC system is assumed to contain only one supply fan, and there is no return fan or central exhaust fan in the system. Return plenums are assumed to be used. This assumption is consistent with the most likely HVAC system design configurations for small single-zone packaged rooftop air conditioners with CAV.

The *EnergyPlus* program simulates fan power by considering three inputs: total fan efficiency including total static pressure, motor efficiency, and fan air flow rate. The total static pressure is estimated below. Fan efficiency without the motor efficiency for the small constant volume systems is assumed to be 55% based on input from technical reviewers of the 50% TSD for Medium Office (Thornton et al. 2009). The motor efficiency, is calculated from Table 10.8 of Standard 90.1- 2004, based on motor nameplate size (assuming enclosed motors operating at 1,800 rpm) and varies with the simulation determined motor size. The fan airflow rate is determined by the sizing of the equipment as described in section 3.7.4.

One method that could be used (but is not used as explained below) to determine the static pressure input is based on Standard 90.1-2004, which specifies maximum fan power allowance that applies to fans with motors exceeding 5 hp (3.73 kW). The Standard 90.1-2004 maximum fan power allowance is expressed as a total fan system nameplate horsepower per total fan airflow in cfm. Fan system power is based on the total of supply fans, return fans, and exhaust fans. Because the small office building includes only supply fans, this requirement is in effect a maximum allowance for the supply fan motor. According to Standard 90.1-2004, the maximum allowance is 0.0012 hp /cfm (2.70 kW/m^3/s) for systems with supply air volume less than 20,000 cfm (9.44 m^3/s). With an assumed brake horsepower (bhp) of 90% of nominal horsepower, and 55% fan efficiency, this formula results in a calculated maximum total static pressure of 3.8 in. (947 Pa). This is excessive for typical systems, especially for the small system sizes in the simulation, most of which are smaller than 5 horsepower (hp) in any case and not subject to Standard 90.1-2004 fan power rules.

Instead of using the maximum static pressure allowed by Standard 90.1-2004, static pressure is estimated from typical system component pressure drop values for a 5-ton, 2,000-cfm system as shown in Table 3.9. The 5-ton size is consistent with the range of system sizes in the baseline simulation. The static pressure drop values are based on the fan static pressure presented in the 30% TSD for Small Office Buildings (Jarnagin et al 2006), which utilizes manufacturer's catalog data. Compared with the previous

30% TSD analysis, this is updated for plenum return rather than ducted return and an increase in average additional pressure drop for dirty filters. *EnergyPlus* requires entering the total system static pressure, so the static pressure in Table 3.9 includes estimated internal static pressure. Internal static pressure is determined from catalog data on brake horsepower of the fan at the estimated external static pressure. The 1.8 in. w.c. (448 Pascal) total static pressure value is used for all of the baseline fan systems.

Table 3.9. Baseline Packaged Rooftop DX Unit Total Static Pressure

Component	5-ton Packaged Rooftop Unit (@2000 cfm)	
	Static Pressure	
	in. w.c.	***Pa.***
External Static Pressure (ESP)		
Diffuser	0.1	*25*
Ductwork[1]	0.3	*75*
Grille	0.03	*7*
Filter, dirty portion	0.5	*125*
Total ESP	0.93	*232*
Internal Static	0.87	
Total Static Pressure	**1.80**	***448***

1. Used standard practice of 0.1 inch/100 ft duct friction rate plus fittings.

3.7.7 Outdoor Air Ventilation Rates and Schedules

Outdoor air ventilation rates used in the baseline building are as required by ASHRAE Ventilation Standard 62.1-2004 (ANSI/ASHRAE 2004). Standard 62.1-2004 provides a methodology for calculating the ventilation requirements based on the type of space. The minimum outdoor air ventilation rate is calculated using the same mix of space types used to calculate the baseline lighting power density in Section 3.6.2mapped to Standard 62.1-2004 ventilation space types. Although the individual space types are not modeled as separate zones, capturing the mix of space types provides a more consistent overall ventilation rate with an actual office buildng. The same ventilation airflow rate per area is applied to all zones.

Requirements are typically calculated based on combining an airflow value per unit of area, and an airflow value per occupant (although in some space types without the per person airflow). For example, for open office space, the airflow is calculated based on 0.06 cfm/ft^2 (3.05E-4 m^3/s/m^2) of floor area plus 5 cfm per person (2.36E-3 m^3/s/person). The number of people for the ventilation calculation is based on the default occupancy in Standard 62.1-2004. For example for open office it is 5 people per 1,000 ft^2 (92.9 m^2) gross area. The resulting ventilation rate without consideration of ventilation effectiveness is 0.105 cfm/ft^2 (5.35E-4 m^3/s/m^2) of gross area. Adjusted for 0.80 ventilation effectiveness (ceiling supply and return for heating), the ventilation rate in the simulation is 0.131 cfm/ft^2 (6.65 E-4 m^3/s/m^2). The calculation is shown in Table 3.10. SI units are only provided for the total results in the table.

Table 3.10. Baseline Ventilation Rate

Space Type-90.1 Lighting	Space-Type, 62.1-2004 Table 6-1	% of total area	People /1000 ft^2	People, Pz	Rp (cfm/ person)	Rp x Pz	Az, ft2	Ra (cfm/ ft^2)	Ra x Az	Total cfm
Offfice - Enclosed	Office Space	29%	5	1.45	5	7.25	290	0.06	17.4	24.7
Office - Open Plan[1]	Office Space	20%	5	1.00	5	5.00	200	0.06	12.0	17.0
Active Storage	Storage Rooms	14%	0	0.00	0	0.00	140	0.12	16.8	16.8
Corridor/Transition	Corridors	12%	0	0.00	0	0.00	120	0.06	7.2	7.2
Conference/ Meeting/ Multipurpose	Conference/ Meeting	8%	50	4.00	5	20.00	80	0.06	4.8	24.8
Lobby	Reception Areas	6%	10	0.60	5	3.00	60	0.06	3.6	6.6
Restrooms[2]		4%	0	0.00	0	0.00	40	0	0.0	0.0
Stairway	Corridors	3%	0	0.00	0	0.00	30	0.06	1.8	1.8
Electrical/Mechanical	none	2%	0	0.00	0	0.00	20	0	0.0	0.0
Lounge/Recreation	Conference/ Meeting	2%	50	1.00	5	5.00	20	0.06	1.2	6.2
Total/1000 ft^2		100%		8.05		40.25	1000		64.8	105.1
Sub-Total, cfm/ft^2										0.105
Ez, ventilation effectiveness (ceiling return and supply heating >15 F deg. above space temp.)										0.80
Ventilation Air (adjusted for effectiveness), cfm/ft^2										0.131
Total Building Ventilation Air, cfm										2,620
SI Units[4]										
Ventilation Air (adjusted for effectiveness),$m^3/s/m^2$										6.65E-04
Total Building Ventilation Air, m^3/s										1.24

[1] Other-5% on lighting space type Table 3.1 added to office - open plan for this calculation

[2] Restroom requires exhaust only, not separate outside air

[3] Assuming primarily reception areas, not main lobby

[4] SI units shown for total ventilation rates only

The small office baseline is constant volume and uses the ventilation rate procedure (62.1-2004 Section 6.2).
Vbz = RpPt +RaAz
Vbz = outdoor air to breathing area
Rp = outdoor air per person
Pt = max zone population, number of people
Ra = outdoor air per unit area
Az = area of zone
Single zone systems equation 6-2 adjusts Vbz for ventilation effectiveness (62.1-2004 Section 6.2.2.3).
Voz = Vbz/Ez
Voz = zone outdoor airflow
Ez = zone air distribution effectiveness (62.1-2004 Table 6-2)

3.7.8 Economizer Use

Table 3.11 shows that an air-side economizer is not required for five climate zones: 1A, 1B, 2A, 3A, and 4A. For those climate zones where an air system has a cooling capacity large enough to trigger the use of an air economizer, the economizer will be controlled by differential dry-bulb temperature, a control option allowed by Standard 90.1-2004. Under this control scenario, when the outdoor air temperature is below the return air temperature, the economizer is enabled. Only some of the core systems in the baseline are large enough to require economizers.

Gravity dampers are allowed for buildings under three stories by Standard 90.1-2004. The gravity dampers are simulated as being open to minimum position whenever the supply fan is running, even when the building is unoccupied. For zones with systems that have economizers, the baseline assumes use of motorized dampers that remain closed during unoccupied hours even when the fan cycles on.

Table 3.11. Economizer Requirements in Standard 90.1-2004

Climate Zone	Representative City	Economizer Required if Cooling Capacity ≥ 65,000 Btu/h (19 kW) and < 135,000 Btu/h (40 kW)	Economizer Required if Cooling Capacity ≥ 135,000 Btu/h (40 kW)
1A	Miami	No	No
2A	Houston	No	No
2B	Phoenix	No	Yes
3A	Atlanta	No	No
3B-CA	Los Angeles	Yes	Yes
3B-other	Las Vegas	Yes	Yes
3C	San Francisco	Yes	Yes
4A	Baltimore	No	No
4B	Albuquerque	Yes	Yes
4C	Seattle	Yes	Yes
5A	Chicago	No	Yes
5B	Denver	Yes	Yes
6A	Minneapolis	No	Yes
6B	Helena	Yes	Yes
7	Duluth	No	Yes
8	Fairbanks	No	Yes

3.8 Service Hot Water System

The baseline service hot water system for the small office is defined as a gas-fired storage water heater that meets the minimum equipment efficiency requirements under Standard 90.1-2004. The small office is modeled with a small commercial water heater with 75-gallon (283-L) storage and rated input of 75,100 Btu/h (22,010 W). A gas water heater was chosen for the baseline to be consistent with the use of gas for heating in the baseline building. The water heater serves a small circulation loop for restrooms, breakrooms and janitorial services assumed to be in the building core. The hot water supply temperature is modeled as 120°F (48.9°C).

To estimate the energy performance of a service water heater with a storage tank, the *EnergyPlus* program requires the user to define the following key input variables as the operating parameters:

- peak hot water flow rate
- hot water use schedule
- the rated storage tank volume
- the maximum heater capacity – the heating capacity of the burner used to meet the domestic hot water load and charge the tank
- the heater thermal efficiency (E_t) – this is a ratio of heating capacity at full load to gas heat input
- the standby heat loss coefficient (UA).

3.8.1 Hot Water Usage

The typical hot water use for office buildings is 1 gallon (3.8 L) per person per day, as shown in Table 7 of Chapter 49 Service Water Heating in ASHRAE Applications Handbook (ASHRAE 2007). This results in a daily hot water consumption of 88 gallons (0.3331 m^3) for the small office building.

To determine the peak hot water flow rate in terms of gph (L/s) the amount per day is divided by the total full load hours calculated from the sum of the prototype weekday hourly schedule fractions of full load (Figure 3.4). This schedule is adapted from the ASHRAE 90.1-2004 User's Manual Service Hot Water Schedule to a water usage flow schedule for *EnergyPlus*. The total full load hours in the weekday schedule is 8 hours. The maximum hourly hot water flow rate is calculated as 11.0 gph (0.0115 L/s). This maximum is the hourly maximum, which is multiplied by the hourly water heating usage schedule each hour to determine the corresponding hourly hot water usage. Saturday schedule and Sunday and holiday schedules are defined separately also based on ASHRAE 90.1-2004 User's Manual schedule.

3.8.2 Storage Tank Size, Maximum Heating Capacity and Recovery Rate

The water heater storage tank volume is sized based on the methodology described in Chapter 49 of the 2007 ASHRAE Applications Handbook (ASHRAE 2007). Setting the usable storage capacity at 0.6 gallons (2.3 L) per person for 88 people, the usable storage capacity is 53 gallons (201 L). The usable storage capacity is 70% of the total capacity so the storage capacity is set at 75 gallons (283 L). According to Figure 19 of Chapter 49 of the ASHRAE Applications Handbook (ASHRAE 2007), a storage capacity of 0.6 gallons (2.3 L) per person corresponds with a minimum recovery rate of 0.25 gph (2.6 E-4 L/s) per person, or 22 gallons (83 L). A typical 75-gallon (283-L) water heater has a maximum heating capacity of 75,100 Btu/h (22,010 W) and a recovery rate in the range of 75 gph (0.079 L/s) recovery at 90°F (32°C) rise. This is more than sufficient recovery capacity, including an allowance for losses.

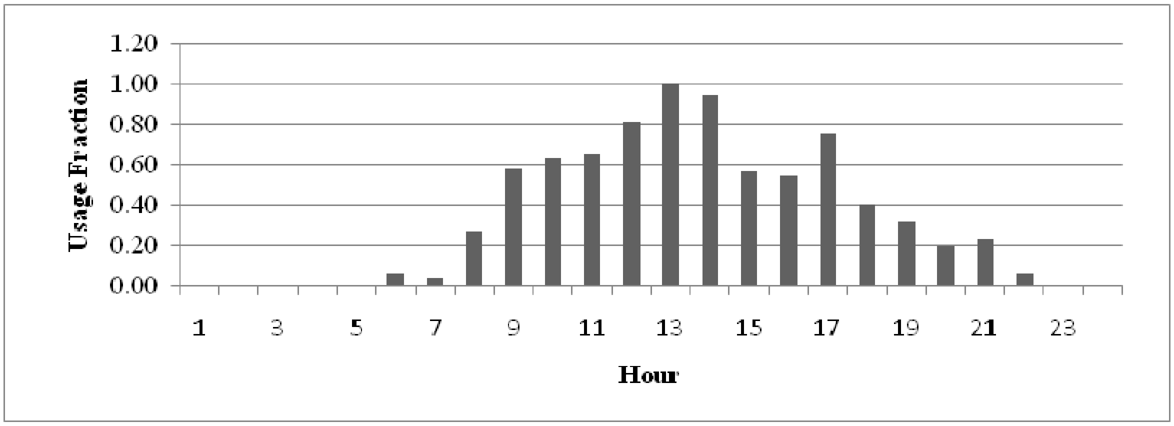

Figure 3.4. Domestic Hot Water Usage Profile for Weekdays

3.8.3 Thermal Efficiency

For a water heater with rated input greater than 75,000 Btu/h (21,975 W), the minimum E_t required is 80%, as shown in Standard 90.1-2004.

3.8.4 Standby Heat Loss Coefficient

The maximum standby loss SL is 1046.5 Btu/h (307 W) using following equation required in Standard 90.1-2004:

$$SL = \frac{Q}{800} + 110\sqrt{V}$$

where *SL* = standby heat loss (Btu/h)
Q = rated input power (Btu/h)
V = rated storage tank volume (gallons)

The standby heat loss coefficient (UA) of the commercial heater is determined using the following equation:

$$UA = \frac{SL \times RE}{70}$$

where *UA* = standby heat loss efficient (Btu/h·°F)
SL = standby heat loss (Btu/h)
RE = recovery efficiency
70 = difference in temperature between stored water thermostat setpoint and ambient air temperature at the test condition (°F)

Inserting the appropriate values for SL and RE, results in a UA of 11.96 Btu/h-°F (6.30 W/K), which is used as one of the input variables for the small office prototype in the *EnergyPlus* program.

4.0 Development of the Advanced Building Model

The advanced building models are developed by adding an integrated package of energy efficiency measures (EEMs) to the baseline building models. The integrated package reduces loads and energy usage by modifiying the envelope and reducing lighting and plug loads, and then meeting those reduced loads with more efficient HVAC strategies.

Two primary goals guided the identification of energy efficiency measures. First, the EEMs should be based on technologies that are commercially available from multiple sources. Second, the EEM packages should result in a simple payback in the range of 5 years. In addition, in order to support the estimation of savings, attention was paid to consider EEMs that can be modeled directly or via a work-around approach by version 4.0 of the *EnergyPlus* simulation program.

The group of energy measures identified that fit these criteria is not large enough to allow for significant measures to be excluded if they achieve more limited savings or are less cost-effective. Instead, a group of reasonable EEMs were identified that together reach the 50% savings goal.

The EEM concepts are developed based on a number of resources including the 50% TSD for Medium Offices (Thornton et al. 2009); the advanced building design guides (ASHRAE 2004, Hydeman et al. 2005, Jarnagin et al. 2006); the approved and proposed addenda to Standard 90.1-2007; a High-Performance Building Database (NBI 2008); the authors' professional experiences; and inputs from industry experts.

All proposed EEMs can be grouped into the following five categories:

- Building envelope measures such as enhanced building opaque envelope insulation and high-performance fenestration.
- Lighting measures that reduce connected lighting load and advanced automatic lighting controls such as daylight harvesting and occupancy-based controls.
- Plug load measures such as using ENERGY STAR labeled office equipment and additional power management and controls.
- HVAC measures including efficient heat pumps and a dedicated outside air system (DOAS) with energy recovery. An alternative variable air volume (VAV) system is also considered.
- Service water heating measures such as higher efficiency equipment.

Another potential target for energy savings is building form and orientation. Opportunities may exist to optimize these building characteristics to maximize passive heating and cooling, and enhance daylighting. However, at many building sites, the form and orientation are constrained by the site and these types of measures may not be feasible. See NREL's *Assessment of the Technical Potential for Achieving Net Zero-Energy Buildings in the Commercial Sector* (Griffith et al. 2007) for some ideas and potential energy savings for EEMs of this type.

This section describes the EEMs that are implemented in the advanced model and have demonstrated energy savings through *EnergyPlus* simulations.

4.1 Envelope

The advanced building models incorporate various energy efficiency measures while maintaining the same building form, orientation, window-to-wall ratios on each façade, and wall and roof construction types as those used in the baseline cases. Small offices are less dominated by interior gains and are affected more by building envelope losses and gains than larger buildings. The building envelope thermal properties were selected from the most stringent among several sources including the *30% AEDG* series, the 50% TSD for Medium Offices (Thornton et al. 2009), and the 50% TSD for Highway Lodging (Jiang et al. 2009), and the 1st and 2nd public review drafts of Addendum bb to Standard 90.1-2007 (BSR/ASHRAE/IES 2009a and 2009b). The envelope selections are not optimized, rather the initial values were tested for success in achieving the 50% savings goal and kept when the goal of 50% savings is met. Optimization of envelope energy measures would be a good subject for future work. The next several sub-sections provide energy efficiency measures related to the advanced building envelope.

4.1.1 Enhanced Insulation for Opaque Assemblies

The advanced insulation requirements for walls and roof are selected to provide superior thermal properties. Baseline values are the non-residential values from Standard 90.1-2004. Exterior walls are the same mass wall construction type as those in the prototype (see Section 3.4.1), but more continuous rigid board insulation is added to improve the overall thermal performance. Table 4.1 shows the wall assembly U-factors and the corresponding insulation R-values for both baseline and advanced models. Roofs have insulation entirely above metal deck construction type (see Section 3.4.2) with enhanced insulation. Table 4.2 shows the roof assembly U-factors and the corresponding rigid insulation R-values. Table 4.3 shows the slab-on-grade insulation F-factors and the corresponding rigid insulation R-values. Only climate zones 6B, 7 and 8 are affected by slab edge insulation.

The enhanced insulation requirements are achieved by changing the insulation layers' thermal resistance. Because only thermal resistance is modeled for the insulation layers in this work, the thermal mass of the opaque assemblies does not change between the baseline and the advanced models.

Values recommended for the advanced case cover only the construction types modeled in this study. Lightweight wall constructions with steel framing was evaluated and insulation levels recommended in the 50% TSD for Medium Offices (Thornton et al. 2009). Additional constructions may be considered during the development of the *50% AEDG for Small to Medium Office Buildings*.

Table 4.1. Thermal Performance for Exterior Mass Walls

	Baseline				Advanced			
	assembly U-factor		insulation R-value continuous insulation		assembly U-factor		insulation R-value continuous insulation	
Climate Zone	Btu/h·ft²·°F	*W/m²·K*	h·ft²·°F/Btu	*K·m²/W*	Btu/h·ft²·°F	*W/m²·K*	h·ft²·°F/Btu	*K·m²/W*
1	0.580	*3.29*	NR	*NR*	0.151	*0.857*	5.7	*1.0*
2	0.580	*3.29*	NR	*NR*	0.123	*0.698*	7.6	*1.3*
3A[1], 3B	0.580	*3.29*	NR	*NR*	0.090	*0.511*	11.4	*2.0*
3A[1], 3C	0.151	*0.857*	5.7	*1.0*	0.090	*0.511*	11.4	*2.0*
4	0.151	*0.857*	5.7	*1.0*	0.080	*0.454*	13.3	*2.3*
5	0.123	*0.698*	7.6	*1.3*	0.047	*0.267*	19.5	*3.4*
6	0.104	*0.591*	9.5	*1.7*	0.047	*0.267*	19.5	*3.4*
7	0.090	*0.511*	11.4	*2.0*	0.047	*0.267*	19.5	*3.4*
8	0.080	*0.454*	13.3	*2.3*	0.047	*0.267*	19.5	*3.4*

1. 3A above warm-humid line in climate zone 3 requires insulation, below warm-humid line does not. Atlanta, which represents climate 3A in this study, is above the warm-humid line.

Table 4.2. Thermal Performance for Roofs with Continuous Insulation Above Deck

	Baseline				Advanced			
	assembly U-factor		insulation R-value continuous insulation		assembly U-factor		insulation R-value continuous insulation	
Climate Zone	Btu/h·ft²·°F	*W/m²·K*	h·ft²·°F/Btu	*K·m²/W*	Btu/h·ft²·°F	*W/m²·K*	h·ft²·°F/Btu	*K·m²/W*
1	0.063	*0.358*	15	*2.6*	0.048	*0.273*	20	*3.5*
2	0.063	*0.358*	15	*2.6*	0.039	*0.221*	25	*4.4*
3	0.063	*0.358*	15	*2.6*	0.039	*0.221*	25	*4.4*
4	0.063	*0.358*	15	*2.6*	0.032	*0.182*	30	*5.3*
5	0.063	*0.358*	15	*2.6*	0.032	*0.182*	30	*5.3*
6	0.063	*0.358*	15	*2.6*	0.032	*0.182*	30	*5.3*
7	0.063	*0.358*	15	*2.6*	0.028	*0.159*	35	*6.2*
8	0.048	*0.273*	20	*3.5*	0.028	*0.159*	35	*6.2*

Table 4.3. Thermal Performance for Slab-on-Grade Unheated Floor

	Baseline				Advanced			
	assembly F-factor		insulation R-value for 24 in vertical		assembly F-factor		insulation R-value for 24 in vertical	
Climate Zone	Btu/h·ft·°F	*W/m·K*	h·ft^2·°F/Btu	*K·m^2/W*	Btu/h·ft·°F	*W/m·K*	h·ft^2·°F/Btu	*K·m^2/W*
1	0.730	*1.264*	0	*0.0*	0.730	*1.264*	0	*0.0*
2	0.730	*1.264*	0	*0.0*	0.730	*1.264*	0	*0.0*
3	0.730	*1.264*	0	*0.0*	0.730	*1.264*	0	*0.0*
4	0.730	*1.264*	0	*0.0*	0.730	*1.264*	0	*0.0*
5	0.730	*1.264*	0	*0.0*	0.730	*1.264*	0	*0.0*
6	0.730	*1.264*	0	*0.0*	0.540	*0.935*	10	*1.8*
7	0.730	*1.264*	0	*0.0*	0.540	*0.935*	10	*1.8*
8	0.540	*0.935*	10	*2.6*	0.520	*0.900*	15	*2.6*

4.1.2 Cool Roof

Considering that cooling is one of the major end uses for office buildings, a cool roof that reflects solar energy can be an effective energy-efficiency measure in hot climates (Jarnagin et al. 2006, Konopacki and Akbari 2001). Therefore, in the advanced models, the exterior layer of the roof system is modeled as a light colored, reflective roofing membrane (such as white EDPM), which has solar reflectance of 0.69 and thermal emittance of 0.87 (LBNL 2009). In contrast, the exterior roof layer in the baseline models is a gray EPDM, with solar reflectance of 0.23 and thermal emittance of 0.87. Following the *AEDG* series (Jarnagin et al. 2006, Liu et al. 2007, Jiang et al. 2008), cool roof is included only in climate zones 1 through 3.

4.1.3 High Performance Windows

The advanced models maintain the same window area as the baseline model, but the window constructions have improved performance in terms of the U-factor and the SHGC value. As noted under the baseline, the analysis is based on the understanding that typical small office fenestration uses manufactured windows in punch style openings. In Table 4.4, the baseline U and SHGC values are presented along with the advanced values to facilitate comparison. The baseline values shown include all framing types and for 20% window-to-wall ratio. Addendum bb has separate values for different framing types, and the advanced values shown are for metal window frames other than curtain wall or storefront.

As described in Section 3, in the current version of *EnergyPlus*, a window's performance including the U-factor and SHGC values are derived from the glazing layers' solar-optical properties. The windows for the advanced case are modeled using the NREL theoretical glass library, as described in Section 3.4.4 and match or very nearly match the performance values in Table 4.4. The effects of window frame and dividers are not modeled explicitly, rather the frames and dividers are included in the overall U-factor recommended values.

Visible transmittance does not have direct impact on space heating and cooling loads unless daylight dimming controls are present. The advanced case VT values shown in Table 4.4 correspond to the available window options in the window library described in Section 3.4.4 to match the target U-factor and SHGC. Further work could be done to optimize the window selections for maximized daylight harvesting.

Table 4.4. Fenestration Performance

	Baseline			Advanced			
Climate Zone	assembly u-factor Btu/h·ft²·°F	assembly u-factor *W/m²·K*	SHGC	assembly u-factor Btu/h·ft²·°F	assembly u-factor *W/m²·K*	SHGC	VT
1	1.220	*6.93*	0.25	0.560	*3.18*	0.25	0.25
2	1.220	*6.93*	0.25	0.450	*2.56*	0.25	0.25
3A, 3B	0.570	*3.24*	0.25	0.410	*2.33*	0.25	0.32
3C	1.220	*6.93*	0.39	0.410	*2.33*	0.25	0.25
4	0.570	*3.24*	0.39	0.380	*2.16*	0.26	0.33
5	0.570	*3.24*	0.39	0.350	*1.99*	0.26	0.33
6	0.570	*3.24*	0.39	0.350	*1.99*	0.35	0.44
7	0.570	*3.24*	0.49	0.330	*1.87*	0.4	0.40
8[1]	0.460	*2.61*	0.45	0.250	*1.42*	0.4	0.40

1. Baseline SHGC is not regulated for climate zone 8. The baseline SHGC shown for climate zone 8 is the SHGC for the modeled window with the code required U-factor for zone 8.

4.1.4 Permanent Shading Devices

Window overhangs are employed in the advanced cases. Overhangs are normally an effective passive solar design strategy for south-oriented facades in the Northern Hemisphere because they limit solar gain during the warmer months when the sun is high while allowing solar gain during the heating season when the sun angle is lower. Overhangs are used only on the south façade for climate zones 1 through 5. The overhang is modeled to have a projection factor of 0.5 and the distance between the overhang and the top of the window is 0.66 ft (0.2 m). Projection factor is the ratio of the horizontal depth of the overhang to the vertical distance of the overhang's intersection with the wall to the lower edge of the window. For this small office prototype, the windows have a height of 5.0 ft (1.52 m). Hence, the overhang projects outward from the wall about (0.66+5)*0.5 = 2.83 ft (0.863 m).

Vertical fins are a method to block low-altitude sunlight for east- and west-oriented facades. PNNL analysed a wide variety of fin depth and configurations in support of the 90.1 SSPC Envelope Subcommittee. This analysis shows that fins provide very modest savings or in many cases increased energy usage when applied to a medium office prototype building in various climate zones.

4.2 Lighting

Energy efficiency measures are used in the advanced cases to reduce both interior and exterior lighting energy consumption. The implemented EEMs that address interior lighting include reduced interior lighting power density, occupancy sensor control, and daylighting with automatic dimming control. The EEMs that address exterior lighting include reduced exterior lighting power and exterior lighting control.

4.2.1 Reduced Interior Lighting Power Density

Lighting power density (LPD) can be reduced via the use of energy efficient lighting systems and the suitable integration and layout of ambient lighting and task lighting. In this work, the space-by-space method is followed to determine the interior lighting power allowance. The LPD for the whole building is derived from the percentage of each space type and the designed LPD for each space. For the advanced case, different lighting systems may be used for a given space type. In this case, the designed LPD for each lighting system is also estimated. The information for the LPD calculation is presented in Table 4.5, where the baseline LPD calculation is also provided for comparison. Illumination levels provided by the advanced lighting are very similar to the illumination levels provided by the baseline lighting.

Table 4.5 shows that the whole building LPD can be reduced from 1.0 W/ft^2 (10.76 W/m^2) in the baseline to 0.79 W/ft^2 (8.5 W/m^2) in the advanced case.

One of the predominate fixtures used in the baseline is a pendant-mounted direct/indirect fluorescent fixture. This is a fixture that shines light upward to the ceiling and downward to the task surface. Because of the upward component, the efficiency of the system is highly dependent on the reflectance of the ceiling.

In the advanced case this direct/indirect fluorescent fixture is replaced by a "high-performance lensed" fluorescent fixture. This fixture is recessed into the ceiling and has a lens or lenses combined with internal and/or external reflectors to direct the light out of the fixture very efficiently. This fixture is neither an old style 1960s flat prismatic lensed fluorescent fixture, nor an "indirect basket" style fixture introduced by manufacturers in the late 1990s. These high-performance lensed fixtures have all been introduced in the last 5 years and are manufactured by five or more major fixture manufacturers and have fixture efficiencies of 85% or higher.

Additional changes in the advanced case include use of "high-performance" instant-start electronic ballast in all non-dimming, non-occupancy sensor controlled T8 applications. These ballast and lamps use approximately 54 to 55 watts for a two-lamp T8, with a normal ballast factor of 0.87 to 0.88. Low ballast factor ballasts may also be used that have wattages of 48 watts and a ballast factor or 0.77 to 0.78. All 4-ft T8 lamps are 3100 lumen "high-performance" lamps in dimming and non-dimming fixtures.

Table 4.5. Lighting Power Reduction

	Baseline			Advanced Model			
Space Type	Percentage of Floor Area[1]	Baseline LPD (W/ft²)	*Baseline LPD (W/m²)*	Lighting Systems	LPD Per Lighting System (W/ft²)	LPD, total for space type (W/ft²)	*LPD, total for space type (W/m²)*
Office – open plan	15%	1.1	*11.8*	Task Lighting	0.06	0.68	*7.3*
				High Performance lensed	0.16		
				HP lensed daylight zone	0.41		
				Downlight	0.04		
Office – private	29%	1.1	*11.8*	HP lensed daylight zone	0.97	0.97	*10.4*
Conference meeting	8%	1.3	*14*	Ambient direct/indirect	0.52	0.77	*8.3*
				Linear wall washing	0.25		
Corridor/transition	12%	0.5	*5.4*	90.1-2004 design with HP lamps and ballasts	0.5	0.5	*5.4*
Active storage	14%	0.8	*8.6*	90.1-2004 design with HP lamps and ballasts	0.64	0.64	*6.9*
Restrooms	4%	0.8	*8.6*	90.1-2004 design	0.82	0.82	*8.8*
Lounge/recreation	2%	1.2	*12.9*	HP lensed	0.73	0.73	*7.9*
Electrical/mechanical	2%	1.5	*16.1*	90.1-2004 design with HP lamps and ballasts	1.24	1.24	*13.3*
Stairway	3%	0.6	*6.5*	90.1-2004 design with HP lamps and ballasts	0.6	0.6	*6.5*
Lobby	6%	1.3	*14*	90.1-2004 design Modified Linear cove (20%) Compact fluorescent (CFL) pendant (30%) CFL downlight (50%)	1.09	1.09	*11.7*
Other	5%	1	*10.8*	90.1-2004 design with HP lamps and ballasts	0.82	0.82	*8.8*
Weighted LPD for the whole building	**100%**	**1**	***10.8***			**0.79**	***8.5***

1. The floor area percentage for each space type is from a National Commercial Construction Characteristics Database developed by Pacific Northwest National Laboratory (Richman et al. 2008).

4.2.2 Occupancy Sensor Control of Interior Lighting During Occupied Periods

Occupancy sensor control is included in the simulation for the advanced building models. In this work, a detailed analysis is made to quantify the potential of energy savings as a result of occupancy sensor control. Table 4.6 presents the breakdown of the lighting control strategies for each space category, the percentage of lights controlled by occupancy sensors, and the percentage of energy saving potential from occupancy sensors. After calculation, it is found that because of the increased use of occupancy sensors during the core occupied period of the day, the advanced case has about 17.4% less lighting energy use than the baseline. Thus, in the *EnergyPlus* models for advanced cases, the peak lighting power in the lighting schedule is reduced by 17.4%, applied for weekdays only during the core occupied hours, as shown in Figure 4.1.

4.2.3 Improved Interior Lighting Control During Unoccupied Periods

After-hour lighting, often designated as "night lighting", "24-hour lighting", or "egress lighting", can be a significant waste of energy when the building is unoccupied. The lighting power management is improved in the advanced case by reductions in this after-hour lighting by including greater use of occupancy sensors, as described in Section 4.2.2 and by reducing egress lighting. The occupancy sensors will turn off the general lights during after-hour periods to provide additional savings relative to the time sweep automated lighting controls in the baseline. Minimizing egress lighting once a security system identifies a building is unoccupied will reduce lighting during unoccupied hours. Adoption of occupancy sensors for general lighting and reduced egress lighting and/or security lock-out leads to the interior lighting schedule being reduced from 0.15 to 0.10 for unoccupied hours for the advanced case (Figure 4.1).

4.2.4 Daylight Harvesting with Interior Lighting Controls

Daylight harvesting combined with automatic dimming controls takes advantage of the available daylight to reduce electrical lighting energy consumption while maintaining desired levels of illumination. Daylighting control can be optimized to achieve the highest potential savings, but such control also requires significant effort in design, installation, calibration and commissioning to ensure that the benefits are fully realized. The results in this study are based on a simplified implementation of daylighting and are considered a reasonable assessment of the potential savings. This study does not provide information on how to design a daylighting system; there are many sources of information on successful daylighting available elsewhere.

Note that this study included additional analysis to evaluate the energy saving impacts from skylights as horizontal skylights and separately as rooftop monitors for a portion of the core zone along with daylight dimming controls. The skylights were not added to the baseline for this analysis. For the horizontal skylights, there were many climate locations that saw a net increase in energy usage or modest energy savings. The roof monitors performed somewhat better and small savings were observed in nearly all climate locations, but not enough to support the substatnital added cost of roof monitors.

In the perimeter zones, daylight enters the space from the perimeter windows, referred to as sidelighting. Interior blinds are simulated including closing of the blinds in response to glare (described in Section 3.4.4).

Table 4.6. Added Occupancy Sensor Control of Lighting

Space Type	Area (%)	Lighting Systems	Lighting Control Strategy Baseline	Advanced	Lighting power controlled by occupancy sensors (%)	Lighting energy savings from occupancy sensor (%)	Notes
Office- open plan	15	task lighting	time sweep	occupancy sensor	7	29	(a)
		downlighting	time sweep	time sweep	49	8.3	
		ambient/ uplight	time sweep	photosensor/ time sweep	29	50	
		ambient/ daylight zone	time sweep	photosensor/ personal dimming			
Office- private	29	ambient	time sweep	occupancy sensor	100	33	(b,c)
Conference meeting	8	ambient direct/ indirect	occupancy sensor	occupancy sensor	0	0	
		linear wall washing	occupancy sensor	occupancy sensor			
Corridor/ transition	12	standard design	time sweep	time sweep	0	0	
Active storage	14	standard design	time sweep	occupancy sensor	100	40	(d)
Restrooms	4	standard design	time sweep	occupancy sensor	100	26	(b)
Lounge/recreation	2	standard design	occupancy sensor	occupancy sensor			
Electrical/ mechanical	2	standard design	time sweep	occupancy sensor	100	40	(d)
Stairway	3	standard design	time sweep	time sweep	0	0	
Lobby	6	standard design	time sweep	time sweep	0	0	
Other	5	standard design	time sweep	time sweep	0	0	
Total lighting energy savings from occupancy sensor control						**17.4%**	**(e)**

(a) Galasiu et al. 2007
(b) VonNeida et al. 2000
(c) DiLouie 2009
(d) LRC 2004
(e) Total energy savings calculated by weighting each lighting type savings by the proportion of the space type in the building served

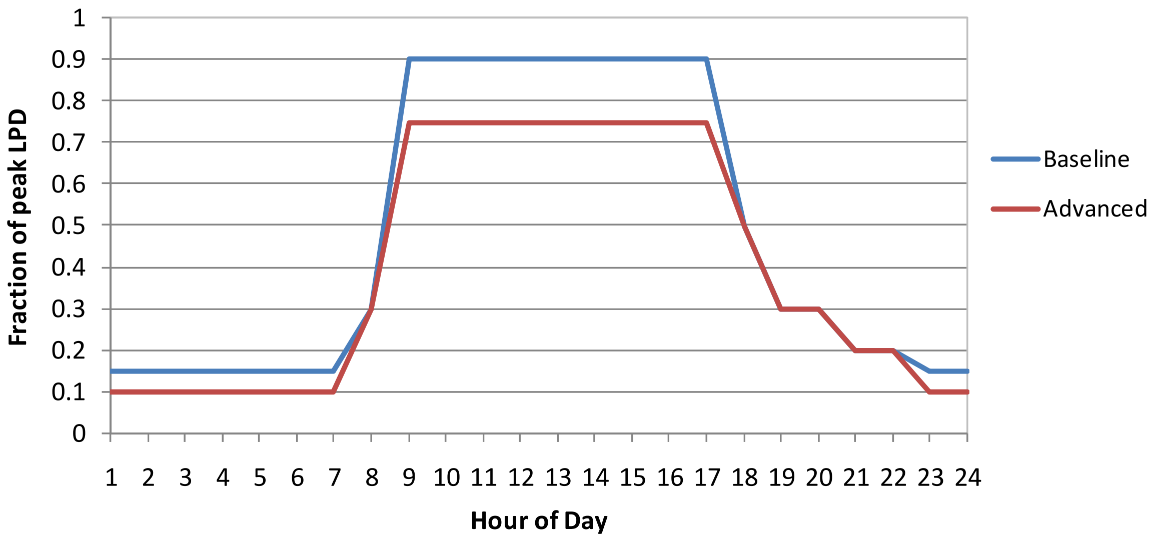

Figure 4.1. Change of Interior Lighting Schedules from Occupancy Sensors

4.2.5 Daylight Harvesting with Interior Lighting Controls

Daylight harvesting combined with automatic dimming controls takes advantage of the available daylight to reduce electrical lighting energy consumption while maintaining desired levels of illumination. Daylighting control can be optimized to achieve the highest potential savings, but such control also requires significant effort in design, installation, calibration and commissioning to ensure that the benefits are fully realized. The results in this study are based on a simplified implementation of daylighting and are considered a reasonable assessment of the potential savings. This study does not provide information on how to design a daylighting system; there are many sources of information on successful daylighting available elsewhere.

Note that this study included additional analysis to evaluate the energy saving impacts from skylights as horizontal skylights and separately as rooftop monitors for a portion of the core zone along with daylight dimming controls. The skylights were not added to the baseline for this analysis. For the horizontal skylights, there were many climate locations that saw a net increase in energy usage or modest energy savings. The roof monitors performed somewhat better and small savings were observed in nearly all climate locations, but not enough to support the substatnital added cost of roof monitors.

In the perimeter zones, daylight enters the space from the perimeter windows, referred to as sidelighting. Interior blinds are simulated including closing of the blinds in response to glare (described in Section 3.4.4).

The sidelighting dimming control is modeled in *EnergyPlus* with the following assumptions:

- The daylight zone extends 12 ft (3.7 m), the depth of the perimeter zones in the model, inward from the exterior walls. In open office areas, 8-ft square cubicles are assumed, so the daylit zone is one-and-one-half cubicles deep. For enclosed offices, the entire space is assumed to be included in the daylight zone.

- In the daylight zones, some or all of the ambient lighting system is dimmed in response to daylight. Daylighting is applied to enclosed offices and to the portion of open offices on the perimeter. This is modeled in *EnergyPlus* by setting 85% of each perimeter sidelit zone subject to dimming control. The 85% is an assumed value to account for internal obstructions and limited areas without daylight access.
- Two lighting sensors are used in each perimeter zone. One sensor faces the window while the other faces the wall between windows. Daylighting controls are modeled so that each sensor controls 50% of the lights subject to dimming. Both sensors are located at 3ft (0.9 m) above the floor or approximately desk height and 8 ft (2.44 m) inward from the exterior wall. The location of these sensors is for the simulation to account for variance in lighting in the space, and does not represent actual light sensor placement. Light sensors placed in other locations can be calibrated to provide the correct dimming control.
- The dimming control system has an illuminance setpoint of 28 footcandles (300 lux). This value corresponds to category D, which is identified for open offices with intensive video display terminal (VDT) usage in the IESNA handbook (IESNA 2000) .
- The dimming controls are continuous. This continuous dimming control can dim down to 10% of maximum light output with a corresponding 10% of maximum power input.

4.2.6 Reduced Exterior Lighting Power Allowances

For the small office prototype, exterior lighting is estimated for parking areas, building entrances and exits, and building facades. In the advanced models, the exterior lighting power density uses and in one case improves on the lighting power allowances included in Addendum I to 90.1-2007 (which will be incorporated in the Standard 90.1 2010 edition). In comparison, the baseline exterior lighting power is set at the lighting power allowed by 90.1-2004.

The major enhancements of the exterior lighting energy efficiency over the baseline are as follows:

- The advanced case uses lower wattage higher efficiency metal halides in similar fixtures as the baseline.
- The advanced case allows a base site allowance of 750 watts, while the baseline includes an additional unrestricted allowance equal to 5% of the sum of the individual exterior power density.
- The advanced case goes beyond Addendum I, and reduces the lighting power allowance for building facades to 50% of the Addendum value because façade lighting is a decorative effect and should be reduced or eliminated in buildings attempting to maximize energy savings.

Addendum I to 90.1-2007 assigns lighting power allowances for each exterior area type based on the location of the building in one of four exterior lighting zones:

- Zone 1 covers the developed areas of national or state parks, forest land, and other rural areas.
- Zone 2 covers the areas predominantly consisting of residential uses and neighborhood business districts with limited nighttime lighting.
- Zone 3 covers all other areas not covered by zones 1, 2 and 4.

- Zone 4 covers high activity commercial districts in major metropolitan areas and must be classified as such by the local jurisdiction.

For the purpose of this analysis, it is assumed that the building is located in lighting zone 3.

Table 4.7 shows the components of the exterior lighting power allowances for both the baseline and the advanced cases. The calculation is based on a number of inputs such as the percentage of parking areas, the number of main entrances and other doors, and the area for each façade (Richman et al. 2008, Village of Wheeling 2009).

4.2.7 Exterior Lighting Control

Parking lot lighting is assumed to have bi-level switching ballasts that will reduce its power between 12 PM and 6 AM. Façade lighting is also controlled to turn off between midnight and 6 AM. Therefore, in the advanced models, the exterior lighting is assumed to be controlled by a combination of photocell and time clock or an astronomical time clock. The time clock sets the exterior lighting power at 10% of the design level when no occupants are present between 12 PM and 6 AM. The photocell plays the role of turning off the exterior lights when the sun is up even if the scheduled lighting power is not zero. In contrast, for the base case, exterior lights are fully energized whenever it is dark outside.

Table 4.7. Reduced Exterior Lighting Power

Items	Baseline IP units	Baseline *SI units*	Advanced IP units	Advanced *SI units*
Base site allowance, advanced case only W (W)	-	-	750	*750*
Parking				
parking area, ft^2 (m^2) [(a)]	32,642	*3,033*	32,642	*3,033*
lighting power allowance for parking W/ft^2 (W/m^2)	0.15	*1.615*	0.10	*1.08*
total lighting power for parking, W (W)	4,896	*4,896*	3,264	*3,264*
Walkways				
walkway area, ft^2 (m^2) [(b)]	1632	*152*	1632	*152*
lighting power allowance for walkway area W/ft^2 (W/m^2)	0.2	*2.153*	0.16	*1.722*
total lighting power for walkway area W (W)	326	*326*	261	*261*
Building entrance and exits [(c)]				
main entries				
linear foot of door width for main entries, ft (m)	3	*0.91*	3	*0.91*
lighting power allowance for main entries W/ft (W/m)	30	*98*	30	*98*
canopy over entry, ft^2 (m^2)	42	*3.90*	42	*3.90*
lighting power allowance for canopy W/ft^2 (W/m^2)	1.25	*13.45*	0.40	*4.31*
total lighting power for main entries W (W)	142.5	*143*	107	*107*
other doors				
linear foot of door width for other doors, ft (m)	9	*2.74*	9	*2.74*
lighting power allowance for other doors W/ft (W/m)	20	*66*	20	*66*
canopy over entry ft^2 (m^2)	140	*13.01*	140	*13.01*
lighting power allowance for canopy W/ft^2 (W/m^2)	1.25	*13.45*	0.25	*2.69*
total lighting power for other doors W (W)	355	*355*	215	*215*
total lighting power for building entrance and exits W (W)	498	*498*	322	*322*
Building facades[(d)]				
façade area lighted ft^2 (m^2)	10,400	*966*	10,400	*966*
lighting power allowance for building facades W/ft^2 (W/m^2)	0.2	*2.15*	0.075	*0.81*
total lighting power for building facades W (W)	2,080	*2,080*	780	*780*
Sum of lighting power for all categories W (W)	7,800	*7,800*	4,627	*4,627*
5% additional allowance W (W)	390	*390*	-	-
Total exterior lighting power W (W)	**8,190**	***8,190***	**5,377**	***5,377***

(a) There are four parking spots per 1000 ft^2 (92.9 m^2) of building area.
Each parking spot occupies 405 ft^2 (37.6 m^2) including associated drives.
(b) Walkways are assumed to be 5% of the parking square footage.
Determined from site plans used in the analysis of Addendum I to 90.1-2007.
(c) There are four exterior doors modeled, one on each face of the building. All doors are 3 ft (0.91 m).
(d) The lighting power allowance for building facades is reduced in the advanced case to 50% of the 90.1-2007 addenda I allowance because façade lighting is a decorative effect and could be eliminated or reduced in buildings attempting to save energy. Therefore, the value is shown as 0.075 W/ft^2 (0.81 W/m^2) instead of 0.15 W/ft^2 (1.61) W/m^2

4.3 Miscellaneous Equipment Loads (plug loads)

Miscellaneous electric equipment is a major energy end use sector. In office buildings, plug loads can account for about 25% of total onsite energy consumption (CBECS 2003). The above percentage may be even higher as other systems within the building become more energy efficient. In the baseline small office building models, miscellaneous electric equipment accounts for 12% to 31% of total building energy use, depending on climate zone. In addition to their own electric energy usage, miscellaneous equipment is also a major source of internal heat gains, which in turn increases cooling loads. With miscellaneous equipment responsible for such a large portion of building energy use, it is clear that reducing this end use must play an important role in achieving the goal of 50% energy savings for the whole building.

A reasonable estimation of the potential to reduce plug load energy consumption requires some detailed information such as the office equipment inventory, the electric power of market available high-efficiency products, the power management strategy of the computer network and the potential for other control strategies. In developing the office equipment inventory for the advanced cases, the number of pieces of electric equipment is kept the same as those for the baseline cases (Section 3.6.4), except for the mix of computers. In estimating the electric power of market-available high-efficiency equipment, the ENERGY STAR standard is used as a reference if that equipment is covered by the ENERGY STAR program; otherwise, a reasonable estimation of energy saving is made for the high-efficiency equipment in the advanced cases, based on other identified sources.

The advanced case incorporates a number of strategies to reduce the energy usage from plug loads.

<u>Strategy 1-Shift towards laptop computers</u> One way to significantly reduce energy from computers is to move towards laptop computers. This strategy is modeled for the advanced case by increasing the proportion of computers that are laptops to two thirds from one half in the baseline.

<u>Strategy 2-Use of ENERGY STAR equipment</u> The use of ENERGY STAR equipment is developed by the reduction in the power associated with each type of equipment, as shown in Table 4.8 and described as follows:

- For desktop computers, monitors, printers, copy machines, fax machines, water coolers, and refrigerators, there are ENERGY STAR labeled products. In addition, a savings calculator is provided at the website (EPA 2009) for each category to estimate the percentage of energy savings in comparison with the corresponding conventional, non ENERGY STAR labeled products. In this case, that percentage of energy saving is used as a factor of the baseline plug load per unit in Section 3.6.4, Table 3.7 to calculate the plug load in Table 4.8. For example, the saving calculator for fax machines indicate that an ENERGY STAR labeled fax machine consumes about 49% less annual energy use than a conventional unit. Thus, the plug load for a high-efficiency fax machine is calculated as 35 * 49% = 17 W, where the 35 W is a conventional fax machine's plug load in Table 3.7.
- For laptop computers, although there are ENERGY STAR labeled products, no savings calculator is found available to calculate energy savings. In this case, it is assumed that an ENERGY STAR labeled laptop computer achieves 10% energy saving in comparison with a conventional laptop.

- The above procedure reduces the peak plug load density from 0.753 W/ft^2 (8.11 W/m^2) in the baseline to 0.564 W/ft^2 (6.07 W/m^2) in the advanced cases. The plug load schedule is not changed with this step in the savings strategies because no additional controls are incorporated. These two strategies result in a 25% reduction in plug load. Note that plug load energy reduction interacts with HVAC energy usage so the effective percentage reduction in the complete energy usage for each model will be different than the plug load only reduction in the complete energy usage for each model.

Strategy 3-Additional controls Additional controls are included – power management software particularly at the network level, occupancy sensor controls of computer monitors and other equipment, Vending Miser, and timer switches for coffee makers and water coolers. Note that timer switches may also be worthwhile for network printers and copiers, although no credit is taken for application to those devices. Table 4.9 shows the estimated energy reductions. Reductions in energy for these strategies will be largest during periods when occupancy is reduced or spaces are unoccupied. Table 4.10 shows how the energy usage is captured by altering the model plug load schedule. This strategy reduces total plug energy usage by an additional 20.7% below that achieved by the first two strategies that directly reduced the power per area. This results in an additional 15.5% from total plug energy. Note that plug load energy reduction interacts with HVAC energy usage so the effective percentage reduction in energy including plug loads and HVAC changes caused by plug loads will be different in the complete energy usage for each model.

Table 4.8. Plug Load Power Reduction Before Additional Controls

	Baseline				Advanced		
Plug Load Equipment Inventory	Quantity	Plug load, each (W)	Plug load (W)	Quantity	Plug load, each (W)	Plug load (W)	
Computers – servers	2	65	130	2	54	108	
Computers – desktop[a]	44	65	2,860	29	54	1,566	
Computers – laptop[a]	44	19	836	59	17	1,003	
Monitors – server – LCD	2	35	70	2	24	48	
Monitors – desktop – LCD	88	35	3,080	88	24	2,112	
Laser printer – network	2	215	430	2	180	360	
Copy machine	2	1,100	2,200	2	500	1,000	
Fax machine	2	35	70	2	17	34	
Water cooler	2	350	700	2	193	386	
Refrigerator	2	76	152	2	65	130	
Vending machine	2	770	1,540	2	770	1,540	
Coffee maker	2	1,050	2,100	2	1,050	2,100	
Portable HVAC (heaters, fans)	18	30	540	18	30	540	
Other small appliances, chargers, network components etc.	88	4	352	88	4	352	
Total plug load (W)			15,060			11,279	
Plug load density, W/ft^2 (W/m^2)			**0.75**	**(8.1)**		**0.56**	**(6.0)**

(a) Note assumes shift towards higher proportion of laptops instead of desktop computers

Estimating potential reductions for these strategies beyond those achieved by ENERGY STAR and altering the mix of laptop and desktop computers is based on information regarding how much of the time equipment is left on when not in use, proportion of equipment that already has power management software, and estimated savings from several sources (Sanchez et al. 2007, EPA 2009). This is a rough estimate; much is not known or up to date on actual current equipment energy usage (as opposed to connected power) and the use of controls in current new buildings for a baseline.

Table 4.10 shows the schedule that is used for the baseline, and then is modified to apply to the advanced case plug load power. The schedule reductions in Table 4.10 by time period are estimated to achieve the same level of savings as that determined in Table 4.9, weighted towards low and no occupancy hours. The weighted by time period columns estimates the total energy for plug loads that occur during each schedule block. This is approximate because the weighting for Sunday is for 1 day in 7 and does not account for holidays.

Table 4.9. Additional Reduction in Plug Loads Energy Usage with Controls

	Advanced with wattage reductions from Table 4.8				Reductions in Plug Loads with Controls	
Plug Load Equipment Inventory	Quantity	Plug load, each (W)	Plug load (W)	% of total watts	Estimated Reduction, %	Effective reduced plug load (W)[b]
Computers – servers	2	54	108	1.0	0.0	108
Computers – desktop[a]	29	54	1,566	13.9	25.0	1,175
Computers – laptop[a]	59	17	1,003	8.9	7.5	928
Monitors – server – LCD	2	24	48	0.4	0.0	48
Monitors – desktop – LCD	88	24	2,112	18.7	7.5	1,954
Laser printer – network	2	180	360	3.2	0.0	360
Copy machine	2	500	1,000	8.9	0.0	1,000
Fax machine	2	17	34	0.3	0.0	34
Water cooler	2	193	386	3.4	20.0	309
Refrigerator	2	65	130	1.2	0.0	130
Vending machine	2	770	1,540	13.7	50.0	770
Coffee maker	2	1050	2,100	18.6	20.0	1,680
Portable HVAC (fans, heaters)	18	30	540	4.8	50.0	270
Other small appliances, chargers	88	4	352	3.1	50.0	176
Total plug load (W)[b]			11,279	100.0		8,941
Plug load density (W/ft^2)[b]			**0.56**	**(6.03)**		**0.45 (4.8)**

[a] Note assumes shift towards higher proportion of laptops instead of desktop computers in both baseline and advanced from earlier equipment power density

[b] Controls reduction are achieved with reductions in operating schedule not in design wattage so reduced values in watts are for comparison only. See Table 4.10 for schedule changes.

Table 4.10. Changes in Plug Equipment Schedules with Added Controls

Schedule Periods		Hours per week	Without Controls: Schedule without controls	Without Controls: Weighted by time period	Without Controls: Share of total plug load, %	With Controls: Schedule with controls	With Controls: Weighted by time period	With Controls: Share of total plug load, %	Reduction: Schedule %	Reduction: Total plug loads, %
Weekdays										
Until:	8:00	40	0.4	16.0	27.7%	0.3	12.0	26.2%	25%	6.9%
Until:	12:00	20	0.9	9.9	17.1%	0.8	8.8	19.2%	11%	1.9%
Until:	13:00	5	0.8	2.2	3.8%	0.7	1.9	4.2%	13%	0.5%
Until:	17:00	20	0.9	9.9	17.1%	0.8	8.8	19.2%	11%	1.9%
Until:	18:00	5	0.5	1.4	2.4%	0.4	1.1	2.4%	20%	0.5%
Until:	24:00	30	0.4	6.6	11.4%	0.3	5.0	10.8%	25%	2.9%
Saturday										
Until:	6:00	6	0.3	1.0	1.7%	0.2	0.7	1.4%	33%	0.6%
Until:	8:00	2	0.4	0.4	0.8%	0.3	0.3	0.7%	25%	0.2%
Until:	12:00	4	0.5	1.1	1.9%	0.4	0.9	1.9%	20%	0.4%
Until:	17:00	5	0.35	1.0	1.7%	0.3	0.8	1.8%	14%	0.2%
Until:	24:00	7	0.3	1.2	2.0%	0.2	0.8	1.7%	33%	0.7%
Sunday										
Until:	24:00	24	0.3	7.2	12.5%	0.2	4.8	10.5%	33%	4.2%
		168		57.8	100.0%		45.8	100.0%		**20.7%**

4.4 HVAC Systems

The advanced HVAC system alternative is packaged rooftop or split system heat pumps serving each zone, with ventilation provided by a dedicated outside air system (DOAS). The DOAS system incorporates energy recovery ventilation (ERV).

An alternative HVAC system approach is also provided. The alternative is a packaged VAV system with premium cooling efficiency, reduced fan power, motorized outdoor air dampers, supply air temperature reset, economizer, energy recovery and indirect evaporative cooling for some climate zones. This alternative is able to achieve 50% or higher savings in some climate zones, but not all 16 climate locations.

Other HVAC systems not considered in this study may also have the potential to achieve 50% energy savings together with other EEMs. These systems could include ground source or ground water heat pumps, radiant or radiant/convective systems, or variable refrigerant flow (VRF) with multi-split units. The project had limited resources to evaluate all alternatives, and two alternatives with readily available equipment and moderate costs were evaluated. Radiant systems with DOAS were analyzed and recommended in the 50% TSD for Medium Offices (Thornton et al. 2009) and may be appropriate for some small office buildings in some climate zones.

4.4.1 Heat Pumps

A heat pump system, either packaged rooftop or split system, is used in each thermal zone to satisfy the heating and cooling loads not met by the DOAS system (Section 4.4.2). The heat pumps do not provide any outdoor ventilation air because the DOAS supplies all the required fresh air. The thermal zoning is the same as for the baseline. Rooftop units and split systems offer similar cooling efficiency and both have premium efficiency compared with the baseline rooftop units. When determining whether to use rooftop or split system units for a specific project, designers should consider the available higher cooling efficiency option, the first cost, and other construction factors such as mechanical space requirements, roof penetrations, and distribution of unit weight. The modeling of rooftop or split heat pumps is the same approach in *EnergyPlus* simulation program. The heat pumps are modeled in this study with the following features:

- The premium cooling efficiency of the heat pumps is shown in Table 4.11. The efficiency is derived from the product engineering catalogue databases maintained by the California Energy Commission (CEC 2010). The selected efficiency values correspond with products that are available from at least two manufacturers. Cooling efficiency for the smaller units with cooling capacity less than 65,000 Btu/h, which are most of the cooling size in the small office prototype, are available in at least 15 SEER and in some sizes up to 22 SEER. The equations in Section 3.7.5 are used to convert SEER or EER to COP as EnergyPlus input variable. The heating efficiency of the heat pumps is shown in Table 4.12. The following equation (Wassmer and Brandemuehl 2006) is used to derive COP from heating seasonal performance factor (HSPF):

$$COP = -0.0255 * HSPF^2 + 0.6239 * HSPF$$

Table 4.11. Premium Cooling Efficiency for Heat Pumps

Size Category	Efficiency (SEER/EER)	*EnergyPlus* Input (COP)
<65,000 Btu/h (<19 kW)	15.0 SEER	4.31
≥65,000 Btu/h (≥ 19 kW)	11.0 EER	3.80

Table 4.12. Premium Heating Efficiency for Heat Pumps

Size Category	Efficiency (HSPF/COP)	*EnergyPlus* Input (COP)
<65,000 Btu/h (<19 kW)	9.0 HSPF	3.55
≥65,000 Btu/h (≥ 19 kW)	3.3 COP	3.3

- The supply air fan cycles on and off together with the compressor to provide heating or cooling to meet the zone thermal loads. As described in the next section, the DOAS meets the minimum outdoor air ventilation requirement and may contribute to meeting space loads, so the heat pump supply fan cycles to address the remaining space load not met by the DOAS.

- Fan total static pressure is shown in Table 4.13. The total static pressure is reduced by designing the duct work consistent with a lower duct friction loss, from 0.1 in w.c. (24.9 Pa) per 100 ft (30.5 m) in the baseline to 0.08 in. w.c. (19.9 Pa) per 100 ft (30.5 m) in the advanced case. This incudes use of low friction fittings. Total static pressure is reduced from 1.80 in. w.c. (448 Pa) in the baseline to 1.74 in. w.c. (433 Pa) in the advanced case. The fan power is calculated according to the same procedure as that for the baseline fans presented in Section 3.7.6.

Table 4.13. Fan Static Pressure for Heat Pumps

Component	5-ton Packaged Rooftop Unit (@2000 cfm)	
	Static Pressure	
	in. w.c.	***Pa.***
External Static Pressure		
Diffuser	0.1	*25*
Ductwork[1]	0.24	*60*
Grille	0.03	*7*
Filter, dirty portion	0.5	*125*
Total ESP	0.87	*217*
Internal Static	0.87	*217*
Total Static Pressure	**1.74**	***433***

Notes:

1. Used good practice of 0.08 inch/100 ft duct friction loss.

- Supplemental heat is provided when the heat pump cannot meet all, or part of the heating load. For climate zones 1 to 6, supplemental heat is provided by electric resistance. The heat pumps are modeled with a low limit of 10°F (-12°C), below which the heat pump is switched entirely to electric resistance heating. For climate zones 7 and 8, gas furnaces are used as the supplemental heating source. In these very cold climates, gas heat is commonly used in practice because there are significant periods where most or all of the heating is provided by the supplemental heating rather than heat pump. In addition, electricity is generally less economical than natural gas for heating in Alaska. The efficiency of the gas furnace for the DOAS units is determined in the same way as for the baseline depending on capacity as shown in section 3.7.5.

Note that *EnergyPlus* currently is limited to allow assigning one air loop system per zone. Thus, with a DOAS already set up, the air-source heat pump system cannot be modeled as an air loop system directly in the current version of *EnergyPlus*. The work-around solution in this study is to model the air source heat pump as a packaged terminal heat pump (PTHP), which is zone-level and can work together with the DOAS as system-level equipment. Further, the cooling and heating efficiency and the equipment performance curves in the PTHP module are modified to match those for the premium air-source heat pump. In this way, the combination of PTHP and DOAS will provide reasonable and reliable energy use analysis results as a model of the recommended system configuration.

4.4.2 Dedicated Outdoor Air System and Energy Recovery Ventilation

In this study, the DOAS is used to condition and deliver the required minimum outdoor ventilation air to each individual zone. The outdoor air flow is the same as for the baseline. The DOAS provides a number of benefits relative to the baseline system, which mixes the outdoor air with return air in each rooftop unit.

- The DOAS system allows the centralized location of the outdoor air intake, which will make it feasible to use only one ERV to pretreat all of the outdoor air. Providing multiple ERV units separately for multiple smaller rooftop units will not likely be cost effective because of the additional first costs.
- Meeting the loads from outside air with the DOAS allows the zonal heat pump systems to be down-sized.
- Meeting the ventilation loads from a central source means that only the DOAS fan needs to run continuously during occupied hours. The zonal heat pump fans only need to run when there are zone heating and cooling loads, and those fans can cycle. Air flow from each heat pump and from the DOAS are supplied in parallel to common diffusers for each corresponding zone. In the baseline, all of the units run continuously during occupied hours to ensure the ventilation is provided.

Different configurations of DOAS are available and have been reported on in the literature. Mumma and Shank (2001) compared five different component arrangements of the DOAS system in terms of their energy performance. They found that the DOAS system (Figure 4.2) performs best, consisting of a preheat coil, an enthalpy wheel, a deep cooling coil and a sensible heat exchanger (e.g., a sensible wheel). McDowell and Emmerich (2005) investigated the energy performance of two DOAS configurations for a building with a water-source heat pump system. One DOAS simply consists of a preheat coil and an enthalpy wheel, while the other DOAS has the same configuration, as shown in Figure 4.2. They found that the latter DOAS setup performs better but has only between 1 and 7% more energy saving than the simple DOAS setup. The simple DOAS configuration is utilized in this study, as shown in Figure 4.3. The DAOS system consists of an enthalpy wheel, a cooling coil, a heating coil and a supply fan.

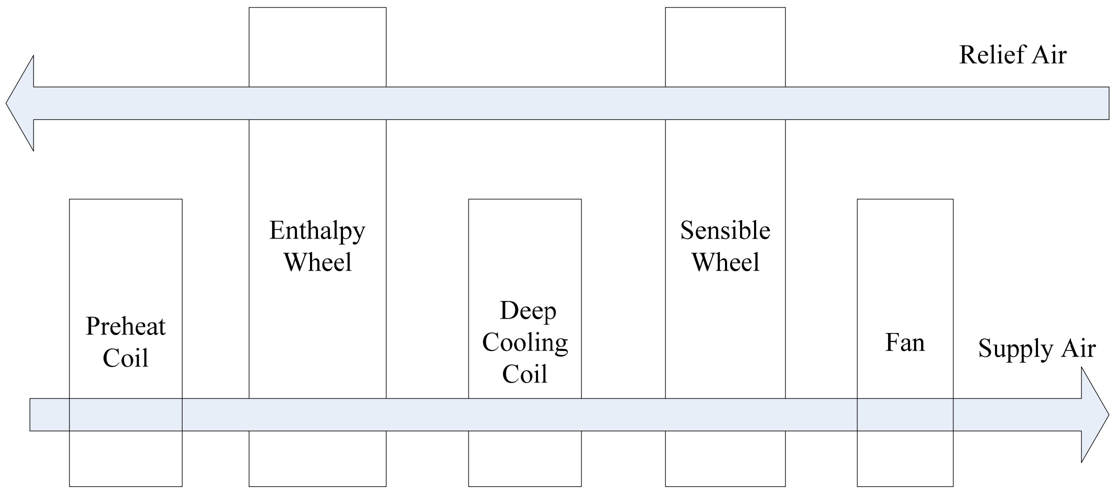

Figure 4.2. DOAS With Dual Wheels and Deep Cooling Coil

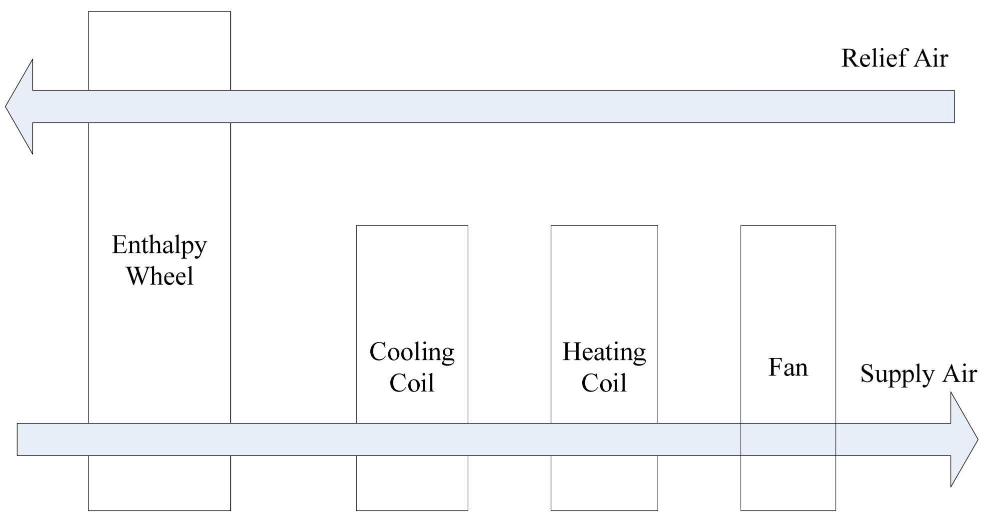

Figure 4.3. DOAS With Enthalpy Wheel, Conventional Cooling Coil and Heating Coil

The DOAS in this study operates with the following major points:

- For the hot and humid climate zones (1A, 2A, and 3A), the DOAS supply air temperature is maintained at 55°F (12.8°C). For mild and cold dry climate zones (3B, 4B, 5B, and 6B), the DOAS supply air temperature is maintained at 68°F (20°C), an approximately neutral supply temperature. For all other climate zones (2B, 3C, 4A, 4C, 5A, 5C, 6A, 7 and 8), the DOAS supply air temperature is reset according to the outdoor air temperature. The reset rule is: the supply air temperature is at 55°F (12.8°C) when the outdoor air temperature is at 64°F (18°C) or higher; it is reset to 68°F (20°C) when the outdoor air temperature drops to 50°F (10°C) and below; it is linearly interpolated when the outdoor air temperature is between 64°F (18°C) and 50°F (10°C).

  There are two major considerations in using this approach for DOAS supply air temperature setpoint in different climate zones. First, the dehumidification requirement determines that a lower discharge temperature is desired to extract moisture from outdoor air in hot and humid climate zones. Second, using the DOAS to partially address the space cooling load determines that a supply air temperature reset is employed. However, there is an implementation issue in *EnergyPlus* when applying supply air temperature reset for the DOAS with ERV. The DOAS system has a fixed outdoor airflow rate. Therefore, the ERV running status can only be controlled by using the economizer status in *EnergyPlus*. It needs to be noted that there is no actual economizer at all because the DOAS system is 100% outdoor air. The economizer setpoint is used just for controlling the ERV status in the simulation. The ERV is on if the economizer status is off; the ERV is off if the economizer status is on. The economizer status depends on whether any air economizer control limits (e.g., economizer minimum limit dry-bulb temperature) are violated. If no economizer control limits are violated, the economizer status is on; otherwise, it is off. Thus, in the *EnergyPlus* model, the ERV status is controlled by the economizer minimum limit dry-bulb temperature, which is set at the same value as the supply air temperature. For the cases with supply air temperature reset, the economizer minimum limit dry-bulb temperature is optimized at 61°F (16°C) based on a number of parametric runs and sensitivity analysis.

- The DOAS provides the minimum outdoor ventilation air and runs when the building is occupied. The DOAS runs from 7:00 AM to 10:00 PM on weekdays and from 7:00 AM to 6:00 PM on Saturday.

- Demand controlled ventilation (DCV) is not considered in this study. The DOAS unit is a constant volume unit with 100% outside air so does not allow a turn-down in the airflow. Although DCV can be applied if the DOAS airflow is variable, it is not implemented in our work because the goal of 50% energy savings has been achieved with other EEMs. For informational purposes, we simulated reduced outside airflow to approximate DCV. Simulation results show that applying DCV can achieve around 2% more energy savings. In the market, there are VAV DOAS products available, which use zone carbon dioxide sensors to regulate the DOAS airflow.

- Energy recovery ventilation (ERV) is an energy efficiency measure to reclaim energy from exhaust airflows to precondition the outdoor ventilation airflows. With a rotary heat exchanger added before the air handling unit, both heat and moisture can transfer between the exhaust air and the outdoor air streams. Offsetting the savings from the ERV is increased fan energy required to overcome the additional static pressure of the device and the parasitic energy for the enthalpy wheel rotation. In the advanced model, it is assumed that the enthalpy wheel has a pressure drop of 0.85 in. w.c (210 Pa) on the supply side and a pressure drop of 0.65 in. w.c (160 Pa) on the exhaust side. The parasitic power used for the enthalpy wheel control is assumed to be 50 watts based on manufacturer data. To correctly account for the change of pressure drop when the ERV is bypassed, the fan power on both the supply side and the exhaust side is modeled as the parasitic power. For example, in this study, the DOAS has a supply airflow rate of 2625 cfm (1.239 m^3/s); the parasitic power for the wheel control and the fan power can be calculated as:

$$\frac{1.239*210}{0.5}+\frac{1.239*0.9*160}{0.5}+50=940W$$

where, the number of 0.5 represents the fan efficiency; the number of 0.9 represents the exhaust flow as a fraction of the supply flow after accounting for leakage.

- The sensible and latent effectiveness of the energy recovery is shown in Table 4.14.

Table 4.14. Rated Performance of the Enthalpy Wheel

	Effectiveness	
Condition	Sensible	Latent
heating @ 100% airflow	70	60
heating @ 75% airflow	70	60
cooling @ 100% airflow	75	60
cooling @ 75% airflow	75	60

- A constant speed supply fan is used in the DOAS. The fan has a static pressure of 1.93 in. w.c. (481 Pa), as shown in Table 4.15. The ductwork static pressure is based on good practice of 0.08 in/100 ft of ductwork and low friction fittings. The fan power is calculated according to the same procedure as presented previously in Section 3.7.6. There is one more enhancement, the fan efficiency is improved from 55% to 65%.

Table 4.15. DOAS Fan Static Pressure

Component	DOAS based on 7.5 ton Packaged Rooftop Unit (@2,600 cfm)	
	Static Pressure	
	in. w.c.	***Pa.***
External Static Pressure		
Diffuser	0.1	*25*
Ductwork[1]	0.4	*100*
Grille	0.03	*7*
Filter, dirty portion	0.5	*125*
Subtotal	1.03	*257*
Internal Static	0.9	*224*
Total Static Pressure	**1.93**	***481***

Notes:

1. Used good practice of 0.08 inch/100 ft friction rate plus fittings.

- The DX cooling efficiency for the DOAS unit is selected from the updated product engineering catalogue databases maintained by California Energy Commission (CEC 2010). In the selection process, attention has been paid to make sure that the selected efficiency represents the products from at least two manufacturers. Table 4.16 lists the selected higher cooling efficiency in terms of SEER or EER. Because COP is the required input in *EnergyPlus*, the corresponding COP values are also presented in this table, and they are calculated using the same method as presented in Section 3.7.5. The efficiency of the gas furnace for the DOAS units is determined as for the baseline furnace according to the furnace capacity as presented in section 3.7.5.

Table 4.16. Cooling Efficiency for the DOAS Units

Size Category	Efficiency (SEER/EER)	*EnergyPlus* Input (COP)
<65,000 Btu/h (<19 kW)	15.0 SEER	4.31
65,000 ~ 135,000 Btu/h (19 ~ 40 kW)*	11.5 EER	3.80
135,000 ~ 240,000 Btu/h (40 ~ 70 kW)	11.3 EER	3.90
240,000 ~ 300,000 Btu/h (70 ~ 88 kW)	10.5 EER	3.63
300,000 ~ 760,000 Btu/h (88 ~ 223 kW)	10.2 EER	3.53

*The size range applies to the DOAS in this work

4.5 Alternative HVAC Systems – Variable Air Volume

A variable air volume (VAV) system with enhancements such as energy recovery is analyzed as an alternative to the recommended heat pump plus DOAS system approach. If for some climate zones, a VAV system can achieve close to 50% energy savings, the VAV system may be a better choice than the heat pump approach in terms of initial cost, maintenance, and reduced roof penetrations for one HVAC unit instead of ten heat pumps and a DOAS unit. The improved VAV system incorporates the following energy efficiency features:

- Premium HVAC equipment efficiency. Cooling efficiency values are the same as those shown for the DOAS unit in Table 4.16.
- Fan static pressure. The fan has a static pressure of 3.11 in. w.c. (775 Pa), as shown in Table 4.17. The fan power is calculated according to the same procedure as presented previously in Section 3.7.6. Ductwork pressure drop is reduced relative to the baseline for good practice including low friction fittings. Fan efficiency is improved from 55% to 65%.
- Energy recovery ventilation (ERV). In the improved VAV system, a rotary energy recovery ventilator is added in the front of the air handling unit. The energy recovery performance is the same as shown in Table 4.14. The desired temperature of the energy recovery ventilator's outlet air is determined by referring to the temperature setpoint right after the mixing box.

Table 4.17. Static Pressure for VAV Fan

Component	25-ton Packaged Rooftop Unit (@10,000 cfm)	
	Static Pressure	
	in. w.c.	***Pa.***
External Static (E.S.P.)		
Diffuser	0.1	*25*
Terminal unit	0.8	*199*
Supply Ductwork[1]	0.48	*120*
Dirty Portion of Filters	0.5	*125*
Grille	0.04	*10*
Economizer w/ exhaust	0.19	*47*
Total ESP	2.11	*526*
Internal Static Pressure	1.0	*249*
Total Static Pressure	**3.11**	***775***

Notes:

1. Used good practice of 0.08 inch/100 ft friction rate plus fittings

- Indirect evaporative cooling. Evaporative cooling offers a cost-effective solution to reduce mechanical cooling in climate zones with hot/warm and dry weather. There are two types of evaporative cooling techniques: direct and indirect. Although *EnergyPlus* version 4.0 has a number of models for both evaporative cooling techniques, only one indirect evaporative cooling model supports the primary air outlet temperature control to avoid overcooling. Therefore, an indirect evaporative cooler is added to each air system for climate zones 2B, 3B, 4B and 5B. The evaporative cooler is located between the outdoor air mixing box and the cooling coil in the air handling unit. It was simulated with the following technical parameters: a maximum wet-bulb effectiveness of 0.7; a secondary fan flow rate of 1,695 cfm (0.8 m^3/s); a secondary fan efficiency of 70%; a pressure drop of 0.8 in. w.c. (200 Pa) for the primary air, and a secondary fan delta pressure of 1 in. w.c. (250 Pa).
- Supply air temperature reset. Multi-zone VAV systems result in reheating cooled air loads when simultaneous heating and cooling loads exist in different thermal zones or when minimum airflow in a zone would result in over-cooling the space at the current supply air temperature if the air were not reheated. Raising the primary supply air temperature when the system is not at peak cooling demand is an effective measure to reduce the energy consumption for reheating cooled air. Therefore, in the VAV system, the primary supply air temperature is reset according to the outdoor air temperature. The reset rule is: the supply air temperature is at 55°F (12.8°C) when the outdoor air temperature is at 70°F (21.1°C) or higher; it is at 60°F (15.6°C) when the outdoor air temperature is at 50°F (10°C) or lower; it is linearly interpolated when the outdoor air temperature is between 50°F (10°C) and 70°F (21.1°C). Generally, increasing the primary supply air temperature involves a trade-off between decreased terminal reheating energy and increased fan energy. Therefore, the overall energy savings

may vary with the maximum allowed supply reset temperature. This measure was applied to all climate zones except 1A and 2A, where humidity control might be an issue from increasing the supply air temperature.

- Demand-controlled ventilation (DCV). DCV modulates the amount of outdoor ventilation air in response to the actual occupancy in a zone as it varies throughout the day. DCV can be accomplished by using sensors that measure the CO_2 changes in occupied spaces, which is a good proxy for the number of occupants present. Although the DCV concept is simple, there is no straightforward approach to model DCV for the VAV system with energy recovery. The DCV is modeled in this work with the following work-around approach: the ventilation rate per person is first discounted by the weighted average of occupancy schedule during the building operating hours between 8:00 AM and 10:00 PM; then the discounted ventilation rate per person is used together with the ventilation rate per floor area to calculate the required ventilation for each zone. The 7 AM to 8 AM hour with limited occupancy was excluded from the weighted average to create a more conservative estimate of the DCV benefit.
- Motorized outdoor air damper control. The advanced case adds motorized outdoor air dampers. Some baseline systems without economizers have gravity dampers (Section 3.7.8). Motorized dampers allow the outdoor air intake to be shut off during unoccupied periods.
- Heating. While not an efficiency measure, note that heating for the building is provided by a central gas furnace when the entire building is in heating, and with electric reheat coils at the zone level.

4.6 Service Water Heating

Service water heating usually consumes less than 5% of total onsite energy use for office buildings (CBECS 2003); therefore, energy savings for this category are not emphasized. The only measure considered is to improve the thermal efficiency (E_t) from 80% in the baseline to 90% in the advanced cases for the gas-fired storage water heater. This increased efficiency can be achieved with condensing water heaters. This recommendation is based on a design with restrooms and other domestic hot water uses such as break room sinks and dishwashers being located near the core so relatively short pipe runs can be achieved, minimizing circulation losses. A single core water heating system also reduces storage losses. If there are peripheral service hot water uses, these may be more efficiently served with on-demand water heaters. Using only on-demand water heaters may be a reasonable alternative way to provide energy efficiency service water heating depending on the location of hot water uses, and the demand for hot water.

5.0 EEM Summary and Energy Results

This section contains a summary of the recommended energy efficiency measures and the energy savings results that are achieved by applying the EEMs described in Section 4. There are other ways of achieving 50% energy savings, and the EEMs in this report are "*a way, but not the only way*" of meeting the energy savings target. Design teams using this TSD should follow an integrated design approach and utilize additional analysis to evaluate the specific conditions of a project. The advanced EEM package with heat pump system achieves 50% or higher energy savings for all climate locations, as presented in Section 5.2, resulting in a national weighted-average site energy savings of 56.6%. The alternative VAV HVAC system achieves 50% or higher energy savings in seven of sixteen climate locations and a national weighted-average savings of 48.5%, as presented in Section 5.3.

This TSD targeting 50% energy savings goes beyond the recommendations from the published *30% AEDG for Small Office Buildings* with more stringent envelope requirements, additional concepts for further reductions in lighting power, plug load wattage reductions and controls, higher DX cooling efficiency for small size units, addition of a dedicated outdoor air system, energy recovery ventilation, and consideration of an alternative VAV system.

5.1 Summary of Recommended Energy Efficiency Measures

This section summarizes the recommended EEMs in this report, which are grouped into envelope, lighting, plug loads, HVAC and water heating measures.

Building Envelope Measures

- Enhanced building opaque envelope insulation for exterior walls and roofs
- Cool roof in selected cooling dominant climates
- High performance window glazing
- Exterior shading on south facing windows

Lighting Measures

- Advanced indoor electric lighting fixtures to reduce interior connected lighting power
- Daylight dimming control for perimeter zones to reduce electric lighting energy use
- Occupancy sensors to achieve lighting on-off control
- Efficient exterior lighting and controls

Plug Loads Measures

- ENERGY STAR labeled and other efficient office equipment and appliances
- Increased proportion of laptop computers relative to PCs
- Plug load controls such as occupancy sensors for plug strips or outlets, computer network power savings software, and timer switches for equipment such as coffee makers

HVAC Measures - Heat Pump and DOAS Package

- Change from packaged DX cooling units with gas furnaces to high-efficiency heat pumps
- DOAS providing all outdoor air ventilation with energy recovery
- Improved ductwork design to reduce the supply fan static pressure
- Premium cooling equipment efficiency for DOAS and heat pump units

HVAC Measures - Alternative VAV Package

- Premium efficiency packaged VAV system
- Efficient duct work and fan
- Energy recovery ventilator
- Indirect evaporative cooling for climate zones 2B, 3B, 4B and 5B
- Supply air temperature reset
- Demand controlled ventilation
- Motorized damper

Water Heating

- Condensing gas water heater

5.1.1 Envelope Measures

The envelope measures cover the range of assemblies for both the opaque and fenestration portions of the building. Opaque elements include the roof, walls, floors and slabs. Fenestration covers the vertical glazing (including doors). For each building element, there are a number of components for which the report provides recommendations. In some cases, these components represent an assembly, such as a flat roof or a concrete masonry unit (CMU) wall, or a portion of an assembly, such as insulation R-value.

Recommendations for each envelope component are contained in Table 5.1, and are organized by climate zone. Consistent with the movement from the hotter to colder zones, the insulation requirements (R-value) increase as the climates get colder, and corresponding thermal transmittance (U-factor) decreases. Control of solar loads is more important in the hotter, sunnier climates, and thus the solar heat gain coefficient tends to be more stringent (lower) in zone 1 and less stringent in zone 8. The reader should note that the recommendations are based on a CMU mass wall construction with punch style openings with manufactured windows. In addition, the TSD recommends using exterior sun control on the south glazing to help control solar cooling loads in warmer climates.

Table 5.1. Energy Savings Recommendations – Building Envelope

Item	Component		Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
Walls-Exterior	Mass wall, continuous insulation	R-value h·ft^2·°F/Btu	5.7	7.6	11.4	13.3	13.3	19.5	19.5	19.5
		R-value K·m^2/W	*1.0*	*1.3*	*2.01*	*2.34*	*2.34*	*3.43*	*3.43*	*3.43*
Roofs	Insulation entirely above deck	R-value h·ft^2·°F/Btu	20	25	25	30	30	30	30	35
		R-value K·m^2/W	*3.5*	*4.4*	*4.4*	*5.3*	*5.3*	*5.3*	*5.3*	*6.2*
	Solar reflectance		0.69	0.69	0.69	NR	NR	NR	NR	NR
	Emittance		0.87	0.87	0.87	NR	NR	NR	NR	NR
Slab-On-Grade Floors	Unheated, insulation vertical, 24 in (*61 cm*) at slab edge	R-value h·ft^2·°F/Btu	NR	NR	NR	NR	NR	10	10	15
		R-value K·m^2/W	*NR*	*NR*	*NR*	*NR*	*NR*	*1.8*	*1.8*	*2.6*
Vertical glazing	U-factor	U-factor Btu/h·ft^2·°F	0.56	0.45	0.41	0.41	0.38	0.35	0.33	0.25
		U-factor W/m^2·K	*3.2*	*2.6*	*2.3*	*2.3*	*2.2*	*2.0*	*1.9*	*1.4*
	SHGC		0.25	0.25	0.25	0.26	0.26	0.35	0.40	0.40
	Exterior sun control (South only)		PF>0.5	PF>0.5	PF>0.5	PF>0.5	PF>0.5	NR	NR	NR

5.1.2 Lighting Measures

The lighting measures are not climate dependent. As such, the same recommendations are provided for all climate zones. Recommendations are provided for interior lighting, as well as exterior lighting, as shown in Table 5.2. Interior lighting recommendations include maximum lighting power density (LPD) requirements for the major space types in small office buildings. Lighting control recommendations are also provided. Exterior lighting recommendations include the lighting power level for parking lot, building façade, walkway, and entrances.

Table 5.2. Energy Savings Recommendations – Lighting

Item	Component	All Climate Zone Locations					
			W/ft²	*W/m²*		W/ft²	*W/m²*
Interior Lighting	Lighting power density	Office, open plan	0.68	*7.3*	Office, enclosed	0.97	*10.4*
		Conference/meeting	0.77	*8.3*	Active storage	0.64	*6.9*
		Corridor/transition	0.5	*5.4*	Restrooms	0.82	*8.8*
		Lounge/recreation	0.73	*7.9*	Stairs	0.6	*6.5*
		Electrical/mechanical	1.24	*13.3*	Lobby	1.09	*11.7*
		Other	0.82	*8.8*	OVERALL	0.79	*8.5*
	Fluorescent lamps	T5HO or T8 high-performance with high-performance electronic ballast and compact fluorescent (CFL) with electronic ballast,					
	Occupancy controls	Added for open-office task lights, enclosed office ambient lighting, active storage, restrooms and electrical/mechanical spaces.					
	Task Lighting	Compact fluorescent (CFL) with electronic ballast					
	Daylighting	Photo-sensor control of lighting is response to daylight in perimeter areas					
Exterior Lighting	Base allowance					750 W	
	Area specific recommendations[1]					W/ft²	*W/m²*
	Parking areas and drives					0.1	1.1
	Walkways					0.16	1.7
	Main entry canopies					0.4	4.3
	Other entry canopies					0.25	2.7
	Façade (use wattage only for façade)					0.075	0.8

1. Wattage per area refers to the area of the corresponding portion of a building

5.1.3 Plug Load Measures

The plug load measures are not climate dependent. As such, the same recommendations for plug equipment and controls are provided for all climate zones, as shown in Table 5.3.

Plug load recommendations include several strategies that reduced the connected wattage and control equipment to further reduce the energy consumption. The connected wattage recommendations include shifting towards greater use of laptop computers from desktop computers, and selection of computers, monitors and other office equipment and appliance with ENERGY STAR labels. The controls strategies include power management software for networked computers, occupancy sensor control of plug strips or outlets for equipment that can be turned off, vending machine occupancy sensor controls, and timer switches for equipment that do not need to be on during off-hours such as coffee makers and water coolers.

Table 5.3. Energy Savings Recommendations – Plug Loads

Component	Recommendations (for all climate zones)
Computers-mix of desktop and laptop computers	Increase proportion of laptop computers to desktop computers for primary computer workstations to at least 67% of computers.
Computers- servers, desktop, laptop Monitors, laser printers, copy machines, fax machines, water coolers, refrigerators	Use ENERGY STAR equipment
Computers – desktop, laptop	Apply power management software and activation across all computers
Computer monitors, portable HVAC (heaters, fans), other small appliances and chargers	Occupancy sensor plug strips, or selected outlet occupancy sensor controls in conjunction with lighting control
Water coolers, coffee makers	Use timer switches set to turn off equipment during off-hours
Plug loads power density without controls	0.56 W/ft^2 (6.0 W/m^2)
Equivalent plug loads power density with controls (due to average reduction in usage, not necessarily peak plug load)	0.45 W/ft^2 (4.8 W/m^2)

5.1.4 HVAC and Water Heating Measures

HVAC measures include systems for space heating and cooling with a DOAS providing ventilation. Table 5.4 summarizes the HVAC measures.

The advanced space heating and cooling system is heat pumps with conditioning of ventilation air through a DOAS serving the entire building. The DOAS uses a DX coil for primary cooling, and a gas furnace for primary heating. Energy recovery is included to temper the outside air (both sensible and latent).

Table 5.4. Energy Savings Recommendations – HVAC and Water Heating

Component	Zones 1-8 or as noted below	
	Primary space heating and cooling	
Heat Pumps	<65,000 Btu/h (<19 kW) (Cooling Mode)	15.0 SEER
	≥65,000 Btu/h (≥ 19 kW) (Cooling Mode)	11.0 EER
	<65,000 Btu/h (<19 kW) (Heating Mode)	9.0 HSPF
	≥65,000 Btu/h (≥ 19 kW) (Heating Mode)	3.3 COP
DOAS	Conditioning of ventilation air	100% outside air
	DX cooling efficiency	
	<65,000 Btu/h (<19 kW)	15.0 SEER
	65-135 kBtu/h (19-40 kW)	11.3 EER
	135-240 kBtu/h (40-70 kW)	11.0 EER
	240-300 kBtu/h (70- 88 kW)	10.5 EER
	300-760 kBtu/h (88-223 kW)	10.2 EER
	Heating – gas furnace	Thermal efficiency 80%
	Energy recovery effectiveness	Heating: sensible 70%; latent 60% Cooling: Sensible 75%; latent 60%
Water heating	Condensing water heater	Thermal efficiency 90%
Alternative VAV System	DX cooling efficiency	Same as DOAS values
	Gas furnace and electric reheat	Thermal efficiency 80%
	Energy Recovery Effectiveness	Same as DOAS values
	Indirect evaporative cooling	Climate zones 2B, 3B, 4B, 5B
	Controls	Supply air temperature reset Demand controlled ventilation Motorized damper

5.2 Energy and Cost Saving Results – Advanced Heat Pump Package

The small office prototype is simulated in each of the 16 climate locations to determine if the 50% energy savings goal is achieved. The whole-building energy savings results for the advanced case are shown in Section 5.2.1 and energy cost savings results in Section 5.2.2. The energy savings are the site energy savings relative to the baseline energy use. .

5.2.1 Energy Use and End Use Results – Heat Pump

The package of advanced EEMs can achieve over 50% onsite energy savings for all of the 16 climate locations, as shown in Figure 5.1. Table 5.5 shows the national weighted-average percentage savings is 56.6%. Table 5.5 also shows the weighted energy savings for each climate zone range from 50% to 59%.

Figure 5.2 shows the energy use intensities (EUI) by energy end use category for both the baseline and advanced cases. The annual energy usage by end use category and total energy units in millions of Btus are shown in Table 5.6. The annual energy usage by fuel type is shown in Tables 5.7 and 5.8.

Figure 5.3 shows the proportion of energy savings from different energy end uses from the national weighted-average savings. Approximately 54% of of the energy savings are HVAC related (heating, cooling, and fan), and the remaining savings are provided mainly from lighting and plug loads. Heating shares the largest category, with 34.9% of the savings. Heating savings come from energy recovery for outdoor ventilation air, envelope improvements, and premium efficiency heat pumps. Fans and to a lesser degree cooling provide the remaining 19.2% of the total savings that are HVAC related. Fan energy savings are largely the result of the incorporation of the DOAS, allowing the heat pump fans to cycle to just meet the space loads instead of running at full airflow continuously to meet ventilation requirements during occupied hours. Additional contributions for fans and cooling come from reduced heat gains from lighting and plug loads, energy recovery, envelope improvements, improved cooling efficiency, and enhanced duct work design. The savings for lighting and plug loads are the direct reduction in electricity usage from that equipment, with any HVAC interaction accounted for in the HVAC energy usage categories.

Section 5.4 provides some additional information on the contribution of different EEM categories (e.g., HVAC EEMs) on the savings.

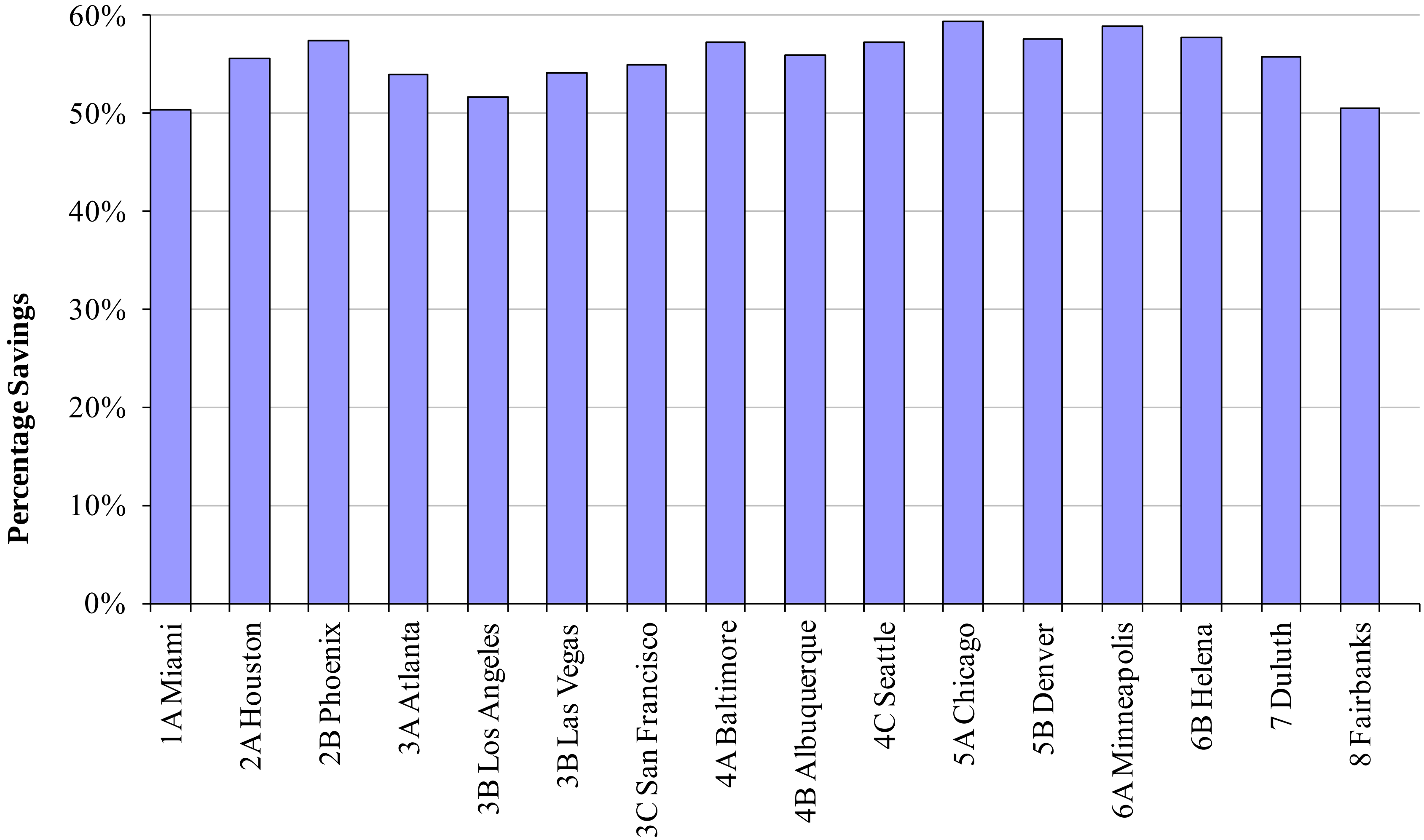

Figure 5.1. Percentage Energy Savings by Climate Zone – Heat Pumps

Table 5.5. Energy Usage Indexes Weighted by Construction Area – Heat Pumps

	1A Miami	2A Houston	2B Phoenix	3A Atlanta	3B-CA Los Angeles	3B-other Las Vegas	3C San Francisco	4A Baltimore	4B Albuquerque
Baseline EUI, kBtu/ft²	45.7	50.7	50.3	49.1	36.9	46.2	41.9	58.3	50.5
Advanced EUI, kBtu/ft²	22.7	22.5	21.5	22.6	17.8	21.2	18.9	25.0	22.3
Savings	23.0	28.2	28.8	26.4	19.0	25.0	23.0	33.3	28.2
Weighting, %	1.50%	18.97%	5.16%	17.17%	1.46%	7.01%	1.39%	16.69%	0.84%

	4C Seattle	5A Chicago	5B Denver	6A Minneapolis	6B Helena	7 Duluth	8 Fairbanks	Total Weighted Average
Baseline EUI, kBtu/ft²	51.6	67.2	55.2	76.2	63.5	84.4	97.5	55.3
Advanced EUI, kBtu/ft²	22.1	27.4	23.5	31.3	26.9	37.4	48.2	24.0
Savings	29.5	39.8	31.8	44.9	36.6	47.0	49.3	31.3
Weighting, %	2.18%	16.40%	5.74%	4.30%	0.54%	0.58%	0.08%	
Weighted % Savings for All Climate Zones								**56.6%**

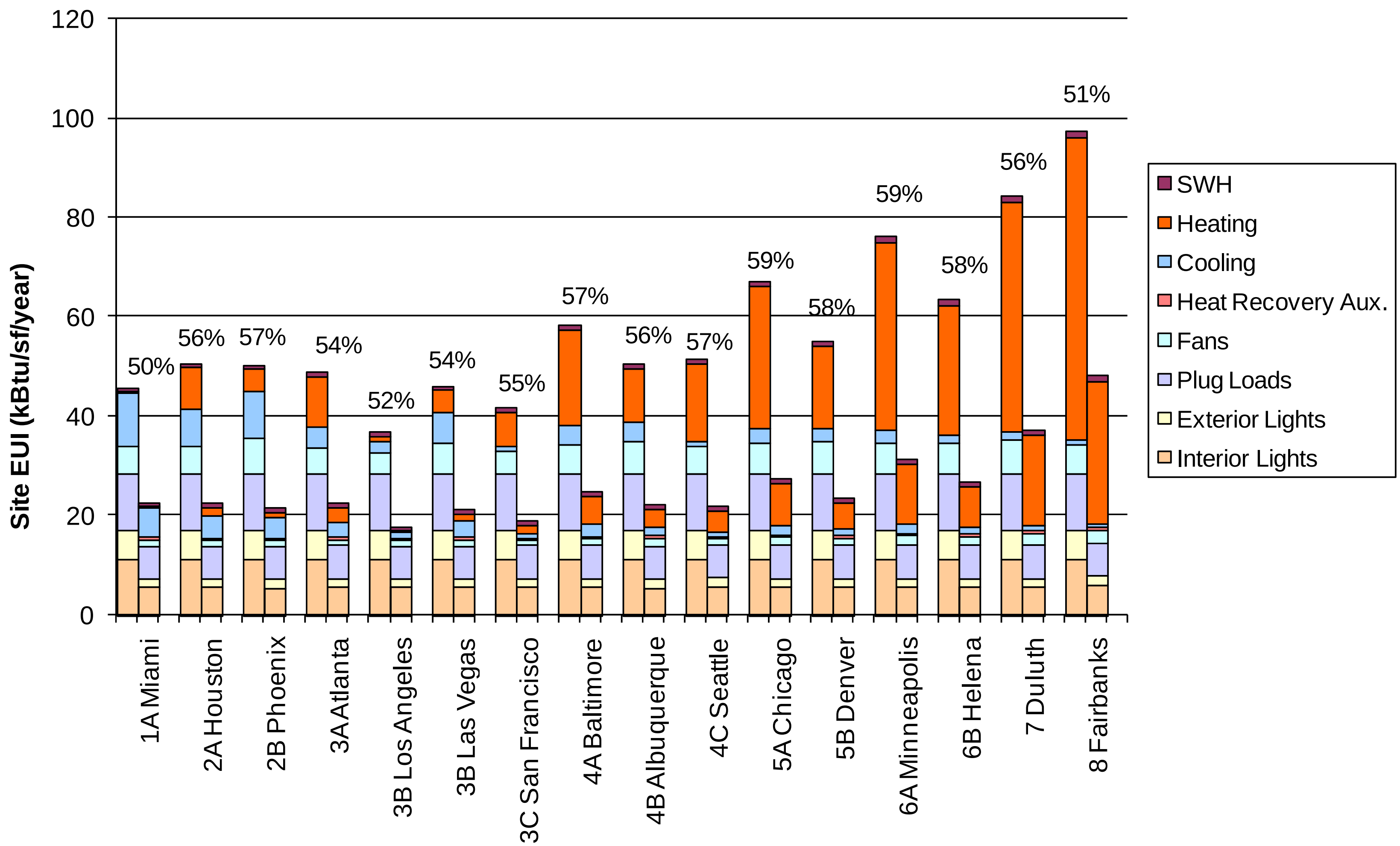

Figure 5.2. Comparison of Energy Use Intensity – Heat Pumps

Table 5.6. Energy Savings Results by End Use – Heat Pumps

Zone	*City*	*Case*	*Heating [MMBtu]*	*Cooling [MMBtu]*	*Interior Lights [MMBtu]*	*Exterior Lights [MMBtu]*	*Plug Loads [MMBtu]*	*Fans [MMBtu]*	*Heat Recovery [MMBtu]*	*Water Heater [MMBtu]*	*Total Energy [MMBtu]*	*EUI [kBtu/SF]*	*Energy Savings (%)*
1A	Miami	Baseline	5	212	222	122	226	111	0	15	915	45.7	50%
		Advanced	9	119	111	35	133	22	12	14	455	22.7	
2A	Houston	Baseline	169	145	222	122	226	111	0	17	1,014	50.7	56%
		Advanced	34	88	111	35	133	22	10	16	450	22.5	
2B	Phoenix	Baseline	90	188	222	122	226	141	0	16	1,007	50.3	57%
		Advanced	21	82	110	35	133	22	11	15	430	21.5	
3A	Atlanta	Baseline	201	90	222	122	226	100	0	19	981	49.1	54%
		Advanced	59	63	111	35	133	25	8	17	452	22.6	
3B	Los Angeles	Baseline	22	44	222	122	226	82	0	19	738	36.9	52%
		Advanced	7	23	111	35	133	20	10	17	357	17.8	
3B	Las Vegas	Baseline	91	125	222	122	226	120	0	17	924	46.2	54%
		Advanced	31	60	111	35	133	26	13	16	424	21.2	
3C	San Francisco	Baseline	136	20	222	122	226	92	0	20	839	41.9	55%
		Advanced	33	19	113	35	133	18	10	18	379	18.9	
4A	Baltimore	Baseline	383	78	222	122	226	114	0	21	1,166	58.3	57%
		Advanced	116	48	112	35	133	26	11	18	500	25.0	
4B	Albuquerque	Baseline	215	74	222	122	226	130	0	20	1,010	50.5	56%
		Advanced	72	36	110	35	133	28	12	18	445	22.3	
4C	Seattle	Baseline	311	22	222	122	226	107	0	22	1,032	51.6	57%
		Advanced	87	19	115	36	133	22	11	19	442	22.1	
5A	Chicago	Baseline	570	62	222	122	226	120	0	22	1,344	67.2	59%
		Advanced	165	40	113	35	133	31	11	20	547	27.4	
5B	Denver	Baseline	334	49	222	122	226	129	0	22	1,104	55.2	58%
		Advanced	102	25	111	35	133	30	12	19	469	23.5	
6A	Minneapolis	Baseline	754	54	222	122	226	122	0	23	1,524	76.2	59%
		Advanced	235	38	112	36	133	40	11	21	626	31.3	
6B	Helena	Baseline	520	32	222	122	226	122	0	23	1,269	63.5	58%
		Advanced	164	22	112	36	133	36	13	21	537	26.9	
7	Duluth	Baseline	927	32	222	122	226	134	0	25	1,687	84.4	56%
		Advanced	365	21	112	36	133	46	12	22	748	37.4	
8	Fairbanks	Baseline	1216	19	222	121	226	118	0	27	1,950	97.5	51%
		Advanced	571	13	118	40	133	53	12	24	964	48.2	

Table 5.7. Electricity (kWh) Savings Results by End Use – Heat Pumps

			Electricity, kWh								
Zone	***City***	***Case***	***Heating***	***Cooling***	***Interior Lighting***	***Exterior Lighting***	***Plug Loads***	***Fans***	***Heat Recovery***	***Water Heater***	***Total Electricity***
1A	Miami	Baseline	0	62,200	65,156	35,811	66,269	32,525	0	0	261,961
		Advanced	2,706	34,781	32,617	10,211	39,100	6,381	3,383	0	129,172
2A	Houston	Baseline	0	42,619	65,156	35,747	66,269	32,550	0	0	242,342
		Advanced	9,864	25,872	32,639	10,200	39,100	6,528	2,986	0	127,186
2B	Phoenix	Baseline	0	55,200	65,156	35,736	66,269	41,453	0	0	263,814
		Advanced	4,847	24,008	32,328	10,250	39,100	6,417	3,289	0	120,236
3A	Atlanta	Baseline	0	26,486	65,156	35,797	66,269	29,264	0	0	222,972
		Advanced	17,222	18,453	32,614	10,350	39,100	7,281	2,472	0	127,492
3B	Los Angeles	Baseline	0	12,894	65,156	35,792	66,269	24,158	0	0	204,267
		Advanced	1,442	6,675	32,592	10,192	39,100	5,931	3,044	0	98,975
3B	Las Vegas	Baseline	0	36,572	65,156	35,756	66,269	35,117	0	0	238,869
		Advanced	6,144	17,578	32,436	10,289	39,100	7,558	3,667	0	116,769
3C	San Francisco	Baseline	0	5,953	65,156	35,717	66,269	27,014	0	0	200,108
		Advanced	7,092	5,439	32,989	10,219	39,100	5,386	2,808	0	103,031
4A	Baltimore	Baseline	0	22,853	65,156	35,753	66,269	33,383	0	0	223,414
		Advanced	21,814	14,178	32,886	10,283	39,100	7,572	3,131	0	128,964
4B	Albuquerque	Baseline	0	21,581	65,156	35,747	66,269	38,167	0	0	226,919
		Advanced	13,886	10,689	32,356	10,192	39,100	8,208	3,564	0	117,994
4C	Seattle	Baseline	0	6,575	65,156	35,694	66,269	31,281	0	0	204,975
		Advanced	15,619	5,428	33,764	10,519	39,100	6,347	3,111	0	113,889
5A	Chicago	Baseline	0	18,239	65,156	35,706	66,269	35,022	0	0	220,389
		Advanced	30,972	11,628	33,089	10,389	39,100	8,950	3,164	0	137,294
5B	Denver	Baseline	0	14,419	65,156	35,711	66,269	37,692	0	0	219,244
		Advanced	18,889	7,347	32,639	10,289	39,100	8,725	3,619	0	120,608
6A	Minneapolis	Baseline	0	15,839	65,156	35,733	66,269	35,747	0	0	218,742
		Advanced	43,983	11,228	32,678	10,425	39,100	11,808	3,175	0	152,397
6B	Helena	Baseline	0	9,522	65,156	35,689	66,269	35,881	0	0	212,517
		Advanced	29,386	6,467	32,761	10,447	39,100	10,689	3,714	0	132,564
7	Duluth	Baseline	0	9,258	65,156	35,681	66,269	39,136	0	0	215,497
		Advanced	17,767	6,208	32,944	10,489	39,100	13,489	3,372	0	123,369
8	Fairbanks	Baseline	0	5,633	65,156	35,467	66,269	34,506	0	0	207,031
		Advanced	15,208	3,719	34,586	11,650	39,100	15,619	3492	0	123,375

Table 5.8. Natural Gas (therms) Savings Results by End Use – Heat Pumps

Natural Gas, therms												
Zone	***City***	***Case***	***Heating***	***Cooling***	***Interior Lighting***	***Exterior Lighting***	***Plug Loads***	***Fans***	***Heat Recovery***	***Water Heater***	***Total***
1A	Miami	Baseline	54	0	0	0	0	0	0	152	206
		Advanced	0	0	0	0	0	0	0	138	138
2A	Houston	Baseline	1,694	0	0	0	0	0	0	173	1,867
		Advanced	0	0	0	0	0	0	0	157	157
2B	Phoenix	Baseline	902	0	0	0	0	0	0	161	1,063
		Advanced	49	0	0	0	0	0	0	146	195
3A	Atlanta	Baseline	2,011	0	0	0	0	0	0	192	2,202
		Advanced	0	0	0	0	0	0	0	172	173
3B	Los Angeles	Baseline	217	0	0	0	0	0	0	188	405
		Advanced	24	0	0	0	0	0	0	168	192
3B	Las Vegas	Baseline	909	0	0	0	0	0	0	175	1,084
		Advanced	99	0	0	0	0	0	0	156	256
3C	San Francisco	Baseline	1,356	0	0	0	0	0	0	205	1,560
		Advanced	87	0	0	0	0	0	0	183	270
4A	Baltimore	Baseline	3,826	0	0	0	0	0	0	207	4,033
		Advanced	411	0	0	0	0	0	0	185	596
4B	Albuquerque	Baseline	2,150	0	0	0	0	0	0	203	2,354
		Advanced	242	0	0	0	0	0	0	181	423
4C	Seattle	Baseline	3,112	0	0	0	0	0	0	215	3,327
		Advanced	340	0	0	0	0	0	0	192	532
5A	Chicago	Baseline	5,696	0	0	0	0	0	0	220	5,915
		Advanced	592	0	0	0	0	0	0	196	788
5B	Denver	Baseline	3,341	0	0	0	0	0	0	219	3,561
		Advanced	379	0	0	0	0	0	0	195	574
6A	Minneapolis	Baseline	7,538	0	0	0	0	0	0	232	7,769
		Advanced	851	0	0	0	0	0	0	206	1,057
6B	Helena	Baseline	5,204	0	0	0	0	0	0	233	5,437
		Advanced	640	0	0	0	0	0	0	207	847
7	Duluth	Baseline	9,267	0	0	0	0	0	0	250	9,517
		Advanced	3,044	0	0	0	0	0	0	222	3,267
8	Fairbanks	Baseline	12,163	0	0	0	0	0	0	272	12,436
		Advanced	5,191	0	0	0	0	0	0	242	5,433

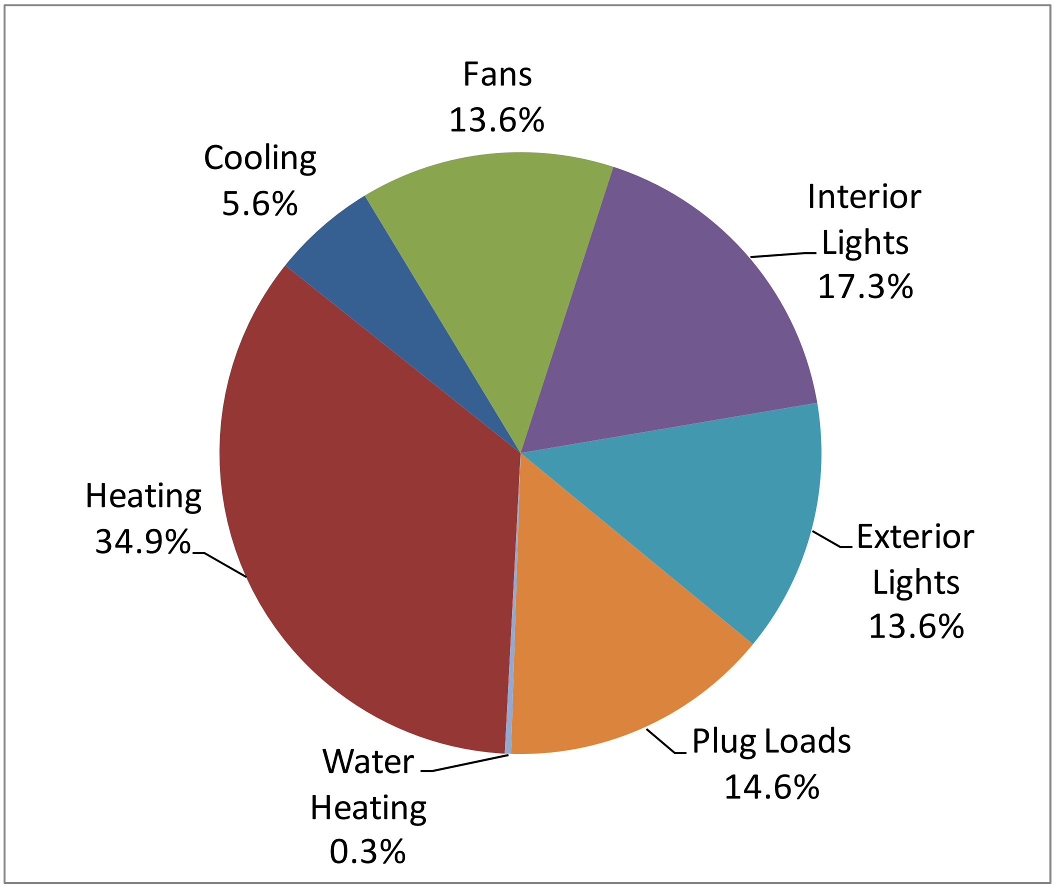

Figure 5.3. Proportion of Energy Savings from Different Usage Categories – Heat Pumps

5.2.2 Energy Cost Savings Results – Heat Pump

Energy cost savings, as shown in Table 5.9, are calculated by using the same energy prices adopted by the SSPC 90.1 in developing the 2010 version of Standard 90.1. These energy prices, derived from EIA values, are $1.16/therm ($0.41/m^3) for natual gas and $0.0939/kWh for electricity (EIA 2007). Energy cost savings range from about $10,000 to $16,000 annually, ranging from 47% to 56%. The national weighted-average cost savings is 50.7%.

Table 5.9. Annual Energy Cost Reduction – Heat Pump

Zone	City	Electricity Savings, kWh	Natural Gas Savings, therms	Electricity Cost Savings	Natural Gas Savings	Total Cost Savings	Baseline Energy Cost	Energy Cost % Savings
1A	Miami	132,789	69	$12,469	$79	$12,548	$24,838	51%
2A	Houston	115,156	1,710	$10,813	$1,984	$12,797	$24,922	51%
2B	Phoenix	143,578	868	$13,482	$1,007	$14,489	$26,005	56%
3A	Atlanta	95,481	2,030	$8,966	$2,355	$11,320	$23,492	48%
3B	Los Angeles	105,292	214	$9,887	$248	$10,135	$19,651	52%
3B	Las Vegas	122,100	828	$11,465	$960	$12,426	$23,687	52%
3C	San Fran.	97,078	1,290	$9,116	$1,497	$10,612	$20,600	52%
4A	Baltimore	94,450	3,437	$8,869	$3,987	$12,856	$25,657	50%
4B	Albuquerque	108,925	1,931	$10,228	$2,240	$12,468	$24,038	52%
4C	Seattle	91,086	2,796	$8,553	$3,243	$11,796	$23,107	51%
5A	Chicago	83,094	5,127	$7,803	$5,948	$13,750	$27,556	50%
5B	Denver	98,636	2,987	$9,262	$3,464	$12,726	$24,717	51%
6A	Minneap.	66,344	6,712	$6,230	$7,786	$14,016	$29,552	47%
6B	Helena	79,953	4,590	$7,508	$5,324	$12,832	$26,262	49%
7	Duluth	92,128	6,250	$8,651	$7,250	$15,901	$31,275	51%
8	Fairbanks	83,656	7,003	$7,855	$8,123	$15,979	$33,865	47%

5.3 Energy Results – Alternative VAV Package

The alternative VAV system combined with the advanced non-HVAC EEMs presented in Section 4 can achieve over 50% onsite energy savings for 7 of the 16 climate locations, as shown in Figure 5.4. Table 5.10 shows the national weighted-average percentage savings is 48.5%.

Figure 5.5 shows the construction weighted energy savings for all climates and the national weighted-average savings. The annual energy usage by end use category and total energy units in millions of Btus is shown in Table 5.11. The annual energy uses by fuel types are presented in Tables 5.12 and 5.13.

Figure 5.6 shows the proportion of energy savings from different energy end uses from the national weighted-average savings.A little over half the savings are HVAC related, and the remaining savings come directly from lighting and plug loads. Heating is the largest category with 27.5% of the savings. Heating savings come from energy recovery, demand controlled ventilation, and envelope improvements. Fans and to a lesser degree cooling provide 19.2% savings. Fan energy savings are largely from the switch to VAV system fans instead of constant volume systems. Cooling and additional fan energy savings come from reduced cooling loads from lower lighting and plug loads. Additional cooling savings come from premium efficiency DX cooling, energy recovery, demand controlled ventilation and indirect evaporative cooling for some climate zones. The savings for lighting and plug loads are the direct reduction in electricity usage from that equipment. Any HVAC savings due to reduced lighting and plus loads is accounted for in the HVAC energy usage categories in this Figure.

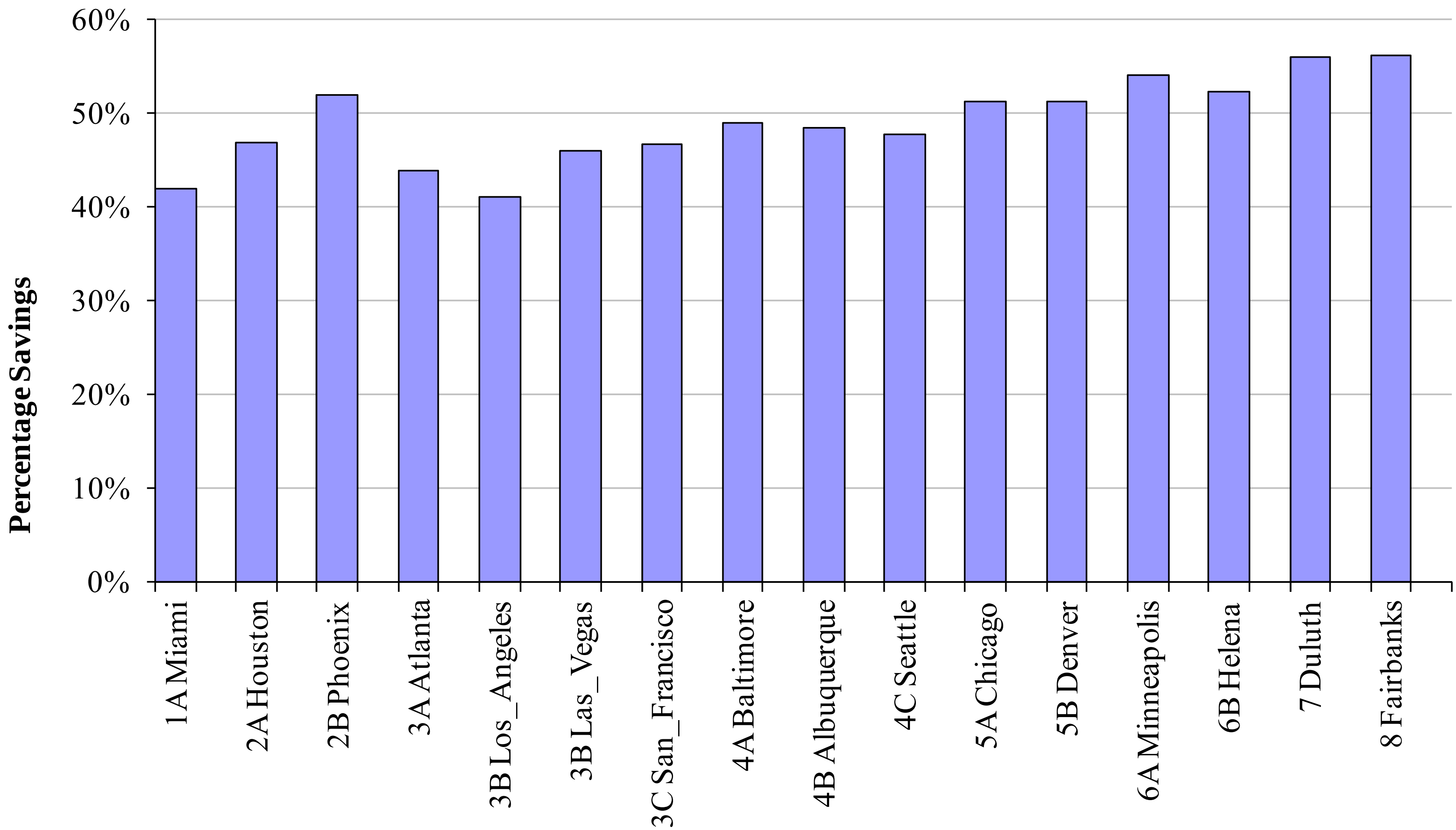

Figure 5.4. Percentage Energy Savings by Climate Zone – VAV

Table 5.10. Energy Usage Indexes Weighted by Construction Areas – VAV

	1A	2A	2B	3A	3B-CA	3B-other	3C	4A	4B	4C	5A	5B	6A	6B	7	8	Total
	Miami	Houston	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks	Weighted Average
Baseline EUI, kBtu/ft²	45.7	50.7	50.3	49.1	36.9	46.2	41.9	58.3	50.5	51.6	67.2	55.2	76.2	63.5	84.4	97.5	55.3
Advanced EUI, kBtu/ft²	26.6	27.0	24.2	27.5	21.8	25.0	22.4	29.8	26.0	27.0	32.8	26.9	35.0	30.3	37.2	42.7	28.5
Savings	19.1	23.7	26.2	21.5	15.1	21.2	19.5	28.5	24.5	24.7	34.4	28.3	41.2	33.2	47.2	54.8	26.9
Weighting, %	1.50%	18.97%	5.16%	17.17%	1.46%	7.01%	1.39%	16.69%	0.84%	2.18%	16.40%	5.74%	4.30%	0.54%	0.58%	0.08%	
Weighted % Savings for All Climate Zones																	**48.5%**

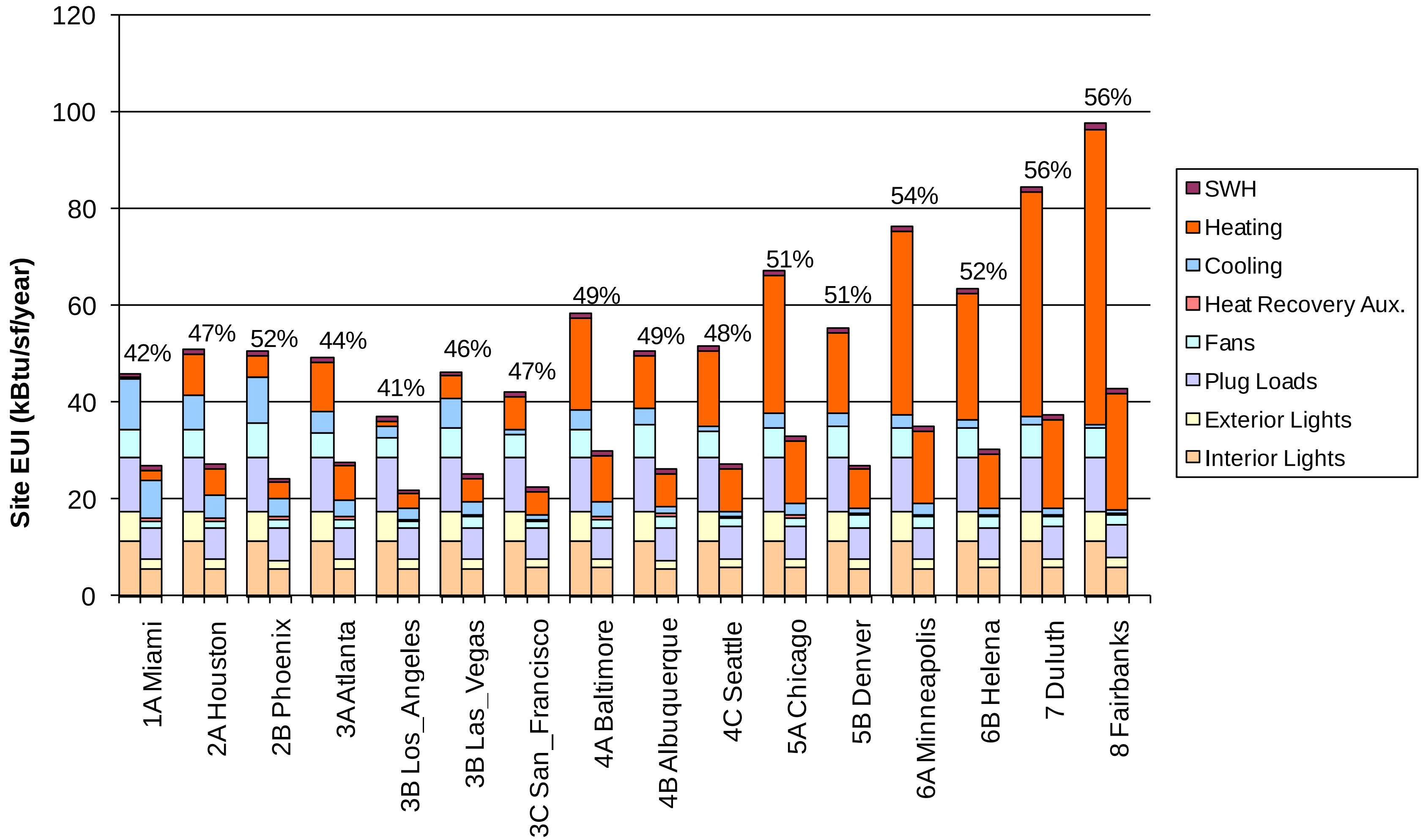

Figure 5.5. Comparison of Energy Use Intensity – VAV

Table 5.11. Energy Savings Results by End Use – VAV

Zone	*City*	*Case*	*Heating [MMBtu]*	*Cooling [MMBtu]*	*Interior Lights [MMBtu]*	*Exterior Lights [MMBtu]*	*Plug Loads [MMBtu]*	*Fans [MMBtu]*	*Heat Recovery [MMBtu]*	*Water Heater [MMBtu]*	*Total Energy [MMBtu]*	*EUI [kBtu/SF]*	*Energy Savings (%)*
1A	Miami	Baseline	5	212	222	122	226	111	0	15	915	45.7	42%
		Advanced	45	152	111	35	133	27	14	14	532	26.6	
2A	Houston	Baseline	169	145	222	122	226	111	0	17	1,014	50.7	47%
		Advanced	108	100	111	35	133	24	12	16	539	27.0	
2B	Phoenix	Baseline	90	188	222	122	226	141	0	16	1,007	50.3	52%
		Advanced	68	76	110	35	133	35	10	15	483	24.2	
3A	Atlanta	Baseline	201	90	222	122	226	100	0	19	981	49.1	44%
		Advanced	138	72	111	35	133	32	10	17	551	27.5	
3B	Los Angeles	Baseline	22	44	222	122	226	82	0	19	738	36.9	41%
		Advanced	61	46	111	35	133	31	2	17	435	21.8	
3B	Las Vegas	Baseline	91	125	222	122	226	120	0	17	924	46.2	46%
		Advanced	97	54	111	35	133	45	9	16	500	25.0	
3C	San Francisco	Baseline	136	20	222	122	226	92	0	20	839	41.9	47%
		Advanced	98	20	113	35	133	26	4	18	448	22.4	
4A	Baltimore	Baseline	383	78	222	122	226	114	0	21	1,166	58.3	49%
		Advanced	193	60	112	35	133	34	10	19	596	29.8	
4B	Albuquerque	Baseline	215	74	222	122	226	130	0	20	1,010	50.5	49%
		Advanced	133	33	110	35	133	49	8	18	520	26.0	
4C	Seattle	Baseline	311	22	222	122	226	107	0	22	1,032	51.6	48%
		Advanced	176	21	115	36	133	32	6	19	539	27.0	
5A	Chicago	Baseline	570	62	222	122	226	120	0	22	1,344	67.2	51%
		Advanced	254	52	113	35	133	39	9	20	655	32.8	
5B	Denver	Baseline	334	49	222	122	226	129	0	22	1,104	55.2	51%
		Advanced	157	22	111	35	133	51	8	20	538	26.9	
6A	Minneapolis	Baseline	754	54	222	122	226	122	0	23	1,524	76.2	54%
		Advanced	297	51	112	36	133	42	9	21	700	35.0	
6B	Helena	Baseline	520	32	222	122	226	122	0	23	1,269	63.5	52%
		Advanced	225	29	112	36	133	43	8	21	605	30.3	
7	Duluth	Baseline	927	32	222	122	226	134	0	25	1,687	84.4	56%
		Advanced	363	24	112	36	133	45	8	22	744	37.2	
8	Fairbanks	Baseline	1216	19	222	121	226	118	0	27	1,950	97.5	56%
		Advanced	477	12	118	40	133	40	9	24	854	42.7	

Table 5.12. Electricity (kWh) Savings Results by End Use – VAV

			Electricity, kWh								
Zone	***City***	***Case***	***Heating***	***Cooling***	***Interior Lighting***	***Exterior Lighting***	***Plug Loads***	***Fans***	***Heat Recovery***	***Water Heater***	***Total Electricity***
1A	Miami	Baseline	0	62,200	65,156	35,811	66,269	32,525	0	0	261,961
		Advanced	13,178	44,575	32,617	10,211	39,100	7,981	4,053	0	151,711
2A	Houston	Baseline	0	42,619	65,156	35,747	66,269	32,550	0	0	242,342
		Advanced	31,047	29,278	32,639	10,200	39,100	7,117	3,492	0	152,869
2B	Phoenix	Baseline	0	55,200	65,156	35,736	66,269	41,453	0	0	263,814
		Advanced	19,250	22,356	32,328	10,250	39,100	10,239	3,053	0	136,572
3A	Atlanta	Baseline	0	26,486	65,156	35,797	66,269	29,264	0	0	222,972
		Advanced	36,911	21,239	32,614	10,350	39,100	9,392	2,942	0	152,547
3B	Los Angeles	Baseline	0	12,894	65,156	35,792	66,269	24,158	0	0	204,267
		Advanced	17,739	13,433	32,592	10,192	39,100	8,958	522	0	122,531
3B	Las Vegas	Baseline	0	36,572	65,156	35,756	66,269	35,117	0	0	238,869
		Advanced	27,503	15,864	32,436	10,289	39,100	13,094	2,625	0	140,911
3C	San Francisco	Baseline	0	5,953	65,156	35,717	66,269	27,014	0	0	200,108
		Advanced	27,142	6,006	32,989	10,219	39,100	7,728	1,175	0	124,361
4A	Baltimore	Baseline	0	22,853	65,156	35,753	66,269	33,383	0	0	223,414
		Advanced	49,878	17,478	32,886	10,283	39,100	9,875	3,033	0	162,533
4B	Albuquerque	Baseline	0	21,581	65,156	35,747	66,269	38,167	0	0	226,919
		Advanced	35,575	9,631	32,356	10,192	39,100	14,367	2,294	0	143,511
4C	Seattle	Baseline	0	6,575	65,156	35,694	66,269	31,281	0	0	204,975
		Advanced	44,844	6,161	33,764	10,519	39,100	9,417	1,808	0	145,614
5A	Chicago	Baseline	0	18,239	65,156	35,706	66,269	35,022	0	0	220,389
		Advanced	62,714	15,200	33,089	10,389	39,100	11,564	2,497	0	174,553
5B	Denver	Baseline	0	14,419	65,156	35,711	66,269	37,692	0	0	219,244
		Advanced	40,856	6,586	32,639	10,289	39,100	14,808	2,303	0	146,578
6A	Minneapolis	Baseline	0	15,839	65,156	35,733	66,269	35,747	0	0	218,742
		Advanced	75,953	14,875	32,678	10,425	39,100	12,347	2,514	0	187,889
6B	Helena	Baseline	0	9,522	65,156	35,689	66,269	35,881	0	0	212,517
		Advanced	56,667	8,375	32,761	10,447	39,100	12,461	2,292	0	162,103
7	Duluth	Baseline	0	9,258	65,156	35,681	66,269	39,136	0	0	215,497
		Advanced	90,250	7,058	32,944	10,489	39,100	13,272	2,369	0	195,483
8	Fairbanks	Baseline	0	5,633	65,156	35,467	66,269	34,506	0	0	207,031
		Advanced	88,161	3,639	34,586	11,650	39,100	11,714	2725	0	191,572

Table 5.13. Natural Gas (therms) Savings Results by End Use – VAV

			Natural Gas, therms								
Zone	***City***	***Case***	***Heating***	***Cooling***	***Interior Lighting***	***Exterior Lighting***	***Plug Loads***	***Fans***	***Heat Recovery***	***Water Heater***	***Natural Gas***
1A	Miami	Baseline	54	0	0	0	0	0	0	152	206
		Advanced	0	0	0	0	0	0	0	139	139
2A	Houston	Baseline	1,694	0	0	0	0	0	0	173	1,867
		Advanced	17	0	0	0	0	0	0	157	174
2B	Phoenix	Baseline	902	0	0	0	0	0	0	161	1,063
		Advanced	23	0	0	0	0	0	0	147	170
3A	Atlanta	Baseline	2,011	0	0	0	0	0	0	192	2,202
		Advanced	125	0	0	0	0	0	0	174	299
3B	Los Angeles	Baseline	217	0	0	0	0	0	0	188	405
		Advanced	1	0	0	0	0	0	0	170	171
3B	Las Vegas	Baseline	909	0	0	0	0	0	0	175	1,084
		Advanced	29	0	0	0	0	0	0	159	188
3C	San Francisco	Baseline	1,356	0	0	0	0	0	0	205	1,560
		Advanced	51	0	0	0	0	0	0	185	236
4A	Baltimore	Baseline	3,826	0	0	0	0	0	0	207	4,033
		Advanced	224	0	0	0	0	0	0	186	410
4B	Albuquerque	Baseline	2,150	0	0	0	0	0	0	203	2,354
		Advanced	118	0	0	0	0	0	0	184	302
4C	Seattle	Baseline	3,112	0	0	0	0	0	0	215	3,327
		Advanced	229	0	0	0	0	0	0	193	423
5A	Chicago	Baseline	5,696	0	0	0	0	0	0	220	5,915
		Advanced	399	0	0	0	0	0	0	198	597
5B	Denver	Baseline	3,341	0	0	0	0	0	0	219	3,561
		Advanced	179	0	0	0	0	0	0	197	377
6A	Minneapolis	Baseline	7,538	0	0	0	0	0	0	232	7,769
		Advanced	381	0	0	0	0	0	0	208	590
6B	Helena	Baseline	5,204	0	0	0	0	0	0	233	5,437
		Advanced	312	0	0	0	0	0	0	210	521
7	Duluth	Baseline	9,267	0	0	0	0	0	0	250	9,517
		Advanced	545	0	0	0	0	0	0	224	770
8	Fairbanks	Baseline	12,163	0	0	0	0	0	0	272	12,436
		Advanced	1,757	0	0	0	0	0	0	244	2,001

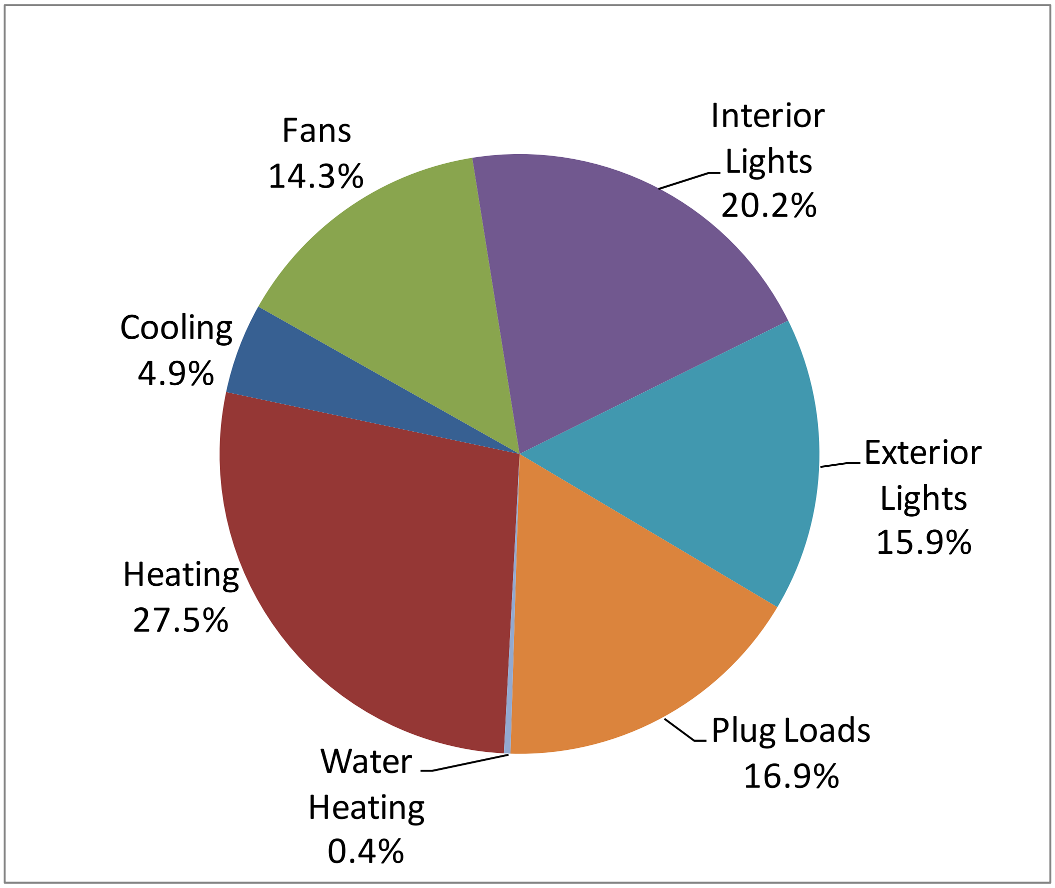

Figure 5.6. Proportion of Energy Savings from Different Usage Categories – VAV

5.3.1 Energy Cost Savings Results – VAV

Energy cost savings are calculated using the energy prices described in section 5.2.2. Table 5.14 shows the calculated annual energy cost savings. Energy cost savings range from about $8,000 to $13,000 annually, varying from 38% to 50%. The national weighted-average cost savings is 40.2%.

Table 5.14. Annual Energy Cost Reduction - VAV

Zone	City	Electricity Savings, kWh	Natural Gas Savings, therms	Electricity Cost Savings	Natural Gas Savings	Total Cost Savings	Baseline Energy Cost	Energy Cost % Savings
1A	Miami	110,250	67	$10,352	$78	$10,430	$24,838	42%
2A	Houston	89,472	1,693	$8,401	$1,964	$10,365	$24,922	42%
2B	Phoenix	127,242	893	$11,948	$1,035	$12,983	$26,005	50%
3A	Atlanta	70,425	1,904	$6,613	$2,208	$8,821	$23,492	38%
3B	Los Angeles	81,736	234	$7,675	$272	$7,947	$19,651	40%
3B	Las Vegas	97,958	895	$9,198	$1,039	$10,237	$23,687	43%
3C	San Fran.	75,747	1,325	$7,113	$1,537	$8,649	$20,600	42%
4A	Baltimore	60,881	3,623	$5,717	$4,202	$9,919	$25,657	39%
4B	Albuquerque	83,408	2,052	$7,832	$2,380	$10,212	$24,038	42%
4C	Seattle	59,361	2,904	$5,574	$3,369	$8,943	$23,107	39%
5A	Chicago	45,836	5,319	$4,304	$6,170	$10,474	$27,556	38%
5B	Denver	72,667	3,184	$6,823	$3,693	$10,517	$24,717	43%
6A	Minneap.	30,853	7,180	$2,897	$8,329	$11,226	$29,552	38%
6B	Helena	50,414	4,916	$4,734	$5,702	$10,436	$26,262	40%
7	Duluth	20,014	8,747	$1,879	$10,147	$12,026	$31,275	38%
8	Fairbanks	15,458	10,435	$1,452	$12,104	$13,556	$33,865	40%

5.4 Further Investigation of Advanced Energy Results

To further qualify the energy savings results for the advanced EEM package with the heat pump systems, two additional investigations are carried out. One, a set of model runs is completed by removing one category of EEMs at a time to show the saving contribution from each of the EEM categories. Two, a more detailed look is presented on fan and heating energy savings for one example climate zone, zone 5A. This breaks out the fan energy and airflow and the heating energy by the type of system and heating components.

5.4.1 Energy Results by EEM Category

For each climate zone, separate energy models are developed and results prepared to show the impact of a category of EEMs. The EEMS are categorized as building envelope, interior lighting, exterior lighting, plug loads, and HVAC. Service water heating is neglected and contributes a small amount to the savings. Each model includes the removal of all of the EEMs of a particular category from the model and generate results for each such model. So each result in Table 5.15 is the percentage savings for the full package without one category of EEMs for each of the climate zones. The percentage of reductions in Table 5.15 do not add up to the total savings. There are interactions between savings categories that impact HVAC sizing or other elements in ways that are not captured in removing one EEM category at a time.

The results show certain trends, such as the increasing importance of the HVAC EEMs in colder climate zones as outdoor air heating and space heating requirements grow. As shown in Section 5.4.2 for the climate zone 5A, and for other colder climate zones, outdoor air and the energy recovery at the DOAS are major contributors to the savings. Savings in the without lighting category diminish in the colder climates in proportion to the total savings both because the total savings increase (primarily for heating), and the lighting savings are offset by increased heating as the lighting provided heating diminishes.

Table 5.15. Energy Savings Results by EEM Category – Heat Pumps

	Location		Energy Saving Difference			
		Full Package	w/o Envelope	w/o HVAC	w/o Lighting	w/o Plug Load
1A	Miami	50.3%	-2.7%	-1.1%	-23.2%	-11.1%
2A	Houston	55.6%	-4.6%	-7.9%	-20.1%	-9.3%
2B	Phoenix	57.3%	-6.6%	-6.8%	-20.8%	-9.9%
3A	Atlanta	53.9%	-2.1%	-18.1%	-20.3%	-9.1%
3B	Los_Angeles	51.6%	-1.4%	-5.7%	-28.6%	-13.7%
3B	Las_Vegas	54.1%	-3.0%	-12.9%	-22.8%	-10.9%
3C	San_Francisco	54.9%	-2.1%	-14.0%	-23.5%	-10.7%
4A	Baltimore	57.1%	-3.1%	-25.4%	-16.6%	-7.3%
4B	Albuquerque	55.9%	-3.4%	-18.6%	-20.3%	-9.3%
4C	Seattle	57.2%	-2.5%	-24.5%	-18.3%	-8.3%
5A	Chicago	59.3%	-4.8%	-28.8%	-14.0%	-6.0%
5B	Denver	57.5%	-4.9%	-20.9%	-18.0%	-8.0%
6A	Minneapolis	58.9%	-5.9%	-30.7%	-12.2%	-5.0%
6B	Helena	57.7%	-5.6%	-25.7%	-15.0%	-6.5%
7	Duluth	55.7%	-8.6%	-29.9%	-10.1%	-3.7%
8	Fairbanks	55.7%	-8.6%	-29.9%	-10.1%	-3.7%

5.4.2 HVAC Energy Savings Details for Climate Location 5A

The heat pump with DOAS systems provides large heating and fan energy savings. Additonal detail on these savings results is provided for one example climate location. Fan energy savings and fan airflow are analyzed for the baseline, the heat pump plus DOAS, and the VAV system alternative. Heating detail is presented for the baseline and the heat pump with DOAS case including the breakdown of heating usage and savings by ventilation and space heating, and by heating device such as gas furnace, heat pump, or supplemental electric resistance heat.

Table 5.16 shows the fan energy consumption for all three types of the HVAC systems. For each HVAC system type, the annual total fan energy includes the energy consumed in two time periods: the scheduled HVAC operating period and the night cycle period. There is a large percentage of fan energy savings for the heat pump with DOAS (74%) and the VAV system (67%) in comparison with the baseline. This is mainly from the reduced average airflow rate in those two systems. As Table 5.17 shows, the average airflow rate for the heat pump with DOAS, and VAV system airflows are reduced substantially relative to the baseline. This significant average airflow rate reduction is caused by:

- The baseline uses packaged single zone (PSZ) systems. Each packaged system supplies a constant airflow rate that is sized according to the peak design load of its served thermal zone. When the HVAC system is scheduled on, the total fan flow rate is the sum of the peak design airflow for each PSZ system, regardless of the zone thermal load.
- The total airflow for the heat pump with DOAS systems includes the DOAS which supplies only the amount of outdoor air required for ventilation. The heat pump systems including the fans cycle on to meet space loads so the airflow is reduced on average. In some cases part of the space loads may be met by the DOAS, reducing the heat pump fan operation further.
- The airflow rate varies with the cooling load in the VAV system subject to minimum terminal unit airflow.
- The space conditioning loads, and therefore the design airflow, are lower for both the heat pumps and for the VAV system because of the improved envelope and reduced internal gains.

Table 5.16. Annual Fan Energy

Period of Operation	Fan Energy, kWh		
	Baseline	Heat Pumps, DOAS	VAV
Scheduled HVAC Operating Period	28,056	6,806	8,389
Night Cycle Period	6,945	2,167	3,167
Annual Total	35,000	8,889	11,667

Table 5.17. Average Supply Fan Airflow Rate

Period of Operation	Average Supply Fan Airflow Rate					
	Baseline		Heat Pumps w DOAS		VAV System	
	cfm	*m³/s*	cfm	*m³/s*	cfm	*m³/s*
Scheduled HVAC Operating Period	13,031	*6.15*	3,581	*1.69*	4,280	2.02
Night Cycle Period	3,666	*1.73*	1,335	*0.63*	1,801	0.85
Annual Average	8,603	*4.06*	2,543	*1.2*	3,115	1.47

Table 5.18 shows the breakdown of heating energy for the baseline and the heat pump with DOAS systems for the 5A climate zone (Chicago climate location). The breakdown distinguishes ventilation heating, and space heating, and which components provide the different parts of the heating. This demonstrates that nearly 70% of the heating energy savings results from the DOAS primarily for heat recovery. This also shows roughly 30% of the energy savings results from the heat pump systems. This is separated into heat pump energy, supplemental electric heat and defrost. The portion of space heating for the advanced case that is electric resistance is 32% of the total. However, the electric resistance heat is only 9% of the baseline heating energy, so the benefit of switching from gas heat in the baseline to

electric resistance for a modest portion of the advanced case heating is a small portion of the total heating change.

Table 5.18. Breakdown of Heating Energy for Climate Zone 5A

	Baseline		Advanced		Savings		% of Savings
	mmBtu	*GJ*	mmBtu	*GJ*	mmBtu	*GJ*	
Total Heating	570	*601*	165	*174*	405	*427*	100%
Ventilation							
Furnace, gas	336	*355*	59	*63*	277	*292*	68.4%
Space Heating							
Furnace, gas	234	*246*					
Heat Pump Heat, electric			53	*56*			
Supplemental Heat, electric			49	*51*			
Defrost, electric			4	*4*			
Total Space Heating	234	*246*	106	*111*	128	*135*	31.6%

6.0 Cost-Effectiveness Analysis

The first cost of EEMs is as relevant as energy cost savings. One of the goals that DOE set for this project was that the advanced energy measure package has a 5-year payback or less. Based on feedback received from DOE, as well as users and promoters of previous AEDG reports, there is a strong interest in understanding the additional costs necessary to meet recommended energy performance levels. The cost data provided in this report intends to represent a reasonable estimate of the incremental costs for an energy-efficient small office building based on the small office prototype used in the energy simulations.

The advanced energy efficiency measures with heat pumps and DOAS are estimated to have an national weighted-average payback of 6.8 years. The primary increased costs are the result of substantially enhanced building envelope, and costs to reduce plug loads. Lighting costs are a little higher for the energy measure packages than for the baseline because of additional controls and more expensive equipment, offset by the reduced number of fixtures. The HVAC system cost estimates take into account significantly reduced system capacity resulting from reduced space loads. Actual project costs will vary, but the cost-effectiveness analysis does suggest that 50% energy savings can be achieved for new small offices with a reasonable added cost.

The alternative VAV system has an weighted-average payback of 8.7 years.

Section 6.1 describes the information sources used to develop the incremental costs. Section 6.2 presents the cost effectiveness for the advanced EEM package with heat pumps and DOAS. Section 6.3 presents the cost effectiveness for the alternative VAV system EEM package.

6.1 Basis for Incremental Energy Efficiency Measure Costs

Incremental costs for the various EEMs are developed based on the difference between the costs for the baseline measure and the costs for the energy savings measure. The incremental costs may be based on a per unit cost such as costs per square foot of wall area, or a total cost for an EEM component such as the cost of a single air conditioning unit that serves an entire building or section of a building. This approach requires that for each measure, both the baseline cost and the EEM cost must be developed or data must be explicitly available on incremental costs.

This analysis uses incremental costs as the basis of comparison to help offset some of the biases in cost data, when the cost data is deemed to be either routinely high or routinely low. For example, cost data from R.S. Means is generally considered to be a bit high in absolute value by consulting engineers who frequently use R.S. Means data as a method of quick estimation for budgeting purposes. Using differences between the baseline and the advanced energy features costs, whether absolutely high or low, may result in costs that are more representative of the actual incremental cost seen in the industry.

Costs are developed for the baseline and the efficiency measures used in the building, and then the measure costs are summed to get the overall cost premium for the advanced building. The advanced costs for lighting and HVAC include added design, calibration, and commissioning costs. Table 6.1 summarizes the basis for estimating both the baseline and EEM costs.

Table 6.1. Cost Calculation Method Summary

Component	Cost Equation	Source
Roof Insulation	Area of roof times incremental cost/area of higher insulation value	RS Means Building Construction Cost Data 2009
Exterior Wall Insulation	Area of exterior wall times incremental cost/area of higher insulation value	RS Means Building Construction Cost Data 2009
Slab Insulation	Area of slab insulation times incremental cost/area of of higher insulation value	RS Means Building Construction Cost Data 2009
Cool Roof	Area of roof times incremental cost/area of higher insulation value	Cool Roof database information from 30% TSD for highway lodging
Sunshade Overhang	Overhang shading structure length times cost per unit length (no overhang in baseline)	RS Means Building Construction Cost Data 2009 - adjusted from basic metal building cost for higher end building
Windows and doors	Area of windows times incremental cost/area of window type based on U-factor	90.1 Envelope Committee supporting fenestration data
Interior Lighting	Incremental cost of lighting, controls and design	Seattle Lighting Lab - Michael Lane
Exterior Lighting	Incremental cost of exterior lighting, controls and design	Seattle Lighting Lab - Michael Lane
Plug Loads	Incremental cost of more efficient plug-in equipment, controls and software	On-line sources primarily EnergyStar.gov
Heat Pumps	Cost of advanced system minus cost of baseline system. Costs based on cost per ton (W), cfm (m^3/s) or ft^2 (m^2) as appropriate	RS Means Building Mechanical Cost Data 2009
Dedicated Outside Air	Added cost. No equivalent system in baseline	RS Means Building Mechanical Cost Data 2009
Service Water Heating	Cost per unit	On-line Sources vidavici.com, PEXSupply.com
VAV Alternative (all costs other than HVAC same as above)		
High Efficiency Packaged VAV with ERV, added controls, and indirect evaporative cooling for selected climates	Cost = Cost of advanced system minus cost of baseline system. Costs based on cost per ton (W), cfm (m^3/s) or ft^2 (m^2) as appropriate Rough estimate for controls based on assumed number of sensors and control points.	RS Means 2009

6.2 Cost Analysis – Advanced Heat Pump Package

For the advanced case, heat pumps are used. The analysis supports using split system or rooftop heat pumps depending on best available efficiency, first cost and other design considerations mentioned in Section 4.4.1. The cost estimate is based on rooftop heat pumps, which were found to be moderately more expensive than the split system heat pumps in RS Means, so the heat pump cost is conservative. This alternative includes the DOAS costs as well.

6.2.1 Incremental Costs

Incremental costs are calculated using the methodology described in Section 6.1. The incremental cost values are shown in Table 6.2. Values shown in red indicate that the costs for the line item in the advanced case are lower than for the baseline. For HVAC, the incremental costs are small as a result of reductions in cooling capacity from decreased loads. The reductions in cooling load are the result of greatly reduced lighting and plug loads, and building envelope improvements. Significant differences in costs for the different city locations also impact the results.

6.2.2 Unit Costs per Area

Another measure of cost is cost per unit of area. Armed with this information, designers and owners can quickly evaluate the estimated cost premiums for meeting the recommendations of the TSD. Within the design and construction community, the quick evaluation of cost premiums versus the expected cost per area may serve as a surrogate for cost effectiveness in many cases. Table 6.3 provides the per unit area cost premiums compared to the median baseline construction.

For offices, the 2009 version of R.S. Means Construction Cost Data (R.S. Means 2009) indicates that the median unit construction cost is $\$120/ft^2$ ($\$1290/m^2$) with a lower quartile value of $\$93/ft^2$ ($\$1000/m^2$) and an upper quartile value of $\$155.00/ft^2$ ($\$1670/m^2$). These values are for 1 to 4 story offices with a typical building size identified as 20,000 ft^2 (1,858 m^2), which matches the small office prototype area, so that costs do not have to be adjusted for size. For this analysis, median unit construction costs are chosen and are then adjusted for Means city cost indexes. Cost premiums are developed using the incremental costs for the energy savings measures in each climate zone. The national weighted-average cost premium is $\$4.28/ ft^2$ ($\$48.12/m^2$), or 3.6%.

Table 6.2. Incremental Costs

Component	1A Miami	2A Houston	2B Phoenix	3A Atlanta	3B-CA Los Angeles	3B-other Las Vegas	3C San Francisco	4A Baltimore	4B Albuquerque	4C Seattle	5A Chicago	5B Denver	6A Minneapolis	6B Helena	7 Duluth	8 Fairbanks
Roof Insulation	$4,000	$8,900	$8,900	$8,900	$8,900	$8,900	$8,900	$12,900	$12,900	$12,900	$12,900	$12,900	$12,900	$12,900	$16,900	$12,900
Exterior Wall Insulation	$9,751	$11,618	$11,618	$14,838	$14,838	$14,838	$5,087	$6,255	$6,255	$6,255	$8,196	$8,196	$6,328	$6,328	$4,977	$3,809
Cool Roof	$5,500	$5,500	$5,500	$5,500	$5,500	$5,500	$5,500									
Sunshade Overhang	$5,449	$5,449	$5,449	$5,449	$5,449	$5,449	$5,449	$5,449	$5,449	$5,449	$5,449	$5,449				
Windows	$17,953	$21,319	$25,597	$7,676	$7,676	$7,676	$25,597	$11,420	$11,420	$11,420	$21,461	$21,461	$21,461	$21,461	$22,531	$26,710
Interior Lighting	$6,210															
Exterior Lighting	($2,043)															
Plug Loads	$28,152															
Packaged Rooftop DX versus Heat Pumps with DOAS	$7,261	$4,468	($2,507)	$14,236	$2,651	$633	($1,718)	$11,911	$4,094	$12,342	$13,617	$4,152	$15,314	$11,136	$12,381	$12,692
Service Water Heater	$1,111															
Sub-total	$83,342	$90,684	$87,987	$90,028	$78,444	$76,426	$82,245	$81,364	$73,547	$81,795	$95,052	$85,587	$89,432	$85,254	$90,218	$89,541
Location Cost Index (RS Means 2009)	90%	88%	89%	90%	108%	106%	124%	93%	90%	104%	115%	95%	110%	90%	102%	121%
TOTAL	$75,258	$80,074	$78,309	$81,206	$84,955	$80,782	$101,820	$75,750	$66,045	$84,985	$109,214	$81,307	$98,196	$76,644	$92,383	$108,613

Table 6.3. Unit Cost Increase

Climate Zone	City	Incremental Cost	Unit Cost Increase, $/ft^2$	*$/m^2$*	Location Adjusted Baseline Median Unit Cost, $/ft^2$	*$/m^2$*	Advanced Unit Construction Cost, $/ft^2$	*$/m^2$*	Percentage of Unit Cost Increase Over Unit Median Baseline
1A	Miami	$75,258	$3.76	*$40.50*	$108	*$1,166*	$112	*$1,207*	3.5%
2A	Houston	$80,074	$4.00	*$43.10*	$106	*$1,141*	$110	*$1,184*	3.8%
2B	Phoenix	$78,309	$3.92	*$42.15*	$107	*$1,150*	$111	*$1,192*	3.7%
3A	Atlanta	$81,206	$4.06	*$43.70*	$108	*$1,165*	$112	*$1,209*	3.8%
3B	Los Angeles	$84,955	$4.25	*$45.72*	$130	*$1,399*	$134	*$1,445*	3.3%
3B	Las Vegas	$80,782	$4.04	*$43.48*	$127	*$1,365*	$131	*$1,409*	3.2%
3C	San Fran.	$101,820	$5.09	*$54.80*	$149	*$1,599*	$154	*$1,654*	3.4%
4A	Baltimore	$75,750	$3.79	*$40.77*	$112	*$1,203*	$116	*$1,243*	3.4%
4B	Albuquerque	$66,045	$3.30	*$35.54*	$108	*$1,160*	$111	*$1,195*	3.1%
4C	Seattle	$84,985	$4.25	*$45.74*	$125	*$1,342*	$129	*$1,388*	3.4%
5A	Chicago	$109,214	$5.46	*$58.78*	$138	*$1,484*	$143	*$1,543*	4.0%
5B	Denver	$81,307	$4.07	*$43.76*	$114	*$1,227*	$118	*$1,271*	3.6%
6A	Minneapolis	$98,196	$4.91	*$52.85*	$132	*$1,418*	$137	*$1,471*	3.7%
6B	Helena	$76,644	$3.83	*$41.25*	$108	*$1,161*	$112	*$1,202*	3.6%
7	Duluth	$92,383	$4.62	*$49.72*	$123	*$1,323*	$127	*$1,372*	3.8%
8	Fairbanks	$108,613	$5.43	*$58.46*	$146	*$1,567*	$151	*$1,625*	3.7%

6.2.3 Cost-Effectiveness

Cost effectiveness can also be considered by looking at simple payback period for the EEMs. Table 6.4 shows simple payback values varying from 5.3 to 9.6 years, with a national weighted-average of 6.8 years. The variability in payback results from multiple factors such as differing energy costs savings, reductions in cooling capacity, differences in the RS Means cost factor for different locations and step changes in component performance such as insulation value and cost. The simple payback for each climate zone is calculated by dividing the total incremental cost of the measures by the energy savings in dollars. The energy cost savings calculation is documented in Section 5.2.

Table 6.4. Simple Payback Period

Climate Zone	City	Incremental Cost	Energy Cost Savings			Simple Payback (Years)
			Electricity	Natural Gas	Total	
1A	Miami	$75,258	$12,469	$79	$12,548	6.0
2A	Houston	$80,074	$10,813	$1,984	$12,797	6.3
2B	Phoenix	$78,309	$13,482	$1,007	$14,489	5.4
3A	Atlanta	$81,206	$8,966	$2,355	$11,320	7.2
3B	Los Angeles	$84,955	$9,887	$248	$10,135	8.4
3B	Las Vegas	$80,782	$11,465	$960	$12,426	6.5
3C	San Fran.	$101,820	$9,116	$1,497	$10,612	9.6
4A	Baltimore	$75,750	$8,869	$3,987	$12,856	5.9
4B	Albuquerque	$66,045	$10,228	$2,240	$12,468	5.3
4C	Seattle	$84,985	$8,553	$3,243	$11,796	7.2
5A	Chicago	$109,214	$7,803	$5,948	$13,750	7.9
5B	Denver	$81,307	$9,262	$3,464	$12,726	6.4
6A	Minneapolis	$98,196	$6,230	$7,786	$14,016	7.0
6B	Helena	$76,644	$7,508	$5,324	$12,832	6.0
7	Duluth	$92,383	$8,651	$7,250	$15,901	5.8
8	Fairbanks	$108,613	$7,855	$8,123	$15,979	6.8

6.3 Cost Analysis – Alternative VAV Package

The alternative VAV package is also analyzed for cost effectiveness. Other analyzed elements of the package of measures are the same as for the heat pump case. The VAV system alternative costs less than the heat pump plus DOAS case, but does not achieve as much energy savings. The energy costs savings for the VAV alternative are in Table 5.14.

Incremental costs are calculated using the methodology described in Section 6.1. The incremental costs are summarized in Table 6.5. Reductions in HVAC cost are achieved by replacing 10 systems with 1 system and by reductions in cooling capacity resulting from decreased cooling loads from other EEMs. Significant differences in costs for the different city locations also impact the results.

Unit costs per area are found for the VAV case, as show in Table 6.6, following the same procedure described in Section 6.2.2. The national weighted average cost premium is \$4.28/ ft^2 (\$46.03/m^2), or 3.6%.

Simple payback is determined by the same methodology as described in Section 6.1.3. Table 6.7 shows that simple payback values vary from 6.2 to 11 years, with a national weighted average of 8.6 years using the construction area weights defined in Section 2.3.

Table 6.5. Incremental Costs - VAV

Component	1A	2A	2B	3A	3B-CA	3B-other	3C	4A	4B	4C	5A	5B	6A	6B	7	8
	Miami	Houston	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Roof Insulation	$4,000	$8,900	$8,900	$8,900	$8,900	$8,900	$8,900	$12,900	$12,900	$12,900	$12,900	$12,900	$12,900	$12,900	$16,900	$12,900
Exterior Wall Insulation	$9,751	$11,618	$11,618	$14,838	$14,838	$14,838	$5,087	$6,255	$6,255	$6,255	$8,196	$8,196	$6,328	$6,328	$4,977	$3,809
Cool Roof	$5,500	$5,500	$5,500	$5,500	$5,500	$5,500	$5,500									
Sunshade Overhang	$5,449	$5,449	$5,449	$5,449	$5,449	$5,449	$5,449	$5,449	$5,449	$5,449	$5,449	$5,449				
Windows & doors	$17,953	$21,319	$25,597	$7,676	$7,676	$7,676	$25,597	$11,420	$11,420	$11,420	$21,461	$21,461	$21,461	$21,461	$22,531	$26,710
Interior Lighting	$6,210															
Exterior Lighting	($2,043)															
Plug Loads	$28,152															
Packaged CAV versus Packaged VAV with Energy Recovery	$9,921	$4,847	($495)	$14,383	$1,305	$11,615	($6,833)	$13,939	$2,636	($1,149)	$11,496	$1,445	$14,938	$6,441	$2,869	($110)
Service Water Heater	$1,111															
Sub-total	$86,003	$91,063	$89,999	$90,176	$77,098	$87,407	$77,131	$83,392	$72,089	$68,304	$92,931	$82,880	$89,056	$80,560	$80,706	$76,739
Location Cost Index (RS Means 2009)	90%	88%	89%	90%	108%	106%	124%	93%	90%	104%	115%	95%	110%	90%	102%	121%
TOTAL	$77,660	$80,408	$80,099	$81,338	$83,497	$92,389	$95,488	$77,638	$64,736	$70,968	$106,778	$78,736	$97,784	$72,423	$82,643	$93,084

Table 6.6. Unit Cost Increase - VAV

Climate Zone	City	Incremental Cost	Unit Cost Increase, $/ft^2	*$/m^2*	Location Adjusted Baseline Median Unit Cost, $/ft^2	*$/m^2*	Advanced Unit Construction Cost, $/ft^2	*$/m^2*	Percentage of Unit Cost Increase Over Unit Median Baseline
1A	Miami	$77,660	$3.88	*$41.80*	$108	*$1,166*	$112	*$1,208*	3.6%
2A	Houston	$80,408	$4.02	*$43.28*	$106	*$1,141*	$110	*$1,184*	3.8%
2B	Phoenix	$80,099	$4.00	*$43.11*	$107	*$1,150*	$111	*$1,193*	3.7%
3A	Atlanta	$81,338	$4.07	*$43.78*	$108	*$1,165*	$112	*$1,209*	3.8%
3B	Los Angeles	$83,497	$4.17	*$44.94*	$130	*$1,399*	$134	*$1,444*	3.2%
3B	Las Vegas	$92,389	$4.62	*$49.72*	$127	*$1,365*	$131	*$1,415*	3.6%
3C	San Fran.	$95,488	$4.77	*$51.39*	$149	*$1,599*	$153	*$1,650*	3.2%
4A	Baltimore	$77,638	$3.88	*$41.78*	$112	*$1,203*	$116	*$1,244*	3.5%
4B	Albuquerque	$64,736	$3.24	*$34.84*	$108	*$1,160*	$111	*$1,195*	3.0%
4C	Seattle	$70,968	$3.55	*$38.19*	$125	*$1,342*	$128	*$1,380*	2.8%
5A	Chicago	$106,778	$5.34	*$57.47*	$138	*$1,484*	$143	*$1,542*	3.9%
5B	Denver	$78,736	$3.94	*$42.38*	$114	*$1,227*	$118	*$1,269*	3.5%
6A	Minneapolis	$97,784	$4.89	*$52.63*	$132	*$1,418*	$137	*$1,471*	3.7%
6B	Helena	$72,423	$3.62	*$38.98*	$108	*$1,161*	$112	*$1,200*	3.4%
7	Duluth	$82,643	$4.13	*$44.48*	$123	*$1,323*	$127	*$1,367*	3.4%
8	Fairbanks	$93,084	$4.65	*$50.10*	$146	*$1,567*	$150	*$1,617*	3.2%

Table 6.7. Simple Payback Period - VAV

Climate Zone	City	Incremental Cost	Energy Cost Savings			Simple Payback (Years)
			Electricity	Natural Gas	Total	
1A	Miami	$77,660	$10,352	$78	$10,430	7.4
2A	Houston	$80,408	$8,401	$1,964	$10,365	7.8
2B	Phoenix	$80,099	$11,948	$1,035	$12,983	6.2
3A	Atlanta	$81,338	$6,613	$2,208	$8,821	9.2
3B	Los Angeles	$83,497	$7,675	$272	$7,947	10.5
3B	Las Vegas	$92,389	$9,198	$1,039	$10,237	9.0
3C	San Fran.	$95,488	$7,113	$1,537	$8,649	11.0
4A	Baltimore	$77,638	$5,717	$4,202	$9,919	7.8
4B	Albuquerque	$64,736	$7,832	$2,380	$10,212	6.3
4C	Seattle	$70,968	$5,574	$3,369	$8,943	7.9
5A	Chicago	$106,778	$4,304	$6,170	$10,474	10.2
5B	Denver	$78,736	$6,823	$3,693	$10,517	7.5
6A	Minneapolis	$97,784	$2,897	$8,329	$11,226	8.7
6B	Helena	$72,423	$4,734	$5,702	$10,436	6.9
7	Duluth	$82,643	$1,879	$10,147	$12,026	6.9
8	Fairbanks	$93,084	$1,452	$12,104	$13,556	6.9

6.4 A Perspective on Costs for Advanced Buildings

As the interest in high-performance buildings grows, so does the desire to understand the real costs of associated energy efficiency measures. Any effort such as the one included in this document is inevitably faced with the challenges of finding credible sources of cost data, particularly when some of the more advanced EEMs are being considered. The sources for cost information include widely published data, i.e., R.S. Means, engineering consulting firm and contractor budget estimates, code development sources such as the SSPC 90.1 Cost database or data found on websites and in testimonials. Clearly it would be desirable to have more robust costs for all measures. Unfortunately cost information is not consistently available with the same degree of accuracy. When confronted with conflicting or ambiguous costs, the general approach is to take the conservative view of not underestimating the costs such that the exercise would yield an inflated assessment of the cost-effectiveness of the EEMs. Conversely, every effort is made to not unduly burden the analysis with costs that are systematically too high, thus biasing the results against undertaking these advanced energy design projects.

This study scope does not include more detailed financial analysis. Simple payback is a limited measure of cost effectiveness and does not account for other operating costs such as maintenance, or for other factors, such as energy price escalation. The result of the cost analysis done in this study is a reasonable estimate of simple payback values for the advanced energy measure packages in the 16 locations, showing that the packages do not create an unreasonably high economic burden in pursuing the 50% energy savings goal.

7.0 Future Work

This Technical Support Document (TSD) is a DOE-supported national laboratory publication that describes the assumptions, methodologies, and analyses used to achieve high levels of energy performance. DOE is also supporting the development of a *50% Advanced Energy Design Guide (AEDG) for Small to Medium Office Buildings*. The *50% AEDGs* will be the publications targetted at architects, engineers, and other design practitioners. They will provide specific guidance on how to achieve high levels of whole-building energy performance in new construction, such as 50% savings relative to the ASHRAE Standard 90.1-2004.

After publication of this TSD, the *50% AEDG for Small to Medium Offices* project committee will be convened, representing ASHRAE, USGBC, IES, AIA and DOE. The committee members will review this TSD and a sister 50% TSD for Medium Office that PNNL published in September 2009. These two TSDs will be used at a starting point to inform the development of the *50% AEDG*. PNNL may conduct additional analyses depending on the project committee's reviews. Examples of additional analyses could include recommended design packages that provided additional climate-specific HVAC systems or changes of the building forms and oritentaion to feature the passive solar designs.

7.1 Purpose and Goals

The small and medium office *AEDG* or future TSD work that goes beyond 50% savings could be expanded to consider more than just onsite energy savings above a certain target for entire packages of energy measures.

- Consider the long-term performance differences between the baseline and advanced options, and maintenance and operations of energy measures including impacts on cost effectiveness.
- More directly address energy efficiency's impact on global climate change by determining source energy changes in addition to site energy and report on the impact of the EEMs on carbon emissions.
- Provide a deeper understanding of the trade-offs between EEMs by expanding the scope of the analysis to allow evaluation of individual energy measures and to determine the marginal benefit and cost of each measure in various combinations of measures.

7.2 Additional Potential Energy Efficiency Measures

Although the *TSD* has proposed a package of EEMs to achieve the 50% onsite energy savings goal, other potential EEMs are worth considering and some already evaluated could be further refined. The new and refined measures have the potential to achieve the 50% goal in a more cost-effective manner or to achieve even more onsite energy savings. The *50% AEDG for Small to Medium Offices*, or future work that goes beyond 50% savings, may provide an opportunity to consider some of these alternatives.

- Building form and orientation. Determine the range of savings for different configurations including options for more constrained sites.
- Passive solar design. Use of thermal mass, solar chimneys etc.

- Acive solar and solar electricity. Potential renewable energy technologies that could be cost effective in the short term include solar thermal energy for tempering ventilation air and domestic hot water use. Photovoltaics will be part of reaching for the net zero goal but currently depend on large subsidies to be cost-effective.
- Enhanced daylight harvesting measures. Investigate most cost-effective ways to provide toplighting. Simulate optimized daylighting with components such as light shelves and baffles.
- Window shading. Consider advanced window shading measures for better control of cooling loads while supporting daylighting. Examples include fins, electrochromic glazing and motorized blinds/shades. Measures that allow shading to vary seasonally or in response to the level of solar gains would be especially worthwhile for consideration in climates with both hot summers and cold winters.
- Window area. Investigate optimal window areas for the combined impact on heating, cooling and daylighting.
- HVAC occupancy controls. Provide occupancy sensor control of HVAC setpoints and terminal unit damper positions.
- Expanded economizer. For some climate zones with good opportunities for use of air-side economizers, consider allowing the outside air systems to bring in more outside air to allow more economizer benefit. This would mean increasing the fan system and duct sizes of a DOAS system. The trade-offs for enlarging air-side economizer opportunities with increased size and cost of the ventilation system could be analyzed. Alternatively, with radiant systems, water-side economizers could be used with the addition of fluid coolers or cooling towers to the design.
- Alternative radiant/convective systems. Systems for office buildings include chilled ceiling panels, chilled beam, radiant floors and perimeter fin tubes for heating. Determine if reasonable opportunities exist for smaller buildings incorporating chillers and boilers.
- Active thermal storage for higher temperature chilled water. For some climate zones with large diurnal temperature changes, it may be an effective energy measure to generate and store cooled water using a cooling tower at night. The cooled water can then be used in daytime for higher temperature cooling systems such as radiant panels.

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Appendix A

Energy Modeling Inputs

Table A.1.a. Baseline and Advanced Model Inputs for Small Office Building IP units

Characteristic	Baseline	Advanced-Heat Pump with DOAS	Data Source/Remarks
ARCHITECTURAL FEATURES			
Exterior Walls			
Construction	Mass wall - 8-in. concrete block wall - insulation - 0.5-in. gypsum board	Same as baseline	CBECS 2003
Overall U-factor (Btu/h·ft²·F)	Zones 1-2: 0.58 Zones 3-4: 0.151 Zone 5: 0.123 Zone 6: 0.104 Zone 7: 0.090 Zone 8: 0.080	Zone 1: 0.151 Zone 2: 0.123 Zone 3: 0.09 Zone 4: 0.08 Zones 5-8: 0.047	ASHRAE 90.1-2004 Addendum bb to ASHRAE 90.1-2007 (review draft)
Roof			
Construction	Flat roof with insulation entirely above deck - roof membrane - continuous rigid insulation - metal deck	Same as baseline	CBECS 2003
Overall U-factor (Btu/h·ft²·F)	Zones 1-7: 0.063 Zone 8: 0.048	Zone 1: 0.048 Zones 2- 3: 0.039 Zones 4-6: 0.032 Zones 7-8: 0.028	ASHRAE 90.1-2004 Addendum bb to ASHRAE 90.1-2007 (review draft)
Solar Reflectance	0.23	Zones 1-3: 0.69 (white EPDM) Zones 4-8: 0.23	LBNL 2009: http://eetd.lbl.gov/coolroofs/
Slab-on-Grade Floor			
Construction	Concrete slab on earth - carpet pad - 8-in. concrete	Same as baseline	ASHRAE 90.1-2004
Floor F-factor (Btu/h·ft·F)	Zones 1-7: 0.730 Zone 8: 0.540	Zones 1-5: 0.730 Zone 6-7: 0.540 Zones 8: 0.520	ASHRAE 90.1-2004 Addendum bb to ASHRAE 90.1-2007 (review draft)
Fenestration			
Window wall ratio	0.20 for all facades	0.20 for all facades	CBECS 2003

Table A.1.a. IP units (continued)

Characteristic	Baseline	Advanced-Heat Pump with DOAS	Data Source/Remarks
Fenestration			
Targeted U-factor/SHGC/ and VT for advanced	Zones 1-2: 1.22/0.25 Zones 3A, 3B: 0.57/0.25 Zone 3C: 1.22/0.39 Zones 4-6: 0.57/0.39 Zone 7: 0.57/0.49 Zone 8: 0.46/0.45	Zone 1: 0.56/0.25/0.25 Zone 2: 0.45/0.25/0.25 Zone 3A,3B: 0.41/0.25/0.32 Zone 3C: 0.41/0.25/0.25 Zone 4: 0.38/0.26/0.33 Zone 5: 0.35/0.26/0.33 Zone 6: 0.35/0.35/0.44 Zone 7: 0.33/0.40/0.40 Zone 8: 0.25/0.40/0.40	ASHRAE 90.1-2004 Addendum bb to ASHRAE 90.1-2007 (review draft)
Actual selected window U-factor/SHGC/ and VT for advanced	Zones 1-2: 1.21/0.25 Zones 3A, 3B: 0.57/0.25 Zone 3C: 1.21/0.39 Zones 4-6: 0.57/0.39 Zone 7: 0.57/0.49 Zone 8: 0.45/0.45	Zone 1: 0.57/0.25/0.25 Zone 2: 0.44/0.22/0.31 Zones 3A,3B: 0.39/0.26/0.32 Zone 3C: 0.40/0.21/0.32 Zone 4: 0.40/0.26/0.34 Zone 5: 0.34/0.26/0.34 Zone 6: 0.35/0.35/0.44 Zone 7: 0.32/0.36/0.38 Zone 8: 0.25/0.35/0.44	Window type chosen from *EnergyPlus* Library with the closest matching U-factor/SHGC
Exterior shading	No	South Windows	AEDG 30pct guides (e.g., Jarnagin et al., 2006)
INTERNAL LOADS			
Occupancy			
People	88	88	Section 3.6.1
Schedule	See Table A.2	Same as baseline	
Radiant/Convective fractions of sensible loads	0.3/0.7	0.3/0.7	ASHRAE Fundamentals Handbook
Lighting			
Peak lighting power density (W/ft^2)	1.0	0.79	ASHRAE 90.1-2004 Lighting design and calculation (see *TSD* Section 4.2)
Occupancy sensors	No	Yes	
Daylight harvesting	No	- Continuous dimming - Illuminance setpoint: 30 foot candles - Minimum input power	

Table A.1.a. IP units (continued)

Characteristic	Baseline	Advanced-Heat Pump with DOAS	Data Source/Remarks
		fraction: 0.1 - Minimum light output fraction: 0.1	
Schedule	See Table A.2	See Table A.3	
Plug load			
Peak plug-load power density (W/ft^2)	0.75	0.56	Section 4.3
Schedule	See Table A.2	See Table A.3	
HVAC SYSTEM			
System type			
Heating/ Cooling	Packaged single zone CAV system - DX packaged air conditioning unit for cooling - gas furnace for heating	Split air-source heat pump + DOAS - Air-source heat pump system for major heating/cooling load - Zone electric resistance -for supplemental heating - Dedicated outdoor air system provide ventilation and secondary cooling	CBECS 2003
HVAC efficiency			
Cooling efficiency	DX cooling coil - EER=9.0-10.1, depending on the sized capacity - performance curves see Table A.4	Air-source heat pump - COP=3.8-4.3, depending on the sized capacity - Heat pump cooling performance curves see Table A.5 DX coil in the DOAS unit - EER=11.0 or 13.5, depending on the sized capacity - DOAS DX performance curves see Table A.6	ASHRAE 90.1-2004 ASHRAE 90.1-2007 Appliances database of California Energy Commission. Manufacturers' Catalog
Heating efficiency	Gas furnace - burner efficiency =0.78 (capacity<=225 kBtu/h); =0.80 (capacity>225 kBtu/h) - part load performance curve see Table A.7	Heat pump with electric resistance heating as backup Heat pump heating efficiency depending on the sized capacity	ASHRAE 90.1-2004 ASHRAE 90.1-2007
HVAC control			
Thermostat setpoint (°F)	75 cooling/ 70 heating	75 cooling/ 70 heating	Design practice

Table A.1.a. IP units (continued)

Characteristic	Baseline	Advanced-Heat Pump with DOAS	Data Source/Remarks
Thermostat setup / setback (°F)	80 cooling / 65 heating	80 cooling / 65 heating	Design practice
Air system	- Supply air temperature: 55°F minimum	- DOAS - Supply air temperature: 55°F (12.8°C) for climate zones 1A, 2A, and 3A - Supply air temperature: 68°F (20°C) for climate zones 3B, 4B, 5B and 6B - Supply air temperature reset based on outside air temperature for all other climate zones	
Ventilation			
Energy recovery	No	- Rotary heat exchanger is used for energy recovery in all climate zones - Heat recovery effectiveness see Table 4.13 - Frost control initiated when the outdoor air temperature is less than 10°F, (-12°C)	
Economizer	No economizer except the core zone on the 2nd floor in climate zones 3B, 3C, 4B, 4C, 5B and 6B.	No economizer	ASHRAE 90.1-2004
Fan System			
Supply fan	- Constant speed fan - Fan mechanical efficiency: 55% - Fan motor efficiency based on motor power from STD 90.1-2004.	- Constant speed fan for the DOAS - Fan mechanical efficiency: 65% - Fan motor efficiency based on motor power	
Exhaust/return fan	Not explicitly modeled.	Same as baseline	
Fan system static pressure	1.8 in. w.c	- 1.93 in. w.c. for the DOAS; 1.74 in. w.c. for the heat pump - Additional 1.5 in w.c pressure drop for ERV (0.85 in. w.c. on the supply side and 0.65 in. w.c. on the exhaust side).	See TSD Section 3.7 and 4.4
SHW System			

Table A.1.a. IP units (continued)

Characteristic	Baseline	Advanced-Heat Pump with DOAS	Data Source/Remarks
Gas-fired water heater	- Conventional type with thermal efficiency = 80% - Tank volume = 75 gallon - Standby heat loss coefficient = 12 Btu/h-°F	- Condensing water heater with thermal efficiency = 90%. - Tank volume = 75 gallon - Standby heat loss coefficient = 12 Btu/h-°F	ASHRAE 90.1-2004 Manufacturers' Catalog

Table A.1.b. Baseline and Advanced Model Inputs for Small Office Building SI units

Characteristic	Baseline	Advanced-Heat Pump with DOAS	Data Source/Remarks
ARCHITECTURAL FEATURES			
Exterior Walls			
Construction	Mass wall - 200 mm concrete block wall - insulation - 13mm gypsum board	Same as baseline	CBECS 2003
Overall U-factor ($W/m^2{\cdot}K$)	Zones 1-2: 3.29 Zones 3-4: 0.857 Zone 5: 0.698 Zone 6: 0.591 Zone 7: 0.511 Zone 8: 0.454	Zone 1: 0.857 Zone 2: 0.698 Zone 3: 0.511 Zone 4: 0.454 Zones 5-8: 0.267	ASHRAE 90.1-2004 Addendum bb to ASHRAE 90.1-2007 (review draft)
Roof			
Construction	Flat roof with insulation entirely above deck - roof membrane - continuous rigid insulation - metal deck -	Same as baseline	CBECS 2003
Overall U-factor ($W/m^2{\cdot}K$)	Zones 1-7: 0.358 Zone 8: 0.273	Zone 1: 0.273 Zones 2- 3: 0.221 Zones 4-6: 0.182 Zones 7-8: 0.159	ASHRAE 90.1-2004 Addendum bb to ASHRAE 90.1-2007 (review draft)
Solar Reflectance	0.23	Zones 1-3: 0.69 (white EPDM) Zones 4-8: 0.23	LBNL 2009: http://eetd.lbl.gov/coolroofs/
Slab-on-Grade Floor			
Construction	Concrete slab on earth - carpet pad - 200mm concrete	Same as baseline	ASHRAE 90.1-2004
Floor F-factor ($W/m{\cdot}K$)	Zones 1-7: 1.264 Zone 8: 0.935	Zones 1-5: 1.264 Zone 6-7: 0.935 Zones 7-8: 0.900	ASHRAE 90.1-2004 Addendum bb to ASHRAE 90.1-2007 (review draft)
Fenestration			
Window wall ratio	0.20 for all facades	0.20 for all facades	CBECS 2003

Table A.1.b. SI units (continued)

Characteristic	Baseline	Advanced-Heat Pump with DOAS	Data Source/Remarks
Targeted U-factor/SHGC/ and VT for advanced	Zones 1-2: 6.9275/0.25 Zones 3A, 3B: 3.2366/0.25 Zone 3C: 6.9275/0.39 Zones 4-6: 3.2366/0.39 Zones 4-6: 3.2366/0.49 Zone 8: 2.612/0.45	Zone 1: 3.1798/0.25/0.25 Zone 2: 2.5552/0.25/0.25 Zone 3A,3B: 2.328/0.25/0.32 Zone 3C: 2.3281/0.25/0.25 Zone 4: 2.1577/0.26/0.33 Zone 5: 1.9874/0.26/0.33 Zone 6: 1.9874/0.35/0.44 Zone 7: 1.8738/0.40/0.40 Zone 8: 1.4196/0.40/0.40	ASHRAE 90.1-2004 Addendum bb to ASHRAE 90.1-2007 (review draft)
Actual selected window U-factor/SHGC/ and VT for advanced	Zones 1-2: 6.878/0.25 Zones 3A, 3B: 3.237/0.25 Zone 3C: 6.878/0.39 Zones 4-6: 3.237/0.39 Zone 7: 3.237/0.49 Zone 8: 2.555/0.45	Zone 1: 3.237/0.25/0.25 Zone 2: 2.499/0.22/0.31 Zones 3A,3B: 2.21/0.26/0.32 Zone 3C: 2.271/0.21/0.32 Zone 4: 2.271/0.26/0.34 Zone 5: 1.93/0.26/0.34 Zone 6: 1.99/0.35/0.44 Zone 7: 1.817/0.36/0.38 Zone 8: 1.42/0.35/0.44	Window type chosen from *EnergyPlus* Library with the closest matching U-factor/SHGC
Exterior shading	No	South Windows	AEDG 30 pct guides (e.g., Jarnagin et al., 2006)
INTERNAL LOADS			
Occupancy			
People	88	88	Section 3.6.1
Schedule	See Table A.2	Same as baseline	
Radiant/Convective fractions of sensible loads	0.3/0.7	0.3/0.7	ASHRAE Fundamentals Handbook
Lighting			
Peak lighting power density (W/m^2)	10.77	8.50	ASHRAE 90.1-2004 Lighting design and calculation (see *TSD* Section 4.2)
Occupancy sensors	No	Yes	
Daylight harvesting	No	- Continuous dimming - Illuminance setpoint: 300 lux - Minimum input power fraction: 0.1	

Table A.1.b. SI units (continued)

Characteristic	Baseline	Advanced-Heat Pump with DOAS	Data Source/Remarks
		- Minimum light output fraction: 0.1	
Schedule	See Table A.2	See Table A.3	
Plug load			
Peak plug-load power density (W/m^2)	8.07	6.03	Section 4.3
Schedule	See Table A.2	See Table A.3	
HVAC SYSTEM			
System type			
Heating/Cooling	Packaged CAV system - DX packaged air conditioning unit for cooling - gas furnace for heating	Split air-source heat pump + DOAS - Air-source heat pump system for major heating/cooling load - Zone electric resistance -for supplemental heating - Dedicated outdoor air system provide high indoor air quality	CBECS 2003
HVAC efficiency			
Cooling efficiency	DX cooling coil - EER=9.0-10.1, depending on the sized capacity - performance curves see Table A.4	Air-source heat pump - COP=3.8~4.3, depending on the sized capacity - Heat pump cooling performance curves see Table A.5 DX coil in the DOAS unit - EER=11.0 or 13.5, depending on the sized capacity - DOAS DX performance curves see Table A.6	ASHRAE 90.1-2004 ASHRAE 90.1-2007 Appliances database of California Energy Commission. Manufacturers' Catalog
Heating efficiency	Gas furnace - burner efficiency =0.78 (capacity<=6,5943 W); =0.80 (capacity>6,5943 W) - part load performance curve see Table A.7	Heat Pump with electric resistance as heating backup	ASHRAE 90.1-2004 ASHRAE 90.1-2007
HVAC control			
Thermostat setpoint (°C)	24 cooling/ 21 heating	24 cooling/ 21 heating	Design practice
Thermostat setup / setback (°C)	26.6 cooling / 18.3 heating	26.6 cooling / 18.3 heating	Design practice
Air system	- Supply air temperature: 12.8°C	- DOAS Supply air temperature: 12.8°C for	

Table A.1.b. SI units (continued)

Characteristic	Baseline	Advanced-Heat Pump with DOAS	Data Source/Remarks
		climate zones 1A, 2A, and 3A - Supply air temperature: 20°C for 3B, 4B, 5B, and 6B - Supply air temperature reset based on outside air temperature for all other climate zones	
Ventilation			
Energy recovery	No	- Rotary heat exchanger is used for energy recovery in all climate zones - Heat recovery effectiveness see Table 4.13 - Frost control initiated when the outdoor air temperature is less than -23°C	
Economizer	No economizer except the core zone on the 2nd floor in climate zones 3B, 3C, 4B, 4C, 5B and 6B.	No economizer	ASHRAE 90.1-2004
Fan System			
Supply fan	- Constant speed fan - Fan mechanical efficiency: 55% - Fan motor efficiency based on motor power from STD 90.1-2004	- Constant speed fan for the DOAS - Fan mechanical efficiency: 65% - Fan motor efficiency based on motor power (See Table 4.14)	
Exhaust/return fan	Not explicitly modeled.	Same as baseline	
Fan system static pressure	450 Pa	- 482 Pa for the DOAS; 435 Pa for the heat pump Additional 370 Pa pressure drop for ERV (210 Pa on the supply side and 160 Pa on the exhaust side)	Derived from fan power limitation in ASHRAE 90.1-2004
SHW System			
Gas-fired water heater	- Conventional type with thermal efficiency = 80% - Tank volume = 75 gallon - Standby heat loss coefficient = 6.32 W/K	- Condensing water heater with thermal efficiency = 90%. - Tank volume = 75 gallon - Standby heat loss coefficient = 6.32 W/K	ASHRAE 90.1-2004 Manufacturers' Catalog

Table A.2. Major Schedules for the Baseline Model

Schedule	Day Type	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Internal Loads Schedules																									
Lighting (Fraction)	WD	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.3	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.5	0.3	0.3	0.2	0.2	0.15	0.15
	Sat	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Sun, Hol	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Plug load (Fraction)	WD	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.8	0.8	0.8	0.8	0.65	0.8	0.8	0.8	0.8	0.35	0.3	0.3	0.3	0.3	0.3	0.3
	Sat	0.2	0.2	0.2	0.2	0.2	0.2	0.25	0.25	0.3	0.3	0.3	0.3	0.25	0.25	0.25	0.25	0.25	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	Sun, Hol	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Occupancy (Fraction)	WD	0	0	0	0	0	0	0.1	0.2	0.95	0.95	0.95	0.95	0.5	0.95	0.95	0.95	0.95	0.3	0.1	0.1	0.1	0.1	0.05	0.05
	Sat	0	0	0	0	0	0	0.1	0.1	0.3	0.3	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.05	0.05	0	0	0	0	0
	Sun, Hol	0	0	0	0	0	0	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0	0	0	0	0	0
Service Hot Water Schedule																									
Hot water (Fraction)	WD	0	0	0	0	0	0.06	0.04	0.27	0.58	0.63	0.65	0.81	1	0.94	0.56	0.54	0.75	0.40	0.31	0.19	0.23	0.06	0	0
	Sat	0	0	0	0	0	0.06	0.04	0.13	0.21	0.34	0.30	0.38	0.32	0.30	0.21	0.15	0.19	0.04	0.04	0.04	0.04	0.09	0	0
	Sun, Hol	0	0	0	0	0	0.06	0	0	0	0	0	0.04	0.04	0.11	0.04	0	0	0	0	0	0	0.06	0	0
HVAC Schedules																									
HVAC system (on/off)	WD	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
	Sat	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
	Sun, Hol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Heating setpoint (ºF)	WD	65	65	65	65	65	66	67	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	65	65
	Sat	65	65	65	65	65	66	67	70	70	70	70	70	70	70	70	70	70	70	65	65	65	65	65	65
	Sun, Hol	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65
Cooling setpoint (ºF)	WD	80	80	80	80	80	78	77	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	80	80
	Sat	80	80	80	80	80	78	77	75	75	75	75	75	75	75	75	75	75	75	80	80	80	80	80	80
	Sun, Hol	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80

Table A.3. Major Schedules for the Advanced Model

Schedule	Day Type	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Internal Loads Schedules																									
Lighting (Fraction)	WD	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.747	0.747	0.747	0.747	0.747	0.747	0.747	0.747	0.747	0.5	0.3	0.3	0.2	0.2	0.1	0.1
	Sat	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Sun, Hol	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Plug load (Fraction)	WD	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.8	0.8	0.8	0.8	0.65	0.8	0.8	0.8	0.8	0.35	0.3	0.3	0.3	0.3	0.3	0.3
	Sat	0.2	0.2	0.2	0.2	0.2	0.2	0.25	0.25	0.3	0.3	0.3	0.3	0.25	0.25	0.25	0.25	0.25	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	Sun, Hol	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Occupancy (Fraction)	WD	0	0	0	0	0	0	0.1	0.2	0.95	0.95	0.95	0.95	0.5	0.95	0.95	0.95	0.95	0.3	0.1	0.1	0.1	0.1	0.05	0.05
	Sat	0	0	0	0	0	0	0.1	0.1	0.3	0.3	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.05	0.05	0	0	0	0	0
	Sun, Hol	0	0	0	0	0	0	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0	0	0	0	0	0
Service Hot Water Schedule																									
Hot water (Fraction)	WD	0	0	0	0	0	0.06	0.04	0.27	0.58	0.63	0.65	0.81	1	0.94	0.56	0.54	0.75	0.40	0.31	0.19	0.23	0.06	0	0
	Sat	0	0	0	0	0	0.06	0.04	0.13	0.21	0.34	0.30	0.38	0.32	0.30	0.21	0.15	0.19	0.04	0.04	0.04	0.04	0.09	0	0
	Sun, Hol	0	0	0	0	0	0.06	0	0	0	0	0	0.04	0.04	0.11	0.04	0	0	0	0	0	0	0.06	0	0
HVAC Schedules																									
HVAC	WD	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
	Sat	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
	Sun, Hol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Heating setpoint (ºF)	WD	65	65	65	65	65	66	67	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	65	65
	Sat	65	65	65	65	65	66	67	70	70	70	70	70	70	70	70	70	70	70	65	65	65	65	65	65
	Sun, Hol	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65
Cooling setpoint (ºF)	WD	80	80	80	80	80	78	77	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	80	80
	Sat	80	80	80	80	80	78	77	75	75	75	75	75	75	75	75	75	75	75	80	80	80	80	80	80
	Sun, Hol	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80

Table A.4. Performance Curves for the DX Coils Used in the Packaged CAV System

curve name	coefficients a	b	c	d	e	f
Total cooling capacity modifier function of temperature $Cap(T_{wb,i},T_{c,i}) = a + b(T_{wb,i}) + c(T_{wb,i})^2 + d(T_{c,i}) + e(T_{c,i})^2 + f(T_{wb,i})(T_{c,i})$	0.8679	0.0142	0.0055	-0.0076	0.000033	-0.00019
Total cooling capacity modifier function of flow fraction $Cap(ff) = a + b(ff) + c(ff)^2$	0.8	0.2	0	-	-	-
EIR modifier function of temperature $EIR(T_{wb,i},T_{c,i}) = a + b(T_{wb,i}) + c(T_{wb,i})^2 + d(T_{c,i}) + e(T_{c,i})^2 + f(T_{wb,i})(T_{c,i})$	0.1170	-0.0285	-0.00041	0.02141	0.00016	-0.00068
EIR modifier function of flow fraction $EIR(ff) = a + b(ff) + c(ff)^2$	1.1552	-0.1808	0.0256	-	-	-
Part load correction function $PLF(PLR) = a + b(PLR) + c(PLR)^2$	0.85	0.15	0	-	-	-

$T_{wb,i}$ – wet-bulb temperature of the air entering the cooling coil (ºC)

$T_{c,i}$ – dry-bulb temperature of the air entering the air-cooled condenser (ºC)

ff – the ratio of the actual airflow rate across the cooling coil to the rated air flow rate

PLR – part load ratio (the ratio between actual sensible cooling load and the rated sensible load)

Table A.5. Performance Curves for the DX Coils Used in the Air-source Heat Pump System

curve name	coefficients					
	a	b	c	d	e	f
Total cooling capacity modifier function of temperature $Cap(T_{wb,i},T_{c,i}) = a + b(T_{wb,i}) + c(T_{wb,i})^2 + d(T_{c,i}) + e(T_{c,i})^2 + f(T_{wb,i})(T_{c,i})$	0.7670	0.0108	-0.00004	0.00135	-0.00026	0.00046
Total cooling capacity modifier function of flow fraction $Cap(ff) = a + b(ff) + c(ff)^2 + d(ff)^3$	0.75875	0.02763	0.000149	0.0000035	-	-
EIR modifier function of temperature $EIR(T_{wb,i},T_{c,i}) = a + b(T_{wb,i}) + c(T_{wb,i})^2 + d(T_{c,i}) + e(T_{c,i})^2 + f(T_{wb,i})(T_{c,i})$	0.29714	0.043093	-0.00075	0.00598	0.000482	-0.00096
EIR modifier function of flow fraction $EIR(ff) = a + b(ff) + c(ff)^2 + d(ff)^3$	0.84	0.16	0	0	-	-
Part load correction function $PLF(PLR) = a + b(PLR) + c(PLR)^2$	1.19248	-0.03	0.001038	-0.000023	-	-

$T_{wb,i}$ – wet-bulb temperature of the air entering the cooling coil (ºC)

$T_{c,i}$ – dry-bulb temperature of the air entering the air-cooled condenser (ºC)

ff – the ratio of the actual air flow rate across the cooling coil to the rated air flow rate

PLR – part load ratio (the ratio between actual sensible cooling load and the rated sensible load)

Table A.6. Performance Curves for the DX Coil Used in the DOAS System

curve name	coefficients					
	a	b	c	d	e	f
Total cooling capacity modifier function of temperature $Cap(T_{wb,i},T_{c,i}) = a + b(T_{wb,i}) + c(T_{wb,i})^2 + d(T_{c,i}) + e(T_{c,i})^2 + f(T_{wb,i})(T_{c,i})$	0.942588	0.009543	0.000684	-0.01104	5.25E-06	-9.7E-06
Total cooling capacity modifier function of flow fraction $Cap(ff) = a + b(ff) + c(ff)^2$	0.8	0.2	0	-	-	-
EIR modifier function of temperature $EIR(T_{wb,i},T_{c,i}) = a + b(T_{wb,i}) + c(T_{wb,i})^2 + d(T_{c,i}) + e(T_{c,i})^2 + f(T_{wb,i})(T_{c,i})$	0.342414	0.034885	-0.00062	0.004977	0.000438	-0.00073
EIR modifier function of flow fraction $EIR(ff) = a + b(ff) + c(ff)^2$	1.1552	-0.1808	0.0256	-	-	-
Part load correction function $PLF(PLR) = a + b(PLR) + c(PLR)^2$	0.85	0.15	0	-	-	-

$T_{wb,i}$ – wet-bulb temperature of the air entering the cooling coil (ºC)
$T_{c,i}$ – dry-bulb temperature of the air entering the air-cooled condenser (ºC)
ff – the ratio of the actual airflow rate across the cooling coil to the rated air flow rate
PLR – part load ratio (the ratio between actual sensible cooling load and the rated sensible load)

Table A.7. Part Load Performance Curve for the Gas Furnace

curve name	coefficients a	b	c
Part load correction function $PLF(PLR) = a + b(PLR) + c(PLR)^2$	0.8	0.2	0

PLR – part load ratio (the ratio between actual sensible heating load and the nominal heating capacity)

Appendix B

Review Comments and Responses on the Draft TSD Report

Table B.1. Review Comments and Responses on the Draft TSD Report

No.	Category	Comment	PNNL Response	PNNL Action
1	General	Energy results are not reported measure-by-measure Section 1 of the review draft indicates that "The purpose of this TSD is to provide design technology packages that indicate, measure by measure, how to achieve 50% Recommendation: for each included city, analyze and report out explicit measure-by-measure energy results for all measures recommended using a method such as: • An analysis of each measure simulated separately from the baseline • Rank the separate measures by results • An incremental cumulative set of analyses of measures in the ranking sequence. energy savings relative to Standard 90.1-2004 for small-sized office buildings." (Sml Ofc 50% TSD, ext. peer review draft, page 1.1)	The scope of the project did not include presenting energy measure analysis results separately for each measure. The measures are described individually on a measure by measure basis. The results do show the energy savings by energy usage category. A breakdown of energy measure results by measure category, such as HVAC, or lighting has been added in Section 5.4.	conducted the additional analysis and modified report
2	General	Recommendations are developed using a mix of methodologies and sources Various methods and sources were used to generate the energy measures recommended in the report. Sources include: • Standard 90.1-2004 prescriptive requirements (some lighting measures in specific spaces) • Standard 90.1-2010 proposed prescriptive requirements (most envelope measures, external lighting LPDs, • Recommendations developed by the 50% TSD team derived from Standard 90.1-2004 credits or from potential 2010 requirements (envelope cool roofs, envelope external shading, many internal lighting systems and LPDs, daylight harvesting, internal and external lighting controls, etc.) • Recommendations developed by the 50% TSD team for end uses not regulated by Standard 90.1-2004 (plug load measures, etc.) The report does not explain why or how the various methods and sources in different instances, or how the final recommendations listed in Section 6 were developed and evaluated, and impacts on energy savings or cost-effectiveness. Recommendation: develop a matrix that relates end uses to sources and methods for developing recommended measures, and describe the variation in sources, methods, energy savings, and cost-effectiveness across end-uses.	The comment has merit. The sources used are identified in the TSD and all are reasonable sources for identifying EEMs. The project did not allow a comprehensive review of all possible EEMs from all sources and a ranking of those EEMs and sources. A process was followed to identify a pool of EEMs. This pool did not identify sufficient EEMs to result in a large excess of EEMs beyond those needed to reach the 50% goal, so there was not a reason to exclude some EEMs based on a ranking in the way described.	no action
3	General	Also, I would examine some behavioral changes. A simple example would be to shift to daytime cleaning and see what impact that would have on the building's operating schedule and consequent energy use (it's having a clearly detectable impact in our offices). As you drive some of the technological changes to lower and lower energy use levels, exploring possible behavioral changes that might be even more cost effective should be in the mix. The fix does not always have to be a technical patch on current (inefficient) behavior.	Would need to characterize typical cleaning operations to establish baseline. Same with other behavioral changes. Possible future research.	no action, possible future research

Table B.1 (continued)

No.	Category	Comment	PNNL Response	PNNL Action
4	General	As these TSDs lay out the technical potential for significant reductions in building energy use, there needs to be a parallel consideration of whether the levels designed can be built and maintained. One of my fundamental arguments with all computer energy analysis (BLAST, DOE-2, E-Plus, etc.) is the underlying assumption that every component is built and operates exactly as designed while the reality of building operation is that mistakes are made in construction and the degradation of building performance is very, very common. Sensors are not calibrated; sensors fail. Brilliant control strategies are overridden by operators who don't understand them. I could go on and on and on, but you get my point. If the concern is shifting from simply being energy efficient to reliably reducing carbon emmissions forever, maintenance and operations have to become part of the discussion. What would be the technical approach and the cost of creating a building that easily can be kept at it's design level of performance for its entire life? How about a TSD adressing that?	These considerations while valid are outside of the scope for this TSD. This may take a separate research project focus on O&M. There is a general need to capture actual operations vs. ideal operation of new buildings in the analysis. Would be the basis for a separate research effort to properly characterize these issues. Previous AEDGs did not focus on these issues either.	no action, possible future research
5	General	Compare Checklist Approach to Integrated Design No attempt to use a whole-building or integrated design approach in the report. Rather, separate prescriptive measures are listed in series without any apparent evaluation of whether they reinforce or conflict with each other. This TSD report indicates that the non-integrated is one way, but not the only way, to obtain results significantly better than standard 90.1. But an issue not addressed is how good the approach is compared to a whole-building integrated approach. For example, will an integrated approach produce more energy saving more cost-effectively than a non-integrated check list approach? The 2006 scoping study did a good job of raising a number of issues on these points, but they are not addressed in this small office 50% TSD report	The report does provide an integrated package of energy measures that first reduce loads by modifiying the envelope and internal gains, and then meeting those with efficient HVAC strategies. The TSD is not a design guide, which may provide a comprehensive review of the integrated design approach.	no action, possible AEDG work
6	General	Table 6.5, Energy Use Indices: Given the widespread support for the 2030 Challenge, I think that it would be useful to add another row to this table to show the corresponding EUIs for the 2030 Challenge for each climate (i.e. the EUIs that are 60% less than the average existing building, as this is the threshold for the year 2010 in the 2030 Challenge).	These values are relative to an existing building baseline, and result in higher values than the EUIs for the advanced case except for Fairbanks. Decided not to include these as this is an apples to oranges comparison.	no action
7	General	Page 3.1: Section 3.1, Data Sources, was a very helpful and valuable addition to your report.	Thank you.	no action
8	General	Section 6.3 Future Steps If funds allow, I would encourage the consideration of a wider palette of options. The question of whether this target can be met only with a narrow range of approaches or with a broader range deserves to be tested.	Scope of work and funding precluded comprehensive approach. AEDG may be able to consider additonal alternatives.	no action, possible AEDG work
9	General	Site Energy Selected as Energy Performance Metric, with no comparison with alternate metrics or discussion of impacts The choice of performance metric can strongly impact results and conclusions. However, the evaluation approach described in section 2.1 of the report does not discuss why site energy and national average fuel costs were selected as the energy performance metric. Nor are references provided to other documents that provide such rationales. Source Energy Alternate Metric: A scoping study done in 2006 for the 50% TSD and related documents recommended the use of source energy. The 50% TSD Document does not discuss that source energy recommendation or why it was not pursued.Local energy Costs Alternate Metric: Also, the 50% TSD report includes no	The scope of work for this project covered savings at the building. National average costs are appropriate for representative climate zones using representative cities across the country. Energy costs and source vs site energy vary by specific utility and would be appropriate to a location specific analysis beyond the	no action

Table B.1 (continued)				
No.	**Category**	**Comment**	**PNNL Response**	**PNNL Action**
		explanation of why the method used in the 50% TSD differs in substantial ways from the method Appendix G of 90.1-2004, which is the selected method in Standard 90.1-2004 for evaluating whole-building energy results that substantially exceed the requirements of Standard 90.1.	scope of this report.	
10	General	For use to develop a design guide, more attention to describing the technologies and envelope components is required.	TSD provides an analysis of the potential to reach 50% savings without renewable energy. Sufficient information is provided to understand what was modeled and what the EEMs are. The AEDG will develop the EEMs further.	no action. Possible AEDG work.
11	General	The use of average energy costs is not appropriate to the differentiated market analysis that was performed throughout with the goal of showing simple payback for each represented market. Energy rates should be used for the specific markets studied.	Energy costs vary by specific utility. The average values used are reasonable to assess the general feasibility of the package of measures. The scope of work did not include detailed assesments of energy costs at a location specific level.	no action
12	General	The use of site energy as an analysis metric should be justified. Source energy may be a better metric, with an absolute goal of carbon reduction being the imperative.	The scope of work for this project is site energy savings as defined by DOE.	no action
13	General	How were the energy savings in Figure 6.3 weighted? It would be more useful to a designer to have the energy savings identified measure by measure, and by region.	Weighting in what is now Figure 5.3 is by the construction area weights described in Section 2.3. Additonal analysis was done to break out results for groups of energy measures such as building envelope, or HVAC. These results are presented in Section 5.4	additional analysis completed and modified report
14	General	No discussion of integrated design process. While only one prescriptive route towards a 50% energy saving building over 90.1-2004 is demonstrated, a strong caution to the reader should be given that indicates that any building that attempts this level of savings using other measures, or perhaps even for a different building configuration, must be done as a part of a collaborative integrated design process to have a chance of success at the levels desired.	The report provides an integrated package of energy measures that first reduce loads by modifiying the envelope and internal gains, and then meeting the remaining loads with efficient HVAC strategies. The TSD in not a design guide and does not provide a comprehensive review of the integrated design approach. A note similar to that suggested is added in the Executive Summary and in Section 5.	modified report
15	General	Most savings are from heating, followed by lighting (interior + exterior), and plug-load. This is due to the use of site energy - magnifying the gas use since one unit of gas is valued as one unit of electricity. Would be nice to see the savings breakdown into source energy or energy cost.	The scope of this project included energy savings at the building. Energy cost results are provided which reflect the mix of fuel types to some degree. Energy results in terms of combined energy units, as well as utility units provide some ability to consider site vs. source	additional analysis completed and modified report

Table B.1 (continued)

No.	Category	Comment	PNNL Response	PNNL Action
			considerations. An example breakdown of heating by heating component is provided in in Section 5.4.2.	
16	General	Need more background of methodology to reach 50% - either by using available technologies and products to reduce individual end use (apparently used in the report), or starting from the baseline end uses and propose a certain percentage energy reduction for the advanced. The idea is some end uses may have more room to save while others don't.	Measures were selected based on a scope which included using off the shelf technology, and achieving payback in the range of 5 years. There was not a large pool of energy measures identified that fit these criteria such that some significant measures could be dropped if they saved less. Instead, an array of reasonable measures were identified and together resulted in reaching the 50% savings goal.	no action
17	General	The use of national average energy cost for all cities is not well justified for the cost-effective analysis. RSMean cost data adjusted by local premium and local energy cost should be used.	First costs of EEMs was adjusted by RS Means cost factors. Energy costs from national averages is a reasonable estimate for this level of analysis. Energy costs vary by specific utility and would be appropriate to a location specific analysis beyond the scope of this report.	no action
18	General	Table 5.2 Incremental Costs. The last entry is "Location Cost Index (RS Means 2009)". Since RS Means 2010 is now available you should use the latest information since this document will be published later in 2010.	Due to time and budget constraints, were unable to revise costs to 2010 RS Means. In a period of low inflation, and the general uncertainty of the Means estimates, this is an acceptable approximation.	no action
19	General	Section 5.3 Cost-Effectiveness Calculation, 1st par. "using the EIA national average natural gas rate of $1.16/therm ($0.41/m3) …. (EIA 2006)". The ASHRAE Board of Directors told SSPC 90.1 to develop a blended heating rate which accounted for both natural gas and electricity. Using EIA data, on March 26, 2007 the blended heating rate was updated for the SSPC 90.1 to be $1.22/therm, see the attachéd email from Merle McBride to Jerry White (90.1 chair). The SSPC then approved this value of $1.22/therm and it was used in the development of the 2010 criteria. If you need a specific citation I am sure that Steve Ferguson can provide the motion number from the Chicago Interim meeting of SSPC 90.1, March 31 – April 2, 2007. 28 – p. 6.65, Section 6.2.2, "EIA national average natural gas rate of $1.16/therm", see comment 26.	Gas and electricity modeled explicitly for HVAC systems modeled. Using separate gas and electricity rates for heating corresponding to the heating energy usage results of the models. Updated electricity and gas rates to March 27, 2007 values used by SSPC 90.1	modified cost analysis and report
20	General	After reviewing the entire report I think it would be beneficial to have a summary of the constructions, features, etc. that were needed to upgrade the energy savings from 30% to 50% for each of the eight climate zones. This would allow one to quickly understand what additional measures it takes to achieve a 50% energy savings assuming they are knowledgeable of the measures that were required to get to the 30% savings.	Added a paragraph to 5. EEM Summary and Energy Results introduction describing differences.	modified report

Table B.1 (continued)

No.	Category	Comment	PNNL Response	PNNL Action
21	General	The entire report needs to be consistent with the use of dual units IP and SI.	Have reviewed report and made additional SI unit conversions. We are choosing not to present energy results tables in Joule or GJ units.	modified report
22	Envelope	Section 6.1.1, Building Envelope Recommendations: For the building envelope, ASHRAE/IESNA Standard 90.1-2010 will have three types of roofs, four types of above-grade walls, one type of below-grade wall, three types of floors over unconditioned space, two types of slab-on-grade floors, two types of opaque doors, four types of vertical fenestration, and one type of skylights.The SM50TSD analyzes one type of roof (roof with insulation above deck), one type of wall (mass wall), one slab-on-grade floor (unheated slab), and one type of vertical fenestration), and makes recommendations for those specific envelope assemblies in Section 6 (Table 6.1). However, the AEDG-SO (published in 2004) contained recommendations for all of the envelope components listed in Standard 90.1-2004. The SM50TSD should contain recommendations for all of the envelope assemblies in Table 5.5 of Standard 90.1-2010. (The latest list of envelope assemblies is contained in addendum bb to 90.1-2007, and has some changes in categories for vertical fenestration and for skylights.) The values in Table 6.1 should not be any less stringent than what you have recommended. As a reference point, our 2006 Seattle Energy Code (Climate Zone 4) requires a minimum of R-30 roof insulation above deck (same as Table 6.1), a minimum of R-15.2 for mass walls with continuous insulation held by 1-inch metal clips (Table 6.1only requires R-13.3 minimum), a minimum of R-10 perimeter insulation for slab-on-grade floors (Table 6.1 has no requirement), and a maximum of U-0.40 for vertical fenestration (Table 6.1 allows U-0.41). For our next code update, we expect to increase the stringency over the 2006 Seattle Energy Code, but the values are still in discussion.	For this TSD, only the recommended changes to envelope components were modeled, so only those changes are recommended. An AEDG for small and medium offices may allow consideration of a broader array of constructions. Recommended changes were sufficienct to achieve 50% target. Additional envelope stringency would add additional first cost. The values recommended are not any less stringent than in the external review version of the report.	modified report possible AEDG work
23	Envelope	The Envelope Recommendations Most envelope recommendations are 90.1 prescriptive requirements from addendum bb to 90.1-2007, which would likely be part of 90.1-2010. There is no explanation or evaluation as to why the 90.1-2010 "minimum standard" prescriptive requirement values have been selected as "high performance" recommendations. 20+ year old regression equations: The regression equations being used by the envelope subcommittee are well over 20 years old. For example, the tables of cooling and heating coefficients shown in Tables C6.8.2 and C6.8.3 of 90.1-2004 are identical to the coefficients shown in Tables 8B-2 and 8B-4 of 90.1-1989. There have been concerns about the current accuracy of these equations, especially considering the major advances in high-performance window technologies that have occurred in the past 20 years . Are the old regression equations able to adequately address the new technologies? Recommendation: for each included city, use the state-of-the-art analysis capabilities in EnergyPlus to analyze the explicit measure-by-measure energy results for all baseline envelope measures and all advanced envelope recommendations. Use these results to provide a more up-to-date basis for making envelope recommendations. Discuss any limitations in the EnergyPlus modeling that might	Envelope recommendations could go further, but further envelope changes were not needed to reach 50% savings goal and would add considerable first cost. We tested changing the SHGC values above or below the addendum bb values on separate building facing and for the whole building in all 16 climate locations and did not identify any significant savings, and in most cases energy usage increased. Further refinement of envelope choices may be possible with development of an AEDG for small and medium offices. In addition, PNNL has conducted a separate in-depth full feature analysis of	no action

Table B.1 (continued)

No.	Category	Comment	PNNL Response	PNNL Action
		impact accuracy (e.g., non-explicit modeling of frames and dividers, etc.)	addendum bb using EnergyPlus program and validated the results.	
24	Envelope	Mass Walls: The description of the baseline external wall in Section 3.3.1 of the 50% TSD report is confusing. • The first sentence says: "The exterior walls of the small office prototype are steel framed with stucco exterior cladding." • But then the third sentence says: "The exterior wall includes the following layers: The exterior walls of the small office prototype are constructed of 8-in. (200 mm) medium weight concrete blocks with …"Later sections of the TSD report assume that the baseline wall is a mass wall. Mass walls may have energy benefits over light weight frame walls. However, if the baseline wall is a mass wall, then the use of thermal mass in the walls becomes "energy neutral." Is this intended? How does this impact Recommendation: Change the baseline condition to a lightweight wall, and add thermal mass as an energy measure. Conduct separate energy analyses against the baseline. Assess the energy savings of advanced mass walls on an equal basis to advanced insulation of light-weight walls.	The baseline is a CMU wall. References to light weight wall construction are in error. The baseline is chosen as CMU based on CBECS data referenced in the report that a mass wall, CMU or concrete is typical for this size office building. Taking credit for the addition of thermal mass was not appropriate given the prevalence of mass walls in typical small office construction.	modified report
25	Envelope	Section 3.3.1 – has two distinctly different envelope wall constructions listed for the prototype model (concrete block and metal stud), with no explanation of which was actually used. a. The layer types are not listed for the metal stud case. b. A light weight metal stud wall should be used as a realistic base case.	The baseline is a CMU wall. References to light weight wall construction are in error. The baseline is chosen as CMU based on CBECS data referenced in the report that a mass wall, CMU or concrete is typical for this size office building.	modified report
26	Envelope	Section 4.1.1 Opaque Assembly – Clarify R-values for both continuous and non-continuous insulation for base case and improved case. Insulation between studs should be the normal condition used for the base case, and is likely to be the first area of insulation for the advanced case. Continuous insulation may be added to improve assembly performance, but it is not reasonable to assume that all insulation will be rigid continuous and attached to a stud frame wall in all cases – attachment method issues at increased thickness will occur (typically over 2-3"). Please verify and state that thermal bridging has been accounted for in overall assembly U-factors.	No metal studs were explicity modeled. A simplified approach was taken to model sufficient insulation to achieve the target U-factor. There are many different options for wall constructions that can meet the target U-factor. The baseline is a CMU wall. References to light weight wall construction are in error. The AEDG may further adress the possible wall constructions.	modified report
27	Envelope	Section 4.1.3, 2nd par., last sentence. "The effects of window frame and dividers are not modeled explicitly." Are frames modeled at all? Define what was actually done.	Window frames and dividers are included in the overall U-factor values. Clarified in report.	modified report
28	Envelope	Section 3.3.1 Exterior Walls -- The first paragraph says the walls are steel framed with stucco and the second paragraph says they are medium weight concrete block. Which is it? This appears to be a conflict. Or are you using two different walls types on different portions of the building? Two wall types in different climates? Or am I just missing something?	The exterior walls are CMU mass walls. The references to stud walls is wrong.	modified report
29	Envelope	Page 3.7, last paragraph: I didn't follow the infiltration discussion that referred to the EnergyPlus design infiltration rate of 0.2016 cfm/s.f. of wall area being equivalent to the base infiltration rate of 1.8 cfm/s.f. of envelope area. The 1.8 cfm/s.f. could mean infiltration exchange rates greater than 10 air changes per hour. That seems extremely high.	The 1.8 cfm/s.f. is at a pressure test pressure differential of 0.3 in. w.c. (75 Pa). The value used in the model is calculated from the methodology described at the estimated infiltration at	modified report

Table B.1 (continued)

No.	Category	Comment	PNNL Response	PNNL Action
			typical wind driven pressure drop conditions. Additional language is added to the report to clarify this.	
30	Envelope	Section 3.3.1 – provide explanation of how U-value of combined metal stud and insulation assembly was derived, including thermal bridging affects.	No metal studs were explicity modeled. The baseline is a CMU wall. References to light weight wall construction are in error. Wall constructions modeled as with continuous insulation sufficient to achieve target U-factor.	modified report
31	Envelope	Section 3.3.4 Fenestration – The terms 'U-factor' and 'U-value' appear to be used interchangeably in the text. Please verify and state that the NREL provided glazing EnergyPlus inputs resulted in close approximations to the desired U-factor as prescribed by ASHRAE 90.1-2004, which includes frame effects.	Corrected in the report.	modified report
32	Envelope	Section 4.2.1.4 Interior blinds are incompletely described.	Added additonal description of modeling of interior blinds to Section 3.4.4.	modified report
33	Envelope	VT should be used to replace VLT to be consistent with ASHRAE and NFRC etc.	Changed in report.	modified report
34	Envelope	Section 5.1, Table 5.1, Cool Roof – "Area of the roof area time" Windows & doors – Change "u-value" to "U-factor" Windows & doors – What is "Leisen-Fen"?	Lesien-Fen were people involved in creating the window cost information used by the 90.1 envelope committee. Corrected to refer to 90.1 Envelope Committee	modified report
35	Envelope	Major architectural strategies excluded without rationale The 2006 scoping study recommended early consideration of building form, aspect ratio, and orientation as part of an integrated approach to developing high performance buildings. The 50% TSD report approach to advanced measures does not address these aspects, and does not have a section for building form, aspect ratio and orientation. Recommendation: consistent with the recommendations of the 50% TSD scoping study done in 2006, add a section on "Architectural Measures" at the beginning of the report section on advanced measure. Include a discussion of the energy potentials of building form, aspect ratio, and orientation in the set of advance measures for high-performance buildings.	A brief discussion of building form and orientation are added in the baseline section (Section 3.2). The report explains the rationale for using a square-shaped baseline and neutral orientation based on CBECs and NC3 datasets suggesting that there is not a clear typical baseline. Building form and orientation are often constrained and outside of the opportunities available to a developer and design team. A reference to an NREL Net Zero study is included in section 3.2 which provides some study results and recommendations on architectural changes and some savings results which suggest the savings are modest. Sufficient savings were developed to reach 50% savings without these types of EEMs. Further development of these concepts	modified report, possible AEDG work.

No.	Category	Comment	PNNL Response	PNNL Action
			may be possible in development of the AEDG.	
36	Envelope	External overhangs: These are also recommended by the proejct team for climate zones 1 to 5. There is no explanation or evaluation as to why these recommendations have been selected, or why the same projection factor of PF=0.5 is recommended in locations with latitudes from 26o (Miami) to 47o (Seattle). The report does not include assessment of variations in external shading energy savings by location. Also, the explanation for excluding vertical fins seems weak, and is not the same as the explanation for excluding fins given that was given in the medium office 50% TSD report. D19Recommendation: for each city where external shading is recommended, show the measure-by-measure energy results for overhangs, fins, and the two combined. Use such results as a basis for the recommendations.	Good comment. We applied overhangs on climate zones 1-5 with the same projection factor of 0.5. This selection was made following the previous published Advanced Energy Design Guide for Small Office Buildings. We agree that ideally, an optimization approach shall be followed to select the optimal parameters for window overhangs and fins.	no action
37	Envelope	Cool Roofs: The discussion of the modeling of cool roofs is very terse, but appears to be significantly different form the modeling of such roofs specified in 90.1-2004 Appendix G, Table TABLE G3.1 Modeling Requirements for Calculating Proposed and Baseline Building Performance, Section 5, Building Envelope, Part (c). Recommendation: Please discuss in more detail the modeling approach and inputs for cool roofs. • If the modeling is different from that specified in Appendix G, discuss the rationale for the differences so that designers and modelers familiar with Appendix G protocols can understand any differences, and how they might impact the level of energy savings obtained and the resulting cost-effectiveness. • Show the specific energy results for this measure as applied to the baseline building separately form other measures. • Also discuss if this measure was examined for possible application and recommendation in 90.1-2004 climate zones 4 and 5.	We modeled the cool roof using the same strategy as that used in the previous work on Advanced Energy Design Guide for Small Office Buildings. We took the material properties from the cited reference based on the choice of the roof membrane. We did not use Appendix G as the modeling guide. We agree that the solar reflectance of cool roof material usually degrades over time. However, the degradation is not considered in the TSD.	no action
38	Envelope	Section 4.1.3 Windows – Indicate whether thermally broken frames were needed to provide the U-factors given for each advanced design case.	The fenestration is described as using manufactured windows. The target u-values can be met with thermal break, or with alternative framing materials. The frames were not modeled explicitly. Some additonal discussion is added to the report. AEDG may provide further design information on fenestration options.	modified report
39	Envelope	Section 3.3.4, Fenestration: I couldn't see why the baseline Fenestration U-F & SHGC's were dropped from this section. I thought they were essential information in your previous report.	Baseline envelope values were included in the advanced section. They have been restored in the baseline section and are still shown in the advance section to facilite comparison.	modified report
40	Lighting	Presentation of Daylight Harvesting Needs an Overhaul The presentation of daylight harvesting in the current 50% TSD report is incomplete and misleading. It seriously underestimates the potential of daylight harvesting as a high performance building	The comment is good, but this technical support document is not a "design guide". Many other design issues, along with this,	no actoin, possible AEDG work

No.	Category	Comment	PNNL Response	PNNL Action
		strategy in small office building. At best, the current treatment of daylighting can be described as "low performance" rather than "high performance." Even the future measures considered in the report are very limited and will not produce high performance results for this measure.	need to be discussed in a companion design guide.	
41	Lighting	Lighting RecommendationsInterior Lighting: Only some interior lighting recommendations are taken from recent Standard 90.1 minimum requirements, or from the 90.1-2010 proposed prescriptive requirement values. Rather, most of the energy savings from lighting appear to come from a combination of measures developed by the project team, including:• reduced interior lighting power density, • occupancy sensor control, and • daylighting with dimming control. This includes the recommendation to replace in the office spaces the direct/indirect fluorescent fixtures of the basecase by "high-performance lensed" fluorescent fixtures recessed into the ceiling. This appears to impact about 45% of the floor area of the office. There is no discussion of visual quality impacts for such replacements, such as changes in ceiling and wall luminance.Recommendation: Discuss the visual quality of comfort impacts of the use of the recommended office lighting system in place of the baseline direct-indirect system.	The comment is relevant, but this technical support document is not a "design guide". Many other design issues, along with this, need to be discussed in a companion advanced energy design guide.	no action, possible AEDG work
42	Lighting	Exterior Lighting -- There are alternative exterior lighting strategies that are not used in this model. One would be to have two-stage lighting, where a minimum lower level of lighting is maintained for security and a higher level is triggered by some other device (a wall-mounted switch for people exiting a building after hours, raising the lighting level for some time period - say 15 minutes - while a person leaves the building; a driveway mat that raises the level for a vehicle entering the parking lot, again for some predetermined time period; an occupancy sensor). For a target as aggressive as a 50% reduction, it seems that simple savings are being left on the table. This approach has been in place near Des Moines, Iowa for over 5 years, so it's not anything special.	These concepts are worth consideration and should be included in developing an Advanced Energy Design Guide. The TSD is not a comprehensive review of measures, and the 50% savings goal is reached with the measures listed. Parking lot lighting is assumed to have bi-level switching ballasts that will reduce its power to 10% between 12 PM and 6 AM. Façade lighting is also controlled to turn off between midnight and 6 AM.	no action, possible AEDG work
43	Lighting	Daylighting is not just a lighting controls measure. It includes the integrated consideration of several building systems including building from and orientation. Factors involved include: • building form to increase daylighted areas • Orientation • Envelope and glazing o Sidelighting strategies o Toplighting strategies o Heat gain/loss objectives or limits o Glare criteria and preferred control devices • Interiors o Surface reflectances o P+D63artition locations, heights & opacity o Level of visual uniformity / contrast desired • Lighting o Illumination criteria o Electric lighting system selection	The comment is good, but this technical support document is not a "design guide". Many other design issues, along with this, need to be discussed in a companion design guide.	no action, possible AEDG work

Table B.1 (continued)

Table B.1 (continued)

No.	Category	Comment	PNNL Response	PNNL Action
		o Daylighting illumination objectives (task / ambient) and variability expected diurnally and seasonally • Controls • Integration with HVAC systems Unfortunately, the building form of the baseline building in the small office 50% TSD does not provide a good basis for high performance daylight harvesting without substantial reworking of its form and orientation. However, the first example building form Sarasota FL in the Small Office 30% AEDG provides a good example of a high-performance approach to daylight harvesting in a small office building. Also, the Wisconsin Department of Natural Resources office building provides another successful example. There are many more. The 2006 scoping study did a good job of providing a general approach for daylight harvesting. Recommendation: better describe the limitations of the daylight harvesting approach being used and proposed in the small office 50% TSD report. Include a summary description of what would be included in a comprehensive whole-building integrated design approach that would include daylight harvesting. Unfortunately, the building form of the baseline building in the small office 50% TSD does not provide a good basis for high performance daylight harvesting without substantial reworking of its form and orientation. However, the first example building form Sarasota FL in the Small Office 30% AEDG provides a good example of a high-performance approach to daylight harvesting in a small office building. Also, the Wisconsin Department of Natural Resources office building provides another successful example. There are many more.The 2006 scoping study did a good job of providing a general approach for daylight harvesting. Recommendation: better describe the limitations of the daylight harvesting approach being used and proposed in the small office 50% TSD report. Include a summary description of what would be included in a comprehensive whole-building integrated design approach that would include daylightharvesting.		
45	Lighting	Was the reduction in the number of lighting fixtures vetted with the partitioned areas of the floor layout? (e.g. individual offices must still have a minimum number of light fixtures in each one, light spill into adjacent spaces can't be used, etc.). a. Was the quality of lighting vetted with the new design, including light levels? There is no indication that this was addressed. Recessed fixtures will cut down on the use of reflective surfaces (e.g. ceiling).	Yes, AGI calculations were used to confirm that the LPD would provide the recommended light levels as found in the 90.1 lighting models.	no action
46	Plug Load	Section 3.5.4 Plug Loads – The number of servers appears low for a tenant (listed as one, for a tenant with 44 occupants). Routers, UPS, etc may also be present.	The total plug load and mix is considered to be representative based on the studies cited in the report. Sources on the exact number of servers, routers and UPS were not identified.	no action
47	Plug Load	Table 3.4 Plug Load Density, There are 44 desktop computers and 44 laptops but then there are 88 Monitors – desktop – LCD. Finally, there are 88 chargers. Do all 88 computers really have charges?	The 88 chargers is an an estimate of one charger or other small load not otherwise accounted for such as radios, or distributed small network components or other devices estimated as 1 per work station.	no action

Table B.1 (continued)

No.	Category	Comment	PNNL Response	PNNL Action
48	Plug Load	Miscellaneous Equipment (Plug Loads) -- It is good to see the focus on controlling plug loads. In our own offices, behavioural changes and system level software to shut down computers and monitors have produced significant reductions in energy use. the exact changes possible are all argueable, but at least the analysis puts something into the discussion for those who may have data on the subject. Our own experience also makes me question the savings from a switch to laptops. Laptops have a tendency to sprout docking stations, supplemental keyboards (the ergonomics of using a laptop on a desk are not great), supplemental monitors, etc. - all of which eat into theoretical savings.	Data on plug loads savings is limited. It would be good to get better information. PNNL is involved in a study to better characterize plug load operations.	possible future research and AEDG work
49	HVAC	In Section 4.4.1, there is some discussion about variable refrigerant flow (VRF) systems. The text in the second paragraph appears to offer a quasi-endorsement of VRF systems, but then the text in the fourth paragraph refers to reports of problems in comfort and control. Also, I would note that VRF systems are generally not installed with economizers, so they need to compensate for the loss of “free cooling” by outside air. Consequently, I would recommend that you consider deleting the text about VRF systems, as the comments are speculation and not based on the rigor of technical analysis that you have used for other measures in the report.	The discussion of VRF has been removed. A mention of this alternative is included in the introductin to Section 4.4, and in Section 7 Future Work	modified report
50	HVAC	I realize the base building is using 90.1-2004 efficiencies but the minimum allowable SEER on packaged rooftops today is 13.0.	We have changed the analysis and report so that the baseline for the small units is 13 SEER.	changed analyis and modified report
51	HVAC	Assumptions in the HVAC section appear valid based on my experience.	Thank you for your comments.	no action
52	HVAC	Section 3.6.6 HVAC Fan Power – The total static pressure figures used in Table 3.6 are likely low for the filter loss and for the duct system loss. Filters are frequently specified and operated with a 1” pressure drop at full loading. It may be more realistic to use a higher static pressure drop across this element. Duct system losses appear low – were elbows and duct transitions accounted for in the pressure calculation? Only straight duct pressure drop methodology was documented (0.1”/100ft). Elbows and fittings account for the majority of pressure drop in duct systems. For a building of this size, a 1.25”E.S.P. on the packaged equipment might not be unexpected, with an expectation of further increase in T.S.P. with filter loading.	Static pressure values were adjusted to add an average 0.5" of static for partially dirty filters, in addition to the clean filter pressure drops incorporated in the internal static pressure. The duct run static pressure values allow for both the straight duct runs and the fittings which is clarified in report. The building is 100 ft per side, and there is one system serving each zones, so the duct runs are not very long.	modified report
53	HVAC	Section 4.4.1 & 4.4.2 – same comments regarding duct static pressure (duct fittings/elbows perhaps not attributed) and filter pressure drop. It may be acceptable to state that the advanced case has the target numbers provided, but it should be clarified that the duct static pressure includes low friction elbows and fittings.	Static pressure values were adjusted to add an average 0.5" of static for partially dirty filters, in addition to the clean filter pressure drops incorporated in the internal static pressure. The duct run static pressure values allow for both the straight duct runs and the fittings which is	modified report

Table B.1 (continued)

No.	Category	Comment	PNNL Response	PNNL Action
			clarified in report. The building is 100 ft per side, and there is one system serving each zone, so the duct runs are not very long.	
54	HVAC	Section 4.4.2 – Was inclusion of an improved efficiency fan motor vetted with at least two product manufacturers? The request for higher efficiency motors in packaged equipment is not always available, or may not be available at the desired level of efficiency.	Premium efficiency fan motors were dropped as many of the fan systems will have motors below the 90.1 regulated size, and may not have an efficient motor option. This is also a very small savings EEM.	modified analysis and report
55	HVAC	Section 6.2.1 – The use of electric resistance heating is mentioned, although it is unclear in this section if it was documented for the base case, or for the improved case. In either condition, electric resistance heating was not described earlier in the document for the base case or improved case. It only appears later in the Appendix. Please verify where this is used, and under what controls scenarios it is applied. Electric resistance heating has a substantial energy use impact. Please also verify and state how the electric resistance heating is accounted for in the energy modeling, including the effect on the COP for the systems in heating mode.	Discussion is added to the report in Section 4.4.1. Section 5.4.2 includes a breakdown of heating energy by heating component for Chicago as an example	additional analysis completed and modified report
56	HVAC	Per the Appendix, it appears that NO relief/exhaust fan was included in the DOAS. If this is true, this will lead to overpressurization of the building, in order to build up enough pressure for the relief air to pass through the relief side of the enthalpy wheel (0.85 in H2O static pressure). This is not a realistic system that could be installed and meet code. A relief fan should be included, with appropriate static pressure for the enthalpy wheel and the ducting in the relief system.	Energy recovery pressure drop and associated fan power is accounted for as described along with the power to rotate the energy recovery wheel in the fourth bullet after Figure 4.3.	no action
57	HVAC	Section 3.6.4 HVAC Equipment Sizing, 2nd par., You use 99.6% for heating and 1% for cooling. Is there any rational for this difference in frequency? Typically, a designer would select one level of stringency e.g. 0.4 %, or 1% and use the same % for both heating and cooling, i.e. 99.6% and 0.4% or 99% and 1%.	Using 99.6% for heating and 0.4% for cooling. Fixed in report.	modified report
58	HVAC	The heating savings in Table 6.6 appear to be too high. Have you checked whether the electric resistance supplemental heat is being used in the cold climates like Chicago and Minneapolis? It does not seem logical that you reduced heating MMBtu by 2/3rds.	The primary reduction in heating energy comes energy recovery by the dedicated outside air system which is served by gas for heating. We added Section 5.4.2, which includes a breakdown of HVAC energy use by heating component for Chicago	additional analysis completed and modified report
59	HVAC	The fan savings in Table 6.6 also appear to too high. Have these values been confirmed on why you are saving this much energy? It may be because you are allowing the heat pumps to cycle to maintain temperature conditions since the DOAS is providing ventilation and humidity control. It would be interesting to understand why the values are so low.	For Chicago, a fan energy test was run and is shown in Section 5.4.2. Fan airflow is reduced substantially with cycling, and reduced cooling and heating also loads further lowers the design airflow.	additional analysis completed and modified report
60	HVAC	Water source heat pumps may save more energy than the air source heat pumps but the incremental cost will also increase. I believe the water source heat pumps would be more appropriate for 40,000+	Water source heat pumps were dropped from further consideration due to inability	dropped from

Table B.1 (continued)				
No.	**Category**	**Comment**	**PNNL Response**	**PNNL Action**
		SF buildings. Ground source heat pumps are also a good choice in some of the climate zones.	to model correctly in combination with DOAS and indications that the system would not allow reaching 50% savings. We also agree with the size of building comment you raise. Ground source heat pumps would work in some climates and costs are high in some areas without a developed well field construction industry.	analysis
61	HVAC	Who is the target audience for this guide? It is not clear who are the main target audiences for this Small Office 50% TSD document. Given the lack of reporting of separate measure-by-measure energy results it appears that the report focuses more to policy-oriented readers than to readers who are owners, developers, designers or modelers of buildings. Recommendation: that the TSD report clearly indicate the main intended audiences and identify the features of the report that address those audiences.	Intent of the TSD is to provide analysis supporting a reasonable path to 50%. The package of savings are described separately, but the intent is that the package be adopted in an integrated way if possible. Additional information has been added breaking out savings by EEM category such as HVAC or lighting. Reception of previous TSDs suggest that this approach may have use for building design teams as well as others. The AEDG will be able to elaborate on the details of the measures and may be able to go into further detail on individual measure results.	additional analysis completed and modified report
62	HVAC	HVAC Systems Were alternative approaches such as ground source heat pumps considered? The discussion on not using demand controlled ventilation (4.43) raises a similar point: the example given reaches the energy reduction goal. How many alternative approaches would do so? How many options would a designer have? How restrictive is the target? This far into the reading, I do not have a clear sense of this issue. Is this one way to reach the goal, one of five ways to reach the goal or one of ten ways to reach the goal?	Unfortunately, our scope did not let us evaluate many alternatives. AEDG for small office project may have opportunity to consider addtional EEMs. We have added results for a VAV alternative to this TSD. Our medium office TSD work indicates a radiant system with DOAS could be another alternative. Ground source heat pumps were considered but it was felt that these systems are not generally appropriate for all climate settings (unbalanced heating and cooling) and are subject to large regional differences in well field costs.	no actoin, possible AEDG work

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