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Technical Support Document: 50% Energy Savings Design Technology Packages for Medium Office Buildings

BA Thornton
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MD Lane
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September 2009

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Executive Summary

The Technical Support Document (*TSD*) for 50% energy savings in medium office buildings documents the analysis and results for a recommended package of energy saving design features. Implementation of these energy measures could allow a new medium office building to achieve 50% energy savings relative to a building that just meets ANSI/ASHRAE/IESNA Standard 90.1-2004, *Energy Standard for Buildings Except Low-Rise Residential Buildings.* This package includes radiant heating and cooling with dedicated outdoor air systems (DOAS). Documentation and results are also presented for a second energy measure package that relies on a more conventional high performance variable air volume (VAV) system but does not achieve 50% energy savings in all 16 climate locations analyzed for this project.

The Department of Energy (DOE) through its Building Technologies Program commissioned this work to support its goal to create technologies and design approaches that enable net-zero energy buildings at low incremental cost by 2025. This work is related to previous technical support documents that were used in the development of *Advanced Energy Design Guides* published by ASHRAE (such as the *Advanced Energy Design Guide for Highway Lodging*). However, unlike those previous *TSD* reports, this effort results in a stand-alone report that is not part of a formal project under ASHRAE's Special Project procedures to develop an *Advanced Energy Design Guide for Medium Offices*. This study may be used to support development of such a design guide, but may also be used separately to demonstrate the feasibility of achieving 50% energy reduction for medium office buildings across the full range of climate zones in the United States.

This report and others under the 50% *TSD* project by DOE may also support DOE's Commercial Building National Accounts 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% savings in existing commercial buildings.

Pacific Northwest National Laboratory (PNNL) performed the research, analysis and documentation for this report with input from many other contributors and sources of information. PNNL developed a prototype building model that just meets the requirements of Standard 90.1-2004 based on the DOE medium office benchmark building. Prescriptive packages of recommended energy measures were developed. PNNL used energy simulation with *EnergyPlus* version 3.0 to determine the energy savings provide by the package of measures. The prototype buildings were simulated in the same 8 climate zones, utilizing 16 city locations used by the prevailing energy codes and standards to evaluate energy savings.

The report documents the modeling assumptions used in the simulations for both the baseline and advanced prototypical buildings. Final efficiency recommendations for each climate zone are included, along with the results of the energy simulations. A primary package of energy measures, which includes radiant heating and cooling with DOAS, provides a national-weighted average energy savings of 56.1% over the Standard 90.1-2004 for 16 climate settings (savings for the different climate zones are weighted by construction square footage per location). A second package of measures is also analyzed and differs from the first package only in the heating, ventilating, and air-conditioning (HVAC) systems, which are VAV systems, and demonstrates weighted average savings potential of 46.3% overall.

A cost estimate of each package of energy measures is provided to evaluate cost-effectiveness relative to the energy savings. The primary package with radiant systems has an average payback of 7.6 years, and the package with VAV systems has an average payback of 4.6 years. Lighting costs are lower for the recommended energy measures than for the baseline because reduced wattage and fixture costs are only partially offset by more expensive per watt lighting equipment. This reduction may not be achievable for projects with very high lighting aesthetic considerations. HVAC system costs take into account greatly reduced system cooling capacity. Some design teams may not be willing to take into account large reductions in equipment sizing relative to typical design. Actual cost premiums may vary but the cost-effectiveness analysis does suggest that 50% energy savings can be achieved for new medium offices with a reasonable cost premium.

Acknowledgments

This document was 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, Team Leader of BTP's Commercial Buildings Integration R&D, for his dedicated support to and thoughtful guidance of 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:

Erin McConahey, *Principal, ARUP*

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

Glenn Hansen, *Project Manager, Portland Energy Conservation Incorporated*

Kent Peterson, *President, P2S Engineering*

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

Michael Lane, *Project Manager, Seattle Lighting Design Lab*

Oliver Baumann, *President, Ebert & Bauman Consulting Engineers, Inc.*

Last, but not least, the authors would 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. Finally, Dr. Jian Zhang at PNNL provided a detailed technical review of this report.

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
Project Manager

Pacific Northwest National Laboratory

Acronyms and Abbreviations

AC	air conditioner
AEDG-SO	Advanced Energy Design Guide for Small Office Buildings
AEDG-SR	Advanced Energy Design Guide for Small Retail Buildings
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
CBECS	Commercial Buildings Energy Consumption Survey
CDD	cooling degree days
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
EPA	Environmental Protection Agency
EPDM	ethylene propylene diene terpolymer membrane
ERV	energy recovery ventilation

GSHP	ground source heat pump
HDD	heating degree days
HP	high performance
HVAC	heating, ventilation, and air conditioning
IECC	International Energy Conservation Code
IESNA	Illuminating Engineering Society of North America
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
NEA	National Energy Alliances
NREL	National Renewable Energy Laboratory
NZEB	net-zero energy buildings
ODP	open drip proof
OSA	outdoor supply air
PLR	part load ratio
PNNL	Pacific Northwest National Laboratory
RA	return air
RTU	roof top unit
SEER	seasonal energy efficiency ratio
SHGC	solar heat gain coefficient
SWH	service water heating
TEFC	totally enclosed fan cooled

TSD	technical support document
USGBC	US Green Building Council
USGS	US Geological Survey
VAV	variable air volume
VLT	visible light transmittance
WWR	window-to-wall ratio

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1.0 Introduction

Buildings account for over 40% of total energy use and over 70% of electricity use in the United States. To tackle this challenge, 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 (ANSI/ASHRAE/IESNA 2004). Beginning in FY2004, DOE has provided financial and technical support for the development 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 of North America (IES), and the U.S. Green Building Council (USGBC)[1].

There are two distinct but related products under this element. 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. A *Technical Support Document* (*TSD*) is a background document describing the assumptions and methodologies used to achieve particular levels of energy performance. AEDGs invariably have concomitant *TSDs* (to document the rationale behind the design decisions), but not all *TSDs* are necessarily associated with AEDGs.

ASHRAE and its partners have, to date, published five 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, and highway lodging[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 (ANSI/ASHRAE/IESNA 1999). The sixth and final *Guide* in this 30% series for small healthcare facilities will be published in FY2010.

The 30% energy savings target is the first step toward achieving net-zero commercial buildings. Having proven the feasibility of 30% energy savings across a variety of building types, DOE now exits 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 *Technical Support Document*, or *TSD*, is to provide design technology packages that indicate, measure by measure, how to achieve 50% energy savings relative to Standard 90.1-2004 for medium-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

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

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

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, 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. These 50% *TSDs* do not necessarily support ASHRAE-published AEDGs, but are intended to be stand-alone reports documenting the technical feasibility of achieving a 50% reduction in whole-building energy use. These reports are intended to demonstrate that exemplary energy performance is feasible today with available technology.

In FY2009, PNNL focused on two building types to analyze 50% energy savings performance: medium offices (this report) and highway lodging (published as a sister report) for three reasons. First, these subsectors use a significant amount of energy and therefore represent significant opportunities for significant energy savings potential. Second, DOE has launched three commercial building energy alliances (CBAs) that include both lodging and offices. Because the goal of the CBEAs is ultimately to realize 50% energy savings in new construction, the *TSDs* will directly support this effort to realize energy efficiency at scale through national account replication. Finally, PNNL possesses technical expertise in both areas, as evidenced by the previous development of the 30% *AEDG for Small Offices* and *Highway Lodging*.

Publication and use of these two design technology packages for office and lodging will lead to additional energy efficient design improvements well beyond code in our nation's new office and motels and will thus significantly contribute to BT's net-zero energy building goal in 2025. For reference, office and lodging are ranked as the first and fourth largest in terms of primary energy consumption in the commercial building sector, respectively, if all size categories are included. The combination of the office and lodging sectors constitutes 26% of the primary energy consumption in existing commercial buildings and represents 24% of the total square footage in the commercial building stock.[3] The design technology packages 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.

[3] 2008 Buildings Energy Data Book, U.S. Department of Energy, Table 3.2.2
http://buildingsdatabook.eren.doe.gov/docs/xls_pdf/3.2.2.pdf

2.0 Energy Saving Analysis Methodology

This section describes the energy savings evaluation approach, the simulation program, and the climate locations that were used to assess and quantify the 50% energy savings goal by implementing the energy efficiency measures recommended by this report.

2.1 Evaluation Approach

The evaluation approach was similar to the one used for the development of the initial 30% *Advanced Energy Design Guide* series, where prototypical buildings were devised, and then simulated in eight climate zones covered in ASHRAE Standard 90.1 (ANSI/ASHRAE/IESNA 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 the Department of Energy in establishing a new set of benchmark buildings. The DOE benchmark buildings are described in the next section, 3.0 Development of the Medium Office Prototype Building. The medium office prototype model used for this analysis is based closely on the DOE medium office benchmark building. The analysis results established that the energy efficiency recommendations in the *TSD* study meet the energy savings target.

The 50% energy savings goal is based on onsite energy savings between minimally code compliant (baseline) medium office buildings and advanced ones that use the recommendations in the *TSD* study. The baseline level energy use was modeled to match buildings built beginning in 2004 and compliant with ASHRAE Standard 90.1-2004. The purpose of this building energy simulation analysis is to assess and quantify the energy savings potential of the Report's final recommendations. A series of steps is taken to reach this goal.

- Develop a prototypical medium office building description. The DOE medium office benchmark building is chosen as a starting point to develop the prototype. 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 ASHRAE Standard 90.1-2004. Section 3.0 documents the model inputs and assumptions for the baseline models.
- Create an advanced model based on the recommended energy-efficient technologies in the Report. At the beginning of the technology selection, technologies are selected from the lists generated for the previous AEDGs (i.e., the most stringent requirements for envelope and lighting from *Advanced Energy Design Guide for Small Office Buildings* [AEDG-SO] and *Advanced Energy Design Guide for Small Retail Buildings* [AEDG-SR. To reach the 50% goal, technologies are also identified nearer to current best practice and in some cases less prevalently used technologies, although commercially available and perhaps used more extensively outside the United States in some cases. 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 the Standard. Various technologies are considered in combination to determine the ability of the combination of measures to allow the energy savings target to be reached. Section 4.0 documents the model inputs and assumptions for the advanced models.
- The cost-effectiveness of the energy efficiency recommendations is presented in Section 5.0.

- Evaluate 50% energy savings in all 16 representative climate cities. A total of 16 climate locations are selected to adequately represent the 8 climate zones in the United States consistent with the DOE benchmark buildings. The summary of energy simulation results for all locations and the final energy saving recommendations by climate zone are described in Section 6.0.

2.2 Simulation Tool Description

EnergyPlus Version 3.0 (released in November, 2008) 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, ventilating, and other energy flows under development by DOE since 1996 (DOE 2008). 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, multi-zone 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 with 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 GPRM, submitting input files to a 50-central processing unit (CPU) computing cluster for batch simulation, and extracting energy end use results.

2.3 Climate Zones and Weighting Factors

Prior to this report, the released *AEDG*s developed to date have standardized climate zones that have been adopted by 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. A specific climate location (city) is selected as a representative of each climate zone. The *AEDG* 30% series selected 15 cities as the representative climate locations.

For this project we selected a revised set of 16 cities that balance the representativeness of the climate zones and the number of buildings in the climate zones as shown below. Two locations were selected for climate zone 3B because we felt that these are two important locations with very different climates, which is evident from the results of the energy simulations of the 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".

[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.

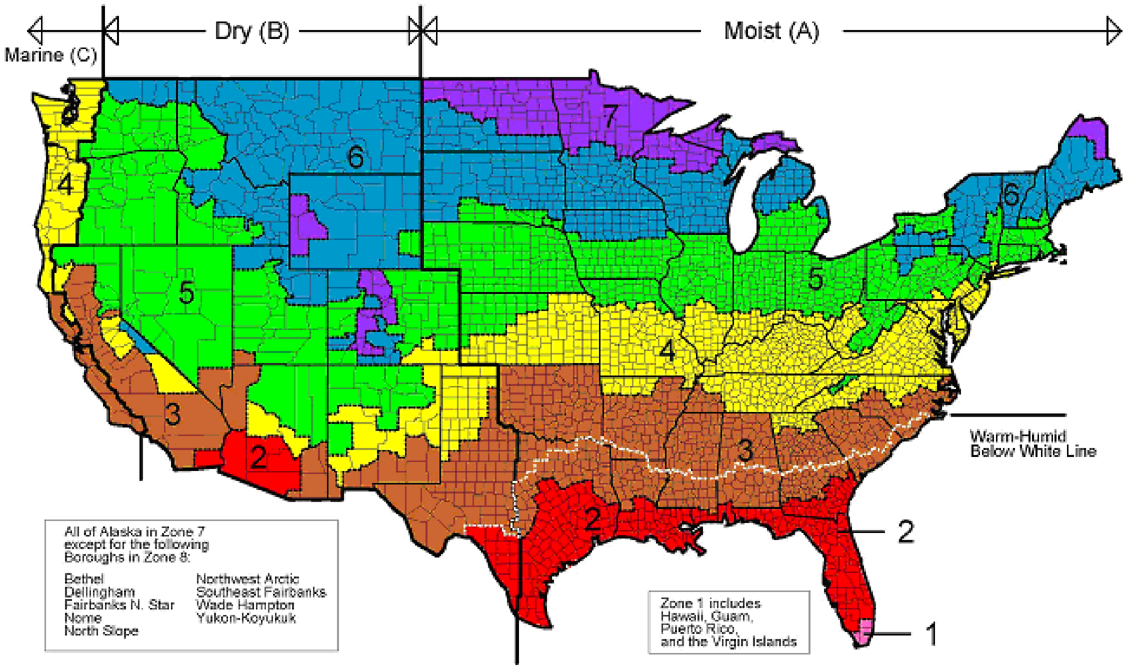

Figure 2.1. DOE-Developed Climate Zone Map

The sixteen cities representing the climate zones are:

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

These representative climate locations are assigned weights based on the square footage of construction from 2003 to 2007 as presented in a draft PNNL study which utilizes the McGraw-Hill Construction Projects Starts Database (MHC) (Jarnagin, Bandyopadhyay 2009). This study presents weighting factors for all 16 DOE benchmark building types as shown in Table 2.1 with medium office shown in bold (see section 2.4 for a description of the benchmark buildings). Table 2.2 shows just the medium office weighting factors normalized to total 100% and labeled according to the representative cities shown above. The weights for medium office by climate locations are used to calculate weighted average energy savings results for the whole country in Section 6.0 including splitting the weight in half for climate zone 3B (dry) for each of two city locations, Los Angeles and Las Vegas.

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

No.	Prototype	1 moist	2 dry	2 moist	3 dry	3 marine	3 moist	4 dry	4 marine	4 moist	5 dry	5 moist	6 dry	6 moist	7	8	National
1	Large Office	0.102%	0.061%	0.326%	0.285%	0.117%	0.445%	0.000%	0.154%	1.132%	0.121%	0.442%	0.000%	0.133%	0.011%	0.000%	3.327%
2	**Medium Office**	**0.129%**	**0.292%**	**0.813%**	**0.715%**	**0.136%**	**0.766%**	**0.036%**	**0.196%**	**1.190%**	**0.342%**	**1.060%**	**0.035%**	**0.298%**	**0.033%**	**0.007%**	**6.047%**
3	Small Office	0.084%	0.289%	1.064%	0.475%	0.078%	0.963%	0.047%	0.123%	0.936%	0.322%	0.920%	0.030%	0.241%	0.032%	0.005%	5.608%
4	Standalone Retail	0.224%	0.507%	2.220%	1.250%	0.191%	2.386%	0.119%	0.428%	2.545%	0.792%	3.429%	0.091%	0.948%	0.109%	0.014%	15.254%
5	Strip Mall	0.137%	0.254%	0.991%	0.626%	0.103%	1.021%	0.023%	0.107%	1.008%	0.201%	1.023%	0.016%	0.153%	0.007%	0.001%	5.669%
6	Primary School	0.064%	0.164%	0.933%	0.446%	0.048%	0.944%	0.030%	0.094%	0.895%	0.224%	0.920%	0.037%	0.168%	0.023%	0.003%	4.994%
7	Secondary School	0.160%	0.230%	1.523%	0.819%	0.109%	1.893%	0.063%	0.243%	2.013%	0.438%	2.282%	0.086%	0.415%	0.075%	0.012%	10.361%
8	Hospital	0.040%	0.096%	0.479%	0.273%	0.039%	0.468%	0.022%	0.106%	0.615%	0.218%	0.812%	0.024%	0.221%	0.034%	0.001%	3.448%
9	Outpatient Health Care	0.037%	0.134%	0.567%	0.275%	0.061%	0.581%	0.023%	0.181%	0.818%	0.218%	1.058%	0.033%	0.342%	0.039%	0.002%	4.371%
10	Restaurant	0.009%	0.025%	0.106%	0.047%	0.006%	0.111%	0.006%	0.010%	0.127%	0.031%	0.143%	0.004%	0.031%	0.004%	0.000%	0.660%
11	Fast Food Restaurant	0.008%	0.020%	0.092%	0.063%	0.007%	0.102%	0.005%	0.014%	0.089%	0.026%	0.128%	0.003%	0.025%	0.004%	0.000%	0.587%
12	Large Hotel	0.109%	0.125%	0.621%	0.793%	0.106%	0.635%	0.037%	0.123%	0.958%	0.200%	0.919%	0.058%	0.227%	0.038%	0.004%	4.951%
13	Small hotel/motel	0.010%	0.030%	0.288%	0.114%	0.022%	0.268%	0.020%	0.039%	0.315%	0.089%	0.365%	0.031%	0.107%	0.020%	0.004%	1.721%
14	Non-refrigerated warehouse	0.349%	0.580%	2.590%	2.298%	0.154%	2.966%	0.068%	0.435%	2.446%	0.688%	3.580%	0.049%	0.466%	0.043%	0.002%	16.716%
15	High-rise apartment	1.521%	0.076%	1.512%	0.741%	0.173%	0.652%	0.000%	0.358%	2.506%	0.115%	1.163%	0.016%	0.125%	0.008%	0.000%	8.967%
16	Mid-rise apartment	0.257%	0.093%	1.094%	0.862%	0.260%	0.825%	0.022%	0.371%	1.694%	0.318%	1.122%	0.056%	0.313%	0.032%	0.000%	7.321%
	Totals	3.242%	2.975%	15.217%	10.081%	1.609%	15.025%	0.522%	2.981%	19.286%	4.344%	19.366%	0.569%	4.214%	0.513%	0.056%	100.0%

Table 2.2. Construction Weights for Medium Office

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	Total
2.13%	13.44%	4.83%	12.67%	5.91%	5.91%	2.25%	19.68%	0.60%	3.24%	17.53%	5.66%	4.93%	0.58%	0.55%	0.12%	100%

2.4 Development of the Medium Office Prototype Building

The first step of the energy savings analysis is the development of a prototype building. The medium office prototype used for this document is based on the US Department of Energy's benchmark building series. DOE's Building Technologies Program, working with DOE's Pacific Northwest National Laboratory, Lawrence Berkeley National Laboratory, and National Renewable Energy Laboratory, developed models for 16 commercial building types in 16 locations representing all U.S. climate zones. These 16 building types cover about 70% of the commercial buildings in the United States.

The benchmark buildings were developed with information from many sources including the Commercial Building Energy Consumption Survey (CBECS), and work done by the national labs and others on previous *Advanced Energy Design Guides* and supporting analysis for the development of the 90.1 Standard. The CBECS data sets are publicly available and provide statistically valid results from a periodic national survey of commercial buildings and their energy suppliers. The study considers new buildings and CBECS covers existing buildings but remains useful as many new building characteristics are consistent with past practice. The CBECS data can provide information about common characteristics of buildings, critical to the prototypical building development.

There are three sets of benchmark buildings representing new construction, post-1980 construction, and pre-1980 construction. The benchmarks were developed to represent more realistic buildings and typical construction practices and follow the minimum requirements of Standard 90.1 but do not always follow the 90.1 Appendix G modeling rules. The medium office analysis is based on the new construction benchmark, consistent with a Standard 90.1-2004 baseline.

Additional Information on these benchmark buildings is available at the US Department of Energy's Energy Efficiency and Renewable Energy news site, and there is another link there that allows anyone to download four components of the national benchmarks.

- An *EnergyPlus* input file (.idf)
- An HTML file showing the results from the *EnergyPlus* simulation (.html)
- A scorecard summarizing the inputs and results for each location (.pdfs)
- Appropriate weather data file for *EnergyPlus* (.epw).

The website address is: http://apps1.eere.energy.gov/news/progress_alerts.cfm/pa_id=132

Tables in Appendix A summarize the building characteristics for the medium office prototype. These inputs were used for developing baseline building models and advanced building models, which are described in Section 4.0 and 5.0, respectively.

3.0 Development of Baseline Building Model and Assumptions

This section summarizes the development of the Medium Office Building baseline models. Many of the assumptions that are used for this analysis originated from PNNL's work on the *Advanced Energy Design Guide for Small Office Buildings* (Jarnagin et al. 2006), the development of the DOE benchmark building series (DOE 2008), and the creation of prototype building models that are being used to support the development of ASHRAE Standard 90.1.

The baseline medium office prototype building is a theoretical building modeled with characteristics typical of buildings of this size and use. The medium office building is a 53,600 ft^2 (4,980 m^2) three-story building. The building is rectangular shaped, 164 ft (50 m) by 109 ft (33 m) (aspect ratio 1.5). Building components regulated by ASHRAE Standard 90.1- 2004 are assumed to "just meet" the minimum prescriptive requirements of that standard. Components not regulated by Standard 90.1 are assumed to be designed as is standard practice for a medium office building. Standard practice is determined from various sources including a review of the Commercial Buildings Energy Consumption Survey (CBECS 2003) and the input of various design and construction industry professionals. The following sections include a topic-by-topic review of the baseline building and how the baseline building is simulated in *EnergyPlus*, including characteristics of the building envelope, building internal loads (people, lighting, miscellaneous equipment, and infiltration), HVAC equipment, and service water heating.

3.1 Building Operating Characteristics

The building is 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 for janitorial functions. For the medium office, Saturday occupancy is modeled at 10-30% of peak and limited Sunday and holiday occupancy (approximately 5%) is assumed. Schedules for lighting and miscellaneous equipment were matched to occupancy schedules with additional limited usage during unoccupied times. HVAC system schedules were matched to the occupancy schedules, and allow for earlier startup times to bring the space to the desired temperature at the beginning of normal occupancy. These schedules are similar to schedules published in ASHRAE/IESNA Standard 90.1-1989 (ASHRAE/IESNA 1989). Figure 3.1 illustrates the typical weekday schedules for occupancy, lighting equipment and HVAC fans for the medium office, as simulated in *EnergyPlus*.

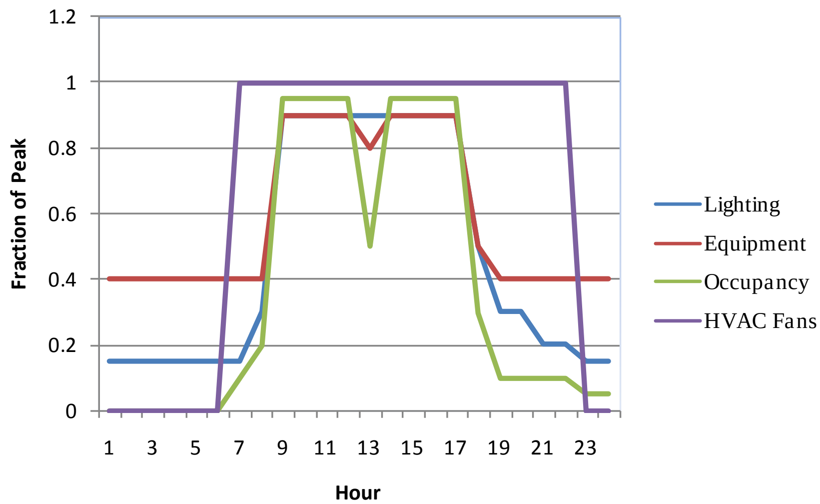

Figure 3.1. Medium Office Weekday Schedules

3.2 Baseline Building Envelope Characteristics

Building opaque constructions include steel-framed walls, flat roof with insulation above the deck and slab–on-grade floors. These envelope structures represent common construction practice for medium office buildings in the U.S. based on information from the CBECS data. Figure 3.2 shows an axonometric view of the building as input in the energy simulation model.

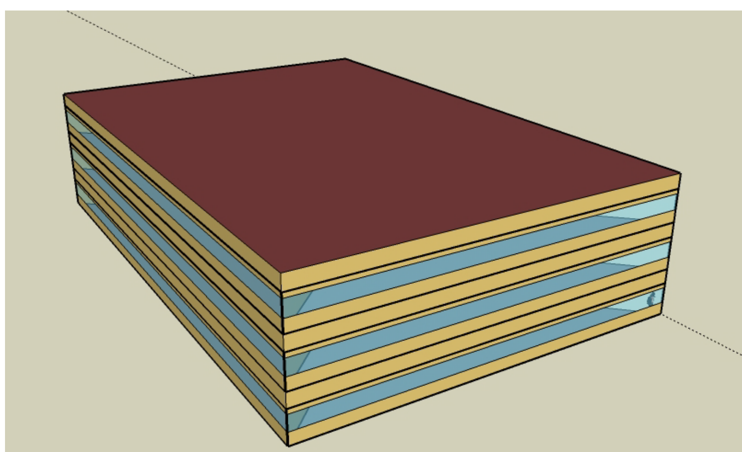

Figure 3.2. Axonometric View of Medium Office Building

The baseline building envelope characteristics were developed to meet the prescriptive design option requirements of ASHRAE 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 properties of materials, layers and construction. This method was 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.

3.2.1 Exterior Walls

The exterior walls of the medium office prototype are steel framed with stucco exterior cladding. There is fiberglass batt insulation within the stud cavity and additional rigid insulation when needed to meet climate zone specific requirements. The exterior wall includes the following layers:

- Exterior air film, R=0.17 $ft^2 \cdot F \cdot h/Btu$ (0.03 $K \cdot m^2/W$)
- 0.75-in. (19 mm) thick stucco, R=0.08 $ft^2 \cdot F \cdot h/Btu$ (0.01 $K \cdot m^2/W$)
- 0.625-in. (16 mm) thick gypsum board, R=0.56 $ft^2 \cdot F \cdot h/Btu$ (0.10 $K \cdot m^2/W$)
- 2-in x 4-in (50 mm x 100 mm) steel studs @ 16-in (400 mm) on center with R=13 $ft^2 \cdot F \cdot h/Btu$ (2.3 $K \cdot m^2/W$) fiberglass batt insulation in stud cavity
- Additional board insulation (varies by climate)
- 0.625-in. (16 mm) thick gypsum board, R=0.56 $ft^2 \cdot F \cdot h/Btu$ (0.10 $K \cdot m^2/W$)
- Interior air film, R=0.68 $ft^2 \cdot F \cdot h/Btu$ (0.12 $K \cdot m^2/W$)

R-values for most of the above layers were derived from Appendix A (*Rated R-Value of Insulation and Assembly U-Factor, C-Factor, And F-Factor Determination)* of the Standard. Insulation R-values were selected to create a wall assembly that just meets the maximum U-value required in Tables 5.5.1 through 5.5.8 of the Standard (ANSI/ASHRAE/IESNA 2004a) for different climate zones.

3.2.2 Roofs

The medium office building prototype uses a flat roof that consists of a roof membrane over rigid insulation, uninterrupted by framing, over a structural metal deck. Roof insulation R-values were also set to match the maximum roof U-value requirements in Tables 5.5.1 through 5.5.8 of the Standard (ANSI/ASHRAE/IESNA 2004a) for different climate zones. The roof construction is defined with the following layers:

- Exterior air film, R=0.17 $ft^2 \cdot F \cdot h/Btu$ (0.03 $K \cdot m^2/W$)
- Continuous rigid insulation (thickness and R-value vary by climate)
- Metal deck, R=0
- Interior air film heat flow up, R=0.61 $ft^2 \cdot F \cdot h/Btu$ (0.11 $K \cdot m^2/W$)

The Standard does not specify either roof reflectivity or emittance. In the baseline prototypes, the roof exterior finish was chosen as a single-ply roof membrane of grey EPDM (ethylene propylene diene terpolymer membrane). From a cool roofing materials database by the Lawrence Berkeley National Laboratory (LBNL 2009), the solar reflectance and the thermal emittance of the EPDM was defined respectively as 0.23 and 0.87.

3.2.3 Slab-On-Grade Floors

The base assembly for the ground floor in the medium office prototype is carpet over 6 in. (150 mm) concrete slab floor poured directly on to the earth (slab-on-grade). Modeled below the slab is 12 in. (300 mm) soil, with soil conductivity of 0.75 Btu/ $ft^2 \cdot F \cdot h$ (1.3 W/m^2K). 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, based on climate. F-factor is expressed as the conductance of the surface per unit length of building perimeter. Chapter 5 of the Standard also provides the corresponding R-values of the vertical insulation when required (e.g., in climate zone 8). This continuous insulation is typically applied directly to the slab exterior, extending downward from the top of the slab for the distance specified in the tables.

One of the advanced features of the *EnergyPlus* program is that the conduction calculations of the ground heat-transfer through ground-contact surfaces (i.e., slab-on-grade floors) are two- or three-dimensional rather than the simplified one-dimensional as in other simulation programs (i.e., *DOE-2).* To use this method, the appropriate ground temperature is determined by the *Slab* program, a preprocessor that is one of the *Auxiliary EnergyPlus* programs. Then the calculated custom monthly average ground temperatures were manually transferred directly into *EnergyPlus* for each of 15 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 set point
- R-value and depth of vertical insulation (if presented)
- Thickness of slab-on-grade
- The floor area to perimeter length ratio for this slab
- Distance from edge of slab to domain edge.

3.2.4 Fenestration

Medium-sized office buildings generally have moderate window-to-wall ratios (WWR), usually in the 20% to 30% range according to the CBECS 2003 data (CBECS 2003). The overall WWR of the entire building used in the modeling was chosen as 33% for the medium office. The windows have an height of 4 ft (1.22 m) and are distributed evenly in continuous ribbons around the perimeter of the building.

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[1], 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 the Standard (ANSI/ASHRAE/IESNA 2004a) for different climate zones.

Based on CBECS, the primary fenestration type in medium office buildings is curtain wall and storefront. The baseline and later the advanced performance values are consistent with these types of window systems. Buildings with fixed frame windows can achieve lower U-factors because of lower frame conductance.

Although window requirements in the Standard are defined by the overall properties of U-factor and SHGC, *EnergyPlus* requires that the thermal/optical properties are defined for the window assembly layer by layer. It is a challenge to manually find a hypothetical window construction that matches given U and SHGC values exactly. To address the above challenge, a simplified strategy was used to find the closest match of a window construction in the *EnergyPlus* window library for given U and SHGC values. In the matching process, a close match to the SHGC value is regarded as a more important criterion for climate

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

zones 1-3, where cooling load is a major consideration. On the other hand, a close match to the U-value is a more important criterion for climate zones 4 through 8, where heating load is the major consideration. Because only a close match can be found, there is a minor deviation between the modeled U and SHGC values and the target values.

Table 3.1 lists the target and actual performance for the selected window constructions in the baseline case. The effects of window frame and dividers are not modeled explicitly.

Table 3.1. Fenestration U-Factor and SHGC Values for the Baseline Models

	Baseline			
	Target Values		Actual Values	
Climate Zone	U-factor Btu/h·ft^2·F (W/m^2·K)	SHGC	U-factor Btu/h·ft^2·F (W/m^2·K)	SHGC
1	1.22 (6.92)	0.25	1.08 (6.13)	0.28
2	1.22 (6.92)	0.25	1.08 (6.13)	0.28
3A, 3B	0.57 (3.23)	0.25	0.51 (2.89)	0.28
3C	1.22 (6.92)	0.34	0.94 (5.33)	0.34
4	0.57 (3.23)	0.39	0.55 (3.12)	0.43
5	0.57 (3.23)	0.39	0.55 (3.12)	0.43
6	0.57 (3.23)	0.39	0.55 (3.12)	0.43
7	0.57 (3.23)	0.49	0.55 (3.12)	0.5
8	0.46 (2.61)	NR	0.48 (2.72)	0.47

In addition to U-factor and SHGC, the simulation accounts for visible light transmittance (VLT). VLT has no direct impact on building loads or energy consumption, and there is no prescriptive requirement for VLT in Standard 90.1. However, VLT will impact the performance of daylighting systems. For the baseline fenestration, VLT values are simply based on the window constructions in the *EnergyPlus* window library that meet the desired U-factor and SHGC.

3.3 Air Infiltration

The Standard does not specify a requirement for maximum air infiltration rate. Building air infiltration is addressed only indirectly in the Standard through the requirements for building envelope sealing, fenestration and door air leakage, etc. For this analysis, the infiltration rate was assumed to be 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 the study by the National Institute of Standards and Technologies (Emmerich et al. 2005).

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 was utilized.

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*:

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 anti-parallel 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/ft^2 (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. The schedule assumes full infiltration when the HVAC system is scheduled "off" and 25% infiltration when the HVAC system is switched "on".

3.4 Internal and External Loads

Internal loads include heat generated from occupants, lights, and miscellaneous equipment (elevator and plug loads such as computers, printers, small beverage machines, etc.). 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 operation 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.

Internal load schedules were developed from schedules previously used in work for the Department of Energy on the Commercial Equipment Standards program. Additional data on occupancy was derived from ASHRAE Standard 62.1-2004 (ANSI/ASHRAE 2004). Figure 3.1 shows a graph of the typical weekday schedule profiles for each of the three internal load categories (plugs, lights and occupancy).

3.4.1 People

The value of the peak occupancy for the medium office building, five persons per 1000 ft^2 (93 m^2) of gross floor area was assumed based on modeling assumptions in the user's manual for ANSI/ASHRAE/IESNA Standard 90.1-2004 (ANSI/ASHRAE/IESNA 2004b). This results in the total of 268 people for the medium office building.

For the computer simulations, the total heat gain is set at 450 Btu/hr (132 W) per person, based on 250 Btu/hr (74 W) sensible heat gain and 200 Btu/hr (58 W) latent heat gain. These values are based on the degree of activity in offices, i.e., standing, light work and walking, and were derived from Table 1 of Chapter 30 in the ASHRAE 2005 Fundamentals Handbook (ASHRAE 2005), and assumes that the occupant activity does not vary with climate.

3.4.2 Interior Lighting

The baseline lighting system is assumed to be a system that just meets the lighting power density requirements of Table 9.5.1, Lighting Power Densities Using the Building Area Method of ASHRAE Standard 90.1- 2004. Ambient lighting power density for the entire building is input at an average of 1.0 W/ft^2 (10.76 W/m^2) for all areas. Standard 90.1 also includes various mandatory interior lighting control requirements including building-wide automatic shutoff and occupancy sensor control in some locations likely to be found in office buildings including conference rooms, meeting rooms, and break rooms. Mandatory controls are not explicitly simulated because the lighting diversity schedule is assumed to have considered these mandatory controls. Figure 3.1 shows the typical weekday lighting schedule with 15% of lights energized during unoccupied hours (also true for weekends and holidays).

3.4.3 Exterior Lighting

The building model assumes exterior lighting on the building façade, at entrances and exits, and for the parking area. Standard 90.1-2004 provides maximum lighting power allowances for each of these areas. The lighting power is based on Watts per lineal foot or Watts per square foot 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. As shown in Table 3.2 the total connected exterior lighting load is calculated as 20.7 kW for the medium office building. 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 percentage of lightened area for each façade. These inputs are from a variety of sources including a building database (Richman et al. 2008), the Internet (e.g., Village of Wheeling 2009) and survey results (Richman 2008).

Table 3.2. Exterior Lighting Power Allowances

Items	Baseline (IP units)	Baseline *(SI units)*
Parking		
parking area, ft^2 (m^2) [1]	87,480	*8,126*
lighting power allowance for parking W/ft^2 (W/m^2)	0.15	*1.6*
total lighting power for parking, W (W)	13,122	*13,122*
Walkways		
walkway area, ft^2 (m^2) [2]	4374	*406*
lighting power allowance for walkway area W/ft^2 (W/m^2)	0.2	*2.2*
total lighting power for walkway area W (W)	875	*875*
Building entrance and exits [3]		
main entries		
linear foot of door width for main entries, ft (m)	16.2	*4.9*
lighting power allowance for main entries W/ft (W/m)	30	*98*
canopy over entry, ft^2 (m^2)	48	*4.5*
lighting power allowance for canopy W/ft^2 (W/m^2)	1.25	*13*
total lighting power for main entries W (W)	546	*546*
other doors		
linear foot of door width for other doors, ft (m)	40.7	*12.4*
lighting power allowance for other doors W/ft (W/m)	20	*66*
canopy over entry ft^2 (m^2)	65	*6.0*
lighting power allowance for canopy W/ft^2 (W/m^2)	1.25	*13.5*
total lighting power for other doors W (W)	895	*895*
total lighting power for building entrance and exits W (W)	1,441	*1,441*
Building facades		
façade area lighted ft^2 (m^2)	21,294	*1,978*
lighting power allowance for building facades W/ft^2 (W/m^2)	0.2	*2.2*
total lighting power for building facades W (W)	4,259	*4,259*
Sum of lighting power for parking, building entrance and facades W (W)	19,697	*19,697*
5% additional allowance W (W)	985	*985*
Total exterior lighting power W (W)	**20,682**	***20,682***

Notes:
1. 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.
2. Walkways are assumed to be 5% of the building square footage. Determined from site plans used in Standard 90.1-2007 addenda *I* analysis.
3. There are about 3.5 doors per 10,000 ft^2 (929 m^2) of building area: one is the main entrance and the rest are other doors. All doors have a width of 3 ft (0.29 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 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 when they are scheduled on and when it is expected to be dark outside.

3.4.4 Miscellaneous Equipment (Plug Loads)

Office buildings generally have appliance (plug) loads, normally associated with office equipment (computers, monitors, copiers, fax machines and printers, etc.); 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 usually increase space cooling energy and reduce space heating energy.

Previous energy analysis work by Pacific Northwest National Laboratory (PNNL 2004) indicates that the peak plug loads for offices range from 0.2 W/ft^2 (2.15 W/m^2) to 0.8 W/ft^2 (8.61 W/m^2), with most falling in the range from 0.6 to 0.8 W/ft^2 (6.46 to 8.61 W/m^2). Off-hour base load lies in the range from 0.0 to 0.4 W/ft^2 (4.31 W/m^2), with many falling near 0.3 W/ft^2 (3.23 W/m^2). To determine the plug load density, a break-down plug load calculations were developed for the medium office building in accordance with ASHRAE's recommended heat gains from various office equipment and appliances (ASHRAE 2005). As shown in Table 3.3, the peak miscellaneous load for the medium office prototype is 0.75 W/ft^2 (8.07 W/m^2). The off-hour load takes the values of 0.30 W/ft^2 (3.23 W/m^2), which is assumed to be 40% of the peak. The above assumption is specified by the user's manual for ANSI/ASHRAE/IESNA Standard 90.1-2004.

The typical office building plug profile is the classic hat-shaped profile, with a single peak period occurring for most of the business hours and a much lower off-hour period (Figure 3.1).

3.5 Baseline Building HVAC Systems

Based on an analysis of CBECS data, it was determined that office buildings with the size of the medium office prototype primarily use packaged rooftop variable air volume (VAV) heating and air conditioning equipment. The study indicated about half of the buildings use gas furnace heat at the main air handler with electric resistance reheat and half use hydronic heat for the main air handler and the reheat coils. Based on the recommendation of ASHRAE Standard 90.1 Mechanical Subcommittee, the gas furnace with electric reheat option was chosen for this prototype.

3.5.1 Building HVAC Operating Schedules

The HVAC system operating schedule is based on the building occupancy. The system is scheduled "on" 1 hour prior to occupancy to pre-condition the space, and the system is scheduled "off" 1 hour after most occupants leave (Figure 3.1). When the system is "on", the fan runs continuously to supply the required ventilation air, while the compressor and furnace cycle on and off to meet the building's cooling and heating loads. During off hours, the system will shut off and only cycle "on" when the setback thermostat control calls for heating or cooling to maintain the setback temperature. A single HVAC system schedule is used for all the packaged units in the building.

Table 3.3. Plug Load Density Calculations for the Baseline Prototype

Occupancy Parameter	**Value**	**Data Source**
Gross floor area, ft^2 (m^2)	54,000 (5,016)	
Office station space ratio	0.5	Richman et al. 2008
Office station space area , ft^2 (m^2)	27,000 (2,508)	
Floor area per workstation , ft^2 (m^2)	100 (10.8)	ASHRAE Handbook Fundamentals 2005
Number of computer workstations	270	
Number of tenants	8	Assumption

Office Equipment Inventory	**Quantity**	**Plug load per unit (W/unit)**	**Plug load (W)**
Computers – servers	8	65	520
Computers – desktop	134	65	8,710
Computers – laptop	134	19	2,546
Monitors – server – LCD	8	35	280
Monitors – desktop – LCD	268	35	9,380
Laser printer – network	8	215	1,720
Copy machine	4	1,100	4,400
Fax machine	8	35	280
Water cooler	8	350	2,800
Refrigerator 18 ft^3 (0.51 m^3) Side Mount Freezer, through-door ice	8	76	608
Vending machine18 ft^3 (0.51 m^3) Side Mount Freezer with through-the-door ice	4	770	3,080
Coffee maker	4	1,050	4,200
Portable HVAC (heaters, fans)	30	30	900
Other small appliances, chargers	250	4	1,000
Total plug load (W)			40,424
Plug load density, W/ft^2 (W/m^2)			**0.75 (8.07)**

Notes:

1. The office workstation space area occupies about 50% of the building area.
2. Each workstation occupies 100 ft^2 (9.3 m^2).
3. There are 8 tenants in the entire building.
4. Each tenant has two computer servers, laser printers, water coolers, and fax machines and one vending machine, one coffee maker and one or two refrigerators.
5. The plug load data is from a previous AEDG study (Jarnagin et al. 2006), with various data resources for the electric equipment including Rivas (2009), Sanchez et al. (2007), and ASHRAE (2009)

3.5.2 HVAC Zoning

The medium office building is also divided into five thermal zones on each of the three floors. The zones are established using a "four and core" approach with each orientation defining a perimeter zone that extends from the exterior wall inward for 15 ft (4.6 m). Each floor is served by an individual HVAC system. Figure 3.3 shows a zoning map of the medium office building.

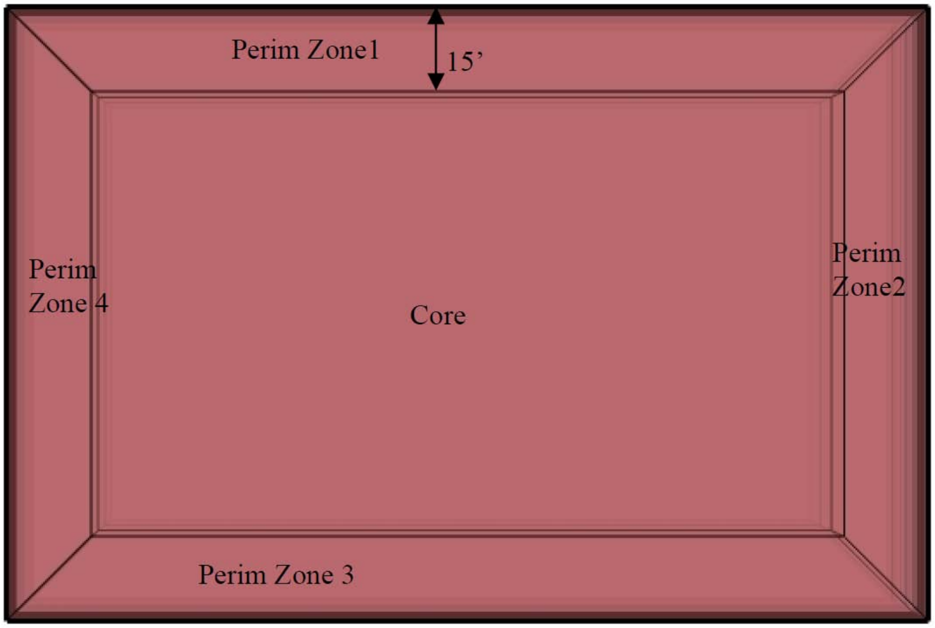

Figure 3.3. HVAC Zoning Map for the Medium Office Building

3.5.3 Heating and Cooling Thermostat Setpoint

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 baseline prototypes, 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.

3.5.4 HVAC Equipment Sizing

HVAC equipment sizing refers to the method used to determine the capacity of the 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.

The design day data for all 16 climate locations were developed based on the “weather data” contained in the accompanying CD-ROM of ASHRAE 2005 Handbook of Fundamentals (ASHRAE 2005). In this data set, heating design day condition is based on the 99.6 annual percentile frequency of occurrence. The 99.6 annual percentile means that the dry-bulb temperature equals or is 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 1% annual cumulative frequency of occurrence in warm conditions. A 1% value of occurrence means that the dry-bulb temperature equals or exceeds the cooling design condition for 88 hours per year. Additionally, the range of the dry-bulb temperature for summer is in compliance with ASHRAE Standard 90.1-2004. 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) were scheduled as zero on the heating design day, and as maximum level on the cooling design day.

3.5.5 HVAC Equipment Efficiency

Standard 90.1-2004 specifies HVAC equipment efficiency based on heating and cooling capacities. For single packaged equipment with cooling capacities less than 65,000 Btu/hr (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). Larger cooling equipment with cooling capacities greater than 65,000 Btu/hr (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/hr to total rate of electric input in Watts at rated conditions.

When determining efficiency requirements, the Standard 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. In *EnergyPlus*, the efficiency of direct expansion 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 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 3.4 shows the cooling efficiency requirements for the HVAC equipment in the small and medium office buildings and the calculated COP for input in the *EnergyPlus* model.

Table 3.4. Single Packaged Air Conditioner Baseline Efficiency

Size Category	Minimum Efficiency from ASHRAE Standard 90.1- 2004	Efficiency as input in *EnergyPlus*
<65,000 Btu/h (<19 kW)[(a)]	9.7 SEER	3.15 COP
65,000 ~ 135,000 Btu/h (19 ~ 40 kW)	10.1 EER	3.50 COP
135,000 ~ 240,000 Btu/h (40 ~ 70 kW)	9.5 EER	3.30 COP
240,000 ~ 760,000 Btu/h (70 ~ 223 kW)	9.5 EER	3.30 COP
≥760,000 Btu/h (≥223 kW)	9.0 EER	3.13 COP

(a) This size category is not applicable for the medium office prototype.

Gas Furnaces less than 225,000 Btu/hr (66 kW) are rated by average fuel utilization efficiency (AFUE), which, like SEER, represents average annual efficiency. The efficiency requirement for these units is 78% AFUE. Furnaces larger than 225,000 Btu/hr (66 kW) must meet an 80% combustion efficiency (E_c).

3.5.6 HVAC System Fan Power

ASHRAE Standard 90.1- 2004 specifies maximum fan power allowances for fans with motors exceeding 5 hp (3.73 kW). Based on system sizing runs, all of the fan systems in the medium office prototype have motors in excess of 5 hp (3.73 kW). In Standard 90.1-2004, the maximum fan power allowance is expressed as a total fan system nameplate horsepower per supply fan airflow in cfm. Fan system power is based on the total of supply fans, return fans, and exhaust fans. Because the medium 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 0.0017 hp /cfm (2.70 kW/m^3/s) for systems with supply air volume less than 20,000 cfm (9.44 m^3/s) and 0.0015 hp / cfm (2.38 kW/m^3/s) for systems with supply air volume greater than 20,000 cfm (9.44 m^3/s). In the Medium Office prototype, there are supply fans both below and above the 20,000 cfm (9.44 m^3/s) threshold depending on served thermal zones and climate locations.

The *EnergyPlus* program simulates fan power by considering three inputs for a variable air volume fan: the design pressure drop through the fan, total fan efficiency, and the motor efficiency. The design pressure drop through the fan can be calculated using the following equation:

Design Pressure Drop = (brake horsepower x fan efficiency x 6356)/cfm

where,

cfm	=	supply fan airflow as determined by *EnergyPlus* sizing runs
fan efficiency	=	65%, based on assumptions used by the ASHRAE Standard 90.1 Committee while developing fan power requirements for the Standard.
brake horsepower	=	brake horsepower is assumed to equal 90% of the maximum nameplate horsepower allowed for the supply cfm by Standard 90.1.

The result of above equation is that the design pressure drop for all systems less than 20,000 cfm (9.44 m^3/s) is input in the *EnergyPlus model* as 6.32 inch water column (1580 Pa) and 5.58 inch water column (1395 Pa) for systems greater than or equal to 20,000 cfm (9.44 m^3/s).

The last required input, motor efficiency, is taken directly from Table 10.8 of Standard 90.1- 2004, based on motor nameplate size, assuming enclosed motors operating at 1,800 rpm.

3.5.7 Outdoor Air Ventilation Rates and Schedules

Outdoor air ventilation requirements used in the base case 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 for offices with HVAC systems that include multiple zones. Initially, 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). Assuming typical office occupancy rates of 5 people per 1,000 square feet (gross), the ventilation rate for the baseline medium office building is 0.085 cfm/ft^2 (4.32E-4 $m^3/s/m^2$) of gross area. This is adjusted for critical zones and ventilation effectiveness resulting in a ventilation rate of 0.1115 cfm/ft^2 (5.66E-3 $m^3/s/m^2$).

For the medium office building in climate zones 4, 5, 6, 7, and 8, Standard 90.1-2004 requires outdoor air systems equipped with motorized dampers that automatically close when the systems served are not in use or when they run to meet night setback or provide morning warm-up. Therefore, in those climate zones, hourly ventilation air schedules were developed in our medium office prototype to simulate a two-step control strategy: 1) during the occupied hours, maintain the outdoor air damper at the minimum intake position, or modulate 100% open if the system operates in the economizer mode; 2) during unoccupied hours, automatically close the outdoor air damper to reduce unnecessary outside air intake into the building. In climate zones 1, 2, and 3, where gravity dampers are allowed by Standard 90.1-2004, the dampers are simulated as being open to minimum position whenever the HVAC system is running, even when the building is unoccupied.

3.5.8 Economizer Use

The baseline HVAC systems are simulated with economizers when required by Standard 90.1- 2004. The Standard does not require economizers if the system cooling capacity is less than 65,000 Btu/hr (19 kW) regardless of climate zone. For cooling capacities greater than 65,000 Btu/hr (19 kW), economizers are required depending on the climate zone and the capacity, as indicated in Table 3.5. The baseline building simulation assumes that the economizer high limit shutoff will be controlled by differential dry-bulb temperature, a control option allowed by the Standard in each of the climate zones simulated. Under this control scenario, when the outdoor air temperature is below both the return air temperature and the high ambient shutoff temperature, the economizer is enabled.

Table 3.5. Economizer Requirements in the Standard 90.1-2004

Climate Zone	Representative City	Economizer Required if Cooling Capacity $\geq$ 65,000 Btu/h (19 kW) and < 135,000 Btu/h (40 kW)	Economizer Required if Cooling Capacity $\geq$ 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

3.6 Service Hot Water System

The baseline service hot water system for the medium office building is defined as a gas-fired storage water heater with a hot water recirculation loop. The equipment meets the minimum equipment efficiency requirements under Standard 90.1-2004. The hot water supply temperature is assumed to be 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:

- the rated storage tank volume
- peak hot water flow rate
- hot water use schedule
- the maximum heater capacity – the heating capacity of the burner used to meet the domestic hot water load and charge the tank
- the standby heat loss coefficient (UA)

- the heater thermal efficiency (E_t) – this is a ratio of heating capacity at full load to gas heat input.

3.6.1 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 268 gallons (1.01 m^3) for the medium office building. From the amount and the profile of daily hot water consumption, the peak hot water flow rate was calculated as 0.832 gpm (0.005 L/s).

3.6.2 Storage Tank Size

The water heater storage tank volume was sized based on the methodology described in the 2007 ASHRAE Applications Handbook (ASHRAE 2007). According to Table 7 of Chapter 49, the maximum hourly hot water demand is about 0.4 gallons (1.5 L) per person. This leads to a peak demand of 107 gallon (0.41 m^3) for the modeled prototype office building. Assuming 70% of the hot water in a storage tank is usable (ASHRAE 2007), the storage tank capacity is sized as 153 gallons (0.58 m^3). Thus, the simulation includes two tanks of 100 gallons (380 L) each.

3.6.3 Rated Input Power and Standby Heat Loss Coefficient

For commercial gas storage water heaters, the minimum performance required is expressed as two values, thermal efficiency (E_t) and the standby loss (SL). A typical input rating for a 100 gallon (380 L) water heater is 199,000 Btu/hr (58 kW). For a water heater with rated input larger than 75,000 Btu/hr (22 kW), the minimum E_t required is 80%. The maximum standby loss SL is 1348.8 Btu/hr (395 W) using following equation required in the Standard:

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

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

Based on commercial water heater manufacturer's equipment specifications, the most common input rating of a 100 gallon (380 L) gas water heater with an input rating of 199,000 Btu/hr (58 kW), is a recovery efficiency of 80%. Furthermore, the standby heat loss coefficient (UA) of the commercial heater was determined using the following equation:

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

where UA = standby heat loss efficient (Btu/hr·°F)
SL = standby heat loss (Btu/hr)
RE = recovery efficiency

70 = difference in temperature between stored water thermostat set point and ambient air temperature at the test condition (°F)

Inserting the appropriate values for SL and RE, results in a UA of 15.414 Btu/hr-°F (8.13 W/K), as one of input variables for the office prototype in the *EnergyPlus* program.

3.6.4 Water Heater Thermal Efficiency

The water heater thermal efficiency E_t was set as 0.80 to match the minimum performance requirement under the Standard for gas storage water heater with rated input ≥ 75,000 Btu/hr (22 kW).

4.0 Development of Advanced Building Model and Assumptions

The advanced building models are developed by adding a number of energy efficiency measures (EEMs) to the baseline building models. The EEM concepts were developed based on a number of resources including the advanced building design guides (Hydeman et al. 2005, Jarnagin et al. 2006), the approved and proposed addenda to ASHRAE Standard 90.1-2007, a High-Performance Building Database (NBI 2008), the authors' professional experiences, and inputs from industry experts. The following two factors were given full considerations in developing EEMs. First, the EEMs should be based on technologies that are commercially available from multiple sources. Second, the EEMs can be modeled directly or via a work-around approach by the current version (v3.0) of the *EnergyPlus* simulation program. 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.
- HVAC measures such as dedicated outdoor air systems, hydronic radiant heating and cooling systems, energy recovery ventilation, high efficiency equipment, and advanced controls.
- Service water heating measures such as higher efficiency equipment.
- Plug load measures such as using ENERGY STAR labeled office equipment and additional power management and controls.

This section describes the EEMs that were implemented in the advanced models 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. In comparison with the baseline, the advanced models incorporate the following building envelope related energy efficiency measures.

4.1.1 Enhanced Insulation for Opaque Assemblies

The advanced insulation requirements for walls and roof are based on the public review draft of Addendum bb to ASHRAE Standard 90.1-2007. Exterior walls are the same steel-framed wall construction type as those in the baseline (see Section 3.3.1) 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. Similarly, roofs have insulation entirely above metal deck construction type (see Section 3.3.2) with enhanced insulation. Table 4.2 shows the roof assembly U-factors and the corresponding rigid insulation R-values.

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.

Table 4.1. Insulation Requirements for Above Grade Steel-Framed Walls

	Baseline		Advanced Model	
Climate Zone	Assembly U-factor Btu/h·ft^2·F (W/m^2/K)	Rated insulation R-value ft^2·F·h/Btu (K·m^2/W)	Assembly U-factor Btu/h·ft^2·F (W/m^2/K)	Rated insulation R-value ft^2·F·h/Btu (K·m^2/W)
1	0.124 (0.705)	R-13.0 (R-2.3)	0.064 (0.365)	R-13.0 + R-7.5 c.i. (R-2.3 + R-1.3 c.i.)
2	0.124 (0.705)	R-13.0 (R-2.3)	0.064 (0.365)	R-13.0 + R-7.5 c.i. (R-2.3 + R-1.3 c.i.)
3	0.124 (0.705)	R-13.0 (R-2.3)	0.064 (0.365)	R-13.0 + R-7.5 c.i. (R-2.3 + R-1.3 c.i.)
4	0.124 (0.705)	R-13.0 (R-2.3)	0.064 (0.365)	R-13.0 + R-7.5 c.i. (R-2.3 + R-1.3 c.i.)
5	0.084 (0.479)	R-13.0 + R-3.8 c.i. (R-2.3 + R-0.7 c.i.)	0.042 (0.240)	R-13.0 + R-15.6 c.i. (R-2.3 + R-2.7 c.i.)
6	0.084 (0.479)	R-13.0 + R-3.8 c.i. (R-2.3 + R-0.7 c.i.)	0.037 (0.212)	R-13.0 + R-18.8 c.i. (R-2.3 + R-3.3 c.i.)
7	0.064 (0.365)	R-13.0 + R-7.5 c.i. (R-2.3 + R-1.3 c.i.)	0.037 (0.212)	R-13.0 + R-18.8 c.i. (R-2.3 + R-3.3 c.i.)
8	0.064 (0.365)	R-13.0 + R-7.5 c.i. (R-2.3 + R-1.3 c.i.)	0.037 (0.212)	R-13.0 + R-18.8 c.i. (R-2.3 + R-3.3 c.i.)

c.i. = continuous insulation

Table 4.2. Insulation Requirements for the Roof with Continuous Insulation Above Deck

Climate Zone	Baseline		Advanced Model	
	Assembly U-factor Btu/h·ft²·F (W/m²/K)	Rated insulation R-value ft²·F·h/Btu (K·m²/W)	Assembly U-factor Btu/h·ft²·F (W/m²/K)	Rated insulation R-value ft²·F·h/Btu (K·m²/W)
1	0.063 (0.360)	R-15 c.i. (R-2.6 c.i.)	0.048 (0.273)	R-20 c.i. (R-3.5 c.i.)
2	0.063 (0.358)	R-15 c.i. (R-2.6 c.i.)	0.039 (0.220)	R-25 c.i. (R-4.4 c.i.)
3	0.063 (0.358)	R-15 c.i. (R-2.6 c.i.)	0.039 (0.220)	R-25 c.i. (R-4.4 c.i.)
4	0.063 (0.358)	R-15 c.i. (R-2.6 c.i.)	0.032 (0.184)	R-30 c.i. (R-5.3 c.i.)
5	0.063 (0.358)	R-15 c.i. (R-2.6 c.i.)	0.032 (0.184)	R-30 c.i. (R-5.3 c.i.)
6	0.063 (0.358)	R-15 c.i. (R-2.6 c.i.)	0.032 (0.184)	R-30 c.i. (R-5.3 c.i.)
7	0.063 (0.358)	R-15 c.i. (R-2.6 c.i.)	0.028 (0.159)	R-35 c.i. (R-6.2 c.i.)
8	0.048 (0.273)	R-20 c.i. (R-3.5 c.i.)	0.028 (0.159)	R-35 c.i. (R-6.2 c.i.)

c.i. = continuous insulation

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 built-up 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 kind of gray EPDM with solar reflectance of 0.23 and thermal emittance of 0.87. Following the *Advanced Energy Design Guide* series (Jarnagin et al. 2006, Liu et al 2007, Jiang et al. 2008), cool roof is used 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 change the window construction to have improved performance in terms of the U-value and the SHGC value. The targeted U and SHGC values are from the public review draft of Addendum bb to 90.1-2007. As noted under the baseline, the analysis is based on the understanding that typical medium office fenestration uses curtain wall or storefront framing systems.

Addendum bb provides values for fixed metal-framed windows distinct from curtain wall or storefront windows other than curtain wall or storefront. In addendum bb, these fixed frame values are less stringent than the U-values for curtain wall and storefront. However, generally curtain wall and storefront systems are not able to achieve as low a U-value as fixed frame windows because of the available framing system conductance. In reviewing the performance values identified in the ASHRAE

Fundamentals 2009 (Chapter 15, Table 4) and industry experience, the fixed frame U-factors in Addendum bb are chosen as appropriate for high performance curtain wall systems (Table 4.3). There are newer curtain wall framing systems available from a few vendors that can achieve very low frame conductance and correspondingly lower overall window U-factors, but these systems have very limited distribution and high cost. In Table 4.3, the baseline U and SHGC values are presented along with the advanced values to facilitate comparison. The baseline values from ASHRAE 90.1-2004 are for all window types, not distinguished by framing type. The U-factor values are overall values for a window assembly including framing elements.

One potential energy efficiency measure not addressed in this document is to reduce the window area. The window-to-wall ratio defined in the baseline is 33% for each facade. Significant energy savings could result from reducing the window-to-wall ratio, in particular for the east and west orientations. This measure was not included in the recommendations because it might trigger significant resistance from architects and developers who believe that a building with larger window areas is more commercially attractive. It may take enforced code changes to make real progress in this area (reduced window-to-wall area maximums are being considered and implemented in development of the 90.1 Standard).

Table 4.3. Fenestration U-factor and SHGC values

	Baseline				Advanced Model			
	Target values		Modeled values		Target values		Modeled values	
Climate Zone	U-factor Btu/h·ft^2·F (W/m^2·K)	SHGC	U-factor Btu/h·ft^2·F (W/m^2·K)	SHGC	U-factor Btu/h·ft^2·F (W/m^2·K)	SHGC	U-factor Btu/h·ft^2·F (W/m^2·K)	SHGC
1	1.22 (6.92)	0.25	1.08 (6.13)	0.28	0.65 (3.69)	0.25	0.51 (2.89)	0.28
2	1.22 (6.92)	0.25	1.08 (6.13)	0.28	0.65 (3.69)	0.25	0.51 (2.89)	0.28
3A, 3B	0.57 (3.23)	0.25	0.51 (2.89)	0.28	0.6 (3.41)	0.25	0.51 (2.89)	0.28
3C	1.22 (6.92)	0.34	0.94 (5.33)	0.34	0.6 (3.41)	0.25	0.51 (2.89)	0.28
4	0.57 (3.23)	0.39	0.55 (3.12)	0.43	0.44 (2.50)	0.26	0.44 (2.50)	0.24
5	0.57 (3.23)	0.39	0.55 (3.12)	0.43	0.44 (2.50)	0.26	0.44 (2.50)	0.24
6	0.57 (3.23)	0.39	0.55 (3.12)	0.43	0.42 (2.38)	0.35	0.42 (2.38)	0.39
7	0.57 (3.23)	0.49	0.55 (3.12)	0.5	0.34 (1.93)	0.4	0.31 (1.76)	0.38
8	0.46 (2.61)	NR	0.48 (2.72)	0.47	0.34 (1.93)	0.4	0.31 (1.76)	0.38

As described in Chapter 3, in the current version of *EnergyPlus*, a window's performance including the U and SHGC values are derived from the glazing layers' solar-optical properties. It is a challenge to manually find a hypothetical window construction that matches given U and SHGC values exactly. To address the above challenge, a simplified strategy was used to find the closest match of a window construction in the *EnergyPlus* window library for given U and SHGC values. In the matching process, a close match to the SHGC value is regarded as a more important criterion for climate zones 1-3, where cooling load is a major consideration. On the other hand, a close match to the U-value is a more important criterion for climate zones 4 through 8, where heating load is the major consideration. Because only a close match can be found, there is a minor deviation between the modeled U and SHGC values and the target values. Table 4.3 also lists the actual performance for the selected window constructions in both baseline and advanced cases. The effects of window frame and dividers are not modeled explicitly.

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 was modeled to have a projection factor of 0.5 and the distance between the overhang and the top of window is 0.66 ft (0.2 m). For this medium office building prototype, the windows have a height of 4.3 ft (1.31 m). Hence, the overhang projects outward from the wall about (0.66+4.3)*0.5 = 2.48 ft (0.75 m).

Vertical fins are effective measures to block low-altitude sunlight for east- and west-oriented facades. However, they are not employed in the design package. This is mainly because the windows are assumed to be continuous ribbons along each orientation. With this assumption, the benefits from vertical fins are limited.

4.2 Lighting

Energy efficient 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 dimming control. The EEMs that address exterior lighting include reduced exterior lighting power allowances and exterior lighting control.

4.2.1 Interior Lighting

4.2.1.1 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. All the information for LPD calculation is presented in Table 4.4, where the baseline LPD calculation is also provided for comparison. Table 4.4 shows that the LPD can be reduced from 1.0 W/ft^2 (10.76 W/m^2) in the baseline to 0.75 W/ft^2 (8.07 W/m^2) in the advanced case.

Table 4.4. Lighting Power Density Calculation for the Advanced Case

Space Type	Percentage of Floor Area[(a)]	Baseline LPD (W/ft^2)	*Baseline LPD (W/m^2)*	Advanced Model: Lighting Systems	Advanced Model: LPD Per Lighting System (W/ft^2)	Advanced Model: LPD (W/ft^2)	Advanced Model: *LPD (W/m^2)*
Office – open plan	16%	1.1	*11.8*	Task Lighting	0.10	0.68	*7.3*
				HP lensed	0.33		
				HP lensed daylight zone	0.20		
				Downlight	0.05		
Office – private	25%	1.1	*11.8*	HP lensed	0.80	0.80	*8.6*
Conference meeting	10%	1.3	*14.0*	Ambient direct/indirect	0.52	0.77	*8.3*
				CFL Downlights	0.47		
				Linear wall washing	0.25		
Corridor/Transition	10%	0.5	*5.4*	90.1-2004 design with HP lamps and ballasts	0.50	0.50	*5.4*
Active storage	15%	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	3%	1.2	*12.9*	HP lensed	0.73	0.73	*7.9*
Electrical/Mechanical	3%	1.5	*16.1*	90.1-2004 design with HP lamps and ballasts	1.24	1.24	*13.3*
Stairway	2%	0.6	*6.5*	90.1-2004 design with HP lamps and ballasts	0.60	0.60	*6.5*
Lobby	6%	1.3	*14.0*	90.1-2004 design Modified	1.09	1.09	*11.7*
				Linear cove (20%)			
				CFL pendant (30%)			
				CFL downlight (50%)			
Other	6%	1.0	*10.8*	90.1-2004 design with HP lamps and ballasts	0.82	0.82	*8.8*
Weighted LPD for the whole building	**100%**	**1.0**	***10.8***			**0.75**	***8.1***

(a) 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).

4.2.1.2 Occupancy Sensor Control

Occupancy sensor control is included in the simulation for the advanced building models. To model occupancy sensor control, the peak lighting power density was reduced by 15% as supported in previous studies (Jarnagin et al. 2006; Jiang et al. 2008). In this work, a detailed analysis was made to quantify the potential of energy savings as a result of occupancy sensor control. Table 4.5 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. The orange shaded rows indicate the spaces or the parts of lighting systems that use occupancy sensor control in the advanced case but not in the baseline. After calculation, it is found that because of the increased use of occupancy sensors, the advanced case has about 16.8% less lighting energy use than the baseline. Thus, in the *EnergyPlus* models for advanced cases, the peak lighting power density is reduced by 16.8%, and this reduction applies for weekdays only. Figure 4.1 shows the comparison of weekday lighting schedules between the baseline without occupancy sensors and the advanced case with occupancy sensor.

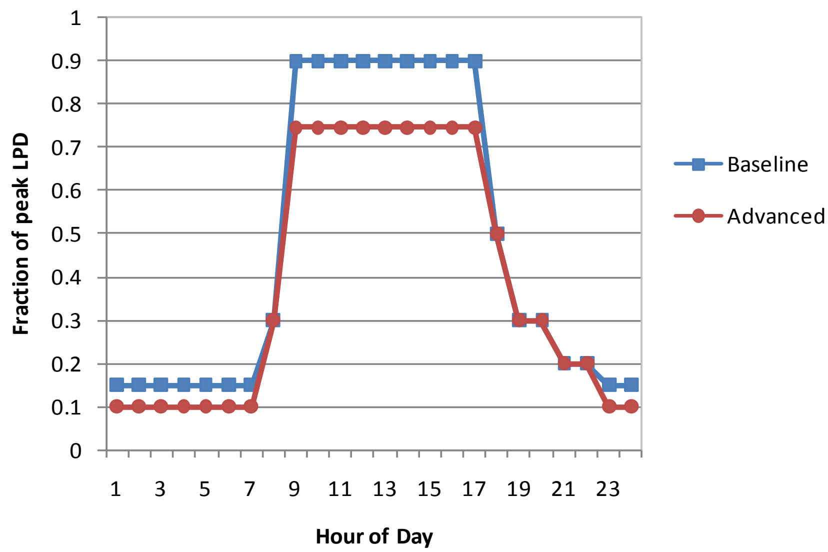

Figure 4.1. The Change of Interior Lighting Schedules from Occupancy Sensors

Table 4.5. Lighting Energy Saving from the Increased Use of Occupancy Sensors

Space Type	Area (%)	Lighting Systems	Lighting Control Strategy: Baseline	Lighting Control Strategy: Advanced	Lighting power controlled by occupancy sensors (%)	Lighting energy savings due to occupancy sensor (%)	Remarks
Office- open plan	16	task lighting	time sweep	occupancy sensor	7	29	(a)
		downlighting	time sweep	time sweep			
		ambient/ uplight	time sweep	photosensor/ time sweep			
		ambient/ daylight zone	time sweep	photosensor/ personal dimming			
Office- private	25	ambient	time sweep	occupancy sensor	100	33	(b,c)
Conference meeting	10	ambient direct/ indirect	occupancy sensor	occupancy sensor	0	0	
		linear wall washing	occupancy sensor	occupancy sensor			
Corridor/ Transition	10	standard design	time sweep	time sweep	0	0	
Active storage	15	standard design	time sweep	occupancy sensor	100	40	(d)
Restrooms	4	standard design	time sweep	occupancy sensor	100	26	(b)
Lounge/Recreation	3	standard design	occupancy sensor	occupancy sensor			
Electrical/Mechanical	3	standard design	time sweep	occupancy sensor	100	40	(d)
Stairway	2	standard design	time sweep	time sweep	0	0	
Lobby	6	standard design	time sweep	time sweep	0	0	
Other	6	standard design	time sweep	time sweep	0	0	
Total lighting energy savings from occupancy sensor control						**16.8%**	

(a) Data from Galasiu et al. (2007)
(b) Data from VonNeida et al. (2000)
(c) DiLouie (2009)
(d) Data from LRC (2003)

4.2.1.3 Improved Interior Lighting Power Management

The lighting power management is improved in the advanced cases including greater use of occupancy sensors, as described in 4.2.1.2. The occupancy sensors are estimated to provide additional savings relative to sweep automated lighting controls in the baseline beyond that provided by the 16.8% reduction used in 4.2.1.2. Minimizing egress lighting, and locking out all use of egress lighting once a security system identifies a building is unoccupied will also reduce lighting during unoccupied hours. Adoption of occupancy sensors and for some buildings 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).

4.2.1.4 Daylight Harvesting

Daylight harvesting takes advantage of the available daylight to reduce electrical lighting energy consumption while maintaining desired levels of illumination. In the current development of the advanced models, only side daylighting was considered for the perimeter open office zones. No attempt was made to optimize glazing specifications or window layout, which is to be considered in future work. The daylighting dimming control was modeled in *EnergyPlus* with the following assumptions:

- The daylight zone extends 8 ft (2.5 m) inward from the exterior walls (the assumed depth of one workstation).
- The lighting sensor lies at the center of each perimeter zone in the ceiling.
- In the daylight zones (perimeter open office zones), The ambient lighting system is dimmed in response to daylight. This was modeled in *EnergyPlus* by setting 75% of each daylight zone subject to dimming control.
- The dimming control system has an illuminance setpoint of 28 footcandles (300 lux) average for the space. 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.

4.2.2 Exterior Lighting

4.2.2.1 Reduced Exterior Lighting Power Allowances

For the medium 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 was calculated according to the lighting power allowances prescribed by Addendum I to 90.1-2007. In comparison, the baseline exterior lighting power was set at the lighting power allowed by 90.1-2004. The major differences between these two approaches are as follows:

- The advanced case allows a base site allowance of 750 watts while the base case includes an additional unrestricted allowance equal to 5% of the sum of the individual exterior power density.
- The lighting power allowance for building facades is reduced in the advanced case to 50% of the Addendum I to 90.1-2007 allowance because façade lighting is a purely decorative effect and should be eliminated or reduced in buildings attempting to save energy. Façade lighting that is installed is assumed to be programmed to turn off between the hours of midnight and 5 AM.

Table 4.6 shows the components of the exterior lighting power allowances for both the baseline and the advanced cases. 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. 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. These inputs are from a variety of sources including a building database (Richman et al. 2008), Internet (e.g., Village of Wheeling 2009) and survey results (Richman 2008).

4.2.2.2 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. 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 4.6. Exterior Lighting Power Allowances

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)]	87,480	*8,126*	87,480	*8,126*
lighting power allowance for parking W/ft^2 (W/m^2)	0.15	*1.6*	0.10	*1.1*
total lighting power for parking, W (W)	13,122	*13,122*	8,748	*8,748*
Walkways				
walkway area, ft^2 (m^2) [(b)]	4374	*406*	4374	*406*
lighting power allowance for walkway area W/ft^2 (W/m^2)	0.2	*2.2*	0.16	*1.7*
total lighting power for walkway area W (W)	875	*875*	700	*700*
Building entrance and exits [(c)]				
main entries				
linear foot of door width for main entries, ft (m)	16.2	*4.9*	16.2	*4.9*
lighting power allowance for main entries W/ft (W/m)	30	*98*	30	*98*
canopy over entry, ft^2 (m^2)	48	*4.5*	48	*4.5*
lighting power allowance for canopy W/ft^2 (W/m^2)	1.25	*13*	0.4	*4*
total lighting power for main entries W (W)	546	*546*	505	*505*
other doors				
linear foot of door width for other doors, ft (m)	40.7	*12.4*	40.7	*12.4*
lighting power allowance for other doors W/ft (W/m)	20	*66*	20	*66*
canopy over entry ft^2 (m^2)	65	*6.0*	65	*6.0*
lighting power allowance for canopy W/ft^2 (W/m^2)	1.25	*13.5*	0.25	*2.7*
total lighting power for other doors W (W)	895	*895*	830	*830*
total lighting power for building entrance and exits W (W)	1,441	*1,441*	1335	*1,335*
Building facades[(d)]				
façade area lighted ft^2 (m^2)	21,294	*1,978*	21,294	*1,978*
lighting power allowance for building facades W/ft^2 (W/m^2)	0.2	*2.2*	0.075	*0.8*
total lighting power for building facades W (W)	4,259	*4,259*	1,597	*1,597*
Sum of lighting power for all categories W (W)	19,697	*19,697*	12,380	*12,380*
5% additional allowance W (W)	985	*985*	-	-
Total exterior lighting power W (W)	**20,682**	***20,682***	**13,130**	***13,130***

(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 building square footage. Determined from site plans used in the analysis of Addendum I to 90.1-2007.

(c) There are about 3.5 doors per 10,000 ft^2 (929 m^2) of building area, one of which is the main entrance and the rest are other doors. All doors have a width of 3 ft (0.29 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 purely decorative effect and should be eliminated or reduced in buildings attempting to save energy.

4.3 Miscellaneous Equipment (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 go higher as the building becomes more energy efficient. In the baseline medium office building models, miscellaneous electric equipment accounts for between 21% and 34% of total building energy use, depending on climate zone. In addition to their own electric energy requirement, 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 appliance 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, except for the mix of computers (see Section 3.5.4). 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.

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

1. Shift towards a higher proportion of laptop computers relative to desktop computers – In the baseline, half the computers at workstations are desktop computers and half are laptop computers. The advanced case includes one third desktop computers and two thirds laptop computers. Laptop computers have lower power demand and better power management and use less energy. This is reflected in the quantity of computers of each type in Table 4.7.
2. Use of ENERGY STAR equipment including computers, monitors, printers, copy machines, fax machines, water coolers, and refrigerators – This is reflected in reduction in the power wattage of each device in proportion to the ENERGY STAR percentage savings. Note that vending machines are addressed in the control strategies in the next item.
3. Use of additional control software and equipment to further reduce energy usage beyond those required for ENERGY STAR and for equipment not covered by the ENERGY STAR label – Additional controls result in further energy savings incorporated into the equipment usage schedules in the advanced models. The starting point for these reductions is the wattage determined from the previous two strategies. Table 4.8 shows the estimated energy reductions and the resulting adjusted schedule for the advanced cases.
    a. Power management software for networked computers
    b. Occupancy sensor controlled outlets including use of plug strips or whole room occupancy control (in conjunction with lighting) to control monitors, portable HVAC, and miscellaneous small appliances
    c. Vending Miser occupancy sensor control

d. Timer switches for coffee makers and water coolers

Table 4.7. Plug Load Calculation for the Advanced Case without Additional Controls

Plug Load Equipment Inventory	Baseline Quantity	Baseline Plug load, each (W)	Baseline Plug load (W)	Advanced Quantity	Advanced Plug load, each (W)	Advanced Plug load (W)
Office Equipment						
Computers – servers	8	65	520	8	54	432
Computers – desktop[a]	134	65	8,710	89	54	4,806
Computers – laptop[a]	134	19	2,546	179	17	3,043
Monitors – server – LCD	8	35	280	8	24	192
Monitors – desktop – LCD	268	35	9,380	268	24	6,432
Laser printer – network	8	215	1,720	8	180	1,440
Copy machine	4	1,100	4,400	4	500	2,000
Fax machine	8	35	280	8	17	136
Water cooler	8	350	2,800	8	193	1,544
Refrigerator	8	76	608	8	65	520
Vending machine	4	770	3,080	4	770	3,080
Coffee maker	4	1,050	4,200	4	1,050	4,200
Portable HVAC (heaters, fans)	30	30	900	30	30	900
Other small appliances, chargers	250	4	1,000	250	4	1,000
Total plug load (W)			40,424			29,725
Plug load density, W/ft^2 (W/m^2)			**0.75 (8.07)**			**0.55 (5.92)**

(a) Assumes shift towards higher proportion of laptops instead of desktop computers in advanced from earlier equipment power density.

<u>Strategy 1-Shift towards laptop computers</u> One way to significantly reduce energy from computers is to move towards laptop computers. This may also be a precursor to a potential movement to simpler terminal units that operate primarily from web and network-based software. 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 4.7 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 Table 3.3 to calculate the plug load in Table 4.7. 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 number of 35 W represents a conventional fax machine's plug load in Table 3.3.

- For laptop computers, although there are ENERGY STAR labeled products, no savings calculator was 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 0.75 W/ft^2 (8.07 W/m^2) in the baseline to 0.55 W/ft^2 (5.92 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 26.5% reduction in plug load energy usage. Note that plug load energy reduction interacts with HVAC energy usage so the effective percentage reduction in energy may be different 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 monitors and other equipment at workstations and other office areas, 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 4.8 shows the estimated energy reductions. Reductions in energy for these strategies will not occur evenly throughout the day and will be largest during periods when occupancy is low or none. Table 4.9 shows how the energy usage is captured by altering the schedule, particularly during low or no occupancy periods. This strategy reduces total plug energy usage by an additional 18.8% below that achieved by the first two strategies that directly reduced the power per square foot. This results in an additional 13.7% from total plug energy. Note that plug load energy reduction interacts with HVAC energy usage so the effective percentage reduction in energy may be different in the complete energy usage for each model.

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. 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. The estimates in Table 4.8 are based on several sources (Sanchez et al. 2007, Rivas 2009, EPA 2009). The schedule reductions in Table 4.9 by time period are estimated to achieve the same level of savings as that determined in Table 4.8, weighted towards low and no occupancy hours. The baseline schedule is shown for comparison.

Table 4.9 shows the schedule that is used for the baseline, and then is modified to apply to the advanced case plug load power as determined in Table 4.7. The weighted by time period columns estimate 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 4.8. Estimated Additional Reduction in Plug Loads Energy Usage with Controls

Plug Load Equipment Inventory	Advanced, with shift to laptops and ENERGY STAR				Reductions in Plug Loads with Controls	
	Qty.	Plug load per unit (W/unit)	Plug load (W)	% of total watts	Estimated Reduction %	Reduction in total plug energy, %
Office Equipment						
Computers – servers	8	54	432	1.5	0.0	0.0
Computers – desktop	89	54	4,806	16.2	25.0	4.0
Computers – laptop	179	17	3,043	10.2	7.5	0.8
Monitors – server – LCD	8	24	192	0.6	0.0	0.0
Monitors – desktop – LCD	268	24	6,432	21.6	7.5	1.6
Laser printer – network	8	180	1,440	4.8	0.0	0.0
Copy machine	4	500	2,000	6.7	0.0	0.0
Fax machine	8	17	136	0.5	0.0	0.0
Water cooler	8	193	1,544	5.2	20.0	1.0
Refrigerator	8	65	520	1.7	0.0	0.0
Vending machine	4	770	3,080	10.4	50.0	5.2
Coffee maker	4	1,050	4,200	14.1	20.0	2.8
Portable HVAC (heaters, fans)	30	30	900	3.0	50.0	1.5
Other small appliances, chargers	250	4	1,000	3.4	50.0	1.7
Plug load density W/ft^2 (W/m^2)			**0.55 (5.92)**	**100.0**		**18.7**

Table 4.9. Changes in Plug Equipment Schedules with Added Controls

Schedule Periods		Without Controls			With Controls			Reduction	
		Schedule without controls	Weighted by time period	Share of total plug load, %	Schedule with controls	Weighted by time period	Share of total plug load, %	Schedule %	Total plug loads, %
Weekdays									
Until:	8:00	0.4	16.0	27.7	0.3	12.0	25.5	25	6.9
Until:	12:00	0.9	9.9	17.1	0.85	9.4	19.9	6	1.0
Until:	13:00	0.8	2.2	3.8	0.75	2.1	4.4	6	0.2
Until:	17:00	0.9	9.9	17.1	0.85	9.4	19.9	6	1.0
Until:	18:00	0.5	1.4	2.4	0.45	1.2	2.6	10	0.2
Until:	24:00	0.4	6.6	11.4	0.3	5.0	10.5	25	2.9
Saturday									
Until:	6:00	0.3	1.0	1.7	0.2	0.7	1.4	33	0.6
Until:	8:00	0.4	0.4	0.8	0.3	0.3	0.7	25	0.2
Until:	12:00	0.5	1.1	1.9	0.35	0.8	1.6	30	0.6
Until:	17:00	0.35	1.0	1.7	0.25	0.7	1.5	29	0.5
Until:	24:00	0.3	1.2	2.0	0.2	0.8	1.6	33	0.7
Sunday/Hol.									
Until:	24:00	0.3	7.2	12.5	0.2	4.8	10.2	33	4.2
Total			57.8	100.0		47.0	100.0		18.8

4.4 HVAC Systems

To achieve the 50% energy saving goal, the packaged VAV system was replaced by a dedicated outdoor air system (DOAS) in combination with a hydronic radiant cooling and heating system. This section presents the system setup and the related energy efficiency measures for both the DOAS and the radiant thermal system.

4.4.1 Dedicated Outdoor Air System

In this study, the DOAS is used to condition and deliver the required outdoor ventilation air to each individual zone. It is also used to address the outdoor and space latent cooling loads. As mentioned in Mumma (2001) and Jeong et al. (2003), a DOAS combined with a parallel mechanical system has the following two major advantages in comparison with a conventional VAV system:

- DOAS can ensure that the required amount of outdoor ventilation air is distributed to every space, while a conventional VAV system cannot easily meet the ventilation requirement for all spaces. The difficulty of meeting ventilation requirement for conventional VAV systems has been observed in the baseline model. It was found that even after the VAV terminal box minimum settings were increased from 0.3 up to 0.7 for some zones, there are still many hours with insufficient supply of ventilation air.
- DOAS has more potential to save energy than a conventional VAV system. The great energy saving potential of DOAS comes from two aspects. First, it removes the necessity of excess outdoor air flow or system supply air flow, which is normally required for a conventional VAV system to meet ASHRAE Standard 62.1-2004. Thus, DOAS can save the energy used for processing that excess amount of air flow. Second, DOAS uses less energy for terminal reheating than a conventional VAV system. Because ventilation air is only part of the supply air for a conventional VAV system, the supply air flow rate to each space is larger than that for a DOAS. This means that a VAV system consumes more terminal reheating energy than a DOAS supplying air at the same temperature.

Different configurations of DOAS are available and have been studied in 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) consisting of a preheat coil, an enthalpy wheel, a deep cooling coil and a sensible heat exchanger (e.g., a sensible wheel) performs best. 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 about 1-7% more energy saving than the simple DOAS setup.

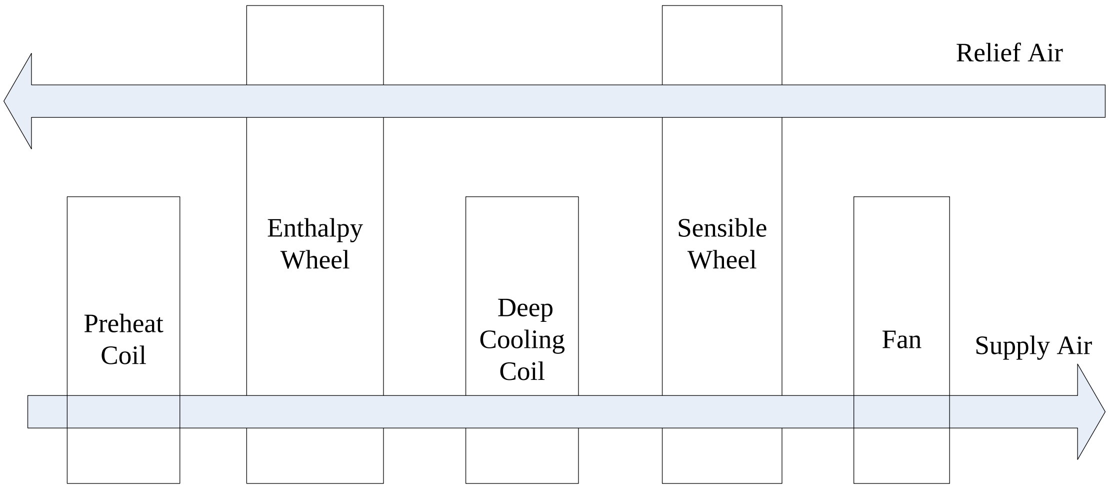

Figure 4.2. DOAS With Dual Wheels and Deep Cooling Coil

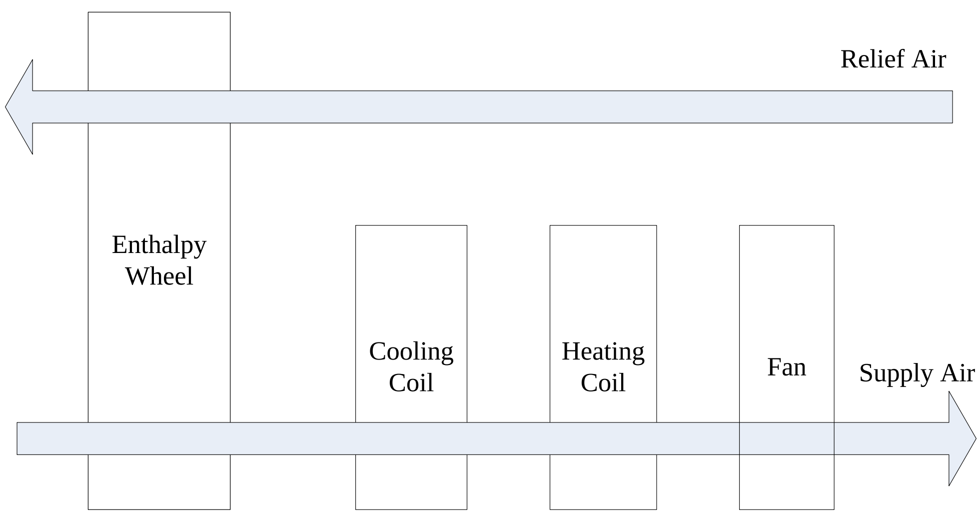

Figure 4.3. DOAS With Enthalpy Wheel, Conventional Cooling Coil and Heating Coil

Two alternative DOAS configurations are employed in this study depending on climate zones. For hot and humid climate zones (1A, 2A, 3A, and 4A), the DOAS configuration shown in Figure 4.2 is used. For other climate zones, the DOAS shown in Figure 4.3 is used and it consists of an enthalpy wheel, a cooling coil and a heating coil. The DOAS operates with the following major points:

- For the climate zones from 1A to 3C, the DOAS supply air temperature is maintained at 55°F (12.8°C). For other climate zones (from 4A to 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 at 62°F (16.7°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 64°F (18°C) and 50°F (10°C).

- DX cooling coil is used for cooling in the considered DOAS configurations. For the configuration shown in Figure 4.2, deep cooling is employed with the temperature after cooling coil set at 45°F (7.2°C). For the configuration shown in Figure 4.3, deep cooling is not employed and the temperature after cooling coil is set by accounting for the system supply air temperature setpoint and the temperature rise caused by fan energy input. Deep cooling is not necessary for those climate zones not represented as hot and humid. This has been verified by investigating the simulation results for Chicago in climate zone 5A: *EnergyPlus* simulation program shows that the humidity ratio lies in the comfort zone for almost all occupied hours and there is almost no surface condensation on the radiant floor.

- Energy recovery ventilation (ERV) is an energy efficient 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. Offsetting the savings from the ERV is an increase in 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 1.5 in. w.c (375 Pa) and a parasitic power of 200 W. Table 4.10 shows the rated performance of the energy recovery ventilators from the product catalogues. Because ERV involves a trade off between reduced heating/cooling coil energy and the additional energy consumption by the supply fan and the rotary wheel motor, parametric simulation runs were pursued to investigate whether ERV has net energy savings. It is found that ERV has net energy savings in all climate locations except Los Angeles (climate zone 3B-CA) and San Francisco (zone 3C). Therefore, ERV is used in all climate zones except 3B-CA and 3C.

Table 4.10. Rated Performance of the Energy Recovery Ventilators

	Effectiveness		
Condition	Sensible	Latent	Total
heating @ 100% air flow	68	61	65
heating @ 75% air flow	72	67	71
cooling @ 100% air flow	68	61	64
cooling @ 75% air flow	72	67	70

- The air temperature after the enthalpy wheel is controlled to avoid overheating of the outdoor air. This was achieved in *EnergyPlus* with an outdoor air pretreat setpoint manager. This setpoint manager determines the desired temperature in the outdoor air stream by accounting for the mixed air setpoint and the mixing air conditions.

- Preheating coil is not explicitly used in the DOAS to avoid frost formation on the enthalpy wheel. Instead, the frost control was achieved by monitoring the temperature of the secondary air leaving the enthalpy wheel. If the exhaust air temperature is below the minimum setpoint of 1.7°C, the enthalpy wheel rotation will slow down with reduced heat exchanger effectiveness. Frost control is modeled with the minimum exhaust air temperature solely for the purpose of simplicity because no preheating coil needs to be added to the DOAS.

It needs to be mentioned that the dual wheel DOAS system (Figure 4.2) cannot be modeled properly in *EnergyPlus* version 3.0. The major difficulty lies in the lack of supply air temperature control for a sensible wheel. Thus, whenever the sensible wheel is in operation, the DOAS supply air temperature goes out of control. To address this problem, the dual wheel DOAS system is simulated in *EnergyPlus* by replacing the sensible wheel with an electric heating coil. With this change, the dual wheel DOAS turns into the same configuration as Figure 4.3 except for the use of a deep cooling coil. This changed DOAS can be modeled in *EnergyPlus*. However, part of the heating coil energy is consumed to heat up the deep cooled air to the system supply air temperature. This situation occurs only in cooling season and that part of heating energy could have been avoided by using a sensible wheel. Thus, for the dual wheel DOAS configuration, the work-around solution may result in underestimated energy savings than the actual design.

4.4.2 Radiant Heating and Cooling System

Initially, the analysis work for medium office proposed to achieve 50% energy savings with VAV systems. It became clear later that the advanced VAV system, along with the rest of the energy measures, would not be adequate to reach 50% in all climate locations. Within this context, hydronic radiant heating and cooling was proposed as an alternative to replace the baseline VAV system. In comparison with the conventional VAV system, the hydronic radiant thermal system has the following major advantages. First, the radiant system can significantly reduce fan energy because it uses water instead of air as the medium for energy transfer. Transporting water via pumps is much more energy efficient than transporting air via fans. Second, the radiant system usually reduces heating and cooling energy because the low temperature hot water and high temperature cold water are helpful to improve the heating and cooling efficiency of the corresponding equipment. Third, the radiant system has the potential to improve occupants' thermal comfort.

Radiant system design and application are still in development in the United States, while they are more widely adopted in Europe. Unlike VAV systems, there is no well established radiant system design. Building surfaces used in a radiant system can be floors, ceilings, and walls, though the first two are most commonly applied. Different radiant surfaces have different heating and cooling capacities. A radiant floor system has a larger heating capacity than its cooling capacity because radiant floor heating has a larger heat exchange coefficient between the floor and the space than radiant floor cooling. According to Babiak et al. (2009), a radiant floor system normally has a maximum heating capacity of about 100 W/ft^2 (1075 W/m^2) and a maximum cooling capacity of about 40 W/ ft^2 (430 W/m^2). In areas exposed to direct sunlight, the radiant cooling capacity can increase up to 100 W/ ft^2 (1075 W/m^2). However, floor carpets may reduce the heating and cooling capacity by as much as 50%. In contrast to a radiant floor system, a radiant ceiling has a maximum heating capacity of about 40 W/ ft^2 (430 W/m^2) and a maximum heating capacity of about 100 W/ ft^2 (1075 W/m^2) (Babiak et al. 2009). Whatever radiant surface is used, unmet heating or cooling load may be supplemented by decentralized conventional air systems or dedicated outdoor air systems.

A hydronic radiant floor system is selected for both heating and cooling in this study. The radiant floor system is used because it can be modeled in a straightforward way in *EnergyPlus*. Although a radiant floor system may not be appropriate for some locations due to its cooling capacity or cost effectiveness issues, it is expected that the findings from the radiant floor system could provide a reasonable general evaluation of the energy saving potential of radiant systems.

The modeled radiant floor system has the following major features:

- Water tubes made of cross-linked polyethylene are embedded in the screed for heating and cooling (Babiak et al. 2009). Figure 4.4 and 4.5 illustrates the construction for the slab-on-grade floor and the floating floor, respectively. A number of simulation runs are used to determine a suitable floor insulation level. Thus, different thicknesses were tried for the expanded polystyrene insulation and the one beyond which no noticeable energy savings can be observed is selected. For the slab-on-ground floor, there are two different insulation levels depending on the climate zone: expanded polystyrene with a thickness of 1.5 inch (38 mm) is used for climate zones 3A, 4A, 5A, 7 and 8, whereas a thickness of 1inch (25 mm) is used in other climate zones. For the floating floor, a thickness of 1inch (25 mm) is used for all climate zones.

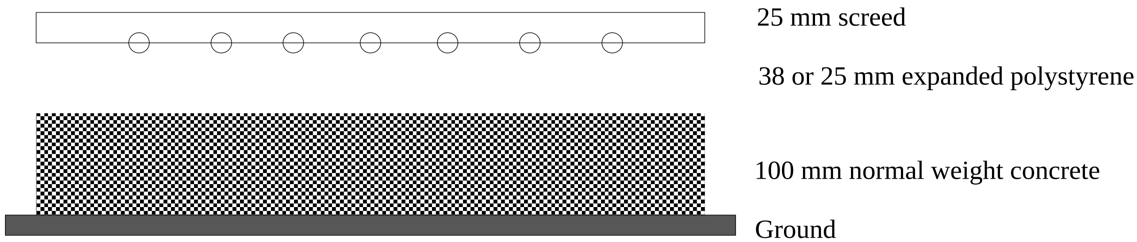

Figure 4.4. Slab-on-Grade Floor Construction

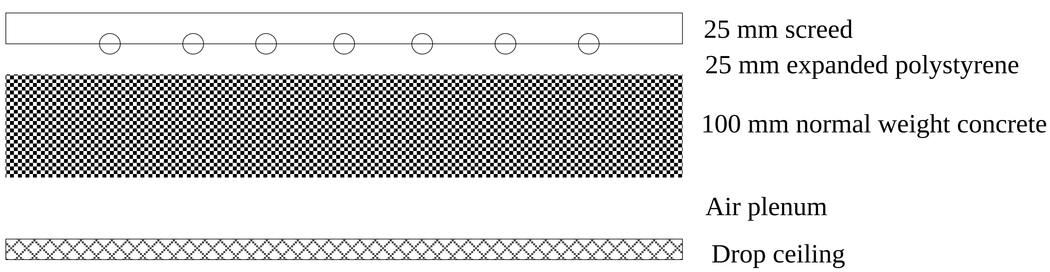

Figure 4.5. Floating Floor Construction

- A condensing boiler and an air-cooled chiller are used, respectively, to provide hot water and chilled water to the radiant floor system. The supply hot water temperature is 113°F (45°C) and the supply chilled water temperature is 59°F (15°C). The supply water temperatures are thus set with two major considerations. First, the floor surface temperature must lie in the comfort range: the maximum surface temperature is 84°F (29°C) for heating and the minimum temperature is 66°F (19°C) for cooling (Olesen 2002, 2008). Second, the temperature is set to avoid surface condensation in cooling seasons.

- Variable flow/fixed temperature is the strategy used to control the radiant system in all thermal zones. This control is accomplished by defining a setpoint and a throttling range for the chosen temperature type (i.e., mean air temperature and operative temperature). The flow rate varies linearly to a thermal zone. It reaches the maximum when the controlled temperature gets above (for cooling) or below (for heating) the setpoint by half of the throttling range. There is no flow when the controlled temperature gets below (for cooling) or above (for heating) the setpoint by half of the throttling range. In the advanced models, mean air temperature is used to control the water flow rate of the radiant system, and it has a throttling range of 3.6°F (2°C). Figure 4.6 shows the mean air temperature setpoint used to control the water flow rate.

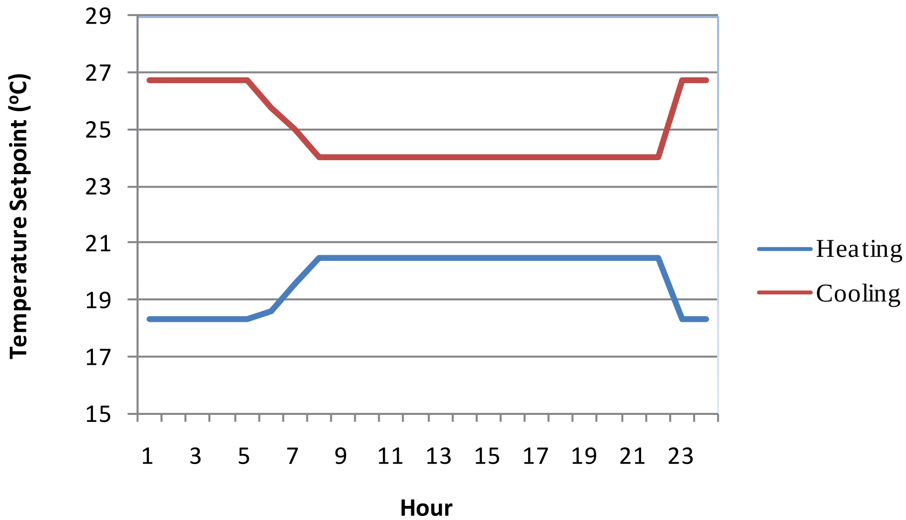

Figure 4.6. Weekday Schedule of the Mean Air Temperature Setpoint

Occupants' thermal comfort in office buildings mainly depends on operative temperature, which is basically the average of air temperature and mean radiant temperature. In comparison with the VAV system, the radiant system has a lower floor surface temperature for cooling and a higher surface temperature for heating. This means that the radiant system can achieve the same level of operative temperature at a lower air temperature for heating and a higher air temperature for cooling (Olesen 2002 and Babiak et al. 2009). Therefore, in the advanced models, the thermostat setpoint is decreased from 70°F (21°C) to 67°F (19.6°C) for heating. The cooling setpoint is not increased, and it maintains at 75°F (24°C). This is mainly because solar radiation can substantially increase the cooling load in east- and west- oriented perimeter zones in a short period of time. Increasing cooling setpoint poses a further challenge for thermal comfort in those zones.

Simulations show that the maximum radiant floor heating capacity is not exceeded except for a few perimeter zones on the top floor in cold climates. However, it is found that radiant floor system cooling capacity is often not sufficient to meet the cooling load for east- and west-oriented perimeter zones with a large window area (recall that a window-to-wall ratio of 0.33 is used in the medium office building prototype). As a result, those perimeter zones have their mean air temperature above the cooling setpoint for many time steps. Despite the above unmet cooling setpoint issue, the radiant floor system is capable of maintaining a comparable operative temperature in east- and west-oriented perimeter zones as those for the baseline VAV system.

4.4.3 Premium HVAC Equipment Efficiency

The advanced models cover the following premium HVAC equipment: the packaged air conditioner for the DOAS, fan motors, the air-cooled chiller, and the gas-fired boiler.

The premium air conditioner is selected from the updated product engineering catalogue databases maintained by California Energy Commission (CEC 2009). In the selection process, attention has been paid to make sure that the selected efficiency represents the products from at least two manufacturers. Table 4.11 lists the selected higher cooling efficiency in terms of SEER or EER. Since 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 3.6.5. The efficiency of the gas furnace for central heating in the packaged units is not improved in the current stage. Packaged units with higher gas furnace efficiency may be explored in future work.

Table 4.11. Higher Efficiency for Packaged Unitary Air Conditioners for the Advanced Case

Size Category	Efficiency (SEER/EER)	*EnergyPlus* Input (COP)
<65,000 Btu/h (<19 kW)	13.5 SEER	4.02
65,000 ~ 135,000 Btu/h (19 ~ 40 kW) [(a)]	11.5 EER	3.97
135,000 ~ 240,000 Btu/h (40 ~ 70 kW) [(a)]	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
≥760,000 Btu/h (≥223 kW)	9.5 EER	3.30

(a) The size range applies to the DOAS in this work

The improved motor efficiency is based on the premium-efficiency motors initiative launched by the Consortium for Energy Efficiency (CEE 2003). Table 4.12 lists the motor efficiency requirement together with the corresponding nameplate motor horsepower. The values in the table assume enclosed motors operating at 1,800 rpm.

Table 4.12. Improved Motor Efficiency

Motor hp (kW)	1 (0.7)	2 (1.5)	5 (3.7)	10 (7.5)	15 (11.2)	20 (14.9)	30 (22.4)	40 (29.8)	50 (37.3)	60 (44.7)	125 (93.2)	150 (112)	200 (149)
Efficiency (%)	85.5	86.5	89.5	91.7	92.4	93	93.6	94.1	94.5	95	95.4	95.8	96.2

In the advanced models, the air-cooled chiller has a rated COP of 3.1, which is available from multiple manufactures. The condensing gas-fired boiler has a thermal efficiency of 95%, which is achievable for many ENERGY STAR labeled boilers (EPA 2009).

4.4.4 Motorized Outdoor Air Damper Control

The advanced case adds motorized outdoor air dampers in climate zones (zones 1, 2, and 3) where gravity dampers are allowed by 90.1-2004. Motorized dampers allow the outdoor air intake to be shut off during unoccupied periods. There is some difference in the strategy of modeling motorized outdoor air damper control between the baseline and the advanced cases. The minimum outdoor air schedule is used in the baseline to match the occupancy schedule, while the DOAS availability schedule is used in the advanced cases. This means that the DOAS is available for occupied hours and not available for unoccupied hours.

4.4.5 Demand-Controlled Ventilation

Demand-controlled ventilation (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. *EnergyPlus* models DCV by dynamically resetting the minimum outdoor ventilation rate based on the floor area and varying number of people. Based on ASHRAE Standard 62.1-2004 (ANSI/ASHRAE 2004), the minimum ventilation rate per unit floor area is 0.06 cfm/ft² (3.05E-4 $m^3/s/m^2$) and the minimum ventilation rate per person is 5 cfm/person (2.36E-3 m^3/s/person) for office buildings.

Although the DCV concept is simple, there is no straightforward approach to model DCV for a DOAS serving multiple zones in the current version of *EnergyPlus*. Hence, 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 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.

4.5 Alternative HVAC Systems – Variable Air Volume

In addition to the hydronic radiant system presented in previous section, an improved VAV system was also investigated to estimate how much energy saving can be achieved with a VAV system. 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 hydronic radiant system in terms of initial cost. The improved VAV system incorporates the following energy efficiency measures:

- Premium HVAC equipment efficiency. Both the DX cooling efficiency and the fan motor efficiency are improved. Their premium efficiency values are shown, respectively, in Tables 4.11 and 4.12.
- Expanded use of air economizer. In the improved VAV system, the use of air economizer is expanded to cover climate zones 1A, 2A, 3A and 4A, where air economizers are not required by 90.1-2004. Economizers controlled by differential enthalpy are used in these hot or warm humid zones (1A, 2A, 3A and 4A) to avoid introducing unwanted moisture into the space while differential dry-bulb temperature based air economizers are used in all other climate zones.
- Motorized outdoor air damper control. The rationale of this measure was explained in Section 4.4. In the VAV system, motorized outdoor air damper control is modeled in *EnergyPlus* by matching the minimum outdoor air schedule to the occupancy schedule: 1 for occupied hours and 0 for unoccupied hours.
- Demand-controlled ventilation. This measure and its modeling strategy were explained in Section 4.4.
- Energy recovery ventilation (ERV). In the improved VAV system, a rotary energy recovery ventilator is added in the front of each air handling unit. Table 4.11 shows the rated performance of the energy recovery ventilators. The temperature of each energy recovery ventilator's outlet air is controlled by specifying a predefined temperature setpoint. This setpoint has a large impact on the amount of energy saving, and it is set at 45°F (7°C) based on a limited number of parametric runs.

- 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* version3.0 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 1695 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. In the baseline, the primary supply air temperature is controlled at a fixed value of 55°F (12.8°C). Because multi-zone VAV systems are used for the medium office building prototype, reheating cooled air occurs when simultaneous heating and cooling loads exist in different thermal zones. 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 improved VAV system, the primary supply air temperature is reset according to the cooling demand of the warmest zone for each air system. 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. Based on a number of trial runs, we found that 61°F (16°C) as the maximum supply reset temperature works well for most cases. This measure was applied to all climate zones except 1A, 2A, 3A and 4A, where humidity control might be an issue from increasing the supply air temperature.
- Revised damper heating action. In the baseline, the damper is maintained at the minimum air flow rate (30% of the maximum for most zones) when the zone temperature is in deadband and when zone heating is required. In contrast, a revised damper heating action measure is used in the improved VAV system. This measure comes from Addendum H to ASHRAE Standard 90.1-2007 and it involves two essential changes. First, the minimum fraction of air is reduced from 30% to 20% when the zone temperature is in deadband. Second, the damper position can open up to 50% to meet the heating load. Thus, the reduced air flow in deadband saves fan energy and cooling energy. The revised terminal damper control is applied only to the east- and west-oriented perimeter zones on the above-ground floors. This is because reducing minimum terminal damper positions would cause insufficient ventilation for those zones with relatively small cooling load.

4.6 Service Water Heating

Because service water heating usually consumes less than 5% of total onsite energy use for office buildings (CBECS 2003), 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 95% in the advanced cases for the gas-fired storage water heater. This increased efficiency can be achieved with high efficiency condensing water heaters. This recommendation is based on a design with restrooms and other domestic hot water uses such as breakroom 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.

5.0 Cost-Effectiveness Analysis

Cost of energy measures is as relevant as savings. Based on feedback received from DOE, as well as users and promoters of previous AEDG reports, there is a strong interest in having some sense of the additional costs necessary to meet recommended energy performance levels. Most of the input was focused on the need to have a sense for the additional construction costs rather than the actual cost-effectiveness. The cost data provided in this report intends to represent a reasonable estimate of the incremental costs for an energy efficient medium office building based on the prototype used in the energy simulations. 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 (i.e., incremental costs), whether absolutely high or low, may result in costs which are more representative of the actual incremental cost seen in the industry.

The recommended energy efficiency measures with radiant systems are estimated to have an average payback of 7.4 years. The alternative package with VAV systems has an average payback of 4.6 years. Lighting costs lower for the energy measure packages than for the baseline because of reduced wattage and number of fixtures partially offset by more expensive per watt equipment. The HVAC system cost estimates take into account significantly lowered system cooling capacity. Actual project costs will vary, but the cost-effectiveness analysis does suggest that 50% energy savings can be achieved for new medium offices with a reasonable added cost.

5.1 Basis for Incremental Energy Savings Measure Costs

The costs for various energy savings measures are developed as incremental costs 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 per building cost, 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 energy savings measure cost must be developed or data must be explicitly available on incremental costs.

The medium office prototype building described in Section 3.0 was used as the basis to develop the cost data. Costs were developed for each of the efficiency measures used in the building, and then the measure costs were summed to get the overall cost premium for the building prototype. The advanced costs for lighting and HVAC include added design, calibration, and commissioning costs. Cost-effectiveness information is provided for both the radiant system with DOAS case that achieves 50% savings and the alternative VAV system case.

Table 5.1 summarizes the basis for estimating both the baseline and energy savings costs for the radiant system cases and Table 5.2 provides the same information for the VAV system case just for the different HVAC systems, as other components are the same as for the radiant system case.

Table 5.1. Cost Calculation Method Summary – Radiant System

Component	Cost Equation	Source
Roof Insulation	Cost = Area of roof x incremental $/ft² ($/m^2) of higher insulation value	RS Means 2009
Exterior Wall Insulation	Cost = Area of exterior wall x incremental $/ft^2 ($/m^2) of higher insulation value	RS Means 2009
Slab Insulation	Cost = Advanced case slab-on-grade perimeter insulation area plus underfloor insulation area for the interior floor radiant systems x corresponding cost/ft² minus the baseline slab insulation area x cost per square foot.	RS Means 2009
Cool Roof	Roof area x $/ft^2 ($/m^2)	Jiang W et. al. 2008
Sunshade Overhang	Overhang shading structure linear feet (m) x cost per linear foot (m) (no overhang in baseline)	RS Means 2009 – For metal building , adjusted for higher end building
Windows & doors	Cost = Area of windows x incremental $/ft^2 ($/m^2) of window type based on overall u-value	90.1 Envelope Committee supporting fenestration data in progress
Interior Lighting	Cost = Incremental cost of lighting, controls and engineering	Seattle Lighting Lab – Michael Lane
Exterior Lighting	Cost = Incremental cost of exterior lighting	Seattle Lighting Lab – Michael Lane
Plug Loads	Incremental cost of more efficient plug-in equipment and added controls including software	on-line sources primarily EnergyStar.gov
Packaged VAV vs. Radiant Systems including chiller and boiler	Cost = Cost of advanced system minus cost of baseline system. Costs based on cost per ton (W), cfm (m^3/s) or square foot (m^2) as appropriate	RS Means 2009 Radiant surfaces[(a)]
Dedicated Outdoor Air	Cost = Added cost, $. No equivalent system in baseline	RS Means 2009

(a) Finding consistent cost data on radiant systems is difficult. Online sources for commercial radiant system cost were not found. Mean's Guide did not provide a system cost. Three sources are provided. PAE Engineering Consulting indicates radiant system costs are not substantially higher that for VAV (experience primarily with radiant ceiling systems). Glumac (engineering consulting firm) estimates a $2.50-$4.00/ft^2 ($26.91-43.06/m^2) added cost for the radiant surfaces, in particular for radiant ceiling systems. SSHC Inc, a vendor and design firm estimates a total system cost of $10-$12/ft^2 ($108-129/m^2) for hydronic radiant systems and shares that floor systems are similar in cost to ceiling systems. A value for the radiant surfaces was entered as $3.50/ft^2 ($37.68/m^2)plus added cost for insulation of about $0.80/ft^2 ($8.61/m^2) . The total average premium for the radiant system is $4.08/ft^2 ($43.92/m^2) over the VAV costs which average $5.23 ($56.30/m^2) per square foot. The total radiant system including plant cost averages $9.31/ft^2 ($100.22/m^2). This radiant system value is lower than the $10-12/ft^2 ($108-129/m^2) because there is a 29% average cooling load reduction from other efficiency measures for the advanced case relative to the code baseline, and the $10-$12/ft^2 ($108-129/m^2) was described as a complete all in cost including ancillary costs such as for the cost of the space for the plant. The VAV estimate also does not include such ancillary costs, so the value for the radiant system in comparison is believed to be reasonable. This premium is 78% on average over the VAV system and is a compromise between views that the radiant system cost is similar to the VAV cost to as much as twice the cost.

Table 5.2. Cost Calculation Method Summary – VAV System
(HVAC costs only, other incremental costs same as for Radiant with DOAS case)

Component	Cost Equation	Source
Packaged VAV vs. High Efficiency Packaged VAV with added controls and climate zone specific system additions	Cost = Cost of advanced system minus cost of baseline system. Costs based on cost per ton (W), cfm (m^3/s) or square foot (m^2) as appropriate Rough estimate for controls based on assumed number of sensors, control points	RS Means 2009

5.2 Comparison of Incremental Costs to Baseline Costs for Construction

Incremental costs were calculated using the methodology described in Section 5.1. Table 5.3 covers the incremental costs for the radiant system alternative, and Table 5.4 covers the incremental costs for the VAV system alternative. Values shown in red indicate that the costs for the advanced case are lower than for the baseline. For lighting, this is due to less lighting equipment for the advanced case. For HVAC in the VAV case, this is primarily the result of large reductions in cooling capacity for the advanced case, except for some climates where the cooling capacity was reduced significantly less than for the climate zones that have a cost reduction.

Another item that needs to be addressed is the baseline costs for construction of typical medium offices. 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 square foot (square meter) estimates may serves as a surrogate for cost-effectiveness in many cases.

For example, the 2009 version of R.S. Means Construction Cost Data (R.S. Means 2009) indicates that for offices, 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 1-4- story offices. The values are very similar for the next size category, mid-rise 5-10-story office buildings. The median unit construction cost is then adjusted based on a multiplier for the ratio of the prototype building size to the typical Means building size, yielding an adjusted median unit construction cost of $111.60/ft^2 ($1200/m^2). Initial construction costs tend to be lower for larger buildings mainly because of economies of scale and the decreased contribution of the exterior walls. Median unit construction costs are also adjusted for Means city cost indexes. Cost premiums are developed using the incremental costs for the energy savings measures in each climate zone. Presumably cost premiums of a few percent of the average construction costs might be deemed to be in the cost effective range, while those in higher ranges of percentage might not.

To address the needs of this segment of the industry the total incremental costs developed in Tables 5.3 and 5.4 are compared to the median baseline construction costs to help evaluate the surrogate cost-effectiveness of the recommendations for each of the climate zones. Tables 5.5 and 5.6 provide this comparison for the radiant system and VAV system alternatives, respectively.

Table 5.3. Incremental Cost – Radiant System

Component	1A Miami	2A Houston	2B Phoenix	3A Atlanta	3B-CA Los Angeles	3B-other Las Vegas	3C San Francisco	4A Baltimore	4B Albequerque	4C Seattle	5A Chicago	5B Denver	6A Minneapolis	6B Helena	7 Duluth	8 Fairbanks
Roof Insulation	$7,155	$15,919	$15,919	$15,919	$15,919	$15,919	$15,919	$23,074	$23,074	$23,074	$23,074	$23,074	$23,074	$23,074	$30,229	$23,074
Exterior Wall Insulation	$28,428	$28,428	$28,428	$28,428	$28,428	$28,428	$28,428	$28,428	$28,428	$28,428	$25,987	$25,987	$30,839	$30,839	$19,407	$19,407
Cool Roof	$9,839	$9,839	$9,839	$9,839	$9,839	$9,839	$9,839									
Sunshade Overhang	$8,925	$8,925	$8,925	$8,925	$8,925	$8,925	$8,925	$8,925	$8,925	$8,925	$8,925	$8,925				
Windows & doors	$21,554	$21,554	$21,554	$21,745	$21,745	$21,745	$21,745	$4,797	$4,797	$4,797	$4,797	$4,797	$7,841	$7,841	$28,787	$25,296
Interior Lighting	($17,732)															
Exterior Lighting	($3,900)															
Plug Loads	$86,642															
Packaged VAV vs. Radiant system with chiller and boiler	$148,644	$167,802	$169,121	$192,238	$231,329	$186,586	$206,280	$192,449	$178,123	$218,755	$201,361	$183,269	$186,729	$186,060	$151,569	$177,693
Dedicated Outside Air	$34,424															
Service Water Heater	$560															
Sub-total	$324,537	$352,460	$353,780	$377,088	$416,179	$371,436	$391,130	$357,667	$343,340	$383,972	$364,137	$346,046	$348,476	$347,808	$329,986	$345,463
Location Cost Index, % (RS Means 2009)	90%	88%	89%	90%	108%	106%	124%	93%	90%	104%	115%	95%	110%	90%	102%	121%

Table 5.4. Incremental Cost - VAV System

Component	1A Miami	2A Houston	2B Phoenix	3A Atlanta	3B-CA Los Angeles	3B-other Las Vegas	3C San Francisco	4A Baltimore	4B Albequerque	4C Seattle	5A Chicago	5B Denver	6A Minneapolis	6B Helena	7 Duluth	8 Fairbanks
Roof Insulation	$7,155	$15,919	$15,919	$15,919	$15,919	$15,919	$15,919	$23,074	$23,074	$23,074	$23,074	$23,074	$23,074	$23,074	$30,229	$23,074
Exterior Wall Insulation	$28,428	$28,428	$28,428	$28,428	$28,428	$28,428	$28,428	$28,428	$28,428	$28,428	$25,987	$25,987	$30,839	$30,839	$19,407	$19,407
Cool Roof	$9,839	$9,839	$9,839	$9,839	$9,839	$9,839	$9,839									
Sunshade Overhang	$8,925	$8,925	$8,925	$8,925	$8,925	$8,925	$8,925	$8,925	$8,925	$8,925	$8,925	$8,925				
Windows & doors	$21,554	$21,554	$21,554	$21,745	$21,745	$21,745	$21,745	$4,797	$4,797	$4,797	$4,797	$4,797	$7,841	$7,841	$28,787	$25,296
Interior Lighting	($17,732)															
Exterior Lighting	($3,900)															
Plug Loads	$86,642															
Packaged VAV vs. Advanced Packaged VAV includes DOAS, evaporative cooling, economizer if applicable to climate zone	$52,523	$62,942	$81,907	$84,507	$36,322	$18,044	$17,605	$80,578	$40,629	$29,480	$37,833	$50,932	$78,655	$14,093	$16,873	$53,002
Service Water Heater	$560															
Sub-total	$193,993	$213,177	$232,141	$234,933	$186,748	$168,470	$168,031	$211,372	$171,423	$160,274	$166,185	$179,285	$205,979	$141,417	$160,866	$186,348
Location Cost Index, % (RS Means 2009)	90%	88%	89%	90%	108%	106%	124%	93%	90%	104%	115%	95%	110%	90%	102%	121%
TOTAL (location adjusted)	$175,176	$188,235	$206,606	$211,909	$202,249	$178,072	$208,022	$196,787	$153,938	$166,525	$190,947	$170,321	$226,165	$127,134	$164,727	$226,041

Table 5.5. Unit Cost Increase – Radiant System

Climate Zone	City	Incremental Cost	Unit Cost Increase, \$/ft²	*\$/m²*	Location Adjusted Baseline Median Unit Cost, \$/ft²	*\$/m²*	Advanced Unit Construction Cost, \$/ft²	*\$/m²*	Percentage of Unit Cost Increase Over Unit Median Baseline
1A	Miami	$293,057	$5.47	*$58.86*	$100.77	*$1,084.84*	$106.24	*$1,143.70*	5.4%
2A	Houston	$311,222	$5.81	*$62.51*	$98.54	*$1,060.81*	$104.35	*$1,123.32*	5.9%
2B	Phoenix	$314,864	$5.87	*$63.24*	$99.32	*$1,069.22*	$105.20	*$1,132.46*	5.9%
3A	Atlanta	$340,133	$6.35	*$68.31*	$100.66	*$1,083.64*	$107.01	*$1,151.95*	6.3%
3B	Los Angeles	$450,722	$8.41	*$90.52*	$120.86	*$1,301.09*	$129.27	*$1,391.61*	7.0%
3B	Las Vegas	$392,607	$7.32	*$78.85*	$117.96	*$1,269.85*	$125.29	*$1,348.70*	6.2%
3C	San Fran.	$484,219	$9.03	*$97.25*	$138.16	*$1,487.30*	$147.19	*$1,584.55*	6.5%
4A	Baltimore	$332,988	$6.21	*$66.88*	$103.90	*$1,118.48*	$110.11	*$1,185.36*	6.0%
4B	Albuquerque	$308,320	$5.75	*$61.92*	$100.22	*$1,078.83*	$105.97	*$1,140.76*	5.7%
4C	Seattle	$398,947	$7.44	*$80.12*	$115.95	*$1,248.23*	$123.40	*$1,328.35*	6.4%
5A	Chicago	$418,394	$7.81	*$84.03*	$128.23	*$1,380.38*	$136.03	*$1,464.41*	6.1%
5B	Denver	$328,743	$6.13	*$66.02*	$106.02	*$1,141.31*	$112.15	*$1,207.33*	5.8%
6A	Minneapolis	$382,627	$7.14	*$76.85*	$122.54	*$1,319.11*	$129.68	*$1,395.96*	5.8%
6B	Helena	$312,679	$5.83	*$62.80*	$100.33	*$1,080.04*	$106.16	*$1,142.83*	5.8%
7	Duluth	$337,906	$6.30	*$67.86*	$114.28	*$1,230.21*	$120.58	*$1,298.07*	5.5%
8	Fairbanks	$419,047	$7.82	*$84.16*	$135.37	*$1,457.27*	$143.19	*$1,541.43*	5.8%

Table 5.6. Unit Cost Increase – VAV System

Climate Zone	City	Incremental Cost	Unit Cost Increase, $/ft²	*$/m²*	Location Adjusted Baseline Median Unit Cost, $/ft²	*$/m²*	Advanced Unit Construction Cost, $/ft²	*$/m²*	Percentage of Unit Cost Increase Over Unit Median Baseline
1A	Miami	$175,176	$3.27	*$35.18*	$100.77	*$1,084.84*	$104.04	*$1,120.02*	3.2%
2A	Houston	$188,235	$3.51	*$37.81*	$98.54	*$1,060.81*	$102.05	*$1,098.62*	3.6%
2B	Phoenix	$206,606	$3.85	*$41.49*	$99.32	*$1,069.22*	$103.18	*$1,110.72*	3.9%
3A	Atlanta	$211,909	$3.95	*$42.56*	$100.66	*$1,083.64*	$104.62	*$1,126.20*	3.9%
3B	Los Angeles	$202,249	$3.77	*$40.62*	$120.86	*$1,301.09*	$124.64	*$1,341.71*	3.1%
3B	Las Vegas	$178,072	$3.32	*$35.76*	$117.96	*$1,269.85*	$121.28	*$1,305.62*	2.8%
3C	San Fran.	$208,022	$3.88	*$41.78*	$138.16	*$1,487.30*	$142.04	*$1,529.08*	2.8%
4A	Baltimore	$196,787	$3.67	*$39.52*	$103.90	*$1,118.48*	$107.57	*$1,158.00*	3.5%
4B	Albuquerque	$153,938	$2.87	*$30.92*	$100.22	*$1,078.83*	$103.09	*$1,109.75*	2.9%
4C	Seattle	$166,525	$3.11	*$33.44*	$115.95	*$1,248.23*	$119.06	*$1,281.67*	2.7%
5A	Chicago	$190,947	$3.56	*$38.35*	$128.23	*$1,380.38*	$131.79	*$1,418.73*	2.8%
5B	Denver	$170,321	$3.18	*$34.21*	$106.02	*$1,141.31*	$109.20	*$1,175.51*	3.0%
6A	Minneapolis	$226,165	$4.22	*$45.42*	$122.54	*$1,319.11*	$126.76	*$1,364.53*	3.4%
6B	Helena	$127,134	$2.37	*$25.53*	$100.33	*$1,080.04*	$102.70	*$1,105.57*	2.4%
7	Duluth	$164,727	$3.07	*$33.08*	$114.28	*$1,230.21*	$117.35	*$1,263.29*	2.7%
8	Fairbanks	$226,041	$4.22	*$45.40*	$135.37	*$1,457.27*	$139.59	*$1,502.66*	3.1%

5.3 Cost-Effectiveness Calculations

Cost- effectiveness can be shown most directly by looking at the simple payback period for the energy savings measures recommended in the report. For the radiant systems case, Table 5.7 shows simple payback values vary from 5.6 to 11.5 years with an average of 7.4 years. For the VAV systems case, Table 5.8 shows simple payback values vary from 3.3 to 6.2 years with an average of 4.6 years. The largest source of the variability in the paybacks is differences in HVAC system and plant heating and cooling capacity, which varies between climate zones. The variability also results in some cases from step changes in component performance and cost such as insulation R-value in the code baseline that are different than the step changes in the advanced case so that the difference in cost varies between climate zones. The simple payback is calculated for the energy savings measures in aggregate by dividing the total incremental cost of the measures by the energy savings in dollars. Energy savings in dollars is calculated by using the EIA national average natural gas rate of $1.16/therm ($0.41/m^3) and the national average electric rate of $0.0939/kWh (EIA 2006). These rates are the same ones being used by the SSPC 90.1 Committee in developing the 2010 version of Standard 90.1.

Table 5.7. Simple Payback Period – Radiant System

Climate Zone	City	Incremental Cost	Energy Cost Savings			Simple Payback (Years)
			Electricity	Natural Gas	Total	
1A	Miami	$293,057	$44,451	$50	$44,501	6.6
2A	Houston	$311,222	$48,583	($314)	$48,268	6.4
2B	Phoenix	$314,864	$49,067	($162)	$48,905	6.4
3A	Atlanta	$340,133	$47,149	($1,061)	$46,088	7.4
3B	Los Angeles	$450,722	$39,045	$1	$39,046	11.5
3B	Las Vegas	$392,607	$45,242	($626)	$44,616	8.8
3C	San Fran.	$484,219	$44,201	($528)	$43,673	11.1
4A	Baltimore	$332,988	$55,265	($1,738)	$53,526	6.2
4B	Albuquerque	$308,320	$47,129	($1,295)	$45,834	6.7
4C	Seattle	$398,947	$49,323	($1,219)	$48,104	8.3
5A	Chicago	$418,394	$55,298	($2,017)	$53,281	7.9
5B	Denver	$328,743	$49,407	($1,619)	$47,788	6.9
6A	Minneapolis	$382,627	$57,825	($1,997)	$55,829	6.9
6B	Helena	$312,679	$52,948	($1,726)	$51,222	6.1
7	Duluth	$337,906	$62,353	($1,718)	$60,634	5.6
8	Fairbanks	$419,047	$66,327	($414)	$65,913	6.4

Table 5.8. Simple Payback Period – VAV System

Climate Zone	City	Incremental Cost	Energy Cost Savings			Simple Payback (Years)
			Electricity	Natural Gas	Total	
1A	Miami	$175,176	$38,897	$68	$38,965	4.5
2A	Houston	$188,235	$39,577	$221	$39,797	4.7
2B	Phoenix	$206,606	$45,183	($21)	$45,162	4.6
3A	Atlanta	$211,909	$33,802	$383	$34,185	6.2
3B	Los Angeles	$202,249	$37,251	$57	$37,308	5.4
3B	Las Vegas	$178,072	$41,428	($144)	$41,283	4.3
3C	San Fran.	$208,022	$40,506	($344)	$40,162	5.2
4A	Baltimore	$196,787	$37,212	$412	$37,623	5.2
4B	Albuquerque	$153,938	$38,993	$124	$39,117	3.9
4C	Seattle	$166,525	$39,965	($589)	$39,376	4.2
5A	Chicago	$190,947	$40,836	$21	$40,857	4.7
5B	Denver	$170,321	$39,955	$252	$40,207	4.2
6A	Minneapolis	$226,165	$40,528	$889	$41,417	5.5
6B	Helena	$127,134	$38,504	$569	$39,074	3.3
7	Duluth	$164,727	$46,797	$194	$46,991	3.5
8	Fairbanks	$226,041	$44,665	$1,030	$45,694	4.9

5.4 A Perspective on Costs for Advanced Buildings

With the growing high performance buildings market, there is a commensurate growth in the desire to understand the real costs associated with 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 measures are being considered. The reader will note that the sources for this work run the gamut of widely published data including 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 robust costs for all measures, collected in a consistent manner. Unfortunately this situation does not exist, and it is for this reason that identifying costs in a consistent and accurate manner is difficult to execute.

Many choices had to be made in choosing sources of cost data for this study, which involved considering the basis for the data as well as considering whether the source was biased high or low relative to other costs. Generally the authors understand that some sources are routinely high or low, and this impact can usually be mitigated by using the differential costs as noted earlier in this section of the report. Sometimes the actual range of cost estimates is so broad that the authors had to struggle to make a reasonable judgment as to which costs to use. When confronted with conflicting or ambiguous costs the general approach followed was to take the conservative view of not underestimating the costs such that the exercise would yield an inflated assessment of the cost-effective nature of the measures. Conversely, every effort was 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.

The result is a reasonable estimate of simple payback values for the advanced energy measure packages in the 16 locations, showing that the packages can do not create an unreasonably high economic burden in pursuing the 50% energy savings goal.

6.0 Recommendations and Energy Savings Results

This section contains the final recommendations for this *TSD* report, as well as the energy savings results that are achieved as a result of applying these recommendations to the prototypical building. The recommendations are applicable for all medium office buildings within the scope of the study as a means of demonstrating the 50% energy savings. There are other ways of achieving 50% energy savings. These recommendations are "*a way, but not the only way*" of meeting the energy savings target. When a recommendation contains the designation "NR", then the *TSD* is not providing a recommendation for this component or system. This analysis used Standard 90.1-2004 baseline or the same values as modeled for the baseline for items not regulated by the Standard.

This section describes the final energy savings recommendations in the *TSD*. The recommendations are grouped into envelope measures, lighting measures, plug load measures, HVAC measures, and service water heating measures.

6.1.1 Envelope Measures

The envelope measures cover the range of assemblies for both the opaque and fenestration portions of the buildings. Opaque elements include the roof, walls, floors and slabs, as well as opaque doors. 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 an attic or a steel-framed wall, or a portion of an assembly, such as insulation R-value.

Recommendations for each envelope component are contained in Table 6.1, and are organized by climate zone, ranging from the hot Zone 1 to the cold Zone 8. 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 higher in Zone 8. The reader should note that the recommendations are based on a steel stud construction with curtain wall style windows (or storefront).

In addition, the *TSD* recommends using exterior sun control on the south glazing to help control solar cooling loads in warmer climates.

Table 6.1. Final Energy Savings Recommendations for Medium Office – Building Envelope

Item	Component		Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
Roof	Insulation entirely above deck	R-value $ft^2·F·h/Btu$	R-20 c.i.	R-25 c.i.	R-25 c.i.	R-30 c.i.	R-30 c.i.	R-30 c.i.	R-35 c.i.	R-35 c.i.
		R-value $K·m^2/W$	*R-3.5 c.i.*	*R-4.4 c.i.*	*R-4.4 c.i.*	*5.3 c.i.*	*5.3 c.i.*	*5.3 c.i.*	*6.2 c.i.*	*6.2 c.i.*
	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
Walls-Exterior	Steel framed	R-value $ft^2·F·h/Btu$	R-13.0 + R-7.5 c.i.	R-13.0 + R-7.5 c.i.	R-13.0 + R-7.5 c.i.	R-13.0 + R-7.5 c.i.	R-13.0 + R-15.6 c.i.	R-13.0 + R-18.8 c.i.	R-13.0 + R-18.8 c.i.	R-13.0 + R-18.8 c.i.
		R-value $K·m^2/W$	*R-2.3 + R-1.3 c.i.*	*R-2.3 + R-1.3 c.i.*	*R-2.3 + R-1.3 c.i.*	*R-2.3 + R-1.3 c.i.*	*R-2.3 + R-2.7 c.i.*	*R-2.3 + R-3.3 c.i.*	*R-2.3 + R-3.3 c.i.*	*R-2.3 + R-3.3 c.i.*
Slabs	Heated	R-value $ft^2·F·h/Btu$	NR	NR	NR	R-10.0 for 24 in.	R-10.0 for 24 in.	R-15.0 for 24 in.	R-15.0 for 24 in.	R-20.0 for 24 in.
		R-value $K·m^2/W$	*NR*	*NR*	*NR*	*R-10.0 for 24 in.*	*R-10.0 for 24 in.*	*R-15.0 for 24 in.*	*R-15.0 for 24 in.*	*R-20.0 for 24 in.*
Vertical glazing	Thermal trans-mittance	U-factor $Btu/h·ft^2·F$	0.51	0.51	0.51	0.44	0.44	0.42	0.31	0.31
		U-factor $W/m^2·K$	*2.89*	*2.89*	*2.89*	*2.5*	*2.5*	*2.38*	*1.76*	*1.76*
	Solar heat gain coefficient (SHGC)		0.25	0.25	0.25	0.26	0.26	0.35	0.4	0.4
	Exterior sun control (South only)		PF>0.5	PF>0.5	PF>0.5	PF>0.5	PF>0.5	NR	NR	NR

6.1.2 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 6.2.

Interior lighting recommendations include maximum lighting power density (LPD) requirements for the major space types in medium office buildings. Occupancy control recommendations are also provided.

Exterior lighting recommendations include maximum LPD requirements for exterior lighting applications for medium office buildings.

Table 6.2 Final Energy Savings Recommendations – Lighting

Item	Component	All Climate Zone Locations					
			W/ft^2	*W/m^2*		W/ft^2	*W/m^2*
Interior Lighting	Lighting power density	Office, open plan	0.68	*7.3*	Office, enclosed	0.8	*8.6*
		Conference/meeting	0.77	*8.3*	Active storage	0.64	*6.9*
		Corridor/transition	0.50	*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	0.75	*8.1*
	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.					
	Plug load lighting	Compact fluorescent (CFL) with electronic ballast					
Exterior Lighting Power Density	Base allowance	750 W					
			W/ft^2	*W/m^2*			
	Parking areas and drives		0.100	*1.08*			
	Walkways		0.160	*1.72*			
	Entry canopies		0.400	*4.31*			
	Façade (use wattage only for façade)		0.075	*0.81*			

6.1.3 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 6.3.

Plug load recommendations include several strategies that reduced the connected wattage, and control equipment to further reduce average energy usage. The connected wattage recommendations include shifting towards greater use of laptop computers from desktop computers, and selection of ENERGY STAR computers, monitors and other equipment for all office equipment with ENERGY STAR ratings. 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 6.3 summarizes these changes.

Table 6.3 Final Energy Savings Recommendations – Plug Loads

Component	Recommendations (for Zones 1-8)
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
Overall plug loads power density	**0.55 W/ft^2 (5.92 W/m^2)**

6.1.4 HVAC Measures

HVAC measures include systems for space heating and sensible cooling with separate conditioning for ventilation air, which also provides latent cooling including dehumidification. Radiant systems with dedicated outdoor air units (DOAS) is recommended and summarized here.

An alternative VAV system approach was originally considered, but achieved a savings of 46.5% (Section 6.2) short of the 50% savings target on a weighted average basis for all climates. This alternative system is described in Section 5.5.

Recommended space heating and sensible cooling system is radiant floors, ceiling and/or wall panels as appropriate to heating and cooling load conditions. Typically for design and cost control the whole building or certainly individual zones would be served by one type of radiant system, typically radiant floor, or ceiling. To allow zonal control for areas that may be in cooling while other zones are in heating, recommended system is provided with a four pipe distribution system with heated and chilled water. The primary heating source for the radiant system is a condensing and modulating gas boiler. The primary cooling source for the radiant system is an air-cooled chiller.

Recommended conditioning of ventilation air and all latent cooling is through a dedicated outdoor air unit serving the entire building. The dedicated outdoor air unit uses a DX coil for primary cooling, and a hot water coil for primary heating (served by the condensing boiler that also serves the radiant system. Energy recovery is included to temper the outside air (both sensible and latent) before it enters the cooling and heating coils. For most dry climate zones, supply air is cooled to as low as 55°F (12.8°C) as required to provide adequate latent load control and supplemental space cooling. In the most humid climates, the supply air is first cooled to as low as 45°F (7.2°C) for dehumidification and is then reheated with an additional sensible heat recovery device. DX cooling efficiency for the DOAS unit is provided in Table 6.4.

Table 6.4 Final Energy Savings Recommendations – HVAC

Component	Zones 1-8 or as noted below	
Radiant systems	Primary space sensible heating and cooling	Floor or ceiling radiant systems as appropriate to meet loads
Chiller – air-cooled	Chilled water for radiant system	3.1 COP/Table A.5 for performance curve
Boiler – condensing	Hot water for radiant system and DOAS	95% Et
Dedicated outdoor air	Conditioning of ventilation air and all latent cooling	100% outside air
	<65,000 Btu/h (<19 kW)	13.5 SEER
	DX cooling 65-135 kBtu/h (19-40 kW)	11.3 EER/11.5 IPLV
	DX cooling 135-240 kBtu/h (40-70 kW)	11.0 EER/11.5 IPLV
	Heating – hot water coil served by boiler	See boiler above
	Energy Recovery	Effectiveness: see Table 4.10.
	Additional dehumidification with sub-cooling and energy recovery reheating	Hot and humid climate zones (1A, 2A, 3A, and 4A)

6.1.5 Service Water Heating Measures

Service water heating is a modest energy use in medium offices. For a medium office building, a circulating water heating system would be typical and appropriate if the restrooms, sinks, and other service hot water supply equipment is located near the core of the building. A single gas-fired condensing water heater, with 95% efficiency and with typical storage is recommended. If there are service water heating uses that are distributed outside the core, it may be more beneficial from an energy (and possibly first cost) perspective to use on-demand water heaters to serve these uses.

6.2 Energy Savings Results

The prototype medium office building was simulated in each of the 16 climate locations to determine if the 50% energy savings goal was achieved. The whole building energy savings results for the recommendations are shown below. In all cases the energy savings are relative to the baseline energy use from Standard 90.1-2004. A radiant system approach with dedicated outdoor air systems is part of the recommended package. During the analysis, a variable air volume HVAC approach was first tried for the advanced case with other measures, and did not quite reach the 50% savings goal.

6.2.1 Results with Radiant Systems and Dedicated Outdoor Air

The recommended package of energy efficient measures presented in Section 4 can achieve over 50% on-site energy savings for all of the 16 climate locations as shown in Figure 6.1. The weighted average percentage savings for the whole country based on the 16 representative cities is 56.1% as shown in Table 6.5 using the construction are weighting factors presented in Section 2.3.

To understand the impact of EEMs on different energy end use sectors, the energy end use intensities for the baseline and the advanced model is illustrated in Figure 6.2. The annual energy usage by usage category is shown in Table 6.6.

- On average, there is about 81% heating energy savings and about 46% cooling energy savings. The percentage of heating and cooling energy saving varies significantly with the climate locations. For heating, the range is between 72% for Minneapolis, and 99% for Miami. For cooling, the range is between 64% for Baltimore and -6% for Fairbanks. The heating and cooling energy savings come from the whole package of energy efficiency measures including building envelope, HVAC, lighting and plug-in equipment.
- There is about 84% fan energy reduction mainly from the use of radiant thermal systems and DOAS.
- The lighting related measures reduce about 50.5% of interior lighting energy and 72% of exterior lighting energy. The above percentages are observed to be nearly the same across all 16 climate locations.
- Plug-in electric equipment energy is reduced by about 31% because of changes in equipment and the controls.
- Water heater efficiency improvement leads to about 16% energy reduction for service hot water.
- For the advanced case, pumping and heat rejection auxiliary energy usage add about 1% to the advanced case energy usage with negligible corresponding energy usage for the baseline.

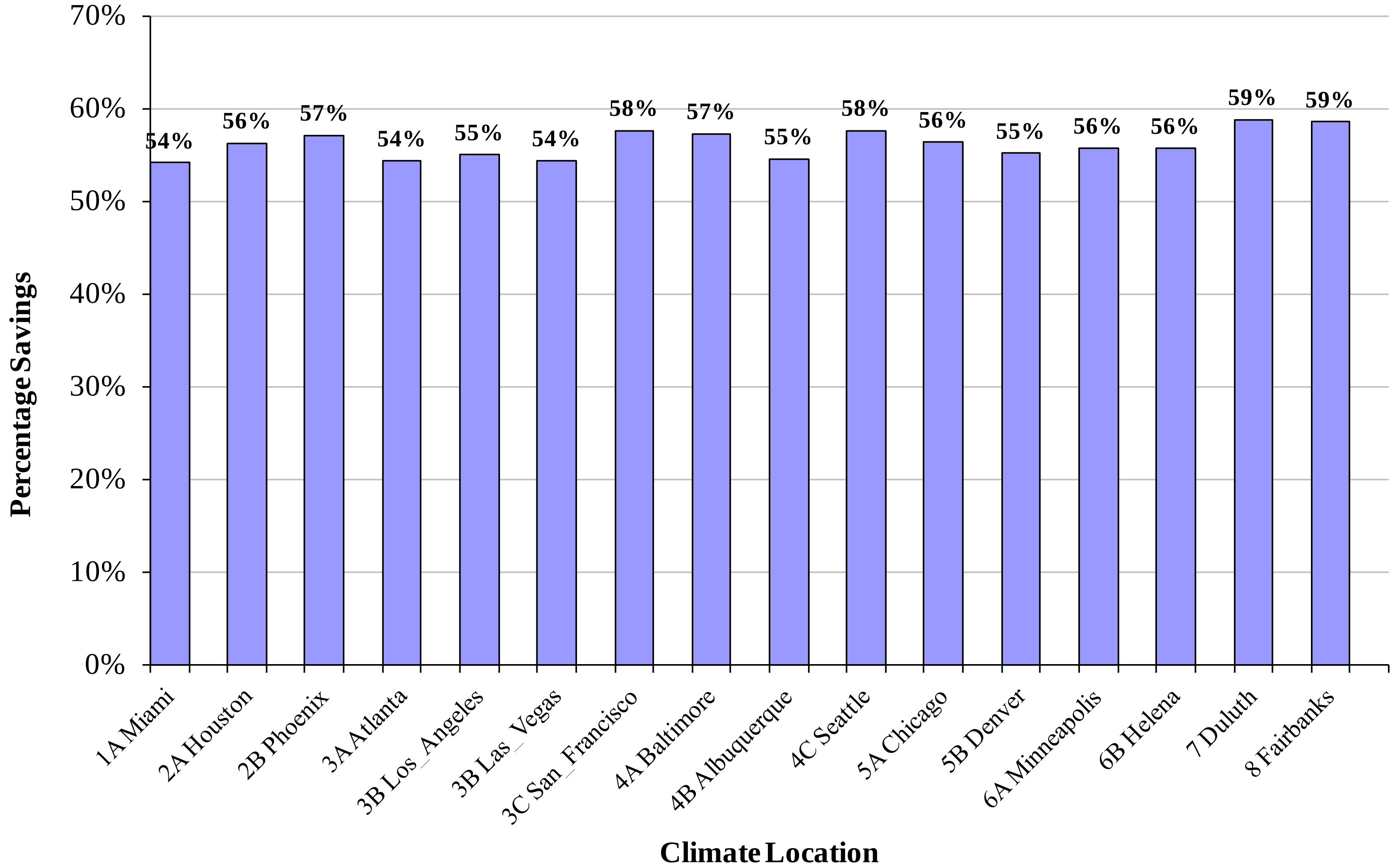

Figure 6.1. Percentage Energy Savings by Climate Zone (Radiant System)

Table 6.5 Weighted Average Energy Savings for Recommended Energy Measures (Radiant System)

	1A Miami	2A Houston	2B Phoenix	3A Atlanta	3B-CA Los Angeles	3B-other Las Vegas	3C San Francisco	4A Baltimore
Baseline EUI, kBtu/ft²	55.8	57.6	57.7	55.6	48.1	54.5	50.5	60.5
Advanced EUI, kBtu/ft²	25.6	25.1	24.7	25.4	21.6	24.9	21.4	25.8
Weighting, %	2.13%	13.44%	4.83%	12.67%	5.91%	5.91%	2.25%	19.68%

	4B Albuquerque	4C Seattle	5A Chicago	5B Denver	6A Minneapolis	6B Helena	7 Duluth	8 Fairbanks	Total Weighted Average
Baseline EUI, kBtu/ft²	54.7	54.6	60.7	56.0	64.5	59.4	67.1	75.6	57.7
Advanced EUI, kBtu/ft²	24.8	23.1	26.4	25.1	28.5	26.3	27.6	31.3	25.3
Weighting, %	0.60%	3.24%	17.53%	5.65%	4.93%	0.58%	0.55%	0.12%	56.1%

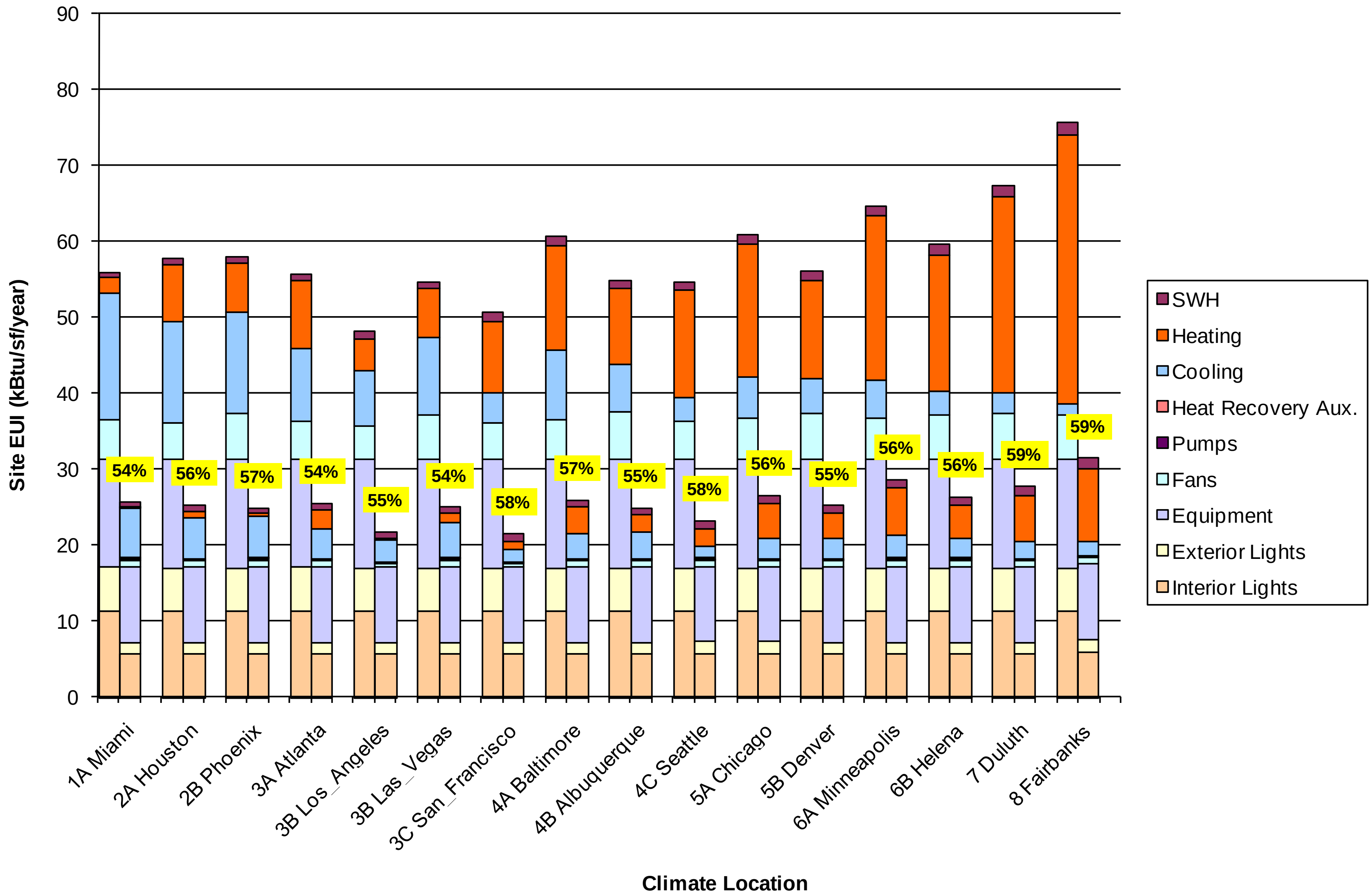

Figure 6.2. Comparison of Energy End Use Intensities Between the Baseline and Advanced Models (Radiant System)

Table 6.6 Energy Savings Results by End Use (Radiant System)

Zone	*City*	*Case*	*Heating [MMBtu]*	*Cooling [MMBtu]*	*Interior Lights [MMBtu]*	*Exterior Lights [MMBtu]*	*Interior Equipment [MMBtu]*	*Fans [MMBtu]*	*Pumps [MMBtu]*	*Heat Recovery [MMBtu]*	*Water Heater [MMBtu]*	*Total Energy [MMBtu]*	*EUI [kBtu/SF]*	*Energy Savings (%)*
1A	Miami	Baseline	114	890	599	309	768	273	0	0	38	2,990	55.8	54%
		Advanced	2	362	295	86	529	48	14	3	32	1,371	25.6	
2A	Houston	Baseline	401	708	599	308	768	256	0	0	46	3,086	57.6	56%
		Advanced	53	283	296	85	529	48	11	2	39	1,348	25.1	
2B	Phoenix	Baseline	339	723	599	308	768	317	0	0	41	3,095	57.7	57%
		Advanced	23	289	295	86	529	48	17	2	35	1,325	24.7	
3A	Atlanta	Baseline	480	513	599	309	768	260	0	0	54	2,982	55.6	54%
		Advanced	128	214	296	87	529	48	11	2	46	1,360	25.4	
3B	Los Angeles	Baseline	230	390	599	308	768	230	0	0	53	2,578	48.1	55%
		Advanced	8	154	297	85	529	30	10	0	45	1,158	21.6	
3B	Las Vegas	Baseline	349	538	599	308	768	314	0	0	47	2,923	54.5	54%
		Advanced	63	250	297	86	529	48	17	2	40	1,332	24.9	
3C	San Francisco	Baseline	510	212	599	308	768	249	0	0	60	2,706	50.5	58%
		Advanced	56	89	297	86	529	30	8	0	50	1,145	21.4	
4A	Baltimore	Baseline	739	488	599	308	768	280	0	0	61	3,242	60.5	57%
		Advanced	186	176	296	86	529	48	9	2	51	1,383	25.8	
4B	Albuquerque	Baseline	525	338	599	308	768	334	0	0	59	2,931	54.7	55%
		Advanced	126	181	295	85	529	48	14	2	50	1,330	24.8	
4C	Seattle	Baseline	758	165	599	308	768	263	0	0	64	2,925	54.6	58%
		Advanced	122	86	300	88	529	48	8	2	54	1,237	23.1	
5A	Chicago	Baseline	930	296	599	308	768	287	0	0	66	3,254	60.7	56%
		Advanced	246	142	297	87	529	48	10	2	56	1,417	26.4	
5B	Denver	Baseline	690	245	599	308	768	323	0	0	66	2,999	56.0	55%
		Advanced	174	140	296	86	529	48	12	2	56	1,343	25.1	
6A	Minneapolis	Baseline	1160	262	599	308	768	292	0	0	71	3,460	64.5	56%
		Advanced	331	165	295	87	529	48	14	2	60	1,530	28.5	
6B	Helena	Baseline	961	169	599	308	768	309	0	0	72	3,185	59.4	56%
		Advanced	235	139	295	88	529	48	13	2	60	1,409	26.3	
7	Duluth	Baseline	1374	154	599	308	768	317	0	0	79	3,598	67.1	59%
		Advanced	320	120	295	88	529	48	12	2	66	1,480	27.6	
8	Fairbanks	Baseline	1897	88	599	306	768	308	0	0	88	4,053	75.6	59%
		Advanced	517	93	306	98	529	48	11	2	74	1,678	31.3	

6.2.2 Results with Variable Air Volume Systems

Although the proposed measures based on the VAV system cannot reach the 50% target for all locations, the energy saving results are still presented in this section. The information is intended to show that: 1) the VAV-based system can achieve close or above 50% energy savings for some climate zones (in this case, the VAV system is an alternative approach to be adopted other than the radiant system); 2) how much the gap is if the VAV system cannot achieve 50% energy saving for a climate zone.

The package of energy efficient measures presented in Section 4 can achieve over 50% on-site energy savings for 4 of the 16 climate locations and over 42% for the remaining 12 climate zones as shown in Figure 6.3. The weighted average percentage savings for the whole country based on the 16 representative cities is 46.3% as shown in Table 6.7 using the construction are weighting factors in Section 2.3.

To understand the impact of EEMs on different energy end use sectors, the energy end use intensities for each baseline and the advanced models are illustrated in Figure 6.4. The annual energy usage by usage category is shown in Table 6.8.

- On average, there is about 58% heating energy savings and about 56% cooling energy savings. The percentage of heating and cooling energy saving varies significantly with the climate locations. For heating, the range is between 79% for Phoenix, and 23% for Atlanta. For cooling, the range is between 80% for San Francisco and 24% for Helena. Building envelope, HVAC and reduced lighting and plug loads all impact these savings.
- There is about 35% fan energy reduction related to heating and cooling reduction.
- The lighting related measures reduce about 51% of interior lighting energy and 72% of exterior lighting energy. The above percentages are observed to be nearly the same across all 16 climate locations.
- Plug-in electric equipment energy is reduced by about 31% because of changes in equipment and added controls.
- Service water heating is reduced 16% through water heater efficiency.

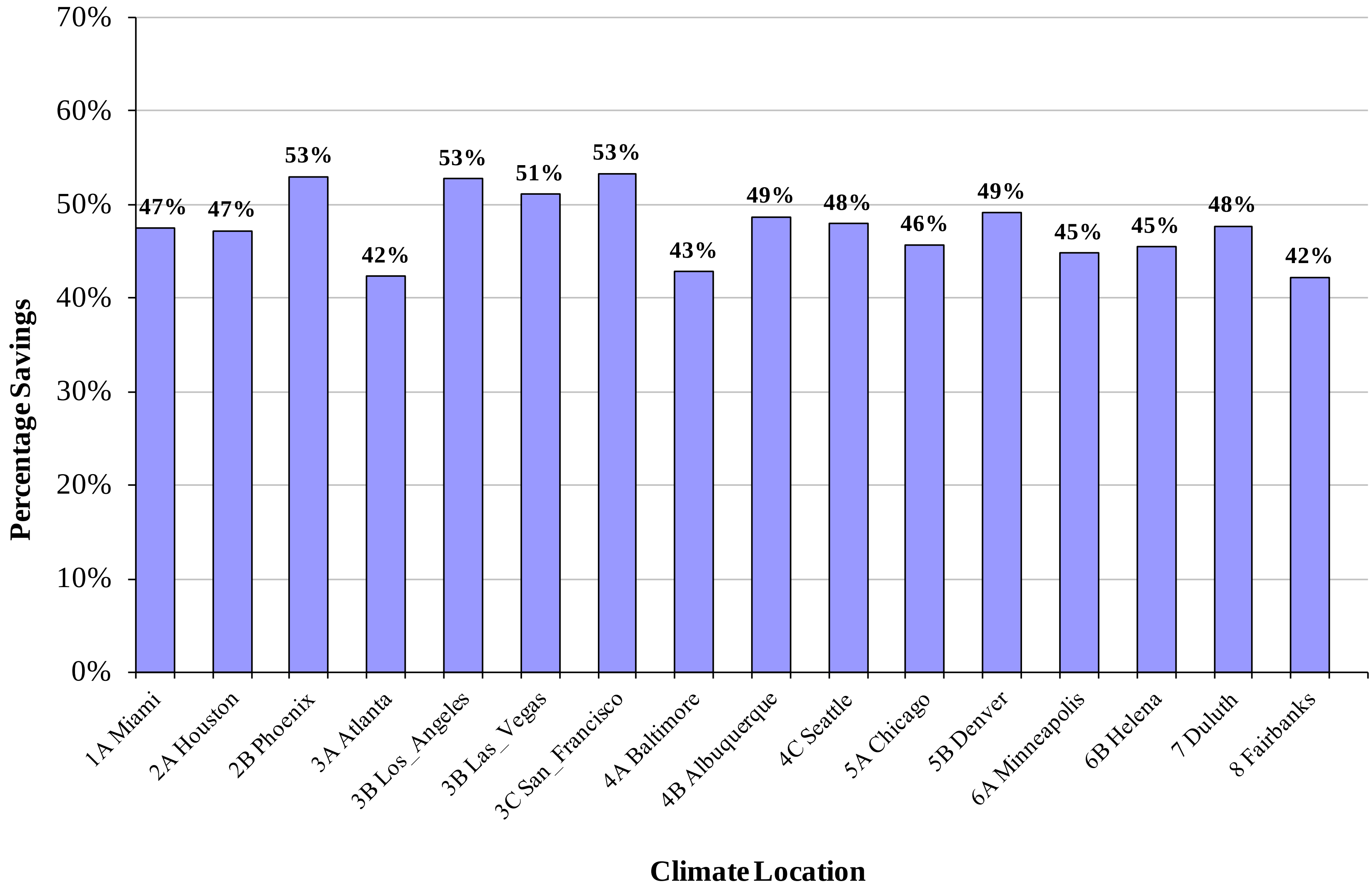

Figure 6.3. Percentage Energy Savings by Climate Zone (VAV System)

Table 6.7 Weighted Average Energy Savings for Recommended Energy Measures (VAV System)

	1A Miami	2A Houston	2B Phoenix	3A Atlanta	3B-CA Los Angeles	3B-other Las Vegas	3C San Francisco	4A Baltimore
Baseline EUI, kBtu/ft²	55.8	57.6	57.7	55.6	48.1	54.5	50.5	60.5
Advanced EUI, kBtu/ft²	29.3	30.4	27.1	32.1	22.7	26.7	23.6	34.6
Weighting, %	2.13%	13.44%	4.83%	12.67%	5.91%	5.91%	2.25%	19.68%

	4B Albuquerque	4C Seattle	5A Chicago	5B Denver	6A Minneapolis	6B Helena	7 Duluth	8 Fairbanks	Total Weighted Average
Baseline EUI, kBtu/ft²	54.7	54.6	60.7	56.0	64.5	59.4	67.1	75.6	57.7
Advanced EUI, kBtu/ft²	28.0	28.4	33.0	28.5	35.6	32.4	35.1	43.7	31.0
Weighting, %	0.60%	3.24%	17.53%	5.65%	4.93%	0.58%	0.55%	0.12%	46.3%

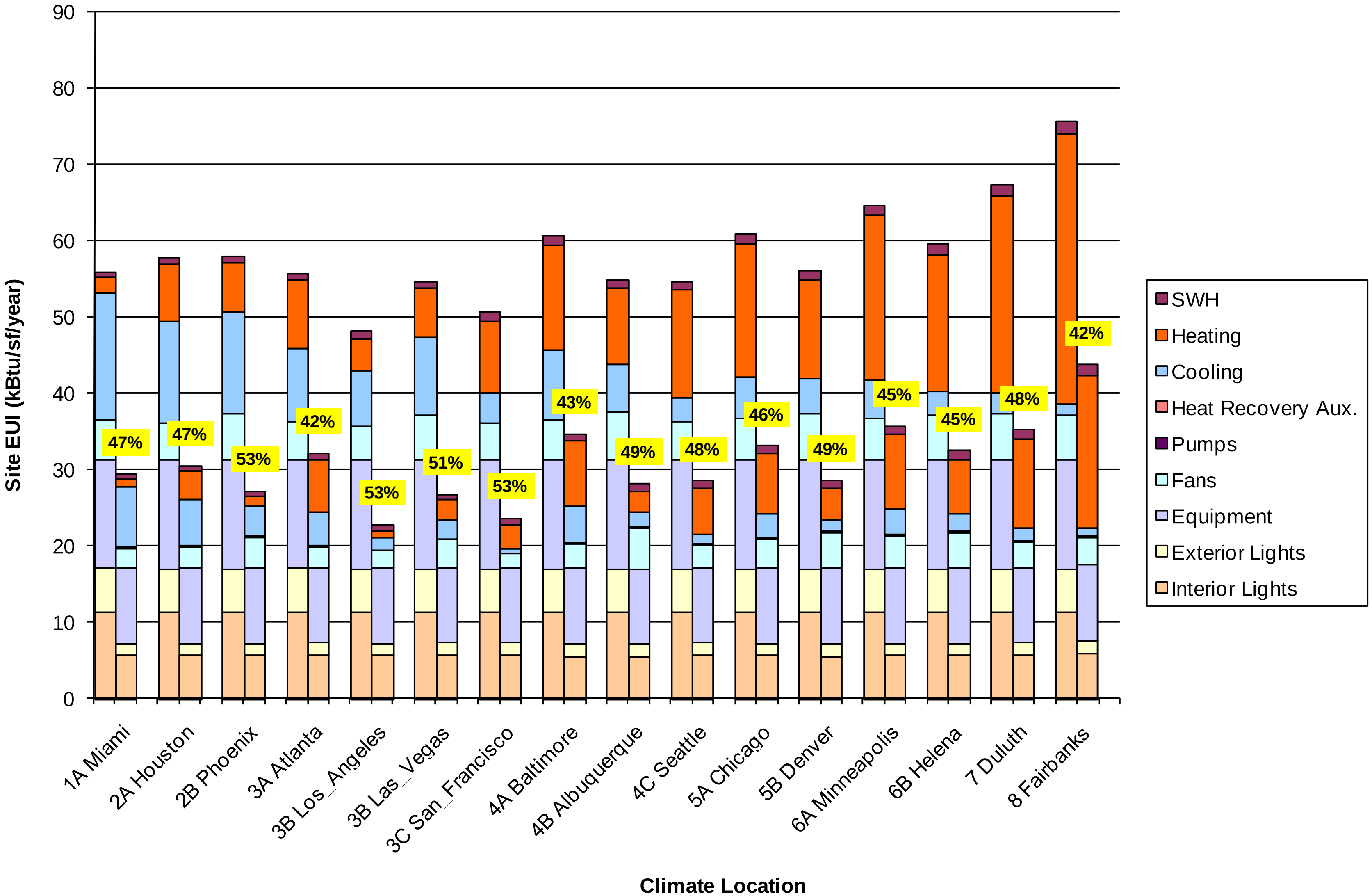

Figure 6.4. Comparison of Energy End Use Intensities Between the Baseline and Advanced Models (VAV System)

Table 6.8 Energy Savings Results by End Use (VAV System)

Zone	*City*	*Case*	*Heating [MMBtu]*	*Cooling [MMBtu]*	*Interior Lights [MMBtu]*	*Exterior Lights [MMBtu]*	*Interior Equipment [MMBtu]*	*Fans [MMBtu]*	*Pumps [MMBtu]*	*Heat Recovery [MMBtu]*	*Water Heater [MMBtu]*	*Total Energy [MMBtu]*	*EUI [kBtu/SF]*	*Energy Savings (%)*
1A	Miami	Baseline	114	890	599	309	768	273	0	0	38	2,990	55.8	47%
		Advanced	51	424	296	86	529	145	0	8	32	1,571	29.3	
2A	Houston	Baseline	401	708	599	308	768	256	0	0	46	3,086	57.6	47%
		Advanced	202	323	297	85	529	146	0	7	39	1,629	30.4	
2B	Phoenix	Baseline	339	723	599	308	768	317	0	0	41	3,095	57.7	53%
		Advanced	71	207	296	86	529	224	0	5	35	1,454	27.1	
3A	Atlanta	Baseline	480	513	599	309	768	260	0	0	54	2,982	55.6	42%
		Advanced	368	241	297	87	529	146	0	6	46	1,720	32.1	
3B	Los Angeles	Baseline	230	390	599	308	768	230	0	0	53	2,578	48.1	53%
		Advanced	50	90	298	85	529	122	0	0	45	1,219	22.7	
3B	Las Vegas	Baseline	349	538	599	308	768	314	0	0	47	2,923	54.5	51%
		Advanced	139	140	298	86	529	197	0	0	40	1,429	26.7	
3C	San Francisco	Baseline	510	212	599	308	768	249	0	0	60	2,706	50.5	53%
		Advanced	161	42	299	86	529	97	0	0	50	1,263	23.6	
4A	Baltimore	Baseline	739	488	599	308	768	280	0	0	61	3,242	60.5	43%
		Advanced	454	255	293	86	529	179	0	6	51	1,854	34.6	
4B	Albuquerque	Baseline	525	338	599	308	768	334	0	0	59	2,931	54.7	49%
		Advanced	148	107	293	85	529	286	0	4	50	1,503	28.0	
4C	Seattle	Baseline	758	165	599	308	768	263	0	0	64	2,925	54.6	48%
		Advanced	317	72	296	88	529	165	0	3	54	1,523	28.4	
5A	Chicago	Baseline	930	296	599	308	768	287	0	0	66	3,254	60.7	46%
		Advanced	419	172	295	87	529	205	0	5	56	1,767	33.0	
5B	Denver	Baseline	690	245	599	308	768	323	0	0	66	2,999	56.0	49%
		Advanced	224	71	294	86	529	262	0	4	56	1,525	28.5	
6A	Minneapolis	Baseline	1160	262	599	308	768	292	0	0	71	3,460	64.5	45%
		Advanced	525	174	294	87	529	236	0	5	60	1,910	35.6	
6B	Helena	Baseline	961	169	599	308	768	309	0	0	72	3,185	59.4	45%
		Advanced	383	128	294	88	529	249	0	5	60	1,736	32.4	
7	Duluth	Baseline	1374	154	599	308	768	317	0	0	79	3,598	67.1	48%
		Advanced	627	79	296	88	529	191	0	5	66	1,881	35.1	
8	Fairbanks	Baseline	1897	88	599	306	768	308	0	0	88	4,053	75.6	42%
		Advanced	1076	56	307	98	529	196	0	6	74	2,341	43.7	

7.0 Suggestions for Future Work

The *TSD* work focuses on onsite energy savings for a package of measures to achieve an overall percentage savings target. There may be additional goals and approaches worth considering for possible future *TSD* work. There are also specific potential adjustments to the prototype and baseline model as well as additional energy measures that can be investigated further.

7.1 Purpose and Goals

The goals for future *TSD* work could be expanded to consider more than just on-site energy savings above a certain target for entire packages of energy measures.

- There may be value in considering the long-term performance differences between the baseline and advanced options, and maintenance and operations of energy measures including impacts on cost-effectiveness.
- With a growing focus for energy efficiency to contribute to combating global climate change by reducing carbon dioxide emissions, may want to consider source energy in addition to site energy reduction and report on the impact of the energy measures on carbon emissions.
- Additional information on trade-offs between energy measures and optimizing cost effectiveness could be provided 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 a package of measures. to allow trade-offs.

7.2 Adjustments to Prototypes and Baseline Model

Some adjustments to the prototype would refine the starting point and facilitate evaluating a number of energy efficiency measures. The following adjustments are suggested:

- Change from ribbon windows to punched windows. Using punched windows offers more opportunities to optimize daylighting and the utilization of solar energy, for example, changing window layouts and using fins.
- Include interior blinds in the prototype. Interior blinds are not considered in the current prototype. However, using interior blinds for glare control may reflect the practice better.
- Consider alternative VAV system configurations. In the current prototype, a VAV system is used for each floor. In many cases, it might be more reasonable to assign thermal zones to VAV systems according to orientation or perimeter and core.
- Consider separate interior zones for computer rooms and conference rooms that have quite different occupancy schedules and equipment loads than general office areas. Separate thermal zones would facilitate the application of specific suitable energy efficiency measures for those functional spaces.

7.3 Advanced Building – Additional Potential Energy Measures

Although the *TSD* has proposed a package of energy efficiency measures to achieve the 50% on-site energy savings goal, a number of new energy efficiency measures are worthwhile to be considered and some proposed measures can be further refined in the future. The new and refined measures have the potential to achieve the 50% goal in a more cost-effective manner or to achieve even more on-site energy savings. The following measures are suggested to be considered in future work:

- Enhanced daylight harvesting measures - Potential measures for more daylighting include the use of skylights and light tubes on the top floor, and the combined use of light shelves and daylight vertical windows to bring daylight deeper into the space.
- Advanced window shading measures for a better control of daylighting and solar energy - Representative examples include electrochromic glazing and motorized blinds/shades. Such kind of measures would be especially worthwhile for consideration in climates with both hot summers and cold winters.
- Reduce window areas particularly for the east and west façades.
- Provide occupancy sensor control of HVAC setpoints and terminal unit damper positions.
- A combination of DOAS and VAV systems - Combining DOAS with VAV systems would potentially create a more cost-effective alternative than radiant systems. It needs to be mentioned that the above combined system cannot be modeled in the current version of *EnergyPlus* which allows only one air system for a thermal zone.
- For some climate zones with good opportunities for use of air-side economizers, allowing the outside air systems to bring in more outside air to allow more economizer benefit may be worthwhile. This would mean increasing the fan system and duct sizes of a DOAS system or designing with a VAV system with full economizer. 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.
- Explore alternative radiant/convective systems. Promising systems for office building include chilled ceiling panels, chilled beams and perimeter fin tubes for heating.
- Active thermal storage for higher temperature chilled water - For some climate zones with large diurnal temperature changes, it might be an effective energy measure to generate cooled water using a cooling tower at night. The cooled water can then be used at daytime for the radiant cooling system.
- The use of renewable energy sources. 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.

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Appendix A

Energy Modeling Input Assumptions

Table A.1.a. Baseline and Advanced Buildings Model Assumptions for Medium Office Building Prototype (53,600 ft^2) IP units

Characteristic	Baseline	Advanced-Radiant	Advanced-VAV	Data Source/Remarks
ARCHITECTURALL FEATURES				
Exterior Walls				
Construction	Steel-framed wall - 0.75-in stucco - 0.625-in gypsum board - 2x4 @ 16-in O.C. stud with fiberglass insulation in cavity - rigid board insulation - 0.625-in gypsum board	Same as baseline	Same as baseline	CBECS 2003
Overall U-factor (Btu/h·ft^2·F)	Zones 1-4: 0.124 Zones 5- 6: 0.084 Zones 7-8: 0.064	Zones 1-4: 0.064 Zone 5: 0.042 Zones 6-8: 0.037	Same as Radiant	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	Same as baseline	CBECS 2003
Overall U-factor (Btu/h·ft^2·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	Same as for Radiant	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	Same as for Radiant	LBNL 2009: http://eetd.lbl.gov/coolroofs/
Slab-on-Grade Floor				
Construction	Concrete slab on earth - carpet pad - 6-in concrete	Fully insulated slab - 2-in screed - rigid insulation (1.5-in EPS for Zones 3A, 4A, 5A, 7, and 8; 1-in EPS for other zones) - 6-in concrete	Same as baseline	ASHRAE 90.1-2004 Jan et al, 2009

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

Characteristic	Baseline	Advanced-Radiant	Advanced-VAV	Data Source/Remarks
Floor F-factor (Btu/h·ft·F)	Zones 1-7: 0.730 Zone 8: 0.540	Zones 3A, 4A, 5A, 7, 8: 0.55 Other zones: 0.64	Zones 1-3: 0.730 Zones 4-5: 0.520 Zones 6-7: 0.510 Zone 8: 0.434	ASHRAE 90.1-2004 Addendum bb to ASHRAE 90.1-2007 (review draft)
Fenestration				
Window wall ratio	0.33 for all facades	0.33 for all facades	0.33 for all facades	CBECS 2003
Targeted U-factor/SHGC	Zones 1-2: 1.22/0.25 Zones 3A, 3B: 0.57/0.25 Zone 3C: 1.22/0.34 Zones 4-6: 0.57/0.39 Zone 7: 0.57/0.49 Zone 8: 0.46/NR	Zones 1-2: 0.65/0.25 Zone 3: 0.60/0.25 Zones 4-5: 0.44/0.26 Zone 6: 0.42/0.35 Zones 7-8: 0.34/0.40	Zones 1-2: 0.65/0.25 Zone 3: 0.60/0.25 Zones 4-6: 0.39/0.38 Zone 7-8: 0.34/0.4	ASHRAE 90.1-2004 Addendum bb to ASHRAE 90.1-2007 (review draft)
Actual selected window U-factor/SHGC/VLT	Zones 1-2: 1.08/0.28/0.16 Zones 3A, 3B: 0.51/0.28/0.20 Zone 3C: 0.94/0.34/0.22 Zones 4-6: 0.55/0.43/0.41 Zone 7: 0.55/0.50/0.51 Zone 8: 0.48/0.47/0.38	Zones 1-3: 0.51/0.28/0.20 Zones 4-5: 0.44/0.24/0.16 Zone 6: 0.42/0.39/0.44 Zones 7-8: 0.31/0.38/0.44	Zones 1-3: 0.51/0.28/0.20 Zones 4-6: 0.42/0.39/0.44 Zones 7-8: 0.31/0.38/0.44	Window type chosen from *EnergyPlus* Library with the closest matching U-factor/SHGC
Exterior shading	No	Overhang with a project factor of 0.5 for zones 1-5; no overhang for other zones	Same as for Radiant	AEDG 30pct guides (e.g., Jarnagin et al., 2006)
Interior shading	No	No	No	
	INTERNAL LOADS			
Occupancy				
Occupant density (person/1000 ft^2)	5	5	5	ASHRAE 62.1-2004
Schedule	See Table A.2	Same as baseline	Same as baseline	
Radiant/Convective fractions of sensible loads	0.3/0.7	0.3/0.7	0.3/0.7	ASHRAE Fundamentals Handbook

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

Characteristic	Baseline	Advanced-Radiant	Advanced-VAV	Data Source/Remarks
Lighting				
Peak lighting power density (W/ft^2)	1.0	0.75	0.75	ASHRAE 90.1-2004 Lighting design and calculation (see *TSD* Section 4.2)
Occupancy sensors	Used in conference and lounge area	Used in conference room, lounge, offices, storage, restrooms, and mechanical room	Same as for Radiant	
Daylight harvesting	No	- Continuous dimming - Illuminance setpoint: 300 lux - Minimum input power fraction: 0.1 - Minimum light output fraction: 0.2	Same as for Radiant	
Schedule	See Table A.2	See Table A.3	See Table A.3	
Plug load				
Peak plug-load power density (W/ft^2)	0.75	0.55	0.55	Plug-load calculation in *TSD* sections 3.5.4 and 4.3
Schedule	See Table A.2	See Table A.3	See Table A.3	
Elevator				
Power (W)	32780	32780	32780	
Schedule	See Table A.2	Same as baseline	Same as baseline	

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

Characteristic	Baseline	Advanced-Radiant	Advanced-VAV	Data Source/Remarks
	HVAC SYSTEM			
System type				
Heating/Cooling	Packaged VAV system - DX packaged air conditioning unit for cooling - gas furnace for heating	Radiant floor heating and cooling + DOAS - air-cooled chiller for radiant cooling - condensing boiler for radiant heating - DOAS unit with DX coil for cooling /dehumidification and hot-water coil for reheating	Packaged VAV system - DX packaged air conditioning unit for cooling - gas furnace for heating - indirect evaporative cooler for precooling in climate zones 2B, 3B, 4B and 5B.	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 cooled chiller - COP=3.1 - Chiller performance curves see Table A.5 DX coil in the DOAS unit - EER=11.3 or 11.5, depending on the sized capacity - DOAS DX performance curves see Table A.6	DX cooling coil - EER=10.2-11.5, depending on the sized capacity - performance curves see Table A.4 Indirect evaporative cooler - effectiveness: 0.7 - pressure drop: 0.8 in. w.c.	ASHRAE 90.1-2004 ASHRAE 90.1-2007 Appliances database of California Energy Commission. Manufactures' 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	Condensing boiler Thermal efficiency = 0.95	Same as baseline	ASHRAE 90.1-2004 ASHRAE 90.1-2007

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

Characteristic	Baseline	Advanced-Radiant	Advanced-VAV	Data Source/Remarks
HVAC control				
Thermostat setpoint (°F)	75 cooling/ 70 heating	75 cooling/ 67 heating	75 cooling/ 70 heating	Design practice Jan et al. 2009
Thermostat setup / setback (°F)	80 cooling / 65 heating	80 cooling / 65 heating	80 cooling / 65 heating	Design practice
Plant loop temperature control	NA	- 59°F for chilled water - 113°F for hot water	NA	Design practice Jan et al. 2009
Air system	- Supply air temperature: 55°F - No supply air temperature reset	- Supply air temperature: 55°F - Supply air temperature reset based on outside air temperature (except climate zones 1-3)	- Supply air temperature: 55°F - Supply air temperature reset based on the warmest thermal zone (except climate zones 1A, 2A, 3A and 4A)	
Hydronic radiant system	NA	- Variable flow based on mean air temperature - Temperature throttling range: 2°C - Radiant heating and cooling setpoints see Figure 4.6	NA	
Ventilation				
Damper control	Gravity damper is used for climate zones 1-3; motorized damper for other zones	Motorized damper is used for all climate zones	Motorized damper is used for all climate zones	ASHRAE 90.1-2004
Demand controlled ventilation	No	Yes	Yes	

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

Characteristic	Baseline	Advanced-Radiant	Advanced-VAV	Data Source/Remarks
Energy recovery	No	- Rotary heat exchanger is used for energy recovery in all climate zones except 3B-CA and 3C. - Heat recovery effectiveness see Table 4.10 - Frost control based on minimum exhaust temperature at 35°F	- Rotary heat exchanger is used for energy recovery in all climate zones except 3B and 3C. - Heat recovery effectiveness see Table4.10 - Frost control based on minimum exhaust temperature at 35°F	
Economizer	No economizer is used in climate zones 1A, 2A, 3A and 4A; differential drybulb based economizer is used for all other zones.	No economizer for DOAS	Differential enthalpy based economizer is used in climate zones 1A, 2A, 3A and 4A; differential drybulb based economizer is used for all other zones.	ASHRAE 90.1-2004
Fan System				
Supply fan	- Variable speed fan - Fan mechanical efficiency: 65% - Fan motor efficiency based on motor power (See Table 4.12) - Part-load performance curve see Table A.8	- Constant speed fan for the DOAS - Fan mechanical efficiency: 65% - Fan motor efficiency based on motor power (See Table 4.12)	- Variable speed fan - Fan mechanical efficiency: 65% - Fan motor efficiency based on motor power (See Table 4.12) - Part-load performance curve see Table A.6	
Exhaust/return fan	Not explicitly modeled.	Same as baseline	Same as baseline	
Fan system static pressure	6.32 in. w.c	- 2.5 in. w.c. - Additional 1.5 in w.c pressure drop for ERV.	- If supply air CFM < 4648, the static pressure is 3.4 in. w.c.; otherwise, the pressure 4.98. - Additional 1.5 in. w.c. pressure if ERV is used. - Additional 0.8 in. w.c. pressure if evaporative cooling is used.	Derived from fan power limitation in ASHRAE 90.1-2004

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

Characteristic	Baseline	Advanced-Radiant	Advanced-VAV	Data Source/Remarks
	SERVICE WATER HEATING			
Gas-fired water heater	- Conventional type with thermal efficiency = 80% - Tank volume = 200 gallon - Standby heat loss coefficient = 15.414 Btu/hr-°F	- Condensing water heater with thermal efficiency = 95%. - Tank volume = 200 gallon - Standby heat loss coefficient = 15.414 Btu/hr-°F	Same as for Radiant	ASHRAE 90.1-2004 Manufacturers' Catalog

Table A.2.b. Baseline and Advanced Buildings Model Assumptions for Medium Office Building Prototype (4,379 m^2) SI units

Characteristic	Baseline	Advanced-Radiant	Advanced-VAV	Data Source/Remarks
	ARCHITECTURALL FEATURES			
Exterior Walls				
Construction	Steel-framed wall - 0.019-m stucco - 0.159-in gypsum board - 0.0508 m x 0.0102 m @ .406 m O.C. stud with fiberglass insulation in cavity - rigid board insulation - 0.159-in gypsum board	Same as baseline	Same as baseline	CBECS 2003
Overall U-factor (W/m2-K)	Zones 1-4: 0.704 Zones 5- 6: 0..477 Zones 7-8: 0.363	Zones 1-4: 0..363 Zone 5: 0.238 Zones 6-8: 0.210	Same as Radiant	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	Same as baseline	CBECS 2003
Overall U-factor (W/m2-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	Same as for Radiant	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	Same as for Radiant	LBNL 2009: http://eetd.lbl.gov/coolroofs/
Slab-on-Grade Floor				
Construction	Concrete slab on earth - carpet pad - 0.152-m concrete	Fully insulated slab - 0.508-m screed - rigid insulation (.0381-m EPS for Zones 3A, 4A, 5A, 7, and 8; 0.0254-m EPS for other zones) - 0.152-m concrete	Same as baseline	ASHRAE 90.1-2004 Jan et al, 2009

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

Characteristic	Baseline	Advanced-Radiant	Advanced-VAV	Data Source/Remarks
Floor F-factor (W/m·K)	Zones 1-7: 1.26 Zone 8: 0.930	Zones 3A, 4A, 5A, 7, 8: 0.952 Other zones: 1.11	Zones 1-3: 1.26 Zones 4-5: 0.900 Zones 6-7: 0.883 Zone 8: 0.751	ASHRAE 90.1-2004 Addendum bb to ASHRAE 90.1-2007 (review draft)
Fenestration				
Window wall ratio	0.33 for all facades	0.33 for all facades	0.33 for all facades	CBECS 2003
Targeted U-factor/SHGC	Zones 1-2: 6.93/0.25 Zones 3A, 3B: 3.2/0.25 Zone 3C: 6.93/0.34 Zones 4-6: 3.2/0.39 Zone 7: 3.2/0.49 Zone 8: 2.6/NR	Zones 1-2: 3.7/0.25 Zone 3: 3.4/0.25 Zones 4-5: 2.5/0.26 Zone 6: 2.4/0.35 Zones 7-8: 1.9/0.40	Zones 1-2: 3.7/0.25 Zone 3: 3.4/0.25 Zones 4-6: 2.2/0.38 Zone 7-8: 1.9/0.4	ASHRAE 90.1-2004 Addendum bb to ASHRAE 90.1-2007 (review draft)
Actual selected window U-factor/SHGC/VLT	Zones 1-2: 6.13/0.28/0.16 Zones 3A, 3B: 2.9/0.28/0.20 Zone 3C: 5.3/0.34/0.22 Zones 4-6: 3.1/0.43/0.41 Zone 7: 3.1/0.50/0.51 Zone 8: 2.7/0.47/0.38	Zones 1-3: 2.9/0.28/0.20 Zones 4-5: 2.5/0.24/0.16 Zone 6: 2.4/0.39/0.44 Zones 7-8: 1.8/0.38/0.44	Zones 1-3: 2.9/0.28/0.20 Zones 4-6: 2.4/0.39/0.44 Zones 7-8: 1.8/0.38/0.44	Window type chosen from *EnergyPlus* Library with the closest matching U-factor/SHGC
Exterior shading	No	Overhang with a project factor of 0.5 for zones 1-5; no overhang for other zones	Same as for Radiant	AEDG 30pct guides (e.g., Jarnagin et al., 2006)
Interior shading	No	No	No	
	INTERNAL LOADS			
Occupancy				
Occupant density (person/92.9 m^2)	5	5	5	ASHRAE 62.1-2004
Schedule	See Table A.2	Same as baseline	Same as baseline	
Radiant/Convective fractions of sensible loads	0.3/0.7	0.3/0.7	0.3/0.7	ASHRAE Fundamentals Handbook

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

Characteristic	Baseline	Advanced-Radiant	Advanced-VAV	Data Source/Remarks
Lighting				
Peak lighting power density (W/ft^2)	10.76	8.07	8.07	ASHRAE 90.1-2004 Lighting design and calculation (see *TSD* Section 4.2)
Occupancy sensors	Used in conference and lounge area	Used in conference room, lounge, offices, storage, restrooms, and mechanical room	Same as for Radiant	
Daylight harvesting	No	- Continuous dimming - Illuminance setpoint: 300 lux - Minimum input power fraction: 0.1 - Minimum light output fraction: 0.2	Same as for Radiant	
Schedule	See Table A.2	See Table A.3	See Table A.3	
Plug load				
Peak plug-load power density (W/ft^2)	8.07	5.92	5.92	Plug-load calculation in *TSD* sections 3.5.4 and 4.3
Schedule	See Table A.2	See Table A.3	See Table A.3	
Elevator				
Power (W)	32,780	32,780	32,780	
Schedule	See Table A.2	Same as baseline	Same as baseline	

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

Characteristic	Baseline	Advanced-Radiant	Advanced-VAV	Data Source/Remarks
	HVAC SYSTEM			
System type				
Heating/Cooling	Packaged VAV system - DX packaged air conditioning unit for cooling - gas furnace for heating	Radiant floor heating and cooling + DOAS - air-cooled chiller for radiant cooling - condensing boiler for radiant heating - DOAS unit with DX coil for cooling /dehumidification and hot-water coil for reheating	Packaged VAV system - DX packaged air conditioning unit for cooling - gas furnace for heating - indirect evaporative cooler for precooling in climate zones 2B, 3B, 4B and 5B.	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 cooled chiller - COP=3.1 - Chiller performance curves see Table A.5 DX coil in the DOAS unit - EER=11.3 or 11.5, depending on the sized capacity - DOAS DX performance curves see Table A.6	DX cooling coil - EER=10.2-11.5, depending on the sized capacity - performance curves see Table A.4 Indirect evaporative cooler - effectiveness: 0.7 - pressure drop: 199 Pa.	ASHRAE 90.1-2004 ASHRAE 90.1-2007 Appliances database of California Energy Commission. Manufactures' Catalog
Heating efficiency	Gas furnace - burner efficiency =0.78 (capacity<=65.9 kW); =0.80 (capacity>65.9 kW) - part load performance curve see Table A.7	Condensing boiler Thermal efficiency = 0.95	Same as baseline	ASHRAE 90.1-2004 ASHRAE 90.1-2007

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

Characteristic	Baseline	Advanced-Radiant	Advanced-VAV	Data Source/Remarks
HVAC control				
Thermostat setpoint (°C)	23.9 cooling/ 21.1 heating	23.9 cooling/19.4 heating	23.9 cooling/ 21.1 heating	Design practice Jan et al. 2009
Thermostat setup / setback (°C)	26.7 cooling / 18.3 heating	26.7 cooling / 18.3 heating	26.7 cooling / 18.3 heating	Design practice
Plant loop temperature control	NA	- 15°C for chilled water	NA	Design practice Jan et al. 2009
Air system	- Supply air temperature: 12.8°C - No supply air temperature reset	- Supply air temperature: 12.8°C - Supply air temperature reset based on outside air temperature (except climate zones 1-3)	- Supply air temperature: 12.8°C - Supply air temperature reset based on the warmest thermal zone (except climate zones 1A, 2A, 3A and 4A)	
Hydronic radiant system	NA	- Variable flow based on mean air temperature - Temperature throttling range: 2°C - Radiant heating and cooling setpoints see Figure 4.6	NA	
Ventilation				
Damper control	Gravity damper is used for climate zones 1-3; motorized damper for other zones	Motorized damper is used for all climate zones	Motorized damper is used for all climate zones	ASHRAE 90.1-2004
Demand controlled ventilation	No	Yes	Yes	

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

Characteristic	Baseline	Advanced-Radiant	Advanced-VAV	Data Source/Remarks
Energy recovery	No	- Rotary heat exchanger is used for energy recovery in all climate zones except 3B-CA and 3C. - Heat recovery effectiveness see Table 4.10 - Frost control based on minimum exhaust temperature at 1.7°C	- Rotary heat exchanger is used for energy recovery in all climate zones except 3B and 3C. - Heat recovery effectiveness see Table4.10 - Frost control based on minimum exhaust temperature at 1.7°C	
Economizer	No economizer is used in climate zones 1A, 2A, 3A and 4A; differential drybulb based economizer is used for all other zones.	No economizer for DOAS	Differential enthalpy based economizer is used in climate zones 1A, 2A, 3A and 4A; differential drybulb based economizer is used for all other zones.	ASHRAE 90.1-2004
Fan System				
Supply fan	- Variable speed fan - Fan mechanical efficiency: 65% - Fan motor efficiency based on motor power (See Table 4.12) - Part-load performance curve see Table A.8	- Constant speed fan for the DOAS - Fan mechanical efficiency: 65% - Fan motor efficiency based on motor power (See Table 4.12)	- Variable speed fan - Fan mechanical efficiency: 65% - Fan motor efficiency based on motor power (See Table 4.12) - Part-load performance curve see Table A.6	
Exhaust/return fan	Not explicitly modeled.	Same as baseline	Same as baseline	
Fan system static pressure	1,574 Pa	- 623 Pa - Additional 374 Pa pressure drop for ERV.	- If supply air m3/s < 2.19, the static pressure is 847 Pa.; otherwise, the pressure 1241 Pa. - Additional 374 Pa pressure drop for ERV. - Additional 199 Pa pressure if evaporative cooling is used.	Derived from fan power limitation in ASHRAE 90.1-2004

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

Characteristic	Baseline	Advanced-Radiant	Advanced-VAV	Data Source/Remarks
	SERVICE WATER HEATING			
Gas-fired water heater	- Conventional type with thermal efficiency = 80% - Tank volume = 0.757 m^3 - Standby heat loss coefficient = 8.118 W/K	- Condensing water heater with thermal efficiency = 95%. - Tank volume = 0.757 m^3 gallon - Standby heat loss coefficient = 8.118 W/K	Same as for Radiant	ASHRAE 90.1-2004 Manufacturers' Catalog

Table A.3. 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	0.8	0.9	0.9	0.9	0.9	0.5	0.3	0.3	0.2	0.2	0.15	0.15
	Sat	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.3	0.3	0.3	0.3	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	Sun, Hol	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Plug load (Fraction)	WD	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.9	0.9	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.5	0.4	0.4	0.4	0.4	0.4	0.4
	Sat	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.35	0.35	0.35	0.35	0.35	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Sun, Hol	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
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
Elevator (Fraction)	WD	0	0	0	0	0	0	0	0.35	0.69	0.43	0.37	0.43	0.58	0.48	0.37	0.37	0.46	0.62	0.12	0.04	0.04	0	0	0
	Sat	0	0	0	0	0	0	0	0.16	0.14	0.21	0.18	0.25	0.21	0.13	0.08	0.04	0.05	0.06	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
Service Hot Water Schedule																									
Hot water (Fraction)	WD	0.05	0.05	0.05	0.05	0.05	0.08	0.07	0.19	0.35	0.38	0.39	0.47	0.57	0.54	0.34	0.33	0.44	0.26	0.21	0.15	0.17	0.08	0.05	0.05
	Sat	0.05	0.05	0.05	0.05	0.05	0.08	0.07	0.11	0.15	0.21	0.19	0.23	0.2	0.19	0.15	0.13	0.14	0.07	0.07	0.07	0.07	0.09	0.05	0.05
	Sun, Hol	0.04	0.04	0.04	0.04	0.04	0.07	0.04	0.04	0.04	0.04	0.04	0.06	0.06	0.09	0.06	0.04	0.04	0.04	0.04	0.04	0.04	0.07	0.04	0.04
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	65	67	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	65	65
	Sat	65	65	65	65	65	65	67	70	70	70	70	70	70	70	70	70	70	65	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	80	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. 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	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	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	0.3	0.3	0.3	0.3	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	0.85	0.85	0.85	0.85	0.75	0.85	0.85	0.85	0.85	0.45	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	0.3	0.3	0.35	0.35	0.35	0.35	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
Elevator (Fraction)	WD	0	0	0	0	0	0	0	0.35	0.69	0.43	0.37	0.43	0.58	0.48	0.37	0.37	0.46	0.62	0.12	0.04	0.04	0	0	0
	Sat	0	0	0	0	0	0	0	0.16	0.14	0.21	0.18	0.25	0.21	0.13	0.08	0.04	0.05	0.06	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
Service Hot Water Schedule																									
Hot water (Fraction)	WD	0.05	0.05	0.05	0.05	0.05	0.08	0.07	0.19	0.35	0.38	0.39	0.47	0.57	0.54	0.34	0.33	0.44	0.26	0.21	0.1	0.17	0.08	0.05	0.05
	Sat	0.05	0.05	0.05	0.05	0.05	0.08	0.07	0.11	0.1	0.21	0.19	0.23	0.2	0.19	0.1	0.13	0.14	0.07	0.07	0.07	0.07	0.09	0.05	0.05
	Sun, Hol	0.04	0.04	0.04	0.04	0.04	0.07	0.04	0.04	0.04	0.04	0.04	0.06	0.06	0.09	0.06	0.04	0.04	0.04	0.04	0.04	0.04	0.07	0.04	0.04
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	65	67	67	67	67	67	67	67	67	67	67	67	67	67	67	67	67	65	65
	Sat	65	65	65	65	65	65	67	67	67	67	67	67	67	67	67	67	67	65	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	80	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.5. Performance Curves for the DX Coils Used in the Packaged VAV System

curve name	coefficients					
	a	b	c	d	e	f
Total cooling capacity modifier function of temperature $Cap(T_{wb,i},T_{c,i}) = a + b(T_{wb,i}) + c(T_{wb,i})^2 + d(T_{c,i}) + e(T_{c,i})^2 + f(T_{wb,i})(T_{c,i})$	1.39072	-0.05291	0.001842	0.000583	-0.00019	0.000265
Total cooling capacity modifier function of flow fraction $Cap(ff) = a + b(ff) + c(ff)^2$	0.718954	0.435436	-0.1419	-	-	-
EIR modifier function of temperature $EIR(T_{wb,i},T_{c,i}) = a + b(T_{wb,i}) + c(T_{wb,i})^2 + d(T_{c,i}) + e(T_{c,i})^2 + f(T_{wb,i})(T_{c,i})$	-0.53616	0.105138	-0.00173	0.014985	0.00066	-0.00174
EIR modifier function of flow fraction $EIR(ff) = a + b(ff) + c(ff)^2$	1.19525	-0.30614	0.110973	-	-	-
Part load correction function $PLF(PLR) = a + b(PLR) + c(PLR)^2$	0.771	0.229	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 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 Air-Cooled Chiller

curve name	coefficients a	b	c	d	e	f
Total cooling capacity modifier function of temperature $Cap(T_{cw,l},T_{con,e}) = a + b(T_{cw,l}) + c(T_{cw,l})^2 + d(T_{con,e}) + e(T_{con,e})^2 + f(T_{cw,l})(T_{con,e})$	1.0215	0.037	0.0002	-0.0039	-0.0001	-0.0003
EIR modifier function of temperature $EIR(T_{cw,l},T_{con,e}) = a + b(T_{cw,l}) + c(T_{cw,l})^2 + d(T_{con,e}) + e(T_{con,e})^2 + f(T_{cw,l})(T_{con,e})$	0.8748	-0.0045	0.0005	-0.0055	0.0005	-0.0007
Part load correction function $PLF(PLR) = a + b(PLR) + c(PLR)^2$	0.0637	0.5849	0.3528	-	-	-

$T_{cw,l}$ – leaving chilled water temperature (ºC)

$T_{con,e}$ – entering condenser water temperature (ºC)

PLR – part load ratio (the ratio between actual chiller load and its available capacity)

Table A.7. Performance Curves for the DX Coil Used in the DOAS System

	coefficients					
curve name	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	0.1	0	-	-	-

See Table A.4 note for the meanings of the variables in the performance curves

Table A.8. Part Load Performance Curve for the Gas Furnace

	coefficients		
curve name	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)			

Table A.9. Part Load Performance Curve for the Variable Speed Fan

	coefficients				
curve name	a	b	c	d	e
Part load correction function $PLF(PLR) = a + b(PLR) + c(PLR)^2$	0.0013	0.147	0.9506	-0.0998	0
PLR – part load ratio (the ratio between actual and the maximum air mass flow rate)					

Appendix B

Review Comments and Responses

Table B.1 TSD Draft Report Review Comments and Responses

No.	**Category**	**Comment**	**PNNL Response**	**PNNL Action**
1	Bldg Form	What is the floor to floor and floor to ceiling heights? Is there a dropped ceiling which represents an additional insulation layer.	13 feet floor to floor, and 9 feet floor to ceiling. Plenum is return air, so moving conditioned air. Drop ceiling also subject to infiltration with conditioned space. Will not add significant insulation value.	No action
2	Bldg Form	Is this a sacred cow? Why not suggest less window area. You're starting at a fairly high value (33%). What would a building look like with 25% window area and what are the integrated design benefits (reduced equipment size, reduced capital costs that could be rolled into other EEMs). At least getting the window area on the east and west orientations minimized would be a good start. As your numbers indicate, we aren't going to get to 50% energy reduction unless with get smarter with architectural design and the use of windows. If a more sustainable building or net-zero energy building means having a discussion about window area, lets start talking. The TSD or Advance Design Guideline products should lead the way and at least show an optional track that highlights the benefit of optimizing window area and window placement. The importance of this issue is climate dependent.	This is a difficult battle to fight and win with the design and developer community. We ran a model with 15% window to wall area on the west and saw about a 1% drop in energy usage. All sides could not be reduced to 15%, so if impact is closer to 0.5% average per side, including daylighting offset, impact for perhaps 25% overall might be closer to 2% total savings.	No further action to incorporate in the model was taken as achieving well over 50% for advanced case with radiant systems. Mention was added in the TSD of the value of reducing window to wall ratio particularly on the east and west. This strategy is worth pursuing in future work such as for the small office. Important to defined prototype model to allow such strategies to be applied more readily--separate windows that can be scaled in width as well as height instead of ribbon windows. However code change may be needed to adopt this more widely because of strong resistance from architects and developer with belief in large window areas selling buildings and attracting occupants.
3	Bldg Form	Interesting that open office area is programmed to be smaller than private office area.	Yes, see footnote on source.	No action

No.	**Category**	**Comment**	**PNNL Response**	**PNNL Action**
4	Bldg Form	I would like to suggest another analysis regarding the shape of the building. Since the internal loads determine the energy consumption of a commercial building, it might be interesting to analyze a building with less depth and, thus, smaller core areas. For example, the building could still be 50 m long, but only 16.5 m wide (aspect ratio 3!). To compensate for the gross floor area, it could have 6 instead of 3 stories. I have no idea what this would mean for the overall energy efficiency, but it would definitely improve day lighting (what means less artificial light) and natural ventilation. Would it be possible to analyze the energy use intensities for the perimeter and core zones individually to get a first idea whether this would bring us in the right direction?	While this is an interesting concept, building aspect ratio is largely driven by site constraints. Such a change would be difficult to implement in reality consistently across projects. This would increase the ratio of building envelope to usable floor area, which would tend to offset savings, and by adding more floors, would increase other costs as well.	No action
5	Envelope	Interesting to see stucco selected. Living in suburbia Portland I have seen a lot of new commercial properties go up and they are almost all tilt up concrete with and without brick veneer.	Stucco has similar thermal properties as many other finishes. Choice of steel framed walls was based on 2003 CBECS data. Most buildings of this type are steel-framed. Concrete or concrete masonry unit follow. We ran baseline model with 6" concrete walls with same insulation R-value as with metal framed wall, and less than a 1% savings resulted.	No action
6	Envelope	Above the rigid insulation there is typically some form of wood sheathing that the roof membrane is attached to.	This is not always the case, particularly with tapered formed rigid insulation that also serves a run-off function. This would add only a modest amount to roof R-value.	No action
7	Envelope	Typically fire proofing under metal deck adds insulation value. Does the rigid insulation sit directly on top of the metal decking or is there a wood or gypsum lay between the deck and insulation?	Fire proofing and sheathing together could add a modest R-value on the margin. Fire-proofing insulation value is subject to inconsistency in application	No action

No.	**Category**	**Comment**	**PNNL Response**	**PNNL Action**
			and more complex heat transfer through joists and/or beams. Penetrations and gaps in roof insulation are not accounted for in the existing R-value, so adding more R-value may not be accurate. Such a change would result in a very small reduction in both baseline and advanced energy usage. This was tested for additional of R3 to roof insulation value for Baltimore, a good average climate for range of analysis. Baseline usage reduced under 1%, advanced by 0.2% and overall savings reduced 0.3%.	
8	Envelope	How are 2nd and 3rd floor slab edges insulated. Many architectural designs have the slab edge exposed to the air or treated with minimal insulation that is less than the wall assembly R-value.	Modeled wall values are simplified to meet code and improve on code. Some jurisdictions do require slab edge insulation and some do apply it routinely depending on the designers.	No action
9	Envelope	Is the slab edge modeled above the ground, exposed to the air or is the slab edge buried and covered with dirt?	Slab edge has an effective F-factor consistent with code. Losses from the slab edge are typically very modest.	No action
10	Envelope	Typical window seal is 2.5 ft. and window height of 5-6 ft. or larger. Getting window height correct will affect daylighting opportunities.	Simulation has sill height of 3 ft. 5in, and window height of 4 ft. 4 in. so top of window is very close to the values cited in comment, and have an impact on daylighting. A review of daylighting results indicated	No action

No.	Category	Comment	PNNL Response	PNNL Action
			getting about 80% of the potential daylighting savings in the areas exposed to side daylighting, so further refinement would not significantly improve savings. expected to be small for changing these values.	
11	Envelope	Unrealistic, Architects will incorporate some form of main entry / lobby that has a mult-floor (i.e. floor to roof) window section that will be built out of curtain wall. Efficiency opportunities and cost-effectiveness of curtain-wall is different than punched or storefront windows.	Model is simplified to allow rapid modeling of changes across many climates. Window performance is defined to code or performance value without specific regard to type of construction. Will review assumptions in cost-effectiveness and consider changing cost values to reflect mix of curtain wall and fixed windows.	No further action. Reviewed assumptions around type of windows modeled. CBECS data showed the bulk of office buildings in this size range use curtain wall or storefront systems. Performance and cost-effectiveness based on curtain wall. Generalization of multi-story lobby facade not demonstrated by evidence other than anecdotal, and the choice of curtain wall performance and overall window to wall ratio of 33% considered to adequately capture the energy impact of the fenestration in typical medium office.
12	Envelope	To reach the standard SHGC and U-factor values, the *EnergyPlus*" close match" SHGC and U-factor could be trued up by adjusting model window area.	Changing window areas would distort SHGC and U-value in different proportions and would also alter wall heat transfer to a minor degree. The closeness of the windows selected to code values is discussed in the report. No further changes to try to correct for this are being	No action

No.	Category	Comment	PNNL Response	PNNL Action
			made.	
13	Envelope	Does this imply that the U-values are not center of glass values and that the U-values represent total window assembly (frame + edge of glass + center of glass).	Yes, modeled U-values are overall U-values including hypothetical framing.	No action
14	Envelope	What is the effective average infiltration value compared to design values. Looking for load – does schedule and varying wind speed drop this design value significantly in model?	Infiltration is set to about 0.2 ft^3/min/ ft^2 of exterior area, is adjusted for wind speed according to DOE-2 formula and is scheduled at 100% during hours when system(s) scheduled off and 25% when fan(s) run (these values based on study at PNNL as a follow on to field data from NIST and 90.1 committee input).	No action
15	Envelope	What are the odds of getting a footnote explaining the difference between assembly U-value and Recommended R-value. Why do I need a R-13 batt (0.077 U-value) when the assembly requirement is only 0.124 U-value? The point is steel-framing has large reduction of effective R-value. Maybe this belongs in the baseline building description.	Does not seem necessary in this technical background report for an experienced audience to explain a basic principle.	No action.
16	Envelope	No look at the benefits of massing, loss opportunity? Many of the commercial office buildings already use massing beyond your assumed baseline and the benefits should be recognized if they are designing with mass. I understand the energy cost-effectiveness may not be the driver, but if they are already doing it for other reasons (esthetics, durability, reduced maintenance), why not book some savings.	PNNL ran models with 6 in. concrete wall added to frame wall. Overall R-value of wall increased for concrete with insulation left the same as with the metal stud wall. Across all climates, impact was about 0.5% improved energy savings. At this modest improvement in energy, adding mass is unlikely to be cost effective. As noted above, CBECS data suggested framed wall significantly more common now than mass wall.	No action
17	Envelope	This would suggest table 3.4 only applies to punched windows, which	Advanced models being	Changed fenestration

No.	Category	Comment	PNNL Response	PNNL Action
		is a small percentage of the commercial construction market. Suggest additional analysis and recommendations for curtain-wall and storefront windows.	changed to addendum bb values for curtain wall.	performance to curtain wall. See response to question 11 above.
18	Envelope	Good example on projection factor below. If higher windows are evaluated (as suggested earlier), this projection factor may need to be reduced, i.e. it's unlikely an architect would but a 3ft.+ overhang on a 5.5 ft.high window. How would you treat or model the tall curtain-wall assembly for shading overhangs?	Window heights are reasonably close to earlier suggestion. Not changing window heights as discussed in response to question on higher windows.	No action
19	Envelope	As for the windows, we would suggest to consider better U-factors. In Europe for example, following values are standard (and I guess in Germany even mandatory): frame 2.0 … 2.2 W/m²K, glass 1.2 W/m²K => Window ~1.5 W/m²K (note, Germany would be Climate Zone 5). It's almost impossible to get windows with higher U-factors.	Advanced models being changed to addendum bb values for curtain wall.	Changed fenestration performance to curtain wall. See response to question 11 above.
20	Envelope	We would also suggest to consider automatic shading controls, at least for some climate zones. The idea is simply a variable SHGC and adjustable daylight level. Here are some examples: www.pacificshades.com.	Will consider automatic shading if 50% not reached. Costly measure.	Automatic shading was not necessary to achieve 50% savings with radiant systems. This could be considered for future work, particularly to enhance the performance of less costly HVAC systems. Automatic shading systems tend to be costly and require maintenance, so would not necessarily be among the first priority high performance energy measures.
21	Envelope	A – One example, steel stud walls in the office can only be improved by adding exterior sheathing. The cavity insulation is roughly derated by 50% due to the steel thermal short circuiting. A 2x6 steel stud wall does not contribute much over a 2x4 steel stud wall. Thus, the challenge is to significantly improve the wall R-value without increasing the wall thickness.	Advance case includes adding exterior rigid insulation.	No action
22	Envelope	C – The 90.1 envelope subcommittee has spent considerable time trying to incorporate continuous air barriers into the standard. This is another item where advanced energy savings can be obtained. Vestibules are another feature to reduce air infiltration loads.	Continuous air barrier savings not available and no reasonable method to estimate identified for this study.	No action

No.	Category	Comment	PNNL Response	PNNL Action
23	General	Typical office occupancy is 7am-7pm. It is unlikely HVAC will need to run to midnight. I don't see a need to run HVAC after 7-8pm, 9pm at the latest. I could see a high raise office running HVAC to midnight, but not a 55K sq. ft. office.	Scheduled operating hours consistent with total hours under CBECS data (CBECS 2003).	No action
24	General	Proven or accepted technology by end user?	Technology for occupancy sensor control of task lighting and other plug loads is commercially available, and well not pervasively used, is being applied in buildings.	No action
25	General	EUIs look unrealistically low. I would expect the baselines to be 60-80 for average climates and up to 90-100 for extreme climates. Fatten up the models. Factor in operational slop – people don't turn things off.	Baseline model EUIs are intended to reflect buildings that meet ASHRAE 90.1-2004, not buildings that don't meet that standard. Advanced case models are expected to be enhancements to an in compliance building. Determining what to assume is not working would create a lot of arbitrary variation that may impact the % savings and performance in unknown ways. That said, attempts to increase the EUIs consistent with reasonable design and operating practice such as adjusting heating setback within comments made by the 90.1 committee have been implemented.	Some adjustments were made to the baseline schedules and outside air. Outside air ventilation was increased based on a calculation of using the multiple zone and critical zone rules in ASHRAE 62.1-2004 Standard. EUI for baseline increased to an average of 58 kBtu/s.f./year with 48 for the mildest climate Los Angeles, and 76 for the most extreme climate Fairbanks. This is an increase from the earlier average of 47. In addition, an extraction of data from CBECS (office, 1990-2004, 10,000-100,000 square feet, packaged AC, no incandescent lighting provided 19 surveyed buildings resulting in EUI of 77. Adjusting this for compliance with 90.1-2004 vs 1999 (-14% according to ASHRAE) and an additional 10% for baseline close to new, compliant performance,

No.	Category	Comment	PNNL Response	PNNL Action
				results in an EUI of 58, suggesting that the average of 58 now calculated is reasonable given the goals of the TSD work.
26	General	Here are some suggestions of measures, which could be technical and/or organizational:• Radiant heating and cooling• Chilled beams• Natural / hybrid ventilation (at least for some climate zones)• Nighttime ventilation• Lighting control for different zones (perimeter / core)• Move janitorial activities from evening/night to regular work time (and adjust schedules, accordingly)• Sophisticated control systems and even more important: sophisticated control strategies (adjustment of setpoints, schedules, etc.)• Geothermal energy (directly for cooling in combination with radiant cooling)• Cogeneration (e.g., in combination with absorption chillers)• Fuel cells???	* Radiant heating and cooling with DOAS in advanced. *Chilled beams primarily convective, require colder water than radiant, may have forced air so may not save as much as radiant. *Natural ventilation not effective in many climates and added cost high for hybrid systems. *Nighttime ventilation considered if missing 50%. *Lighting controls include different % savings in different types of spaces, with daylighting in perimeter. *Reducing evening janitorial services if missing 50%, and possible for future work, although an operator issue not a design issue. *Simulation includes added controls for VAV case, see TSD. *geothermal (GSHP) is being explored for other TSD work. Limited application in dense urban areas due to thermal contamination. *Cogeneration and fuel cells reduce energy and carbon primarily if renewable fuel source, and part of reduction beyond 50% goal on path to net	50% goal met for radiant system with DOAS case. Budget and schedule limitations precluded analysis of additonal measures. Will recommend future work on night ventilation, consideration of reducing evening hours for shifting janitorial towards working hours, occupancy sensor control of HVAC setpoints/damper positions, inclusion of on-site generation including co-generation and fuel cells as well as solar opportunities.

No.	Category	Comment	PNNL Response	PNNL Action
			zero.	
28	HVAC	This isn't realistic. Cost of duct work would suggest two units that serve ½ the floor area on all three floors, i.e. north/south or east /west zone orientation. Common supply and return air ducting shaft / chase would run from roof to the 1st floor.	Simplification of systems done to facilitate modeling. Not able to revise geometry of model at this point to accomadate re-zoning to east-west systems.	Include recommendation for future work to explore east west and or/core perimeter configurations
29	HVAC	This may be the ASHRAE Std 55 recommendation, but likely not maintained in the real would. If you want to maintain a 5F deadband I suggest other temperature ranges (68H/73C, 69H/74C, 70H/75C) are assigned for different climate zones. The cooling setpoint in humid climates is generally lower (72F) in an effort to control humidity.	For consistency across models and with 5 degree deadband in 90.1 setpoints left at original settings. No data available to set any different values for different climates and buildings in medium office category.	No action
30	HVAC	Check for load data, (i.e. Fan – CFM/Sqft, Cooling – Sqft/Ton, Heating – BTU/Sqft) is this information going to be presented.	Loads information not provided at this time.	No action
31	HVAC	Another approach I have seen is to use ASHRAE extreme weather for design day and apply a smaller or no sizing factor.	Part load hours considered with stated sizing and appears reasonable distribution.	No action
32	HVAC	I recommend a section describing the air distribution system: materials (hard duct vs. flex duct) duct sizing & velocities (target pressure drop per 100' for main and run out legs), type of VAV terminal units, return plenum or ducted return, air diffusers, etc.	Systems are not fully designed, and design elements suggested are incorporated in broader factors such as static pressure that are shown in the TSD report.	No action
33	HVAC	More importantly than COP is the part load efficiency assigned in model. What set of efficiency curves are used in your analysis? Is there any accounting for de-gradation in equipment performance that is common with packaged rooftop equipment?	Include identified performance curves with any more detailed system descriptions adressed under above comment. Study reflects new building performance and does not try to capture degradation of systems over time. Such a modeling approach has	Performance curves included in Appendix A. Mention of considering long-term performance, and maintenance and operations is included in the recommendations for future work.

No.	Category	Comment	PNNL Response	PNNL Action
			not been generally adopted and would require significant changes in modeling approach with the need to collect significant industry information on experience in the field. There may be an increased relative savings from high performance equipment in the advanced case caused by higher quality equipment but this would likely be offset by operator changes due to unfamiliarity with newer systems.	
34	HVAC	(fan power ratio)	agree to change in report	No action
35	HVAC	With or without gas heat 0.2 credit?	Text discusses 0.2 credit for gas (non-electric) heat. Values in tables are with credit, except 240,000 to 760,000 Btuh.	Fixed value for 240-760 kBtuh.
36	HVAC	Like cooling, more importantly than AFUE and Ec is the part-load efficiency assigned in model. What set of efficiency curves are used in your analysis?	Include identified performance curves with any more detailed system descriptions adressed under above comment.	Part load performance curves provided in Appendix A
37	HVAC	Does this imply that the gas furnace part-load efficiency curve is hold fixed at 100% and a constant 78% value is used. I recently modeled a gas furnace in a DOE2 model and the default curves resulted in an annual efficiency of 65%, which I thought was unrealistically low.	Include identified performance curves with more detailed system descriptions addressed under above comment.	Part load performance curves provided in Appendix A
38	HVAC	With one RTU (rooftop unit) per floor I can see you would have units under 20,000 sq. ft. But if there was only two units (as previously suggested) I suspect all units would be over 20,000 cfm.	Simulation will continue to use three units because building size will vary in reality, not just at modeled square footage, some units will be less than 20,000 cfm. The fan power varies in the model by climate	No action

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			zone according to airflow and the code allowed power. This is reasonable given the range of building sizes and climates represented by the analysis.	
39	HVAC	This would represent good design practice in custom AHU (air handling unit) that uses a plug fan. If Packaged RTUs are using plug fans, I would suspect an efficiency range of 55-60% is more realistic. I suggest looking at vendor product data.	Fan efficiency values and assumption of a 90% ratio for fan bhp to design are both worth considering further. If fan efficiency were lower, and ratio of bhp to nameplate were lower, allowed static would be lower as well. Note that model includes a supply fan only, so any relief fan or return fan static is not accounted for directly, and the pressure drop for this is included.	Determined that effective fan power is set at appropriate level for code baseline. Baseline is set to just meet 90.1-2004.
40	HVAC	These pressures look excessive. Can packaged RTUs even be selected and built that can meet these pressures? These pressures would suggest high external static pressure and horrific duct design.	See response to 40 above	See response to 40 above
41	HVAC	Assuming a minimum design airflow of 1 cfm/ sq. ft., this ventilation rate is low <10%. From a practical standpoint I see most designs coming in at 20% outside air (OSA). Designers often use 10 people per 1000 sq. ft. (egress level) in office buildings even though actual occupancy is closer to 5 per 1000 sq. ft. Remember there are high occupancy areas (conference rooms) which will define the critical ventilation zone that will also drive the need for higher OSA rates.	Reviewing outside air is appropriate.	Changed to 62.1-2004 calculation of outside air for multiple-zone system rules which account for spaces with different uses such as conference rooms. Increased outside air as a result about 20% above earlier model.
42	HVAC	Remember excessive ventilation is good for us, at least according to LEED, who gives an additional point for excessive ventilation.	OK--but modeling to code.	No action
43	HVAC	I think it is your only hope at getting to 50%. Air is an inefficient means of heat transfer. Radiant water systems are the way of the future.	We are modeling radiant systems.	No action
44	HVAC	Is there a case of double counting here? I thought one of the ways RTU efficiency (EER) was improved was the use of premium	The efficiency ratings are based on minimal static, so	No action

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		efficient motor by the manufacturers.	the benefit of motor efficiency is greatly understated. It is reasonable to take credit for the effect of the improved motor efficiency on fan energy.	
45	HVAC	TEFC (totally enclosed fan) vs. ODP (open drip-proof)?	TEFC, report indicates this at the end of 2.6.6.	No action
46	HVAC	Are economizers recommended for all RTU sizes or will there be a size cut off, i.e. 3 tons?	Model capacities all greater than 6 tons, so including economizers for all units. Designers should know to exclude from units that are too small to have effective economizers.	No action
47	HVAC	What is the assumed supply air temperature at the 45F OSA cut out temperature?	Heat recovery modeling inputs in final TSD description of DOAS section 4.4.1 and in the alternative VAV case in section 4.5	No action
48	HVAC	What is your supply air to return air ratio for the listed efficiencies? Supply airflow is generally higher than return airflow since air is lost for building pressurization and toilet or other exhaust is generally not recovered. How is efficiency during cold weather down graded to account for exhaust air frosting / heat exchanger icing up. Is the wheel slowed up or bypassed?	See above question 47	No action
49	HVAC	Don't understand this. Is direct evaporative cooling excluded, if so why? I would encourage you to look at indirect/direct cooling with a small direct expansion (DX) coil sized for latent heat removal to control humidity during the unusual hot and humid days. To limit build up of humidity, operate in 100% OSA mode with no return air re-circulated	Indirect/direct is only applicable to a limited set of the drier climate zones. *EnergyPlus* modeling of indirect/direct is also not functioning. Will pursue modeling indirect only for some climate zones.	Indirect evaporative cooling modeled for climate zones 2B, 3B, 4B and 5B for the VAV alternative advanced case. Not needed for radiant system advanced case to meet savings target and because of added cost, is not included for that case.
50	HVAC	Don't understand reference to three evaporative coolers.	This refers to the three packaged VAV units, each	No action

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			with a separate evaporative cooler.	
51	HVAC	What is the assumed pressure drop on the primary air side?	Reviewing indirect evaporative cooling inputs	0.8 pressure drop on primary air side. Now included in TSD
52	HVAC	Aren't there zones that will have ventilation demands that will require higher terminal unit box minimum airflow settings, i.e., conference rooms?	Model is being corrected to set minimums so that outside air requirements are met.	See response to question 41 above
53	HVAC	Evaluate getting rid of gas hot water heater. Tank and piping heat losses and associated circulation pump energy probably exceeds actual hot water load.	Piping runs are small and localized to core restrooms and break rooms in many cases for this size and type of building. Service water heating is a small energy usage. Will describe in report potential benefit of on-demand water heaters. Advanced case includes condensing water heater, so additional savings from on-demand are not substantial.	Added mention of on-demand water heaters as alternative to serve peripheral loads to advanced case in TSD.
54	HVAC	Recommend switch from all air systems to water based systems for heating and cooling. This could be radiant slab heating and cooling, chilled beams (passive/active), chilled ceilings, etc.	Radiant heating and cooling being modeled for TSD.	No action
55	HVAC	The HVAC options explored do not include geothermal (or ground source) heat pumps. While not applicable to all climates, it certainly would be in many.	Because of the difficulties in modeling multiple system types, and the time available for this project ground source heat pumps were not modeled at this point. An effort is underway to develop an effective working model for ground source heat pumps under the Lodging TSD development effort.	No action
56	HVAC	B – Another example is the HVAC systems. Should other equipment types be considered for the advanced cases?	Radiant heating and cooling with DOAS being modeled	No action

No.	Category	Comment	PNNL Response	PNNL Action
			for TSD. Insufficient time to consider other options, and see above on ground source heat pumps. Note that ground source systems may be inherently limited in dense urban settings because the ground and/or groundwater may become thermally contaminated by adjacent systems	
57	HVAC	D – Thermal comfort is never addressed when assessing the benefits of advanced buildings. What are the energy savings from changing thermostat set point temperature while still maintaining the same or possibly even providing the thermal comfort?	Varying air setpoints while reducing thermal gains and losses with air movement and different radiant heat transfer from exposed surfaces such as the interior of windows (through lower U-value glazing) is a good topic for future work. Radiant systems are recommended as the primary HVAC system and can provide comfort at a larger range of air temperatures.	The radiant system model accounted to some degree for comfort at a larger range of air temperature since the radiant system can achieve the same level of operative temperature at a lower air temperature. Therefore, in the advanced models, the thermostat setpoint was increased from 75°F (24°C) to 77°F (25°C) for cooling and decreased from 70°F (21°C) to 67°F (19.5°C) for heating.
58	Lighting	How is task lighting that is common to modular office furniture accounted for, i.e. additional 0.2 watts/sq. ft.	ASHRAE 90.1 included task lighting in the allowed lighting power density limits, and this is incorporated in the model.	No action
59	Lighting	Egress lighting levels have been creeping up. I did a design review on one building and egress lighting was 20% of normal lighting density. A 10% egress lighting level would be more realistic. Actual metering records by Eugene Water and Electric Board demonstrated unoccupied load factors of 40% associated with lighting and equipment loads. Remember to account for people leaving lights and equipment on during unoccupied periods.	Baseline model changed to 15% schedulled on lighting during off hours to account for egress lighting, task lighitng and other lighting left on for at least part of the unoccupied hours.	No action
60	Lighting	This may be a reasonable number for general office use, but the electronic / server room energy needs to be factored in. Somewhere in	Electrical equipment loads have been reviewed against	No action

No.	Category	Comment	PNNL Response	PNNL Action
		the building there will be a main electronics / server room with additional load, i.e. uninterruptible power supply, phone switch, networking gear, security electronics, storage drives, back up servers, Liebert AC system, etc.	available literature. Some additions for small appliances which can include chargers and routers and other distributed networking gear were added. Overall power density, operating schedule and resulting energy usage per square foot are consistent with available information.	
61	Lighting	Low, it is a challenge for designers to reach this level. For some reason there is an impression that corridors needs to be light and bright. I have seen cases where there is more LPD in the corridor than the office workspace. I see corridors having at least 0.8 W/sq. ft. in the baseline and the goal could be 0.5 W/sq. ft.	Modeling to ASHRAE 90.1-2004 for baseline. Designers are working towards this value, and are implementing this in some buildings.	No action
62	Lighting	High number	Advanced model reduced overall to 0.76 W/sq. ft. Providing updated table in report.	Final advanced case includes 0.64 W/s.f. for active storage based on a lighting layout from the Lighting Design Lab in Seattle.
63	Lighting	It would be disappointing if this value couldn't be reduced.	see above	see above, lobby now at 1.09 W/s.f.
64	Lighting	I thought code implied that sweep control was limited to common areas and not individual rooms, i.e., private offices, restrooms, storage, elec/mech rooms.	90.1-2004 requires a minimum of sweep in all of these areas, and occupancy sensors in some enclosed areas.	No action
65	Lighting	Most storage rooms have wall switches. They may not be turned off during the day, but generally are turned off at night by janitorial staff.	Manual switching may or may not provide savings. 90.1-2004 requires at least sweep. Occupancy sensors modeled to improve on sweep.	No action
66	Lighting	I don't see stairway lighting being switched off – code egress issues.	Stairs identified as 2% of area so minimal impact either way. Stairs can be	No action

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			turned off with fail on occupancy sensor controls in some jurisdictions. Stairs are not exempted from 90.1 requirement for sweep control.	
67	Lighting	Even those daylighting designs with a lot of intentional design (added daylight windows, overhangs, light shelves, etc) there is an issue with achieving modeled savings. Even with the best of daylighting designs there is a percentage of time the blinds get adjusted downward to reduce glare. Modeled savings should be discounted to account for the blind usage, i.e., link to weather file during sunny days. Daylighting in the east and west exposures shouldn't even be tried, south is doable if done right and the north orientation generally has a high probability of success. Without any special daylighting design (increased window height, overhangs, light shelves, etc) getting light into an open office area with systems furniture (5 ft. high walls) will be difficult.	Daylighting with side daylighting is possible and applied in buildings. Simulation assumes a careful design of daylighting and estimates a reasonable potential savings for such a design. The savings are not optimized. Obstacles raised in comment can and should be overcome as much as possible to achieve important and possible daylighting savings.	Simulation of daylighting and glare control is an area recommended for further development. Savings results from current models are a reasonable fraction of the lighting energy in the daylit areas.
68	Lighting	Suggest clarifying which lights will be turned off at midnight to 6 AM and which lights will remain on but at a reduced level. Does the proposed analysis assume a dark building between midnight and 6 am, if so this isn't realistic. There are esthetics, code safety and security issues which warrant some lighting to remain on	Baseline lighting schedule now at 15% for unoccupied hours, and Advanced lighting schedule at 5%. Difference based on occupancy controls vs. sweep, better egress lighting design, and some use of security lock-out so that in some buildings, all of the lights can be turned off.	No action
69	Lighting	On parking lot lighting, an option not explored is bi-level lighting. In an installation with which I am familiar, each light fixture can operate at two lighting levels. Full lighting would produce levels such as those in your advanced case. A reduced level would kick in by a time clock for generally unoccupied times. The lighting can be brought up to full level during off-hours by one of two means: a switch inside the office allows someone exiting the building to raise the lighting for, say, 15 minutes while they leave the building; alternatively, a pressure	Changed to 10% minimum 1am to 6 am	No action

No.	Category	Comment	PNNL Response	PNNL Action
		mat at the entrance to the lot raise the level for some period of time when a car enters.		
70	Lighting	Are there any canopies at the entries? I would have assumed at least a 50 sq. ft. canopy at each main entry	Exterior lighting values allowed by 90.1-2004 are likely higher than for real design, so no additional lighting needs to be added.	No action
71	Lighting	Each parking spot occupies 405 ft^2. How was this determined? A typical stall is 18x9 ft. Are you including some of the drive?	Values from 90.1 Lighting sub-committee	No action
72	Lighting	A number of changes on the lighting design. With those changes, LPD reduced from 0.88 to 0.85 W/ft^2.	Now reduced to 0.76 W/ft^2	No action
73	Lighting	What is the assumption of how much of the open plan office is within 15 ft.? What saving are you assuming from daylighting??	See final TSD Section 4.2.1.4	No action
74	Lighting	Will the exterior lighting control cause the site to be completely dark? This seems a little extreme. Maybe leave 10% of the lights on.	Changed to 10% minimum 1 AM to 6 PM	No action
75	Lighting	I would argue that you have over estimated the office station floor area. If "Table 3.5. Lighting power density calculation for the advanced case" shows that 16% of the space is open office and 25% is private office, is not the total office station space area (54,000 sq. ft.*0.41= 22140 sq. ft.) and a private office is larger than 100 sq. ft. (I would assume 120 sq. ft.) so the floor area per workstation would be closer to 112 sq. ft. This would get you down to 198 workstations.	Overall plug load of 0.75 W/sq. ft. is consistent with PNL studies and other published value. See also next comment, even if number of workstations is low, other electrical loads could add to that. Number of workstations is based on number of occupants. Number of workstations is a reasonable value given the uncertainties in the estimates and the fact that some users now have more than one computer and/or display.	No action
76	Plug Load	Another general observation that I would pass along is one I heard from Paul Torcellini related to his work on very low energy buildings. As the traditional loads shrink, the importance of small peripheral loads that are generally considered background "noise" in the analysis (for example, battery chargers for emergency lighting in the building) grows proportionally. A 5% load becomes 10% when you cut other loads in half. You may want to explore the extent to which these can	See above	No action

No.	Category	Comment	PNNL Response	PNNL Action
		be incorparated into the analysis and treated as variables.		
77	SWH	Feels excessive, you can trade off storage with larger burner input. What is calculated peak hot water in gpm? An exaggerated example: assume all hot water (268 gallons) is needed in one hour with a 70F temperature difference = 156,270 Btuh. I think I could buy one hot water heater to meet the exaggerated load. Unless you had a shower room, some would argue design should be representative of a series of small 2-3 gallon hot water heaters serving sinks. In theory, aren't sinks regulated at ½ gpm, that is a small load.	The domestic hot water usage is a reasonable share of total energy usage and is a small part of the total.	No action
78	SWH	For water heating, consideration of a desuperheater for heat recovery from the air conditioning system would seem worth consideration. Rather than rushing right to solar thermal systems, you might want to consider this much less costly approach first.	Tends to be an involved installation that still needs a redundant system because the desuperheater is not always operating. For the small loads in the building, a condensing water heater or on demand water heater is a reasonable solution.	No action
79	HVAC	1. evaporatively cooled condensers	Specialized to a narrow size range. Considered high maintenance.	No action
80	HVAC	2. ice storage (Ice Bear- http://www.ice-energy.com/technology/IceBear/howitworks/tabid/163/Default.aspx) the ice is made at night when outdoor air temperatures are reduced and you can get better efficiency out of the refrigeration cycle running all out building ice instead of trying to modulate in response to load.	Does not reduce energy usage, but rather peak demand.	No action
81	HVAC	3. Dedicated outdoor air system -- decouple outside air loads and run them through an independent tempering system (i.e. get OSA to room temperature and relative humidity separate from coil that mixes the air and overcools all of it -- saves on reheat and consolidates the major part of cooling in one coil). Makes doing an ERV a little easier too. You can still have openings to allow economizer cycles, but they are independent of the DOAs airstream.	Incorporated in advanced model with radiant systems.	No action
82	HVAC	4. If you look at a DOAS, then consider doing a fan-powered box system to minimize cooling and reheat.	DOAS provides modest flow of tempered air with supply air temperature reset. Primary comfort is provided by the radiant systems. Fan-powered	No action

No.	**Category**	**Comment**	**PNNL Response**	**PNNL Action**
			boxes would likely add expense for modest benefit.	
83	HVAC	5. Take a quick look at your placement for the indirect evaporative coolers -- is seems like you mix return air (RA) & OSA, then go into the indirect unit. You should just hit the incoming OSA with indirect first and then post-mix in order to get the greatest effectiveness in dry climates. Once you mix, you've already pulled down the temperature of the OSA and the delta T is not big enough for the wet-bulb depression to be so effective.	The configuration with indirect allows greater energy savings, though the temperature drop is not as large since this configuration also provides cooling of the portion of the return air that is not exhausted.	No action
84	HVAC	6. Question your pressure drops for fan energy. What does upsizing the unit by one size do for your filter and coil pressure drops? What was the buildup of your assumptions for distribution pressure drop?	Advanced model incorporates radiant systems so distribution and system pressure drops not applied for final advanced case, but worth considering for VAV systems.	No action
85	HVAC	7. Consider a lower pressure underfloor air conditioning system that does not require a 0.6 in. back pressure on the VAV boxes for controllability.	Using radiant systems, so fan powered boxes not part of advanced model. Insufficient time to run underfloor air distribution model, and not expected that this would save more than the radiant/DOAS alternative.	No action
86	HVAC	8. consider reducing amount of glass below 33%.	See response under item 2	See response under item 2
87	HVAC	9. Consider providing the air handler serving just the core and a separate unit for the perimeter with VAV boxes for control -- what is happening now is that all of the air is pulled down to the worst case zone required supply temperature (which will be solar driven), but what you can do instead is to have the core unit do cooling all the time to pick up local heat loads (which look to be a substantial amount of area under this criteria), and then a cooling/heating unit for dealing with the perimeter fluctuations caused by outside air conditions. Your perimeter unit ends up staying fairly small because it is following the sun around the perimeter and usually running at 55F regardless during the cooling season. It helps for comfort in the winter as well and your reheat can track outside in a compensated loop. Some people	Advance model with radiant and DOAS. Otherwise this is a good strategy, but not sufficient to get to 50% based on initial modeling of improvements to packaged VAV systems.	No action

No.	Category	Comment	PNNL Response	PNNL Action
		also do this with fan coil units.		
88	HVAC	10. Since you're using electric reheat, you might consider hydronic as an energy efficiency measure.	Hot water heat would reduce energy cost, but increase site energy usage if from fossil fuel boiler. Analysis considers site energy usage. Will discuss potential to consider source energy usage in recommendations for future work. Electric boiler does not offer advantages versus electric reheat.	No action

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