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Technical Support Document: Strategies for 50% Energy Savings in Large Office Buildings

Matthew Leach, Chad Lobato, Adam Hirsch,
Shanti Pless, and Paul Torcellini

Technical Report
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Prepared under Task No. BEC7.1309

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Executive Summary

This Technical Support Document (TSD) was developed by the Commercial Buildings Group at NREL, under the direction of the DOE Building Technologies Program. Its main goal was to evaluate the potential for new large office buildings in the United States to achieve a 50% net site energy savings compared to a baseline defined by minimal compliance with respect to ANSI/ASHRAE/IESNA Standard 90.1-2004, *Energy Standard for Buildings Except Low-Rise Residential Buildings* (ASHRAE 2004c).

The work presented here extends the *50% Energy Savings Design Technology Packages for Medium Office Buildings* TSD developed at the Pacific Northwest National Laboratory (Thornton, Wang et al. 2009) to encompass office buildings with larger footprints and high-rise design. It is 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 Large Offices*. It may be used to support such a project in the future and should be considered a preliminary feasibility study for achieving 50% energy reduction in large office buildings across the different climates found in the United States. Detailed design recommendations were not provided in recognition that they will be a focus of future work to develop a corresponding *Advanced Energy Design Guide* and that many design details will likely be project specific when reaching for the 50% energy reduction goal. Many of the assumptions in Thornton, Wang et al. (2009) have been changed for this report to more accurately portray the practices followed in designing large office buildings, especially pertaining to heating, ventilation, and air conditioning (HVAC) design. For example, the baseline variable air volume (VAV) system included central chillers and boilers with hot and cold water coils where the Medium Office TSD assumed a rooftop VAV with direct expansion cooling coils and direct gas-fired heating. As in the Medium Office TSD, in-slab hydronic radiant heating and cooling with a dedicated outdoor air system (DOAS) was adopted as a primary energy-saving strategy, but with the radiant heating and cooling assumed to be via a slab ceiling rather than a slab floor. While this design is uncommon in the United States, it has been identified as a promising energy-saving strategy (Thornton, Wang et al. 2009).

The intended audience for this report includes energy modelers who wish to simulate low-energy large office buildings as part of the design process and for engineers who want to delve into the detailed assumptions underlying the results presented in the report to inform low-energy building design. While ASHRAE Standard 90.1-2004 was used to define code-compliant baseline models, we included all building energy consumption terms in the analysis, both those regulated by code and so-called "unregulated" loads, such as miscellaneous plug loads and data center energy consumption. Energy savings was also compared to an ASHRAE 90.1-2007 compliant baseline to analyze how energy code changes impact energy savings. Site energy (the energy delivered to the building) was used as our primary energy performance metric, consistent with the original statement of work for this project. Source energy savings, energy cost savings, and energy-related emissions savings were defined in the report and presented for comparison with site energy savings (Torcellini 2006; Deru and Torcellini 2007).

A 50% site energy savings was found to be feasible in all climate zones analyzed. Five-year total lifecycle costs were included in the results for baseline and low-energy building designs to allow cost comparisons.

Methodology

To account for energy interactions between building subsystems, we used EnergyPlus (DOE 2010) to model the energy performance of baseline and low-energy buildings to verify that 50% net site energy savings can be achieved. EnergyPlus computes building energy use based on the interactions between climate, building form and fabric, internal gains, HVAC systems, and renewable energy systems. Percent energy savings were based on comparison with a minimally code-compliant building as described in Appendix G of ASHRAE 90.1-2004, and used whole-building net site energy use intensity (EUI) to measure performance, defined as: the amount of energy a building consumes for regulated and unregulated loads, minus any renewable energy generated within its footprint, normalized by building area.

The following steps were used to generate low-energy building models:

1. Architectural-program characteristics (design features not addressed by ASHRAE 90.1-2004) for typical large office buildings were chosen to create low-rise and high-rise prototype models.
2. Baseline energy models were created for each climate zone by specifying features of the prototype models to be minimally compliant with ASHRAE 90.1-2004.
3. A list of candidate EEMs was defined.
4. Baseline energy model and EEM assumptions were reviewed by industry representatives.
5. Combinations of EEMs were selected in each climate zone that achieved at least 50% net site energy savings. Preference was given to strategies that had low five-year total life cycle cost.

The simulations supporting this work were managed with the NREL commercial building energy analysis platform, Opt-E-Plus (NREL 2010). Opt-E-Plus employs an iterative search technique to find EEM combinations that achieve a given level of whole-building energy savings at the lowest total life cycle cost. The primary advantages of the analysis platform are its abilities to: (1) transform high-level building parameters (building area, internal gains per zone, HVAC system configuration, etc.) into a fully functional input file for EnergyPlus; (2) conduct an automated search to find an optimal solution, subject to assumptions made about EEM performance and cost; and (3) manage multiple EnergyPlus simulations run on both a local CPU and remote supercomputer processors. The economic criterion used to filter the recommendations was five-year total life cycle cost (using the 2010 OMB real discount rate, 1.6%) (OMB 2010). The five-year analysis period was established in our statement of work and was assumed acceptable to a majority of developers and owners.

The building architectural prototypes that were developed for this project defined the basic building characteristics such as floor plate dimensions, orientation, and thermal zoning. Both high-rise and low-rise prototypes contained 460,800 ft^2 (42,810 m^2) of total floor area and had an aspect ratio of 1.5. The low-rise prototype had four stories and a footprint of 115,200 ft^2 (10,700 m^2); the high-rise prototype had 12 stories and a footprint of 38,400 ft^2 (3,570 m^2). The prototype envelope constructions were based on typical design practice for their respective building configurations: the low-rise prototype had precast concrete exterior wall panels and punched-hole glazing; the high-rise prototype had spandrel glass exterior wall panels (opaque panels with insulation) and glass curtain glazing. Both prototypes had roofs with insulation above deck.

Construction types and other building parameters were chosen to transform the building prototypes into representations of minimally code-compliant and low-energy building representations to calculate energy savings. Code compliant baseline models (low-rise and high-rise) had a 40% window-to-wall ratio (WWR) as per minimal code compliance with ASHRAE Standard 90.1-2004. A non-compliant high-rise case with 69% WWR was also considered in order to analyze what additional investment in EEMs was required to reach the target of 50% better than the code-compliant baseline. For this case, all EEMs were available except for changes to WWR and wall insulation. The baseline HVAC system configuration was a variable air volume (VAV) system with hydronic heating via a natural gas-fired boiler and hydronic cooling via a water-cooled, electric, centrifugal chiller. A baseline plug load density of 0.9 W/ft^2 (9.7 W/m^2) was assumed, including the electricity consumption of a centralized data center. The EEMs used in this work fell into the following categories:

- **Form EEMs** affecting building aspect ratio, façade glazing coverage, and overhangs used to shade glazing.
- **Fabric EEMs** addressing opaque envelope insulation, glazing construction, and envelope air barriers and entrance vestibules.
- **Equipment EEMs** specifying the properties of: the radiant heating/cooling and DOAS equipment, energy recovery equipment, waterside economizing, reduced lighting power densities, occupancy controls, daylighting controls, higher efficiency HVAC and service water heating (SWH) equipment, and photovoltaic (PV) electricity generation.

Findings

The results show that 50% net site energy savings can be achieved in both low-rise and high-rise large office buildings in a range of climates representative of the spectrum of U.S. weather conditions (Table ES-1).

Table ES-1 Standard 90.1-2004 Baseline Model Performance

Climate Zone	Climate Type	Representative City	Low-Rise Savings	High-Rise Savings
1A	Hot and Humid	Miami, Florida	57.6%	57.5%
3B	Hot and Dry	Las Vegas, Nevada	56.7%	58.2%
4C	Marine	Seattle, Washington	54.1%	57.1%
5A	Cold and Humid	Chicago, Illinois	54.0%	55.1%
5B	Cold and Dry	Boulder, Colorado	55.5%	58.3%
7	Very Cold	Duluth, Minnesota	55.0%	57.8%

On-site generation technology (in this case, PV) was not necessary to meet the energy savings goal except for the non-compliant, poorly insulated high-rise case. The following EEMs played important roles in reaching the 50% energy savings target:

- The baseline hydronic VAV system was replaced with radiant heated and cooled slab ceilings with DOAS for ventilation.
- The DOAS design was tailored to address climate-specific requirements as follows: sensible and latent energy recovery equipment was used in humid climates, sensible energy recovery equipment was used in marine and very cold climates, and indirect evaporative cooling (IDEC) was included in dry climates.

- Waterside economizing was incorporated in dry climates.
- Lighting power density was reduced to 0.63 W/ft^2 in offices spaces and occupancy sensors were assumed in infrequently occupied zones.
- Daylighting controls tuned to maintain a 27.9 fc (300 lux) set point.
- Entrance vestibules and envelope air barriers were included to reduce infiltration. These features were important to avoid condensation on radiant cooling surfaces in humid climates.
- High efficiency boilers (condensing, nominally 98% efficient), chillers (COP of 7), air distribution units (69% total fan efficiency), and service water heating (SWH) equipment (90% thermal efficiency) was installed.
- Façade WWR was reduced to 20% and window properties were modified to reduce solar gain, improve overall envelope insulation, and reduce construction costs. In low-rise buildings, double pane windows with low-emissivity film and argon fill (U-0.235, SHGC-0.416, VLT-0.750) were installed; in high-rise buildings, double pane windows with low-emissivity film and tinted glass constructions (U-0.288, SHGC-0.282, VLT-0.55) were used.
- Exterior wall insulation was added in cold climates (up to R-19.5 continuous insulation (c.i.) for the low-rise case and R-22.5 c.i. for the high-rise case).
- Total plug loads were reduced by 23% to 0.68 W/ft^2 (7.3 W/m^2) by purchasing high efficiency electronic equipment and employing control strategies to eliminate plug loads when equipment was not being used.

Energy use intensities for the ASHRAE 90.1-2004 baselines were similar for the code compliant low-rise and high-rise cases, but larger for the high-rise case with non-compliant envelope design (by an average of 11%). The non-compliant high-rise model EUIs were much higher in severe climates where already large heating and/or cooling loads were magnified by the highly glazed, poorly insulated building envelope.

Energy savings was also compared to a baseline specified to minimally satisfy the requirements of ASHRAE 90.1-2007 rather than 90.1-2004, to analyze how code changes impact percent savings. The 90.1-2007 baseline models had EUIs similar to the ASHRAE 90.1-2004 baseline models. In climate zone 7 (Duluth), a baseline building built to satisfy ASHRAE 90.1-2007 was found to be slightly more expensive than one built to ASHRAE 90.1-2004 due to additional envelope insulation requirements; however, over five years this additional capital cost was more than offset by energy cost savings. In all other climates, replacing ASHRAE 90.1-2004 with ASHRAE 90.1-2007 as the baseline building standard resulted in little or no energy savings and slightly increased capital and life cycle costs.

An economic analysis calculating simple payback period was performed for the final low-energy EEM combinations selected in each climate zone. Low-energy high-rise large office buildings featuring well integrated energy efficiency measures demonstrated simple payback periods of less than ten years; low-energy low-rise large office buildings had simple payback periods of between nine and 16 years; and low-energy high-rise large office buildings with high glazing fraction and minimal insulation had simple payback periods of greater than 20 years.

While the energy goal for this study was defined with respect to net site energy, low-energy buildings were also evaluated with respect to net source energy, energy-related carbon dioxide emissions, and energy cost for comparison (Torcellini 2006; Deru and Torcellini 2007). A simplified analysis was performed using national average site-to-source and site-to-emissions multipliers and a national average electricity tariff. The low-energy buildings (not considering the non-compliant high rise case) performed well with respect to net source energy savings (52.8% average), energy emissions savings (52.4% average), and energy cost (50.3% average), but not quite as well as they performed with respect to net site energy savings (56.4% average). This was because these alternative metrics are heavily weighted toward electricity savings, due to the high site-to-source multiplier of electricity versus natural gas on average in the United States, reflecting the efficiency losses during electricity generation, transmission, and distribution (Torcellini 2006; Deru and Torcellini 2007). Peak electricity demand only decreased by 10%, on average. Further research is needed to analyze how design recommendations change when (1) energy savings using an alternative performance metric (even including peak electrical demand) is considered as a design objective and (2) region-to-region variability in electricity tariffs and conversion factors between site energy and the other metrics is included in the analysis.

Future analyses of large office building energy efficiency may benefit from adopting some of the recommendations outlined in Section 5.0 of the report. For instance, several EEMs deserve attention as this work progresses to the *AEDG* stage but were omitted here due to lack of reliable input data or lack of model validation for these advanced strategies. They include:

- Alternative HVAC systems, such as a high efficiency VAV system (as a low-energy alternative to the baseline VAV system), though this strategy was found to limit energy savings to under 50% in some climate zones in the medium office 50% savings TSD.
- Exploring the effect building thermal mass characteristics have (through manipulations of the constructions of exterior walls, radiant slabs and interior furnishings) on radiant system operation and control.
- Natural ventilation, especially cross ventilation for high aspect ratio designs.
- Advanced daylighting strategies, including: different combinations of view glass and daylighting glass, with function-specific material properties; and, installation of light redirection devices to allow deeper penetration of daylight into the building interior.

Nomenclature

5-TLCC	five-year total life cycle cost
ACH	air changes per hour
AEDG	Advanced Energy Design Guide
AHU	air handling unit
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
CBECS	Commercial Buildings Energy Consumption Survey
c.i.	continuous insulation
CO_2	carbon dioxide
COP	coefficient of performance
DCV	demand control ventilation
DOAS	dedicated outdoor air system
DOE	U.S. Department of Energy
DX	direct expansion
EEM	energy efficiency measure
EIA	Energy Information Administration
EMS	Energy Management System
ERV	energy recovery ventilator
EUI	energy use intensity
GSD-1	general service demand
HVAC	heating, ventilation, and air conditioning
IDEC	indirect evaporative cooling
IECC	International Energy Conservation Code
IESNA	Illuminating Engineering Society of North America
LEED	Leadership in Energy and Environmental Design
LPD	lighting power density
MCF	1000 cubic feet
MRT	mean radiant temperature
NREL	National Renewable Energy Laboratory
OA	outside air
O&M	operations and maintenance
OMB	Office of Management and Budget
PC	personal computer
PLR	part-load ratio
PMV	predicted mean vote
PNNL	Pacific Northwest National Laboratory
PUE	power usage effectiveness
PV	photovoltaic
QA/QC	quality assurance/quality control
RH	relative humidity
RSF	Research Support Facility
SHGC	solar heat gain coefficient

SOW	Statement of Work
SWH	service water heating
TSD	Technical Support Document
UFAD	under floor air distribution
USGBC	U.S. Green Building Council
VAV	variable air volume
VLT	visible light transmittance
w.c.	water column
WD	weekday
WWR	window-to-wall ratio
XML	Extensible Markup Language
ZEB	zero energy building

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1.0 Introduction

According to the 2003 Commercial Building Energy Consumption Survey (CBECS), office buildings in the United States comprise roughly 12 billion ft^2 (1.1 billion m^2) of floor space and consume about 93 $kBtu/ft^2 \cdot yr$ (1055.5 MJ/m^2) of site energy (177.8 $kBtu/ft^2 \cdot yr$ [2017.8 MJ/m^2] primary energy) on average. Office buildings represent nearly one-fifth of all delivered energy consumed by commercial buildings, and are therefore an important focus for energy efficiency improvements (EIA 2005).

Our goal is to investigate the feasibility of reducing energy use by 50% in newly constructed large office buildings across the United States relative to one built to comply with the minimum requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004 (ASHRAE 2004c). We build on earlier research about energy savings opportunities in small office buildings (Jarnagin, Liu et al. 2006) and medium office buildings (Thornton, Wang et al. 2009). Additional analysis is required for the large office case because office buildings are designed differently depending on their size, especially their mechanical heating, ventilating, and air conditioning (HVAC) equipment. Our intended audience includes energy modelers who wish to simulate low-energy large office buildings as part of the design process and engineers who wish to delve into the detailed assumptions underlying our results as part of designing low-energy buildings. We make design recommendations at a conceptual level of detail as a basis for the future development of more detailed design and implementation recommendations for a prospective *Advanced Energy Design Guide for Large Office Buildings*.

Large office buildings, where *large* refers to total floor area, are built in diverse shapes and sizes. This report attempts to capture energy savings in low-rise large office buildings, using a 4-floor prototype, and high-rise office buildings, using a 12-floor prototype. Both have the same total floor area of 460,800 ft^2 (42,810 m^2), identical to the U.S. Department of Energy (DOE) Reference Building large office model (Deru, Field et al. 2010). We recognize that many factors drive large office building envelope design and that a glass curtain wall construction with high window-to-wall area ratio (WWR) is a popular architectural choice (Wilson 2010). Although this construction may not meet the prescriptive requirements of ASHRAE 90.1-2004 in many locations, we explore whether it limits the achievable whole-building energy savings.

We use Appendix G of ASHRAE 90.1-2004 (ASHRAE 2004b) to define certain aspects of our baseline building design, but it includes only a subset of building energy uses and specifies energy cost as a performance metric. This report encompasses all building energy consumption terms and uses site energy (the energy delivered to the building) as the primary energy performance metric, as required by the original project mandate. Savings are also presented using other commonly used metrics of energy consumption. Aspects of the baseline not governed by ASHRAE Standards, such as miscellaneous electric loads, are defined according to industry feedback and industry case studies.

Reports like this one are often referred to as Technical Support Documents, or TSDs. They are detailed compilations of modeling assumptions, analysis techniques, and results that provide the technical basis for recommending building design packages that achieve a desired level of net energy savings compared to a baseline model. Historically, a separate series of TSDs was written for a particular energy savings level covering multiple commercial building types. Some of these have led to the production of volumes in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) *Advanced Energy Design Guide* (AEDG) series. The AEDGs are user-friendly publications containing the TSD design recommendations plus relevant case studies and best practices tips. The TSDs and AEDGs are part of an interorganizational effort to facilitate the design, construction, and operation of more efficient buildings, with the eventual goal of achieving buildings so efficient that their operational energy consumption can be cost effectively met by on-site renewable energy generation (Torcellini 2006). The first phase of AEDGs concentrated on achieving 30% energy savings versus buildings designed to meet the minimum requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004 (ASHRAE 2004c).

This study is part of a second phase to provide technical guidance that architects, designers, contractors, developers, owners, and lessees of large office buildings can use to achieve whole-building net site energy savings of at least 50% compared to a baseline defined according to the minimum requirements of ASHRAE Standard 90.1-2004 (and ASHRAE 62.1-2004 (ASHRAE 2004b), needed to specify minimum ventilation requirements which also impact building energy use) for new construction. This TSD will result in the production of a prospective Large Office 50% AEDG, in support of the ASHRAE Vision 2020 Committee and AEDG Scoping Committee goals to enable interested parties to achieve 50% energy savings by 2010 (Mitchell, Brandmuehl et al. 2006; Jarnagin, Watson et al. 2008). This work will also reach its intended audience through the DOE-sponsored Retailer Energy Alliance (DOE 2008b).

Our recommendations are tailored by climate zone and address building envelope, including infiltration through walls and doors, fenestration quantities and types, electrical lighting systems, daylighting, HVAC systems, outside air (OA) treatment, plug load schedules, and photovoltaic (PV) systems. The recommendations should be used as starting points only; they are not intended to be part of a code or standard. Our approach can be taken as a model of a simulation-based approach to preliminary design of a large office building with a specific advanced energy savings target.

This TSD was developed by the Commercial Buildings Research Group at the National Renewable Energy Laboratory (NREL), under the direction of the DOE Building Technologies Program. It builds on previous work (Hale 2008; Hale, Macumber et al. 2008) at NREL that established a basic methodology for finding building designs that achieve 50% energy savings over ASHRAE 90.1-2004 using the EnergyPlus (DOE 2010) model in Opt-E-Plus (NREL 2010), an optimization framework developed at NREL. Fundamental energy modeling inputs have been vetted through internal and external reviews. The number of climate zones was reduced from 16 to 6 to reduce overall simulation time and allow more time for analysis. These zones still capture climate variability across the country.

This analysis begins with a low-energy configuration inspired by Thornton, Wang et al. (2009) and real case studies of high-performance office buildings rather than a “blind” sequential-search optimization to completely determine the low-energy design as used by Hale, Leach et al. (2009) and Leach, Hale et al. (2009). This choice was made for two reasons:

- A large number of data and analyses on energy-efficient office buildings are available from which best practices can be drawn (DOE and NREL 2010).
- The optimization platform Opt-E-Plus, which was used in previous TSD efforts, does not allow substitution of HVAC mechanical systems in the same way as many other energy efficiency measures (EEMs).

We had to specify an HVAC system for the low-energy case *a priori* and then use Opt-E-Plus to optimize its parameters and other building features, such as wall insulation and WWR, to "tune" the low-energy design to maximize energy savings or achieve similar savings (at least 50%) at lower cost.

The design of NREL's Research Support Facility (RSF) is particularly relevant. This new 220,000 ft^2 (20,440 m^2) four-story large office building with a central data center was designed to use 35 $kBtu/ft^2 \cdot yr$ (400 $MJ/m^2 \cdot yr$)—half the energy used by a minimally ASHRAE 90.1-2004 code-compliant building in the same climate zone (Colorado) and less than 40% of that used by an average U.S. office building. Consistent with the recommendations of Thornton, Wang et al. (2009), the RSF uses a radiant in-slab heating and cooling system with a dedicated outdoor air system (DOAS) featuring energy recovery and demand control ventilation (DCV). The RSF also features a 60-ft (18.3-m)-wide cross section and high aspect ratio along an east–west axis that is designed to maximize access to daylight. Because the RSF represents the state-of-the-art in low-energy large office building design, it is an excellent reference for low-energy large office mechanical system design and baseline and low-energy large office construction performance and cost specifications. Because our low-energy building configurations are largely based on the RSF design, an added benefit is that it allows us to assess how well the RSF design might perform in different climate zones. A data center is included in the baseline and low-energy prototypes; its energy savings are modeled based on best practices implemented in the RSF design.

The radiant heating and cooling with DOAS strategy of the RSF and recommended by Thornton, Wang et al. (2009) represents one way, but not necessarily the only way, to achieve 50% energy savings. The reasons for this choice are explained in the following sections. Exploring the full range of possible mechanical HVAC systems for low-energy design is outside the scope of this study and is left to future work.

1.1 Objectives

The modeling and analysis described in this report are intended to:

- **Develop recommendations that meet a quantitative goal**. The energy savings goal is a specific relative energy savings value, not an approximate target. We used whole-building energy simulation to verify all recommendation sets to give at least 50% net site energy savings compared with Standard 90.1-2004. The savings are calculated on a whole-building energy consumption basis, which includes unregulated loads. Low-energy building configurations exceeding 50% savings are included in the results; however, the final energy savings numbers are inherently uncertain.

- **Present a basic economic analysis of the selected design package**. The capital and energy costs of the baseline and low-energy designs are compared, and simple whole-building payback analysis is performed for the low-energy design package.

- **Investigate and communicate the benefits of integrated design.** An EnergyPlus-based building optimization tool, Opt-E-Plus, is used to capture the interaction between building systems. It enables us to identify design measures that work together to achieve the desired energy savings level most cost effectively, so one building subsystem is not optimized at the expense of others.

- **Incorporate review of modeling assumptions by industry representatives.** We circulated a condensed compilation of baseline and low-energy cost and performance assumptions to industry partners and engineering firms. We incorporated many of their comments, and will consider others for future work.

- **Explore the implications of energy metrics on low-energy building configurations.** Although the analysis uses site energy use to determine 50% savings, low-energy building performance is also compared to baseline simulations using source energy, energy cost, and energy-related emissions to show how relative savings change when viewed through these metrics.

- **Compare ASHRAE 90.1-2004 to ASHRAE 90.1-2007 as they apply to large office buildings.** Low-energy building energy use and cost are benchmarked against ASHRAE 90.1-2007 (ASHRAE 2007b) as well as 90.1-2004 so interested parties can evaluate the progression of Standard 90.1. It also demonstrates how a percent energy savings target is influenced by a moving baseline.

- **Investigate sensitivity to building footprint.** We analyzed the impact of building aspect ratio on energy use and building life cycle cost. We used energy simulation for the low-rise prototype to study the trade-off between increased HVAC loads caused by energy transfer through greater envelope area and energy savings through increased access to daylight when a building is stretched.

- **Assess the impact of glass curtain constructions on energy use intensity (EUI).** Glass curtain constructions are used prevalently in large office design, especially in high-rise construction, to reduce construction costs and improve aesthetics. Among glass curtain constructions, those with high WWRs and low spandrel panel insulation values are especially common. We used a 12-story high-rise construction (which has the same whole-building floor area as the 4-story low-rise construction) to assess the impact of this practice. We explore how this high WWR, low wall insulation case differs from an ASHRAE 90.1-2004-compliant glass curtain construction case and how it affects the achievability of 50% net site energy savings with respect to a minimally code-compliant case.

1.2 Scope

We provide recommendations and technical guidance to help office design teams decrease their fossil fuel energy use in new construction, and possibly in retrofit projects. To ease the burden of designing and constructing energy-efficient large office buildings, we describe a set of designs that reach the 50% energy savings target for each climate zone (see Section 4.2) for new construction. They represent one way, but not the only way, to reach 50% energy savings.

This TSD is not intended to substitute for rating systems or other references that address the full range of sustainable issues, such as acoustics, productivity, indoor environmental quality, water efficiency, landscaping, and transportation except as they relate to operational energy consumption.

1.3 Report Organization

Section 2.0 introduces our modeling methodology, including definitions, analysis framework, post-processing of results, and industry review. Section 3.0 describes our modeling assumptions, starting with extensible prototype models, followed by detailed cost and performance data for climate-specific baseline buildings and EEMs, which may provide energy savings in one or more climates. Section 4.0 contains the results of the modeling study, including cost and EUI of baseline and low-energy models, and the EEMs chosen in different climate zones to reach the energy savings goal. We show how the baseline energy use changes when using ASHRAE 90.1-2007 instead of 90.1-2004, and compare baseline results with the 2003 CBECS dataset. We also investigate the impact of glass curtain construction on energy use and trade-offs in high-aspect-ratio offices between increased envelope energy transfer and increased savings from passive strategies such as daylighting. Section 5.0 includes suggestions for future work, and Section 6.0 provides conclusions. The appendices contain schedules for prototypes, baseline and low-energy models, and metric unit tables.

2.0 Methodology

This section describes the methodology and assumptions used to develop early-stage building designs that achieve 50% energy savings. We begin with an overall approach to modeling energy savings in large office buildings, including energy and economic metrics and the scope of EEMs we consider. We describe how models that meet the 50% energy savings goal were determined and conclude with a summary of our solicitations for industry and engineering review and the results of that activity.

2.1 Guiding Principles

Our objective is to find large office building conceptual designs that achieve 50% energy savings compared to an equivalent building designed to meet the minimum requirements of ASHRAE 90.1-2004 and ASHRAE 62.1-2004. Percent net site energy savings and Five-Year Total Life Cycle Cost (5-TLCC) are used as the primary performance metrics for candidate buildings. Of course, other objectives could be used; these choices best fit the project mandate. Careful attention is paid to simulated comfort indices to ensure indoor environmental quality is not sacrificed in the interest of energy savings or costs (see Section 2.4.4.2).

Achieving 50% energy savings cost effectively requires an integrated building design—an approach that analyzes buildings as holistic systems rather than as disconnected collections of individually engineered subsystems. We analyze the complex interactions between building systems and ensure the building will operate as efficiently as possible. Consider the building envelope, which influences energy use in multiple ways by separating the building from the exterior environment and by providing daylight to the interior. Integrated design weighs the daylighting and view benefits of increasing WWR and analyzing the impact on heat transfer. This enables a design team to strike an optimal balance between daylighting and heat gain or loss.

Candidate low-energy designs are chosen by applying one or more design features to a minimally code-compliant baseline building. These EEMs have an impact on energy use. We use the following guiding principles to develop a list of prospective EEMs:

- We recommend off-the-shelf technologies that are available from multiple sources, as opposed to technologies or techniques that are available only in limited quantities or from one manufacturer.
- The EEMs are limited to technologies that can be modeled with EnergyPlus.

The methodology for developing candidate integrated designs is discussed in Sections 2.4.2 and 2.4.3. The quality assurance and quality control (QA/QC) protocols for assessing occupant comfort, sizing equipment, and evaluating thermal performance are detailed in Section 2.4.4. The designs are also expected to be reasonably cost effective, but not necessarily the most cost effective, given the difficulty of obtaining accurate and timely cost data on all the technologies required to reach 50% savings in all climate zones. Costs can also differ dramatically by project, across the country, and over time. We thus do not rely heavily on cost criteria to select a low-energy design; rather, we begin with a preliminary low-energy strategy based on energy efficiency best practices and then refine it with Opt-E-Plus, which optimizes net site energy savings with respect to life cycle cost. We then compare the life cycle cost of the optimized 50% design to that of the baseline building and report the results of a simple payback analysis.

2.2 Definitions

This section specifies how we calculate building energy use and percent energy savings relative to ASHRAE 90.1-2004. We describe the site boundary used to calculate net site energy use, how Appendix G of ASHRAE 90.1 is applied, and how energy uses outside the scope of the ASHRAE Standards are incorporated.

2.2.1 Energy Use

Building energy use can be calculated in several ways, depending on where the energy is assumed to originate and which categories of energy consumption are included in the calculation. For example, one must decide whether to measure energy consumption at the utility meter or to consider all the generation, transmission, and distribution losses between the extraction of the energy carrier and its eventual consumption. Our assumptions follow.

2.2.1.1 Energy Metrics

The percent energy savings goal is based on net site energy use: the amount of energy (typically electricity or natural gas) the utility delivers to a building minus any renewable energy generated within its footprint and exported. Reducing building energy consumption through integrated design and energy efficiency is considerably more cost effective than adding renewable generation (see Section 4.2.5).

Net site energy savings are the primary energy metric by which we evaluate building models; however, other metrics, such as source energy savings, energy cost savings, and energy emission savings, could also be used (Torcellini 2006; Deru and Torcellini 2007). The energy metrics used for this study are defined as follows:

- **Site Energy.** The energy directly consumed at the building. It is typically measured with utility meters.
- **Source Energy.** The sum of the energy consumed at the building and the energy required to extract, convert, and transmit that energy from the source to the building. To calculate a building's total source energy, imported and exported energy are multiplied by the appropriate site-to-source conversion multiplier.
- **Energy Cost.** The economic cost of energy services and energy used by the building.
- **Energy Emissions.** The emissions produced from the building's energy use, including emissions for processes such as extraction and transportation.

Each metric has advantages and disadvantages for calculation and interpretation, and each favors different technologies and fuel types. This TSD uses net site energy savings to be consistent with the previous TSD and AEDG work. For completeness, however, and to explore how the choice of an energy metric might affect the optimization results, selected low-energy building models are evaluated against the energy metrics of source energy savings, energy cost savings, and emissions savings.

We convert from site energy to source energy using multiplication factors of 3.37 for site electricity use and 1.09 for site natural gas use (Deru and Torcellini 2007); we convert site energy to energy cost using our utility tariff structure (see Section 3.1.2.5). We convert from site energy to energy emissions using multiplication factors of 1.574 $lbCO_2/kWh$ (0.714 $kgCO_2/kWh$) of electricity use and 0.134 $lbCO_2/1000ft^3$ (2.146 $kgCO_2/1000m^3$) of natural gas use (0.012 $lbCO_2/1000ft^3$ [0.186 $kgCO_2/1000m^3$] for precombustion emissions and 0.122

$lbCO_2/1000\ ft^3$ [$1.960\ kgCO_2/1000\ m^3$] for on-site combustion emissions) (Deru and Torcellini 2007).

2.2.1.2 Whole-Building Energy Use

Historically, energy savings have been expressed in two ways: for regulated loads only and for all loads (the whole building). Regulated loads do not include plug loads, which are not regulated by energy code. Whole-building energy savings calculations, on the other hand, include regulated and unregulated loads. Achieving whole-building savings is usually more challenging, but more accurately captures a building's impact on the national energy system.

We use the whole-building energy savings method to determine 50% energy savings, in line with the current ASHRAE and Leadership in Energy and Environmental Design (LEED) practices specified in Appendix G of ASHRAE 90.1-2004 and in LEED 2.2 (USGBC 2006). We do not, however, limit our recommendations to the regulated loads, as in the 30% AEDGs; we also make recommendations for plug load densities, which comprise a large fraction of large office building energy use.

2.2.2 Percent Energy Savings

Percent energy savings are measured with respect to a minimally code-compliant building as described in Appendix G of ASHRAE 90.1-2004 (ASHRAE 2004c). We took the following steps to determine 50% savings:

1. Define architectural program characteristics (design aspects not addressed by ASHRAE 90.1-2004 such as schedules, constructions, plug load densities, and building geometry) for typical large office buildings, thereby defining prototype models.
2. Create baseline energy models for each climate zone that are elaborations of the prototype models and are minimally compliant with ASHRAE 90.1-2004 and ASHRAE 62.1-2004.
3. Create a list of EEMs that can be applied to the baseline models to create candidate low-energy models.
4. Select low-energy models for each climate zone that achieve 50% energy savings compared to the baseline models, giving preference to solutions that have low 5-TLCCs.

2.2.3 ASHRAE 90.1-2004 Baseline

The 50% savings achieved by each low-energy building model is demonstrated in comparison with a baseline model that minimally satisfies the requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004 (ASHRAE 2004c). The baseline models are constructed in a manner similar to what was used in the previous TSDs (Hale 2008; Hale, Macumber et al. 2008), and in compliance with Appendix G of Standard 90.1-2004 when appropriate. Notable deviations from Standard 90.1-2004 Appendix G include:

- Glazing amounts (window area and skylight area) and properties are allowed to vary between the baseline and low-energy models. We thereby demonstrate the effects of optimizing window area for daylighting and thermal considerations.
- Net site energy use, rather than energy cost, is used to calculate energy savings.

- Mass walls are modeled in the baseline and low-energy low-rise models and spandrel glass wall panels are modeled in the baseline and low-energy high-rise models to ensure our baselines accurately reflect typical design practice.

See Sections 3.3.4.2 and 3.3.4.3 for baseline assumptions regarding unregulated loads (generated by plug load equipment and data center).

2.3 Building Energy Modeling Methodology

2.3.1 EnergyPlus

EnergyPlus Version 5.0 (DOE 2010), a publicly available building simulation engine, was used for all energy analyses. The simulations were managed with the NREL analysis platform, Opt-E-Plus, which transforms user-specified, high-level building parameters (building area, internal gains per zone, HVAC system configuration, etc.) stored in eXtensible Markup Language (XML) files into an input file for EnergyPlus. Opt-E-Plus can automatically generate the XML files, or it can manage XML files that have been assembled or modified elsewhere. Working with the XML files is much faster than modifying EnergyPlus input files directly, because a single XML parameter can map to multiple EnergyPlus inputs.

We selected EnergyPlus because it is a detailed DOE simulation tool that computes building energy use based on the interactions between climate, building form and fabric, internal gains, HVAC systems, and renewable energy systems. The simulations were run with EnergyPlus Bug Fix Version 5.0.0.036 compiled on local personal computers. EnergyPlus is a heavily tested program with formal ASHRAE Standard 140 validation protocol repeated for every release (ASHRAE 2007a).

2.3.2 Climate Zones

The AEDGs and TSDs contain a unique set of energy efficiency recommendations for each International Energy Conservation Code (IECC)/ASHRAE climate zone. The 8 zones and 15 subzones in the United States are depicted in Figure 2-1. The zones are categorized by heating degree days and cooling degree days, and range from the very hot zone 1 to the very cold zone 8. Subzones indicate varying moisture conditions. Humid subzones are designated by the letter A, dry subzones by B, and marine subzones by C. This document may also be beneficial for international users, if the location of interest can be mapped to a climate zone (ASHRAE 2006).

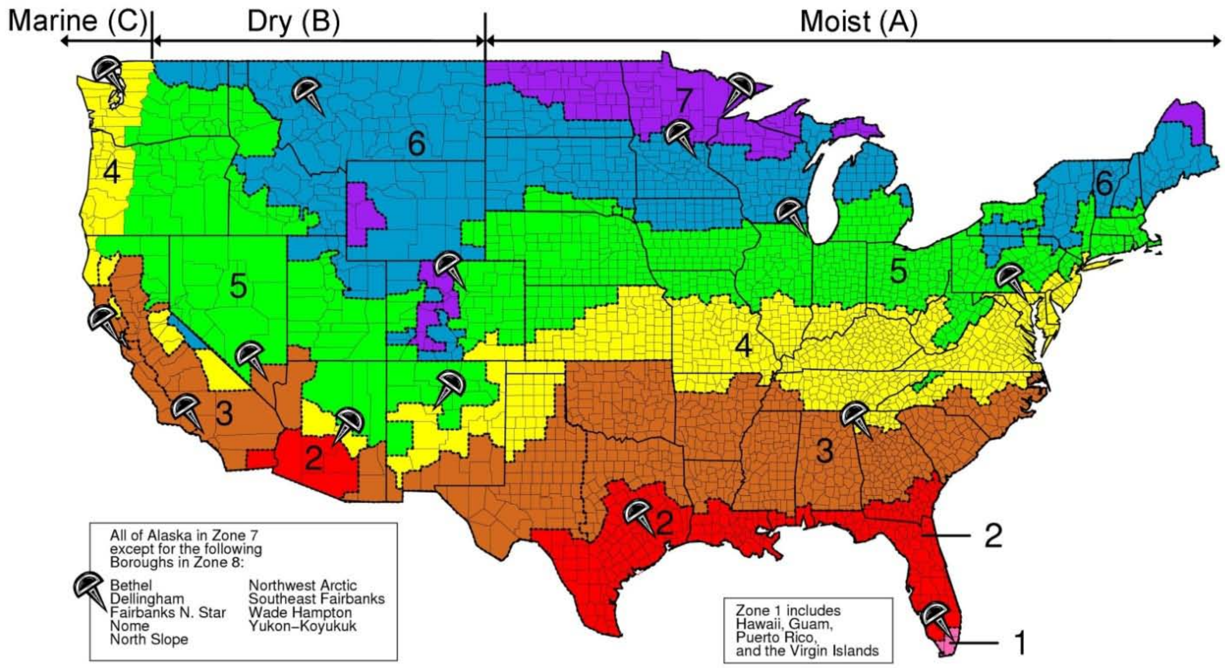

Figure 2-1 DOE climate zones and representative cities

To provide a concrete basis for analysis, we designate the 16 specific locations (cities) used by Deru, Field et al. (2010) as representatives of their climate zones. The cities are marked in Figure 2-1 and listed here. We chose larger cities, as their weather and utility data directly apply to a large fraction of building floor area. Two cities are provided for Zone 3B to account for the microclimates in California.

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

In a departure from previous TSD work, in which simulations were run for each of the 16 locations, simulations in this study were run for a subset of six cities that we feel represent a more general, but still all-encompassing, categorization of climate types: hot and humid (Miami, 1A), hot and dry (Las Vegas, 3B-NV), cold and humid (Chicago, 5A), cold and dry (Denver, 5B), marine (Seattle, 4C), and very cold (Duluth, 7). We use the same Typical Meteorological Year weather files in each city for baseline and low-energy simulations.

2.4 Modeling Protocol

Our modeling process followed a four-step sequence, each of which is described in more detail in Sections 2.1.4 to 2.1.4:

1. Establish minimally code-compliant baseline models.
2. Create a preliminary 50% energy savings model.
3. Refine the preliminary low-energy model using Opt-E-Plus.
4. Perform a QA/QC assessment on the baseline and low energy models to ensure the simulated buildings can meet their loads and provide a comfortable indoor environment; if not, rerun the models. Figure 2-2 visualizes the process.

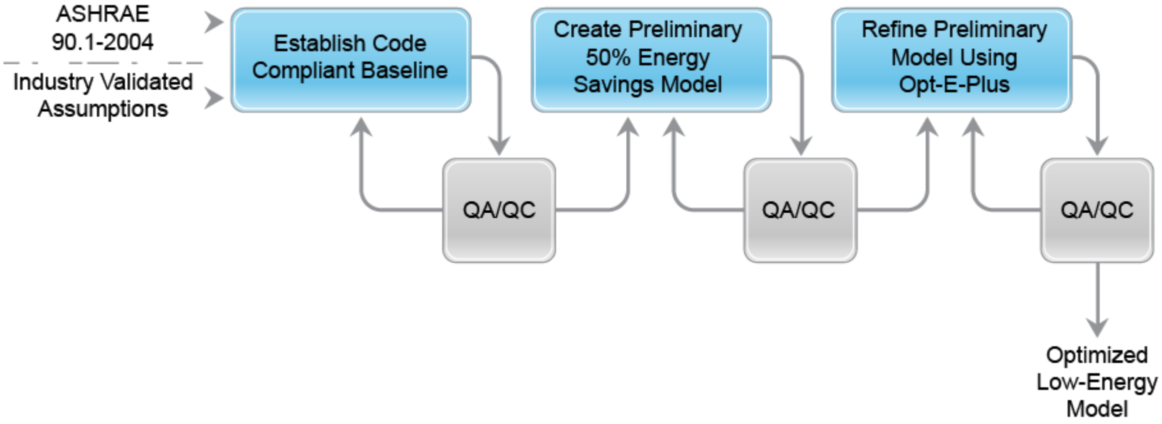

Figure 2-2 Modeling Protocol Flowchart

2.4.1 Baseline Model Specification

To establish a benchmark for assessing energy savings, we chose building parameters (such as wall construction to provide particular minimum opaque envelope R-values and OA delivery rates) to meet the minimum requirements of ASHRAE 90.1-2004 and ASHRAE 62.1-2004. We applied these parameters to a generic high-level building prototype model to create a code-compliant building for each location, then manually added airside economizers to the baseline buildings in climate zones 3B-NV, 4C, 5A, 5B, and 7 (see Section 2.3.2 for climate zone definitions and Section 3.3) for details of the baseline model definitions.

2.4.2 Preliminary 50% Energy Savings Design Selection

The EEMs (see Section 3.4) represent the palette of design options we considered to craft 50% energy saving designs. This choice was influenced by Thornton, Wang et al. (2009) and DOE and NREL (2010). The strategies reflect the experience of the NREL Commercial Buildings Group with analyzing low-energy building design and performance and the example provided by the RSF.

We used engineering judgment and considered optimization engine limitations to select a subset from the full list of strategies to be included in all low-energy models. Opt-E-Plus is limited in HVAC system substitution, so we used the RSF design and the results of Thornton, Wang et al.

(2009) to fix our low-energy HVAC system as a radiant heated and cooled system with DOAS. Because of the aggressive energy savings target, we also designed the DOAS with climate-specific energy recovery considerations. We added air barriers and vestibules to reduce uncontrolled OA infiltration as default options to the low-energy design to help ensure occupant comfort and to avoid condensation on the radiant cooling surfaces.

We then used the results from Hale, Leach et al. (2009) and Leach, Hale et al. (2009) to construct preliminary low-energy designs aimed at achieving the 50% savings goal in each climate zone. In some cases, the preliminary designs were able to reach the 50% savings goal, so the optimization goal (see Section 2.4.3) was to determine the full range of energy savings available and to maximize cost effectiveness from a life cycle standpoint at each savings level. If the preliminary designs fell short of the 50% savings goal, the optimization process also helped determine whether 50% net site energy savings were achievable and, if so, whether it was possible without an on-site renewable energy source.

2.4.3 Low-Energy Model Refinement

Once we identified preliminary 50% savings low-energy designs, we used Opt-E-Plus to alter design parameters (such as window solar heat gain coefficient [SHGC] or exterior wall insulation) and to refine those designs in each climate. This further increased net site energy savings and decreased 5-TLCC (see Section 3.1.2.6). The Opt-E-Plus environment generates new building energy models with altered designs from a specified palette of options, manages EnergyPlus simulations, and graphs the 5-TLCC and energy use of the many building permutations.

The building models are first specified in high-level XML files. The Opt-E-Plus preprocessor then translates them into EnergyPlus input files. The output of the optimization is a 5-TLCC (described in Section 3.1.2.6 and calculated using the economic data in Sections 3.1.2.4, 3.3, and 3.4) versus percent energy savings plot (see Figure 2-3 for an example) that includes one data point for each building, and a curve that represents a design path from the preliminary 50% energy saving building to the building with maximum percent savings along which each incremental step represents the most cost-effective method to configure a building to achieve that level of energy savings.

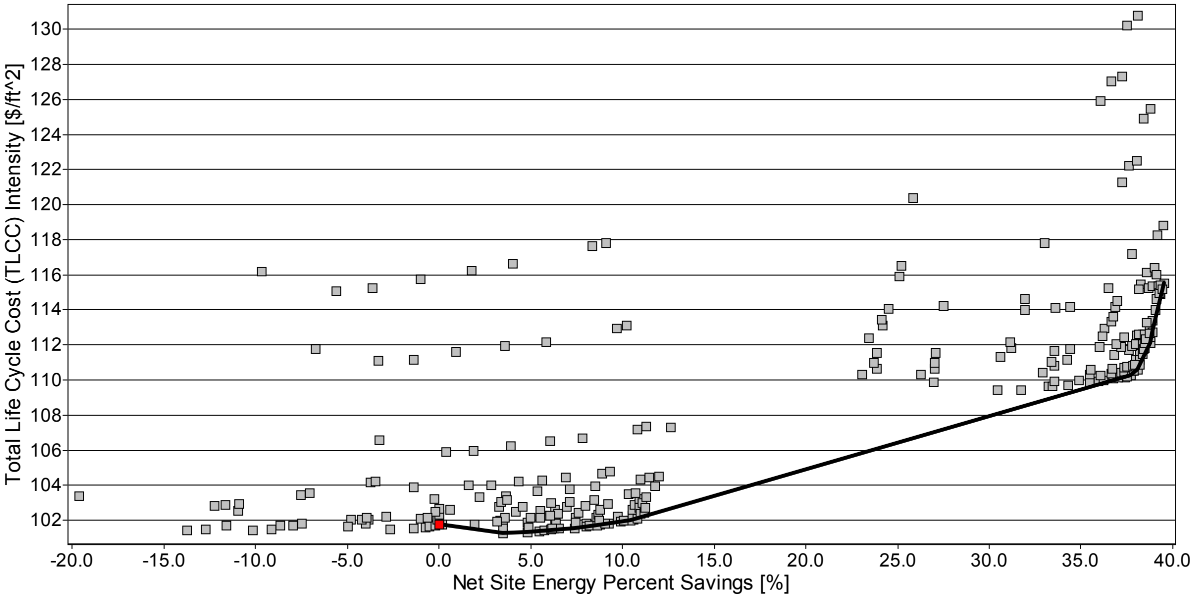

Figure 2-3 Example Opt-E-Plus output: climate zone 1A (Miami, Florida)

The data points (low-energy building configurations) along the portion of this curve which starts at the minimum cost point and continues toward higher percent energy savings are called *Pareto points*. Between Pareto points is a trade-off between energy savings and cost. For a given Pareto point, moving to a less expensive building necessitates that it will have a lower energy savings level, and moving to a more energy-efficient building necessitates higher 5-TLCC. The set of Pareto points determines a Pareto front, which is generally a curve that represents the most cost-effective pathway to achieving low-energy buildings (given the limitations of our input data and search algorithm). An iterative search algorithm is used to avoid an exhaustive search of all possible EEM combinations. Each iteration starts at the most recently found Pareto point, and then configures, simulates, and analyzes the full set of models that are single parameter perturbations from that point. The least-cost perturbation of the set becomes the next Pareto point. The algorithm stops when it cannot find additional Pareto points.

2.4.4 Quality Assurance/Quality Control Protocol

An important aspect of simulation-based analysis is establishing a protocol to manage QA/QC. We focused our QA/QC analysis on system sizing and operation as they relate to EnergyPlus simulations of conditioning capacity and control, as well as occupant comfort, safety, and well-being.

2.4.4.1 System Sizing

Sizing determines whether (1) a given system can meet thermal loads; and (2) how much energy it consumes. If a system is undersized, it may be unable to operate as designed; if it is oversized, it may use more energy than an equivalent, properly sized system. In EnergyPlus, some systems are sized automatically based on the results of design day-based sizing routines; others are hard-sized with precalculated capacities. Regardless, we used a QA/QC protocol to ensure the resulting building model operates as intended and monitored the following system metrics:

- **Hours outside heating and cooling set points during occupied hours.** Hours outside heating and cooling set points indicate space conditions are outside the desired operational dead band, possibly because of undersized system components. For cases with significant hours outside these set points, we examined equipment run time fraction (or part load ratio) values to determine if components were running at full capacity for extended periods (an indication of undersizing) and adjusted the sizing factors accordingly.

- **HVAC component part-load ratios (PLRs).** A component operating at PLR lower than 80% of sized capacity at all times throughout the year indicates oversizing. We tracked these and adjusted the sizing factors accordingly to ensure all components operated at PLRs above 80% during periods of peak load.
- **Space ventilation rates.** Proper ventilation (as specified by ASHRAE 62.1-2004) is vital to occupant well-being. We confirmed that the scheduled OA delivery rates specified as model inputs were being supplied during all occupied and unoccupied periods. This is especially important with VAV systems for which flow to a given zone depends on load.

2.4.4.2 System Operation

Even a properly sized system must be controlled to operate as desired and use the minimum amount of energy. In EnergyPlus, control is often determined through scheduling; for more advanced control requirements, EnergyPlus features an energy management system (EMS) tool that allows users to update system operation based on simulated indoor and outdoor environmental conditions. To ensure proper system operation, we tracked the following conditions:

- **Time not comfortable based on simple ASHRAE 55-2004.** Standard 55 (ASHRAE 2004a) uses space air temperature and relative humidity (RH) to determine occupant comfort; accordingly, monitoring the number of hours outside of comfort can be useful in identifying humidity issues. When the number of hours in violation of Standard 55 was large, we used output variables to analyze RH levels. RH values above 60% (based on typical comfort requirements for an office space) indicated that system operation needed to be modified to mitigate humidity issues. This led us to implement nighttime humidity control logic to allow the HVAC system to cycle for humidity control (in addition to the standard temperature control cycling) to keep RH levels below 60% during unoccupied hours. It also enabled us to confirm that daytime system operation produced humidity levels within the comfort range.
- **Zone dew point exceeding radiant surface temperature.** A major concern with radiant cooling as it relates to occupant safety, occupant satisfaction, and building equipment—especially in humid climates—is condensation. If the radiant surface temperature falls below the dew point, condensation will begin to form on the radiant surface, posing a potentially serious health risk to occupants. Accordingly, we used EMS to monitor for conditions in which condensation might be expected to occur. We specified control of the radiant system such that it would temporarily turn off when normal operation, as currently defined by our control logic (see Section 3.4.4.5.1), would result in condensation. In the future, we may further develop this control to allow for the system to continue operating during such periods; by increasing the supply water temperature to raise the radiant surface temperature above the space dew point, we will in many cases be able to provide a reduced level of cooling as opposed to none at all.

3.0 Model Development and Assumptions

This section documents the development of model inputs. Section 3.1 describes assumptions that apply to the entire study, including our economic assumptions and methodology. Section 3.2 describes the programmatic characteristics of a typical large office building and uses them to develop high-level prototype models. Section 3.3 elaborates on Section 3.2 to define the EnergyPlus baseline models that provide a reference for determining percent energy savings and are minimally compliant with Standard 90.1-2004. Section 3.4 describes the EEMs used to create low-energy models.

3.1 Analysis Assumptions

Most of Section 3 is concerned with the assembly of building energy and cost models, component by component. Here we touch on two types of assumptions that color our entire analysis: (1) the often implicit assumptions required to conduct building energy simulation studies; and (2) our economic model.

3.1.1 Integrity of Simulation Models

We made the following assumptions:

1. The models developed in this work represent typical large office buildings well enough to provide climate-specific guidance for the kinds of design strategies that should be considered first when planning a high-performance large office building.
2. These virtual buildings are well maintained and operated.

The models created for this report do not represent actual buildings, and as such have not been tested against measured data; however, they are informed by EIA (2005), Deru, Field et al. (2010), and Thornton, Wang et al. (2009). They include detailed suggestions from industry experts. The model results are subjected to quality checking to ensure simulated comfort is not sacrificed to energy savings. Anticipated energy savings are often not achieved, or erode over time, because buildings are not properly commissioned, operated, or maintained. For example, economizer dampers are notorious for failing.

3.1.2 Economics

One outcome of this project is a recommended cost-optimized design package for achieving 50% energy savings over code in a large office building. The objective economic function of interest is 5-TLCC, which is further described in Section 3.1.2.6.

3.1.2.1 Building Economic Parameters

Our SOW mandates that the recommended design package be analyzed for cost effectiveness based on a five-year analysis period, which is assumed to be acceptable to a majority of developers and owners. The other basic economic parameters required for the life cycle cost calculation were taken from Balboni (2008) and OMB (2010).

This analysis uses the real discount rate, which accounts for the projected rate of general inflation in the Report of the President’s Economic Advisors, Analytical Perspectives, and is equal to 1.6% for a five-year analysis period (OMB 2010). By using this rate, we avoid explicitly accounting for energy and product inflation rates.

The economic parameters that help shape the cost side of this study are summarized in Table 3-1.

Table 3-1 Economic Parameter Values

Economic Parameter	Value	Data Source
Analysis period	5 years	DOE
Discount rate	1.6%	OMB
O&M cost inflation	0%	OMB
Gas cost inflation	0%	OMB
Electricity cost inflation	0%	OMB
Bond fee	10%	RSMeans
Contractor fee	10%	RSMeans
Contingency fee	12%	RSMeans
Commissioning fee	0.5%	Assumption

3.1.2.2 Energy Efficiency Measure Cost Parameters

Each EEM has its own cost data. The cost categories for each are the same, but the units vary:

- **Units** define how the EEM is costed (e.g., \$/m^2, \$/kW cooling, \$/each).
- **Expected life** is the time (in years) that the EEM is expected to last. Once that period has expired, the EEM is replaced; that is, the full materials and installation costs are added to that year's cash flows. Note that replacement costs are negligible when using a five-year analysis period.
- **Capital cost** is the per-unit cost of all materials and installation required for the EEM.
- **Fixed operations and maintenance (O&M)** is a per-unit, per-year cost.
- **Variable O&M** is a per-unit, per-year cost.

We report fixed and variable O&M costs as a single, fixed, annual maintenance cost.

3.1.2.3 Costing Methodology

Unless otherwise stated, all costs are in 2010 dollars. Costs originally from another year are adjusted according to the Consumer Price Index inflation calculator (Labor 2010).

The cost data used for the EEMs and the baseline walls, roofs, windows, lighting systems, and HVAC equipment are adapted from multiple sources. The cost data sources and values are listed explicitly throughout Section 3.3 and Section 3.4.

3.1.2.4 Baseline Capital Costs

Cost estimates in the early planning stages are not necessarily accurate. This report includes data about some technologies that are not widely implemented, so the reported costs may be less accurate than anticipated. To start with reasonable baseline costs, we adjust our baseline cost per unit area to match that found for large office buildings by Balboni (2008) (\$115.77/ft^2 [\$1,246/m^2] for low-rise buildings and \$124.86/ft^2 [\$1,344/m^2] for high-rise buildings). The cost is implemented in Opt-E-Plus under a category that is not affected by any EEMs. The baseline capital cost is therefore fixed, enabling realistic estimates of the percent change in 5-TLCC when the low-energy models are compared to the baselines.

3.1.2.5 Utility Tariffs

One set of utility tariffs is used for all locations to make the results from each climate zone easier to compare and to focus comparisons between climates on energy performance rather than utility variability. We chose Florida Power & Light's 2008 General Service Demand (GSD-1) electricity tariff because of data availability, the closeness of Florida's average commercial electricity rates to the national average, and the electricity demand of our models (Florida Power & Light 2008; EIA 2009). The tariff is summarized in Table 3-2. The tax rate is a population-weighted average of state plus average county and city sales taxes from Sales Tax Clearinghouse (Sales Tax Clearinghouse 2009). Even though a single tariff is used across climate zones, demand charges are included because they can represent a significant fraction of building operational costs.

Table 3-2 Electricity Tariff

Tariff Name	General Service Demand
Monthly charge	$33.10
Base demand charge	$5.10/kW
Demand capacity charge	$1.63/kW
Nonfuel energy charge	$0.01392/kWh
Fuel energy charge	$0.05564/kWh
Conservation energy charge	$0.00133/kWh
Environmental energy charge	$0.00038/kWh
Taxes	7.1%

We calculated multiple years of a national average gas tariff by averaging the Energy Information Administration (EIA) compilation of national average monthly prices for April 2006 through March 2009 (EIA 2007; EIA 2009) rather than taking the previous year's data, because recent prices have been volatile. The resulting tariff and source data are reproduced in Table 3-3 (see Table D-1 for metric units). Although using a national-average tariff might lead to some design solutions that are suboptimal because of regional tariff variability, it enables us to isolate climate variability as a driving factor in designing buildings to save energy. For specific case studies, we recommend considering regional tariff structures and incentives in the economic side of the analysis.

Table 3-3 National Average Natural Gas Tariff and Source Data in $/MCF

Month	Year				Tariff
	2006	2007	2008	2009	
January	–	$11.15	$11.01	$11.04	$11.07
February	–	$11.21	$11.32	$10.68	$11.07
March	–	$11.79	$11.81	$10.10	$11.23
April	$11.57	$11.49	$12.44	–	$11.83
May	$11.61	$11.48	$13.24	–	$12.11
June	$11.09	$11.86	$14.39	–	$12.45
July	$10.98	$11.61	$15.45	–	$12.68
August	$11.20	$11.16	$14.04	–	$12.13
September	$11.16	$10.90	$13.02	–	$11.69
October	$10.05	$10.90	$11.83	–	$10.93
November	$11.05	$11.19	$11.45	–	$11.23
December	$11.61	$11.02	$11.32	–	$11.32

3.1.2.6 Total Life Cycle Cost

Our objective is to simultaneously achieve 50% net site energy savings and minimize 5-TLCC. The 5-TLCC is the total expected cost of the whole building (capital, maintenance, and energy costs) over the five-year analysis period. The 5-TLCC calculation uses the real discount rate to account for inflation of energy and O&M costs instead of using the nominal discount rate paired with explicit estimates of energy and O&M inflation.

The annual cash flow is summed over the analysis period to calculate the 5-TLCC. The annual energy use is assumed to be constant throughout the analysis period. Equation 3-1 defines the annual cash flows.

$$C_n = \left(\sum_{j=0}^{J} CC_n + FOM_n + VOM_n \right) + C_g + C_e \tag{3-1}$$

where

C_n = cost in year n
J = total number of unique EEMs
CC_n = capital cost
FOM_n = fixed O&M cost
VOM_n = variable O&M cost
C_g = annual cost of gas consumption
C_e = annual cost of electricity consumption

The 5-TLCC is determined by Equation 3-2.

$$5 - TLCC = \sum_{n=0}^{5} \frac{C_n}{(1+d)^n} \tag{3-2}$$

where

5-TLCC = present value of the 5-TLCC
C_n = cost in year n
d = annual discount rate

3.1.2.7 Simple Payback Calculation

We also report simple payback for the low-energy models to indicate the timeframe required for the incremental capital and maintenance costs associated with EEM packages to be paid back by energy cost savings. Simple payback, in years, is determined by Equation 3-3 (Thornton, Wang et al. 2009).

$$t_P = \frac{CC_0}{C_{es}} \tag{3-3}$$

where

t_P = simple payback in years
CC_0 = initial capital cost
C_{es} = annual energy cost savings

Equation 3-3 assumes all incremental capital costs associated with EEM implementation are incurred up front and do not recur, and that overall O&M costs are consistent between the baseline and low-energy cases.

3.2 Prototype Model

We surveyed a number of reports and datasets to develop typical large office building characteristics and obtain energy performance estimates (see individual sections for references). Descriptions and assumptions relevant to each building characteristic are organized into functional groupings. This section details aspects of the large office building models that are common between the baseline and low-energy cases.

We consider a 12-story high-rise prototype and a 4-story low-rise prototype. Although the high-rise prototype has more floors than the low-rise prototype, its footprint area is reduced such that both contain the same total floor area of 460,800 (42,810 m^2), matching Deru, Field et al. (2010). We used *CBECS 2003* data to validate the size of the floor plate for the low-rise prototype (115,200 ft^2 [10,700 m^2]). These indicate that 7 of 30 office buildings built since 1980 with total floor areas larger than 150,000 ft^2 (13,935 m^2) and five or fewer floors have floor plates between 100,000 ft^2 (9,290 m^2) and 150,000 ft^2 (13,935 m^2) (EIA 2005).

We modeled the low-rise baseline building as three floors: a ground floor, a top floor, and an interior floor (with a multiplier of two to represent the second and third floors). The high-rise building, for which energy consumption is dominated by the interior floors, was modeled as a single interior floor with adiabatic boundary conditions on its top and bottom exterior surfaces (such that it represents an interior floor, as opposed to a single-story building that is exposed to the sky and ground on top and bottom, respectively). There are two reasons to model the high-rise case:

- To explore energy implications associated with low aspect ratio high-rise constructions, such as energy use being dominated by interior floors that are largely isolated from the outside elements.
- To assess the performance of glass curtain constructions, both in terms of common (high WWR, low exterior opaque envelope insulation) and best practice, code-compliant implementation.

For this study, height dependence of wind speed and stack effect driven infiltration are not considered.

3.2.1 Program

This section addresses building size, space types, and certain aspects of internal loads that are common between the baseline and low-energy models.

3.2.1.1 Space Types

To allow building geometry (especially aspect ratio) to be manipulated during optimization, we modeled the prototypes such that each floor consists of a large rectangular central core zone surrounded by perimeter zones, measuring 20 ft (6.1 m) deep from the exterior walls on each side. This captures the localized thermal effects near exterior walls and the benefits of certain EEMs, such as daylighting, natural ventilation, and exterior wall thermal mass design. We selected the 20-ft [6.1-m] perimeter depth as an average characteristic length for the effects captured by the perimeter zones. For each category of internal loading, we calculated the overall building average and applied it to each zone. To facilitate the calculation of average building loads, we estimated a distribution of typical office space types for each prototype (low-rise and high-rise).

Averaging space-specific ventilation requirements and internal loads across a simplified building geometry has drawbacks. For example, compliance with ASHRAE 62.1-2004 requires that space types meet ventilation requirements individually. Also, savings from strategies such as supply air temperature reset can be inflated when staggered loading caused by space-specific scheduling is not taken into account. However, the benefits associated with capturing the impact of aspect ratio on building energy use outweighed the drawbacks.

The space type breakdown for each prototype is presented in Table 3-4. Space type breakdowns are based on the layouts of a number of large office case studies, including the RSF.

Table 3-4 Large Office Space Types and Sizes

Space Type	Low-Rise			High-Rise		
	Floor Area (ft^2)	Floor Area (m^2)	Percent of Total	Floor Area (ft^2)	Floor Area (m^2)	Percent of Total
Office	393,332	36,542	85.4%	380,700	35,368	82.6%
Conference	17,992	1,672	3.9%	17,412	1,618	3.8%
Break room	7,112	661	1.5%	6,888	640	1.5%
Elevator	6,716	624	1.5%	20,148	1,872	4.4%
Restroom	11,192	1,040	2.4%	11,196	1,040	2.4%
Stairs	7,860	730	1.7%	7,860	730	1.7%
Mechanical/electrical room	16,596	1,542	3.6%	16,596	1,542	3.6%
Total	460,800	42,810	100%	460,800	42,810	100%

The elevator, restroom, stairwell, and mechanical room space types make up a larger fraction of the overall floor area in the high-rise prototype than in the low-rise prototype (12.1% versus 9.2%). This is based on a comparison of examples of high-rise (a DOE Commercial Building Partnerships project) and low-rise (RSF) office floor plans, and more generally on the assumption that elevator floor area scales with occupancy density rather than building footprint.

3.2.1.2 Internal Load Densities

Internal loads include the heat generated by occupants, lights, and appliances (plug and process loads). This section details occupancy densities, which are common between the baseline and low-energy models. Electric lighting and plug and process loads are detailed separately in the baseline and low-energy model descriptions (see Sections 3.3.4.2 and 3.4.4.3, respectively).

3.2.1.2.1 Occupancy

Where possible, occupancy density values are defined (by space type) according to the prescriptions of ASHRAE Standard 62.1-2004 (ASHRAE 2004b). The mappings between space type and Standard and the resulting occupancy density values, both for individual space types and for the prototypes as a whole, are presented in Table 3-5. Values for space types without direct mapping to the Standard were estimated. We assumed mechanical rooms, stairways, and elevators would be empty most of the time, and assigned them occupancy density values of zero.

Table 3-5 Occupancy Density Mapping and Peak Values

Space Type	Mapping to 62.1-2004	Low-Rise Occupancy Density		High-Rise Occupancy Density	
		(#/1,000 ft^2)	(#/100 m^2)	(#/1,000 ft^2)	(#/100 m^2)
Office	Office::Office Space	5	5.38	5	5.38
Conference	Office::Conference/Meeting	50	53.82	50	53.82
Break room	Food & Beverage::Restaurant Dining Rooms	70	75.35	70	75.35
Elevator	CUSTOM VALUE	0	0.00	0	0.00
Restroom	Office::Office Space	5	5.38	5	5.38
Stairs	CUSTOM VALUE	0	0.00	0	0.00
Mechanical/electrical room	CUSTOM VALUE	0	0.00	0	0.00
Average		7.42	7.99	7.19	7.74

The internal gains from occupants were calculated assuming 132 W (450 Btu/h) of heat per person (81 W [276 Btu/h] of sensible heat, and 52 W [174 Btu/h] of latent heat), which corresponds to the value listed for “moderately active office work” in Chapter 30 of the *ASHRAE 2005 Fundamentals Handbook* (ASHRAE 2005). Occupant comfort was calculated assuming clothing levels of 1.0 clo October through April, and 0.7 clo May through September; and an in-building air velocity of 0.83 ft/s (0.25 m/s).

3.2.1.3 Prototype Schedules

We determined our prototype schedule set through a combination of industry validated assumption and schedule set data from the Medium Office TSD (Thornton, Wang et al. 2009) and the Reference Building project (Deru, Field et al. 2010), for which schedules were largely based on the recommendations of ASHRAE Standard 90.1-1989 (ASHRAE 1989). Prototype weekday schedules for occupancy, interior equipment (plug and process loads), and lighting equipment are presented in Figure 3-1; the prototype schedule set is summarized in table form in Appendix A.

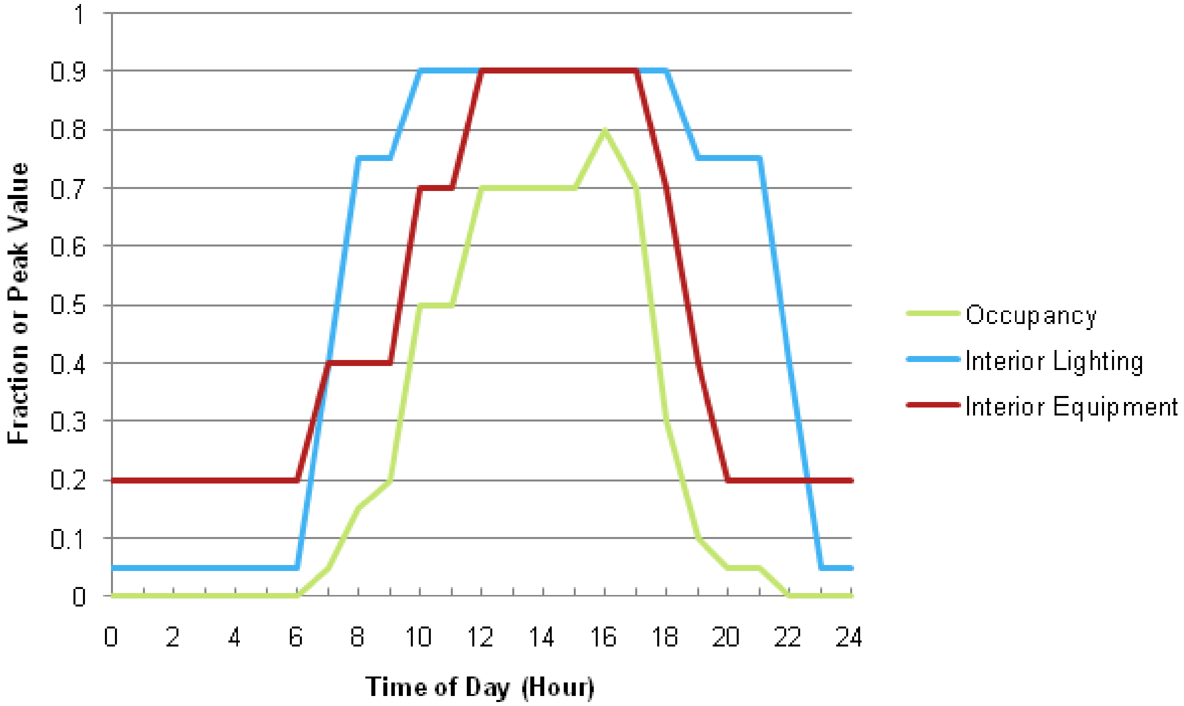

Figure 3-1 Prototype weekday schedules: occupancy, plug load equipment, and lighting equipment

3.2.2 Form

The number of floors, floor-to-floor height, and floor-to-ceiling height are the same in the baseline and low-energy cases. Aspect ratio and fenestration amount and placement, however, vary and are defined in Sections 3.3.2 and 3.4.2, respectively.

3.2.2.1 Building Shape

For the high-rise prototype, the floor-to-floor height and number of floors match those from Deru, Field et al. (2010). The low-rise prototype was modeled with the same overall floor area as the high-rise prototype and the large office Reference Building model, but as a 4-story building rather than a 12-story building. The characteristics that define the shape of each prototype are presented in Table 3-6.

Table 3-6 Prototype Shape Characteristics

Building Shape Characteristic	Low-Rise Prototype	High-Rise Prototype
Number of floors	4	12
Floor-to-floor height	13 ft (4 m)	13 ft (4 m)
Floor-to-ceiling height	13 ft (4 m)	13 ft (4 m)

Note that the prototypes were modeled with 13-ft (4-m) floor-to-ceiling and floor-to-floor heights. Plenums were not explicitly modeled in the prototypes; this is because aspect ratio can be varied automatically by the Opt-E-Plus program during building optimization only for very simple geometries that do not contain plenums. Rather than specifying specific designs for the air distribution systems of the baseline and low-energy models, we simply assumed a prototypical mixed air condition with limited temperature stratification and made no assumptions regarding baseline or low-energy air distribution methods. We assumed a fixed aspect ratio for the high-rise prototype, which seemed appropriate based on the constraints posed by many high-rise large office building sites, which tend to be in densely developed areas.

3.2.3 Fabric

This section specifies the types of envelope and interior constructions used in the prototype models. Specific fenestration constructions and insulation levels are listed in Sections 3.3.3, as prescribed by Standard 90.1-2004 (ASHRAE 2004c), and 3.4.3 for the baseline and low-energy models, respectively.

3.2.3.1 Exterior Constructions

The low-rise prototype, like the large office Reference Building, was modeled with punched-hole windows and masonry construction exterior walls. The high-rise prototype, on the other hand, was modeled as a glass curtain construction with insulated spandrel exterior wall panels. The low-rise prototype, like the large office Reference Building, was modeled with an insulation-above-deck roof. The high-rise prototype represents an interior floor and therefore was not modeled with a roof construction; its floor and ceiling constructions are interior constructions.

For the low-rise office case, the ground floor was modeled with a slab-on-grade construction, made up of carpet pad over 8-in. (0.2-m)-thick heavyweight concrete. In addition, 20 in. (0.5 m) of ground (earth) was modeled below the slab to capture more accurately the temperature gradient that occurs between the bottom of the slab and the ground (at some depth below the surface) that remains unaffected by the building. Capturing the effect of the building on the ground below it and vice versa is important from a thermal mass and a thermal storage perspective. A separate program, *slab.exe*, was used to model the coupling between the slab-on grade construction, including the 20 in. (0.5 m) ground layer and the ground below it (DOE 2008a). The program determines the ground temperature under the slab construction, based on the slab area and building location. It reports the perimeter and core ground monthly temperatures and average monthly temperatures. For this analysis, the core ground average monthly temperatures were passed to EnergyPlus to specify the ground temperatures under the slab construction.

The high-rise large office case does not contain ground floor constructions because only an interior floor was modeled.

3.2.3.2 Interior Partitions and Mass

We assumed interior wall partitions that separate core and perimeter zones are composed of 4-in. (0.1-m)-thick steel-frame walls covered with gypsum board, and that interior floors and ceilings are composed of carpet pad above 4-in. (0.1-m)-thick concrete on metal decking. Internal mass was modeled as 2 ft^2 (~0.2 m^2) of 6-in. (0.15-m)-thick wood per ft^2 (m^2) of floor area, totaling 921,600 ft^2 (85,620 m^2) for the whole building (Deru, Field et al. 2010).

3.2.4 Equipment

This section specifies the types of HVAC and service water heating (SWH) equipment used in the prototype and baseline models; performance and cost data are discussed in Sections 3.3.4.4 and 3.3.4.5, respectively.

3.2.4.1 Heating, Ventilating, and Air-Conditioning

The large office prototypes are assumed to be fully heated and cooled. Setup and setback schedules are implemented during unoccupied hours (nighttime), when the HVAC system is set to cycle to maintain temperature requirements for setup and setback and maintain RH requirements. Although humidity may not typically be controlled during unoccupied periods, avoiding mold and moisture is good practice. (See Sections 3.3.4.4 and 3.4.4.5 for details about the specification and operation of the baseline and low-energy HVAC systems, respectively.)

3.2.4.2 Service Water Heating

SWH is facilitated by tank storage natural gas water heaters. The type and number of hot water fixtures was determined from the design layout for the RSF; storage capacity was then calculated using the hot water demand table in the Service Water Heating chapter of the *HVAC Applications Handbook* (ASHRAE 2003). The RSF has two wings (one has a floor area of 21,800 ft^2 [2025 m^2], the other 27,360 ft^2 [2542 m^2]). Each has the same number of hot water fixtures: four lavatories, two for a men's restroom and two for a women's restroom; two kitchen sinks, one per break room; and one service sink in a janitorial closet. We used these data to estimate the following distribution of fixtures for the large office models: 18 lavatories, 9 kitchen sinks, and 5 service sinks for each floor of the low-rise building, and 6 lavatories, 3 kitchen sinks, and 2 service sinks for each floor of the high-rise building. We used the hot water demand table in ASHRAE (2003) to calculate per-floor SWH storage capacities of 271 gal (1.03 m^3) and 96 gal (0.36 m^3) for the low-rise and high-rise buildings, respectively. Accordingly, we specified 300 gal (1.14 m^3) of storage per floor for the low-rise building and 100 gal (0.38 m^3) of storage per floor for the high-rise building, in increments of 100 gal (0.38 m^3) units. Calculations were based on demands of 2 gal/h (0.008 m^3/h) per lavatory, 20 gal/h (0.08 m^3/h) per kitchen sink, and 20 gal/h (0.08 m^3/h) per service sink, an overall demand factor of 0.3, a storage capacity factor of 2, and a tank usable volume factor of 0.7.

3.2.5 Prototype Model Summary

This section summarizes the building characteristics that define the large office prototype models. To reiterate, prototype characteristics are those not specified by ASHRAE Standards 90.1-2004 and 62.1-2004 but that are needed to develop baseline and low-energy models. Prototype characteristics are summarized in Table 3–7.

Table 3-7 Large Office Prototype Model Characteristics and Data Sources

Building Characteristic	Low-Rise Large Office TSD Prototype	High-Rise Large Office TSD Prototype	Source
Program			
Size	460,800 ft^2 ($42,810 m^2$)	460,800 ft^2 ($42,810 m^2$)	DOE Reference Building Large Office
Space types	See Table 3-4	See Table 3-4	DOE Reference Building Large Office, RSF
Occupancy	See Table 3-5 for density; see Table A-1 for schedule	See Table 3-5 for density; see Table A-1 for schedule	ASHRAE 90.1-1989; DOE Reference Building Large Office; PNNL Medium Office TSD; Assumption
Lighting	See Table A-2 for schedule	See Table A-2 for schedule	ASHRAE 90.1-1989; DOE Reference Building Large Office; PNNL Medium Office TSD; Assumption
Plug and process	See Table A-3 for schedule	See Table A-3 for schedule	DOE Reference Building Large Office; PNNL Medium Office TSD; Assumption
Form			
Number of floors	4	12	DOE Reference Building Large Office; Assumption
Floor-to-floor height	13 ft (4 m)	13 ft (4 m)	DOE Reference Building Large Office
Fabric			
Wall type	Precast concrete	Spandrel glass	DOE Reference Building Large Office; Assumption
Roof type	All insulation above deck	Not modeled	DOE Reference Building Large Office
Slab Type	Slab-on-grade: carpet pad on 8 in. (20 cm) heavyweight concrete above 20 in. (51 cm) of ground	Not modeled	Assumption*
Interior walls	2 x 4 steel-frame with gypsum boards	2 x 4 steel-frame with gypsum boards	Assumption*
Interior floors	Carpet pad on 4 in. (10 cm) concrete	Carpet pad on 4 in. (10 cm) concrete	Assumption*
Internal mass	921,600 ft^2 ($85,620 m^2$) of 6 in. (15 cm) wood	921,600 ft^2 ($85,620 m^2$) of 6 in. (15 cm) wood	DOE Reference Building Large Office
Equipment			
HVAC controls	Setup and setback during unoccupied hours	Setup and setback during unoccupied hours	DOE Reference Building Large Office
SWH	Natural gas heating with storage tank; see Table A-4 for schedule	Natural gas heating with storage tank; see Table A-4 for schedule	DOE Reference Building Large Office; PNNL Medium Office TSD; ASHRAE 90.1-1989

* Verified by industry reviewers

3.3 Baseline Model

This section contains a topic-by-topic description of the baseline building models' EnergyPlus inputs, including: form and footprint; envelope characteristics; internal loads; HVAC equipment efficiency, operation, control, and sizing; and SWH. We also list associated costs, which were used by Opt-E-Plus to compute 5-TLCC for each building configuration.

For the high-rise case, two baseline models were considered: one representing common glass curtain construction practices and one representing minimal code compliance with respect to ASHRAE 90.1-2004.

The common practice high-rise baseline was set up as a high-WWR, low-exterior insulation case. Many high-rise buildings are designed with floor-to-ceiling view glass in occupied spaces; that design style is approximated in the common practice case by a continuous band of 9-ft (2.7-m) tall glass curtain view glass around the perimeter of each floor, resulting in an overall WWR of 69%. We assumed that the remaining 4 ft (1.2 m) of the 13 ft (4 m) floor-to-floor height would house some combination of air distribution components and electrical and mechanical equipment and would be finished at the perimeter with spandrel glass wall panels. Spandrel wall constructions were defined to provide a wall assembly insulation value of roughly R-3 in each climate zone. Low-energy configurations of the common practice high-rise baseline were considered, but with fixed window and wall constructions and spatial distributions (fixed WWR and sill height).

The code-compliant high-rise baseline was assigned climate-specific ASHRAE 90.1-2004-compliant window and wall constructions and spatial distributions (defined by WWR and sill height values) that were allowed to vary in search of configurations that decrease energy use. We assessed implications of common glass curtain construction practices for achievable energy savings by comparing the low-energy versions of the high-rise common practice and code-compliant building configurations. Building programs and equipment were changed to save energy in both cases, but only the high-rise prototype with the code-compliant baseline was free to vary its glazing fraction and opaque envelope insulation to potentially increase those savings.

3.3.1 Program

3.3.1.1 Baseline Schedules

Our baseline model schedule set was determined through a combination of industry validated assumption and schedule set data from the Medium Office TSD (Thornton, Wang et al. 2009) and the Reference Building project (Deru, Field et al. 2010), for which schedules were largely based on the recommendations of ASHRAE Standard 90.1-1989 (ASHRAE 1989).

Baseline model weekday schedules for occupancy, HVAC operation, and infiltration are presented in Figure 3-2. "Ground floor" infiltration applies to the ground floor in the low-rise baseline and "interior floor" infiltration applies to all other low-rise baseline floors and to the high-rise baseline. The HVAC system is activated one hour before occupancy (to allow for ramp up to the desired space conditions during occupancy) and infiltration is reduced to 25% of its peak value during HVAC operation. For the ground floor, infiltration is increased during periods with above minimum occupancy to account for infiltration when doors are opened (see Section 3.3.3.4 for details on infiltration).

Baseline weekday schedules for heating and cooling set point, which include setup and setback during unoccupied periods, are displayed in Figure 3-3; see Section 3.3.4.4 for details on baseline VAV HVAC operation.

For the full set of baseline schedules, see Appendix B.

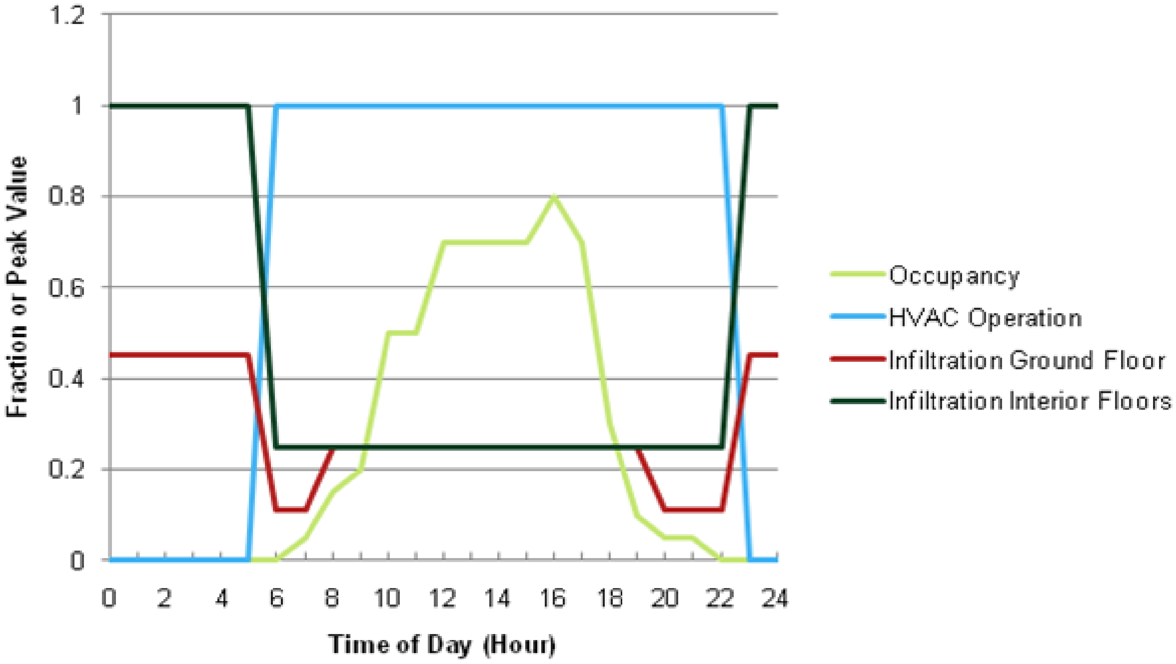

Figure 3-2 Baseline weekday schedules: occupancy, HVAC operation, and infiltration

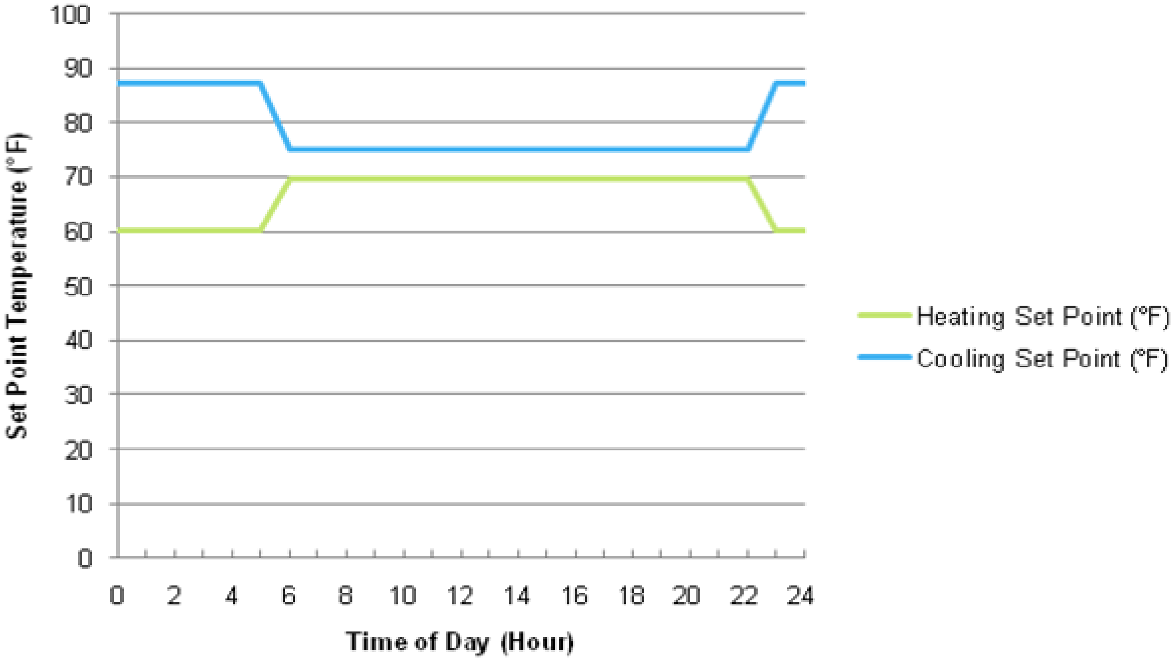

Figure 3-3 Baseline weekday schedules: heating and cooling set points

3.3.2 Form

3.3.2.1 Building Shape

For the high-rise baseline building, the aspect ratio and footprint match those for the large office Reference Building. For the low-rise baseline model, the aspect ratio matches that for the large office Reference Building, but the footprint is three times larger to accommodate the same floor area within 4 floors instead of 12. Table 3-8 presents the aspects of the baseline models' shape that are not defined in the corresponding prototypes.

Table 3-8 Baseline Shape Characteristics

Building Shape Characteristic	Low-Rise Baseline	High-Rise Baseline
Aspect ratio	1.5	1.5
Length	415.7 ft (126.7 m)	240 ft (73.2 m)
Width	277.1 ft (84.5 m)	160 ft (48.8 m)

See Figure 3-4, Figure 3-5 and Figure 3-6 for isometric views of the low-rise and high-rise (code-compliant and common practice) baseline models. These provide visuals of the zoning described in Section 3.2.1 and the envelope characteristics described in Section 3.3.

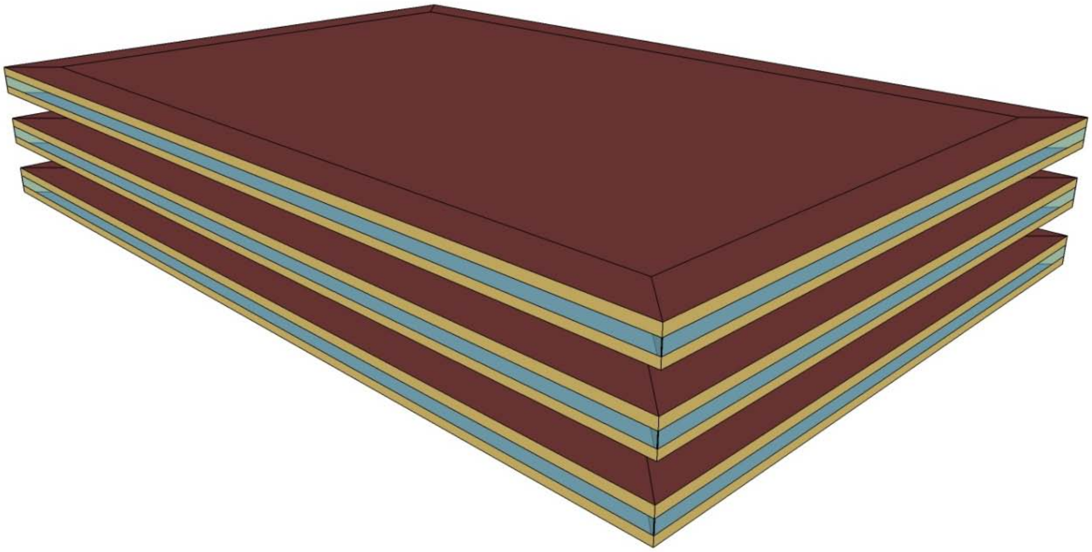

Figure 3-4 Isometric view of the low-rise baseline model

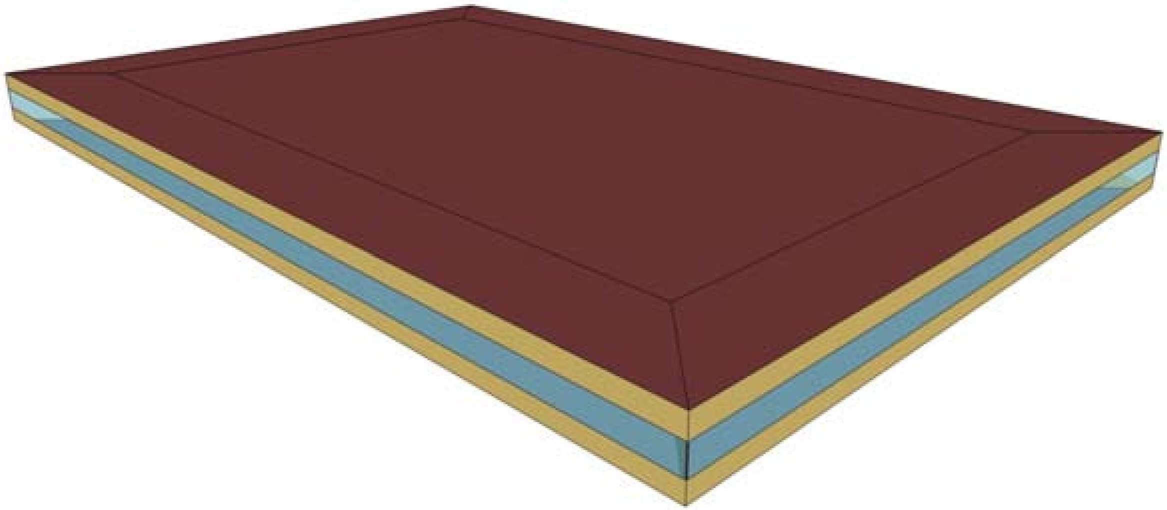

Figure 3-5 Isometric view of the code-compliant high-rise baseline model

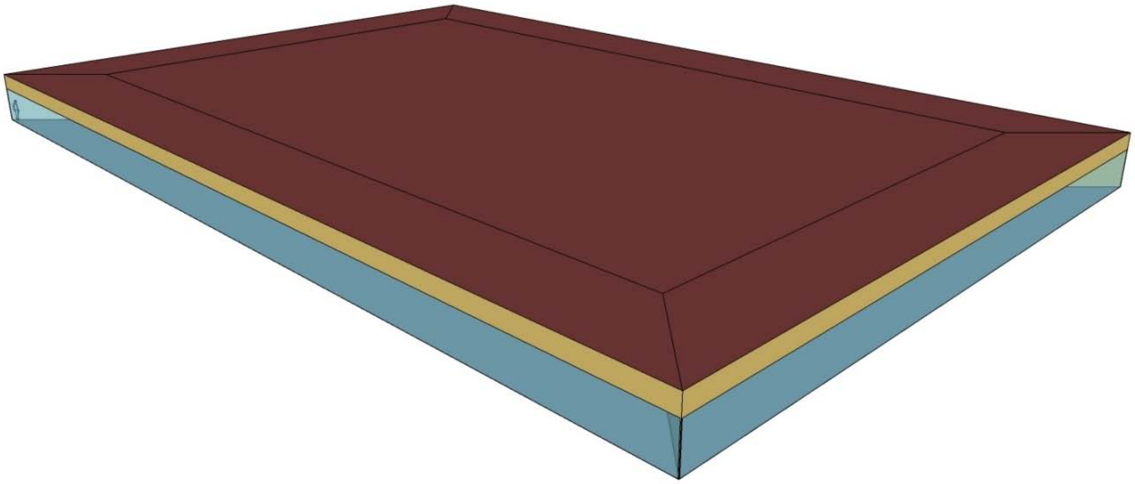

Figure 3-6 Isometric view of the common practice high-rise baseline model

3.3.2.2 Fenestration

The WWR was set to 40% for the low-rise and code-compliant high-rise baselines; this matches the value in the large office Reference Building model and is the maximum value allowed for ASHRAE 90.1-2004 Appendix G compliance. The common practice high-rise baseline is modeled with a WWR of 69%, approximating a design with floor-to-ceiling glass in its occupied spaces.

Sill height for the low-rise and code-compliant high-rise baselines was set to 3.61 ft (1.1 m) above the floor, such that the view glass reaches up to 9 ft (2.7 m) above the floor. Sill height for the common practice high-rise baseline was set to zero, such that the view glass in all baseline cases has a consistent header height of 9 ft (2.7 m).

Per Appendix G of ASHRAE 90.1-2004, overhangs were not included in the baseline models. Neither prototype includes skylights or daylighting controls.

3.3.3 Fabric

The exterior constructions chosen for each large office prototype were further developed to meet the prescriptive design option requirements of ASHRAE 90.1-2004 Section 5.5 (except for the exterior wall construction and WWR for the common practice high-rise baseline) (Wilson 2010). Layer-by-layer descriptions of the exterior surface constructions were used to model the building thermal envelope in EnergyPlus.

3.3.3.1 Exterior Walls

This section details the baseline exterior wall constructions for the low-rise and high-rise large office baseline models. For a given prototype and construction, assembly U-factors vary based on the climate zone and are adjusted to account for standard film coefficients. R-values for most layers are derived from Appendix A of ASHRAE Standard 90.1-2004. Continuous insulation (c.i.) R-values were selected to meet the minimum R-value requirements of Section 5.5 in ASHRAE Standard 90.1-2004 (except in the common practice high-rise case), which vary by climate zone (ASHRAE 2004c).

The low-rise large office baseline was modeled with precast concrete wall panels. Noninsulated panels are made up of 8 in. (20.3 cm) of solid heavyweight concrete (140 lb/ft^3) [2,240 kg/m^3]). Insulated panels are sandwich constructions with concrete and rigid isocyanurate insulation layers, arranged as follows:

- Exterior air film (calculated by EnergyPlus)
- 3-in. (7.6-cm) solid heavyweight concrete, 140 lb/ft^3 (2,240 kg/m^3)
- Rigid isocyanurate insulation (R-value varies by climate)
- 6-in. (15.2-cm) solid heavyweight concrete, 140 lb/ft^3 (2,240 kg/m^3)
- Interior air film (calculated by EnergyPlus).

The low-rise baseline exterior walls' performance metrics, including costs, are listed in Table 3-9 (see Table D-2 for metric units). Insulation R-values were selected to meet the minimum requirements for mass wall constructions in Section 5.5 of ASHRAE 90.1-2004. The capital costs were provided by The Abo Group (Priebe 2010).

Table 3-9 Low-Rise Baseline Exterior Wall Constructions

Properties	Climate Zone 1A	Climate Zones 3B-NV and 4C	Climate Zones 5A and 5B	Climate Zone 7
Key	**Baseline Wall Construction No c.i.**	**Baseline Wall Construction R-5.7 c.i.**	**Baseline Wall Construction R-7.6 c.i.**	**Baseline Wall Construction R-11.4 c.i.**
Assembly U-factor (Btu/ h·ft^2·°F)	1.010	0.173	0.137	0.097
Capital cost ($/ft^2)	$36.15	$44.05	$44.40	$45.10

The high-rise large office baseline was modeled as a curtain wall construction with spandrel glass exterior wall constructions. The layers consist of spandrel glass, rigid isocyanurate insulation, and gypsum board, arranged as follows:

- Exterior air film (calculated by EnergyPlus)

- 0.25-in. (0.64-cm) exterior spandrel glass, 113 lb/ft^3 (1,810 kg/m^3)
- Rigid isocyanurate insulation (R-value varies by climate)
- 0.5-in. (1.3-cm) thick gypsum board, 49 lb/ft^3 (785 kg/m^3).

The high-rise baseline exterior walls' performance metrics, including costs, are listed in Table 3-10 for the code-compliant case (according to the minimum requirements for steel-framed wall constructions in Section 5.5 of ASHRAE 90.1-2004) (ASHRAE 2004c) and in Table 3-11 for the common practice case, as required, in combination with a corresponding code-compliant window construction (see Section 3.3.3.3), to provide an approximate exterior wall assembly R-value of 3. (See Table D-3 and Table D-4, respectively, for metric units.) Priebe (2010) provided the capital costs.

Table 3-10 High-Rise Code-Compliant Baseline Exterior Wall Constructions

Properties	Climate Zones 1A, 3B-NV, and 4C	Climate Zones 5A, and 5B	Climate Zone 7
Key	Baseline Wall Construction R-13.0	Baseline Wall Construction R-13.0 + R-3.8 c.i.	Baseline Wall Construction R-13.0 + R-7.5 c.i.
U-factor (Btu/ h·ft^2·°F)	0.139	0.091	0.068
Capital cost ($/ft^2)	$35.75	$36.65	$37.15

Table 3-11 High-Rise Common Practice Baseline Exterior Wall Construction

Properties	All Climate Zones
Key	Baseline Wall Construction Whole Wall Assembly R-3.0
U-factor (Btu/ h·ft^2·°F)	0.173
Capital cost ($/ft^2)	$34.80

For each construction, the thermal performances of the interior and exterior air films were calculated with the EnergyPlus "detailed" algorithm for surface heat transfer film coefficients, which is based on linearized radiation coefficients separate from the convection coefficients determined by surface roughness, wind speed, and terrain.

3.3.3.2 Roofs

For the low-rise large office case, the baseline model roofs are built up with rigid insulation above a structural metal deck. The layers consist of roof membrane, insulation, and metal decking. The assembly U-factors vary based on the climate zone and are adjusted to account for standard film coefficients. R-values for most of the layers were derived from Appendix A of ASHRAE Standard 90.1-2004. Continuous insulation R-values were selected to meet the minimum R-value requirements of Section 5.5 in ASHRAE Standard 90.1-2004, which vary by climate zone (ASHRAE 2004c). The thermal performance metrics and construction costs are listed by climate zone in Table 3-12 (see Table D-5 for metric units). The capital costs were provided by Priebe (2010) and assume:

- A 60-mil (0.15-cm) thick, mechanically fastened ethylene propylene diene monomer single-ply membrane
- Polyisocyanurate insulation, including a tapered drainage piece finished with 7/16-in. (1.11-cm) strand board
- 0.05-in. (0.13-cm) base flashing and edging around the perimeter of the roof.

Table 3-12 Low-Rise Baseline Roof Constructions

Properties	Climate Zones 1–7
Key	**Baseline Roof Construction, R-15 c.i.**
U-factor (Btu/h·ft^2·°F)	0.066
Capital cost (\$/ft^2)	\$9.15

The prescriptive portion of Standard 90.1-2004 does not specify performance characteristics such as roof reflectance or absorption. Appendix G of the Standard states that the reflectivity of reference buildings should be 0.3. We assumed the baseline roof ethylene propylene diene monomer membrane has a solar reflectance of 0.3, a thermal absorption of 0.9, and a visible absorption of 0.7.

The high-rise large office baseline models do not contain roof constructions because only an interior floor was modeled.

3.3.3.3 Fenestration

The baseline fenestration systems for the low-rise and high-rise large office buildings were modeled as four banded windows per floor, one for each exterior wall surface. Each banded window spans the width of its exterior wall surface and, as a single fenestration object, represents the combined fenestration area of the individual windows that would populate the exterior wall surface in an actual construction. To reduce model complexity and to make the EnergyPlus simulations run faster, we did not modeled frames explicitly; however, the window properties (U-factors and SHGCs) are whole-assembly values that include the effects of frames. Performance criteria were set to match the requirements of Appendix B in ASHRAE Standard 90.1-2004. If the Standard does not provide an SHGC recommendation for a given climate zone, the SHGC value for that climate zone was set to that of the next warmest climate zone for which a recommendation is given.

The multipliers from Table C3.5 in ASHRAE 90.1-2004 Appendix C (ASHRAE 2004c) were used to calculate VLT values for the baseline windows. An iterative process is used to refine the material properties in the layer-by-layer descriptions to just match the required assembly performance level. Capital costs assume punched-hole constructions for the low-rise case (Table 3-13 and Table 3-14) and glass curtain constructions for the high-rise case (Table 3-15 and Table 3-16); see Table D-6 to Table D-9 for metric units. Priebe (2010) provided the capital costs.

Table 3-13 Low-Rise Baseline East-, South-, and West-Facing Punched-Hole Window Constructions

Properties	Climate Zone 1A	Climate Zone 3B-NV	Climate Zones 4C, 5A, and 5B	Climate Zone 7
Key	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**
SHGC	0.250	0.250	0.390	0.490
VLT	0.250	0.318	0.495	0.490
U-factor (Btu/h·ft^2·°F)	1.21	0.570	0.570	0.570
Capital cost (\$/ft^2)	\$46.29	\$49.81	\$47.24	\$47.24
Fixed O&M cost (\$/ft^2)	\$0.22	\$0.22	\$0.22	\$0.22

Table 3-14 Low-Rise Baseline North-Facing Punched-Hole Window Constructions

Properties	Climate Zone 1A	Climate Zone 3B-NV	Climate Zones 4C, 5A, and 5B	Climate Zone 7
Key	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**
SHGC	0.440	0.390	0.490	0.640
VLT	0.440	0.622	0.622	0.640
U-factor (Btu/h·ft^2·°F)	1.21	0.570	0.570	0.570
Capital cost (\$/ft^2)	\$45.21	\$41.39	\$46.66	\$40.84
Fixed O&M cost (\$/ft^2)	\$0.22	\$0.22	\$0.22	\$0.22

Table 3-15 High-Rise Baseline East-, South-, and West-Facing Glass Curtain Constructions

Properties	Climate Zone 1A	Climate Zone 3B-NV	Climate Zones 4C, 5A, and 5B	Climate Zone 7
Key	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**
SHGC	0.250	0.250	0.390	0.490
VLT	0.250	0.318	0.495	0.490
U-factor (Btu/h·ft^2·°F)	1.21	0.570	0.570	0.570
Capital cost (\$/ft^2)	\$73.30	\$76.82	\$74.25	\$74.25
Fixed O&M cost (\$/ft^2)	\$0.22	\$0.22	\$0.22	\$0.22

Table 3-16 High-Rise Baseline North-Facing Glass Curtain Constructions

Properties	Climate Zone 1A	Climate Zone 3B-NV	Climate Zones 4C, 5A, and 5B	Climate Zone 7
Key	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**
SHGC	0.440	0.390	0.490	0.640
VLT	0.440	0.622	0.622	0.640
U-factor (Btu/h·ft^2·°F)	1.21	0.570	0.570	0.570
Capital cost ($/ft^2)	$72.22	$68.40	$73.67	$67.85
Fixed O&M cost ($/ft^2)	$0.22	$0.22	$0.22	$0.22

Skylights were not considered for either the high-rise or low-rise baseline cases, as they are not baseline equipment.

3.3.3.4 Infiltration

Building air infiltration is addressed indirectly in ASHRAE 90.1-2004 through requirements for building envelope sealing, fenestration, door air leakage, etc. The air infiltration rate, however, is not specified. Baseline office building envelope leakage rates are based on data taken from ASTM E779 fan pressurization tests on U.S. office buildings (Emmerich, McDowell et al. 2005); exterior door leakage rates are based on the door opening event model of Yuill et al. (2000). The resultant whole building baseline leakage rates for the low-rise and high-rise cases, respectively, are 0.080 air changes per hour (ACH) and 0.072 ACH during operating hours, when the HVAC system is on and occupants are entering and leaving the building, and 0.244 ACH and 0.213 ACH at night, when the HVAC system is off and the exterior doors are closed. Envelope infiltration is averaged and applied evenly to each floor. Infiltration through entrances and exits is applied only to the ground floor. Half the infiltration on each floor is assigned to the perimeter zones, and half is assumed to pass beyond the 20-ft (6.1-m) deep perimeter and into the core zone. The per-zone infiltration rates are presented in Table 3-17.

Table 3-17 Baseline Infiltration Rates per Zone

Floor	Low-Rise		High-Rise	
	Operating Hours (ACH)	Non-Operating Hours (ACH)	Operating Hours (ACH)	Non-Operating Hours (ACH)
Ground floor core	0.088	0.158	NA	NA
Ground floor perimeter	0.300	0.540	NA	NA
Other floor core	0.040	0.160	0.043	0.170
Other floor perimeter	0.135	0.540	0.070	0.280

Ground floor zone infiltration rates were not modeled for the high-rise case because only an interior high-rise floor was modeled.

Infiltration through an envelope surface depends on the pressure gradient acting on the surface. We calculated pressure gradients for both cases according to the following assumptions:

- For each of the six climate zones used for this study, an average wind velocity was calculated from the weather file data for the representative city.
- An average infiltration-inducing wind pressure coefficient (0.375) was calculated using the findings from Akins et al. (1979) and Wiren (1984) for typical low-rise, low aspect ratio (less than 3) rectangular buildings and a random wind direction (all wind directions are assumed to be equally probable). Note that, for lack of data, we also apply these assumptions to high-rise and high aspect ratio (greater than 3) low-rise cases.
- Based on the assumption of random wind direction, the average infiltration-inducing wind pressure coefficient is the same for each exterior surface.
- Average wind speeds are similar for each climate zone (ranging from 9.0 mph to 10.5 mph [4.0 m/s to 4.7 m/s]); for simplicity, we used a climate-averaged wind speed of 9.8 mph (4.4 m/s) to calculate an average wind pressure coefficient of 0.375, which corresponds to an average infiltration driving pressure of 0.017 in. w.c. (4.33 Pa). This driving pressure was used in all climate zones for both the low-rise and high-rise cases.
- When the HVAC system is on, total infiltration is reduced by 75% (applied equally to envelope leakage infiltration and exterior door opening-event infiltration). This assumption is based on an EnergyPlus Airflow Network analysis, for which internal building pressurization during HVAC operation was approximated by creating a supply leak in the occupied space equivalent in flow rate to that of the space's HVAC system (the supply leak flow was brought in from a secondary zone such that mass flow balance could be maintained for the primary HVAC loop).
- When the HVAC system is off, the building is not pressurized with respect to the exterior environment.
- The current infiltration rates do not take into account temperature-driven infiltration via stack effect, which is difficult to model accurately. See Section 5.2 for details.

3.3.4 Equipment

This section describes the performance and cost of the baseline buildings' lighting, HVAC, and refrigeration equipment.

3.3.4.1 Electric Lighting

The baseline interior lighting power density (LPD) for each space type was derived by using the space-by-space method defined in ASHRAE 90.1-2004 (ASHRAE 2004c). The space type-specific LPD values were then used to calculate an area-weighted whole-building average LPD, which is applied to the perimeter and core zones of the baseline models. The mappings between space type and Standard and the resulting LPD values, both for individual space types and for the baseline models as a whole, are presented in Table 3-18.

Table 3-18 Baseline Lighting Loads by Space Type

Space Type	Mapping to ASHRAE 90.1-2004	Low-Rise		High-Rise	
		LPD (W/ft^2)	LPD (W/m^2)	LPD (W/ft^2)	LPD (W/m^2)
Office	Office-enclosed (or open plan)	1.1	11.84	1.1	11.84
Conference	Conference/meeting/multipurpose	1.3	13.99	1.3	13.99
Break room	Dining area	0.9	9.69	0.9	9.69
Elevator	CUSTOM VALUE	0.0	0.0	0.0	0.0
Restroom	Restrooms	0.9	9.69	0.9	9.69
Stairs	Stairs-active	0.6	6.46	0.6	6.46
Mechanical/ electrical room	Electrical/mechanical	1.5	16.15	1.5	16.15
Whole building		1.09	11.73	1.06	11.38

The baseline cost of the lighting system for both the low-rise and high-rise large office cases is estimated at \$10.36/ft^2 (\$111.51/m^2) for capital costs and \$77.24/kW·yr for maintenance, where kW refers to the installed lighting power. Because office space dominates the floor plan of the building, we used office space equipment and baseline LPD prescription to estimate building lighting costs. For baseline lighting equipment (32-W T8 lamps), a spacing of 80 ft^2 (7.4 m^2) per fixture would result in a space LPD of 0.8 W/ft^2 (8.6 W/m^2); to achieve a space LPD of 1.1 W/ft^2 (11.8 W/m^2), a spacing of 58 ft^2 (5.4 m^2) is required. The cost of the baseline lighting fixture was estimated at \$366 per fixture, resulting in an area-normalized fixture cost of \$6.29/ft^2 (\$67.70/m^2). For a lighting power density of 1.1 W/ft^2 (11.8 W/m^2), we calculated a power-normalized capital lighting cost of \$9,418/kW. Likewise, we calculated an area-normalized maintenance cost of \$0.08/ft^2·yr (\$0.91/m^2·yr). The capital costs are estimated based on Balboni (2008); the maintenance costs are estimated using Plotner (2009).

Exterior lighting is not included in the large office baseline models. In previous TSD work, 1 W/ft (3.3 W/m) of exterior façade lighting was applied to the baseline models as per the allowance for lighting of exterior walkways in ASHRAE 90.1-2004, Table 9.4.5. Parking lot lighting is also not included in the current study. Compared to the interior lighting and plug and process loads, 1 W/ft (3.3 W/m) of exterior lighting represents a very small load that has a negligible effect on overall building energy usage; accordingly, we chose not to model exterior lighting.

3.3.4.2 Plug and Process Loads

Peak plug and process loads are largely based on Deru, Field et al. (2010) and current NREL operations. The Reference Building large office model specifies a plug and process load density of 0.75 W/ft^2 for office spaces and conference rooms; for this study, we reduced that density to 0.404 W/ft^2 for those space types. The reduction is based on the assumption that a significant portion of the building's computing equipment would be housed in a central data center. We assume that the data center would be separated from occupied spaces (in a basement, for example) and that it would not influence system interactions in the rest of the building; accordingly, we separated data center loads (for both equipment and conditioning) from the rest of the building loads for modeling purposes (see Section 3.3.4.2 for details on data center loads). We assigned the elevator space a plug load density of zero based on the assumption that the electrical equipment associated with elevator operation would be contained within a basement utility room, and not affect the occupied space. We assumed that baseline plug and process loads costs are included in the overall baseline capital costs (see Section 3.1.2.4). The baseline plug and process loads are presented in Table 3-19.

Table 3-19 Peak Baseline Plug Loads

Space Type	Low-Rise		High-Rise	
	Plug Load Density (W/ft^2)	Plug Load Density (W/m^2)	Plug Load Density (W/ft^2)	Plug Load Density (W/m^2)
Office	0.40	4.35	0.40	4.35
Conference	0.40	4.35	0.40	4.35
Break room	2.60	27.99	2.60	27.99
Elevator	0.00	0.00	0.00	0.00
Restroom	0.10	1.08	0.10	1.08
Stairs	0.00	0.00	0.00	0.00
Mechanical/electrical room	0.00	0.00	0.00	0.00
Average	0.40	4.34	0.39	4.20

3.3.4.3 Data Center

According to current NREL operations, we estimated a data center IT load of 65 W of computational power per building occupant. Assuming typical data center operations and an average Power Usage Effectiveness (PUE) of 1.9, we estimated data center HVAC (conditioning) and lighting loads totaling 58.5 W per person (Google 2010). Table 3-20 details per-occupant data center loads.

Table 3-20 Baseline Data Center Load per Person

	Low-Rise	High-Rise
PUE	1.90	1.90
IT equipment (W/person)	65.00	65.00
HVAC and lighting equipment (W/person)	58.50	58.50

Assuming 3,494 occupants in the low-rise office building and 3,453 occupants in the high-rise office building, we calculated annual baseline data center energy usage of 28.01 kBtu/ft^2·yr (146.5 MJ/m^2); see Table 3-21 (Table D-10 for metric units) for details. Data center energy usage was not explicitly modeled using EnergyPlus; it was added to the building end uses and overall energy consumption in postprocessing.

Table 3-21 Baseline Data Center EUIs

	Low-Rise	High-Rise
IT equipment (kBtu/ft^2)	14.74	14.74
HVAC and lighting equipment (kBtu/ft^2)	13.27	13.27
Total data center (kBtu/ft^2)	28.01	28.01

3.3.4.4 HVAC Systems and Components

We assumed, in agreement with the large office Reference Building model, that a VAV system with hydronic heating and cooling represents an appropriate HVAC baseline for a large office building.

3.3.4.4.1 Hydronic VAV: System Control

Each floor of the baseline models is conditioned by a dedicated VAV system that supplies air at a constant 55°F (12.8°C) to zone level reheat terminal boxes. The central hot and cold water coils and the hot water coils in the zone-level reheat terminal boxes are supplied by a central boiler and chiller. Boiler, chiller, and pump loop specifications were taken from the large office Reference Building. The boilers are natural gas-fired, hot water models. The chillers are water-cooled, electric, centrifugal compressor models paired with a water-cooled rooftop cooling tower with a dual-speed fan. Central heating coils may not be needed except in very cold climates; however, they were included in all models for completeness. They were used sparingly (or not at all) in most climates and otherwise had no impact on energy use.

We considered a lower central supply temperature (45°F [7°C]) for humid climates (Miami and Chicago) to ensure space RH levels would be maintained below 60%, but we determined that 55°F (13°C) supply air was sufficient in all climates to maintain specified humidity control during occupied times.

The baseline hydronic VAV system operates within a daytime dry bulb dead band of 70°–75°F (21°–24°C). Assuming an occupant metabolic rate of 1.27 (for moderately active office work; see Section 3.2.1.2.1) and clothing levels of 0.7 clo for summer and 1.0 clo for winter, this corresponds to predicted mean vote (PMV) values of 0.12 (at 60% RH) and –0.17 (at 50% RH) for summer and winter, respectively. This falls within the acceptable comfort range for PMV values of –0.5 on the cold side to 0.5 on the warm side, according to standard design practice.

We specified the minimum ventilation requirement as per the prescriptions of ASHRAE 62.1-2004 (ASHRAE 2004b) (see Section 3.3.4.4.3). We also specified a minimum total outdoor air fraction of 0.25 and minimum VAV terminal box flow fractions of 0.3 as per typical VAV design for office environments. Specifying a minimum outdoor air fraction of 25% captures the peak design requirements for critical zones such as conference rooms, mitigating many of the drawbacks associated with lumped ventilation requirements.

Reheat at the VAV terminals is supplied according to dual maximum logic, where hot water flow to the reheat coil is ramped up at the minimum air flow rate until the maximum hot water flow is reached and the air damper is gradually opened from its minimum stop position to further increase heating capacity (PG&E 2007).

During unoccupied periods (nighttime), the HVAC system cycles to maintain setup and setback temperature and RH requirements. If the temperature in any zone rises above the setup set point of 87°F (30.6°C), the HVAC system for that floor powers on and cools recirculated air until the temperature in every zone is reduced to at least 3°F (1.7°C) below the setup temperature. Likewise, if the temperature in any zone falls below the setback set point of 55°F (15.6°C), the HVAC system powers on and heats recirculated air until the temperature in every zone is increased to at least 3°F (1.7°C) above the setback temperature. If the RH in any zone rises above 70%, the HVAC system powers on and cools recirculated air until every zone has an RH of 60% or lower. During nighttime humidity mitigation, the heating set point is temporarily raised to its daytime operation point of 70°F (21°C) to avoid overcooling. If the RH in a zone has not yet been lowered to 60% and the temperature falls below 70°F (21°C), reheat is employed to maintain that temperature while the cold water coils continue to remove moisture from the air. No OA is brought into the building during unoccupied hours; conditioning occurs through recirculation.

3.3.4.4.2 Hydronic VAV: System Sizing

We used the design-day method to autosize heating (boilers, central hot water coils, and reheat coils in VAV terminal boxes) and cooling (chillers, central cold water coils) capacities, and air system flow rates. The design-day data for each climate location were developed from ASHRAE (2005). From the design-day data set, we chose a heating design condition based on 99.6% annual percentiles and a cooling design condition based on 0.4% annual percentiles. The internal loads (occupancy, lights, plug and process loads, etc.) were set to zero throughout the heating design day, and to their peak values throughout the cooling design day. A global sizing factor of 1.2 was applied to all autosized heating and cooling capacities and air flow rates during initial sizing runs. The resulting baselines were evaluated for equipment operating PLRs; boiler and chiller sizing factors of 0.5 and 0.8, respectively, were subsequently applied to ensure max PLR values reached above 80% at some point during the annual baseline runs (see Section 2.4.4.1).

3.3.4.4.3 Outside Air

Ventilation rates by space type were defined according to the prescriptions of ASHRAE Standard 62.1-2004 (ASHRAE 2004b). Rates for individual space types were combined to calculate an area-weighted whole-building average, which was applied to the perimeter and core zones of the baseline models. The mappings between space type and Standard and the resulting ventilation rates, both for individual space types and for the baseline models as a whole, are presented in Table 3-22. Rates for spaces without direct mapping to the Standard were estimated. ASHRAE 62.1-2004 requires 50 cfm (24 L/s) of OA per toilet for restrooms; assuming an area of roughly 48 ft^2 (4.5 m^2) per toilet, we calculated a per area restroom ventilation requirement of 1.04 cfm/ft^2 (5.28 L/s·m^2). Mechanical rooms, stairways, and elevators (the elevator shafts, in particular) were assigned ventilation rates of zero, based on the assumption that they are unoccupied most of the time.

Table 3-22 Low-Rise and High-Rise Baseline Minimum Ventilation Rates

Space Type	Mapping to ASHRAE 62.1-2004	Ventilation per Person		Ventilation per Area	
		cfm/person	L/s·person	cfm/ft^2	L/s·m^2
Office	Office::Office Space	5	2.36	0.06	0.30
Conference	Office::Conference/Meeting	5	2.36	0.06	0.30
Break room	Food & Beverage::Restaurant Dining Rooms	7.5	3.54	0.18	0.91
Elevator	Office::Office Space	0	0.00	0.00	0.00
Restroom	Office::Office Space	0	0.00	1.04	5.28
Stairs	Office::Office Space	0	0.00	0.00	0.00
Mechanical/electrical room	CUSTOM VALUE	0	0.00	0.00	0.00

OA intake follows the same schedule as the HVAC system, which turns on an hour before the building is occupied in the morning and turns off when occupants leave in the evening. No outdoor air is brought into the building during night cycling for temperature and humidity control.

3.3.4.4.4 Economizers

In accordance with ASHRAE 90.1-2004, Section 6.5.1, an economizer is required in climate zones 2B, 3B, 3C, 4B, 4C, 5A, 5B, 6A, 6B, 7, and 8 for systems with cooling capacities larger than 135,000 Btu/h (40 kW). All systems for all climate zones for both cases fall into this category, so economizers were applied as baseline to all large office models in climate zones 3B-NV, 4C, 5A, 5B, and 7 (for this study, only the baselines in climate zone 1A were not equipped with economizers). Economizers control is based on air enthalpy.

3.3.4.4.5 Minimum Efficiency

The code-minimum efficiencies for heating and cooling equipment depend on system type and size. ASHRAE 90.1-2004 (Table 6.8.1F) requires natural gas-fired, water boilers larger than 2.5 million Btu/h (732.7 kW) to have a minimum efficiency of 80% of the combustion efficiency (100% minus flue losses). We modeled baseline boiler efficiency with a cubic curve that varies from 79% efficiency at 15% part load up to 83% efficiency at 50% part load and back down to 81% efficiency at full capacity (Figure 3-7). ASHRAE 90.1-2004 (Table 6.8.1C) requires centrifugal chiller models of this size (larger than 300 tons) to have a minimum coefficient of performance (COP) of 6.1 (ASHRAE 2004c).

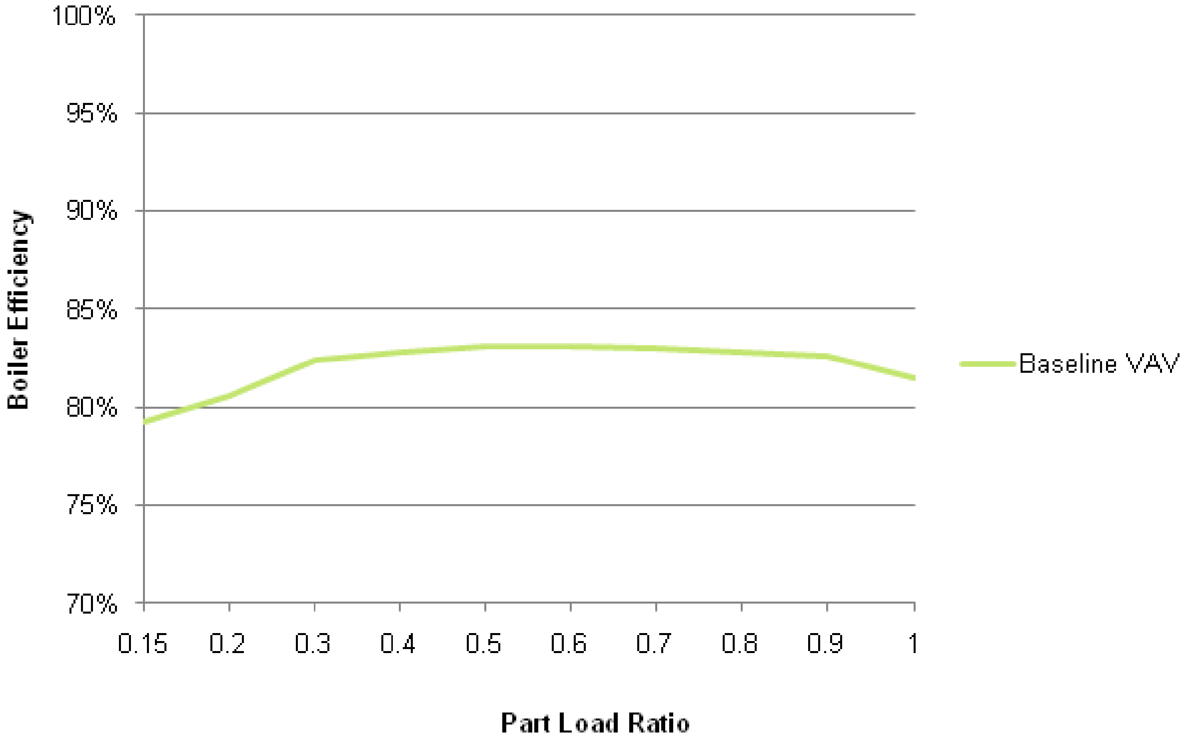

Figure 3-7 Baseline Boiler Efficiency Curve

We set boiler and chiller pump loop specifications to match those in the large office Reference Building model; the boiler and chiller pump loops each have 60 ft (18 m) of head and variable-speed pump motors with efficiencies of 87.5% and 90.0%, respectively (Deru, Field et al. 2010).

Pump part load ratio (PLR) curves are cubic to accurately account for reduced power consumption at low PLRs.

3.3.4.4.6 Variable Air Volume Fan Power Assumptions

We modeled the baseline VAV HVAC system with supply fans only. We did, however, account for the static pressure drop of the return air stream (including that for return fans and exhaust fans); basically, we combined all system fan objects into a single supply fan for each air distribution unit and thus assumed the same total efficiency for each fan type. We assumed a nominal 4 in. w.c. (1000 Pa) of static pressure drop for the supply air path and 1.75 in. w.c. (438 Pa) of static pressure drop for the return air path, for a total nominal static pressure drop of 5.75 in. w.c. (1438 Pa). For a supply air path static pressure drop of 4 in. w.c. (1000 Pa), we calculated baseline total (supply) fan efficiencies of 52.1% and 50.1% for the low-rise and high-rise cases, respectively, using the equations in Appendix G.3.1.2.9 of ASHRAE 90.1-2004. To account for the reduction of return air flow caused by 6 ACH of restroom exhaust, we calculated reduced total air path static pressure drops of 5.67 in. w.c. (1417 Pa) and 5.68 in. w.c. (1421 Pa) for the low-rise and high-rise baseline models, respectively.

Installing an economizer adds 0.1 in. w.c. (25 Pa) of static pressure drop (Liu, Jarnagin et al. 2007). We modeled static pressure reset to 0.5 in. w.c. (125 Pa) (PG&E 2007).

3.3.4.4.7 Costs and Summary

Baseline VAV HVAC cost estimates, provided by the RMH Group, were based on the average sizing results from a preliminary round of EnergyPlus simulations for the baseline models of each building type (low-rise, high-rise code-compliant, and high-rise common practice) (Table 3-23; see Table D-11 for metric units).

Table 3-23 Baseline HVAC System Cost Estimation Sizes

Climate	Low-Rise Baseline			High-Rise Baseline: Code-Compliant			High-Rise Baseline: Common Practice		
	Boilers (kBtu/h)	Chillers (tons)	Fans (cfm)	Boilers (kBtu/h)	Chillers (tons)	Fans (cfm)	Boilers (kBtu/h)	Chillers (tons)	Fans (cfm)
Average	17068	925	419536	20353	1153	453438	24888	1446	542430

The cost of the baseline hydronic VAV system was estimated at \$18.59/ft^2 (\$200.10/m^2) for the low-rise case and at \$21.52/ft^2 (\$231.63/m^2) for the high-rise case. For the equipment sizes in Table 3-23, capacity-based costs of \$9,261.49/ton of cooling (\$2,633.35/kW) and \$7,630.69/ton of cooling (\$2,169.66/kW) for the low-rise and high-rise cases, respectively, were calculated and applied to simulations to allow for cost variations based on differences in required system capacities for different climate zones. The low-rise estimate assumes the use of rooftop units (RTUs) for the air distribution system; the high-rise estimate assumes air distribution via AHUs (two units per floor), which is more practical from a ducting standpoint for a high-rise building. Table 3-24 provides an equipment breakdown and Table 3-25 (see Table D-12 for metric units) provides a detailed cost breakdown for the baseline VAV systems (RMH Group 2010a).

Table 3-24 Baseline HVAC System Cost Estimate Equipment Breakdown

HVAC Component	ASHRAE 90.1-2004 Baseline Hydronic VAV Low-Rise	ASHRAE 90.1-2004 Baseline Hydronic VAV High-Rise
Chillers and cooling tower (#)	3	3
Boilers (#)	5	5
Air distribution units (#)	8	24
VAV terminal boxes (#)	310	312
Pumps (#)	11	11

Table 3-25 Baseline HVAC System Cost Breakdown

HVAC Input	ASHRAE 90.1-2004 Baseline Hydronic VAV Low-Rise	ASHRAE 90.1-2004 Baseline Hydronic VAV High-Rise
Chillers and cooling tower ($/ft^2)	$1.40	$1.40
Boilers ($/ft^2)	$0.49	$0.66
Air distribution units ($/ft^2)	$7.59	$10.36
VAV terminal boxes ($/ft^2)	$0.84	$0.85
Pumps ($/ft^2)	$0.39	$0.39
Ductwork ($/ft^2)	$4.46	$4.77
Water distribution network ($/ft^2)	$1.88	$1.64
Life safety ($/ft^2)	$0.35	$0.17
Air and water balance ($/ft^2)	$0.20	$0.26
Temperature controls ($/ft^2)	$1.00	$1.00
Total ($/ft^2)	$18.59	$21.52

The cost of an economizer, including controls and an additional relief hood, is estimated at $100.20/ton of cooling ($28.48/kW) (RMH Group 2006). Economizers are assumed in the estimated HVAC system costs; accordingly, their cost is removed from the cost of the baseline HVAC systems in climate zone 1A (Miami, Florida), where they are not required by ASHRAE 90.1-2004 (ASHRAE 2004c). We estimated annual HVAC maintenance costs (for repair and replacement) as a fixed fraction (7.8%) of the overall system costs based on maintenance cost estimates from previous TSD work (Hale, Leach et al. 2009; Leach, Hale et al. 2009); low-rise and high-rise O&M costs are estimated at $767.23/ton of cooling ($218.15/kW·yr) and $636.40/ton ($180.95/kW·yr), respectively.

A summary of the primary HVAC performance characteristics for the low-rise and high-rise large office baseline models is presented in Table 3-26.

Table 3-26 Baseline HVAC Models Summary

HVAC Input	ASHRAE 90.1-2004 Baseline Hydronic VAV Low-Rise	ASHRAE 90.1-2004 Baseline Hydronic VAV High-Rise
Chiller COP	6.1	6.1
Boiler heating efficiency	79%–83% (see Figure 3-7)	79%–83% (see Figure 3-7)
Fan static pressure	5.67 in. w.c. (1418 Pa)	5.68 in. w.c. (1421 Pa)
Fan static pressure with economizer	5.77 in. w.c. (1443 Pa)	5.78 in. w.c. (1446 Pa)
Fan efficiency	52.1%	50.1%

3.3.4.5 Service Water Heating

The baseline SWH system for the large office buildings is a gas-fired storage water heater that meets the ASHRAE 90.1-2004 requirements; a thermal efficiency of 80% meets the requirements for units with rated input power greater than 75,000 Btu/h (22 kW) and expending less than 4000 Btu/h·gal (309.7 kW/m^3). The costs associated with the SWH system are assumed to be included in the baseline per unit area capital costs (see Section 3.3.4.4.7).

3.4 Energy Efficiency Measures

The preliminary design phase and the optimization algorithm (described in Sections 2.4.2 and 2.4.3) determined which EEMs were applied to the baseline models to create low-energy models that meet the 50% energy savings target. This section contains a topic-by-topic description of the EEMs that we considered (Table 3-27).

Table 3-27 Scope of Energy Efficiency Measures Considered

Building Form EEMs	Building Fabric EEMs	Building Equipment EEMs
• Varying building aspect ratio • Varying levels of façade glazing • Overhangs to shade the façade glazing	• Enhanced opaque envelope insulation • Glazing constructions • Reduced infiltration via an air barrier and/or vestibule	• Radiant heating and cooling with DOAS • Energy recovery equipment • Waterside and airside economizing • Reduced LPD and occupancy controls • Higher efficiency HVAC equipment • Reduced plug load densities • PV electricity generation • Daylighting controls • DCV • Natural ventilation • Higher efficiency SWH

The low-energy building models were configured by perturbing the baseline models with the EEMs described here. Any aspect of the building previously discussed but not mentioned here was fixed across all models (baseline and low-energy).

3.4.1 Program

3.4.1.1 Low-Energy Schedules

Our low-energy model schedule set was determined through a combination of industry validated assumption and schedule set data from the Medium Office TSD (Thornton, Wang et al. 2009) and the Reference Building project (Deru, Field et al. 2010), for which schedules were largely based on the recommendations of ASHRAE Standard 90.1-1989 (ASHRAE 1989).

Low-energy model weekday schedules for occupancy, DOAS operation, infiltration, and radiant system availability are presented in Figure 3-8. “Ground floor” infiltration applies to the ground floor in the low-rise low-energy case and “interior floor” infiltration applies to all other low-rise low-energy floors and to the high-rise low-energy case. The DOAS system activates one hour before the radiant system is available (such that air temperature ramp-up is facilitated by the air system as opposed to the radiant system), the radiant system is available for conditioning one hour before occupancy (to ensure the desired space conditions) and infiltration is reduced to 25% of its peak value during DOAS operation. For the ground floor, infiltration is increased during periods with above minimum occupancy to account for infiltration from doors opening (see Section 3.3.3.4 for details on infiltration and Section 3.4.4.5 for details on low-energy HVAC operation).

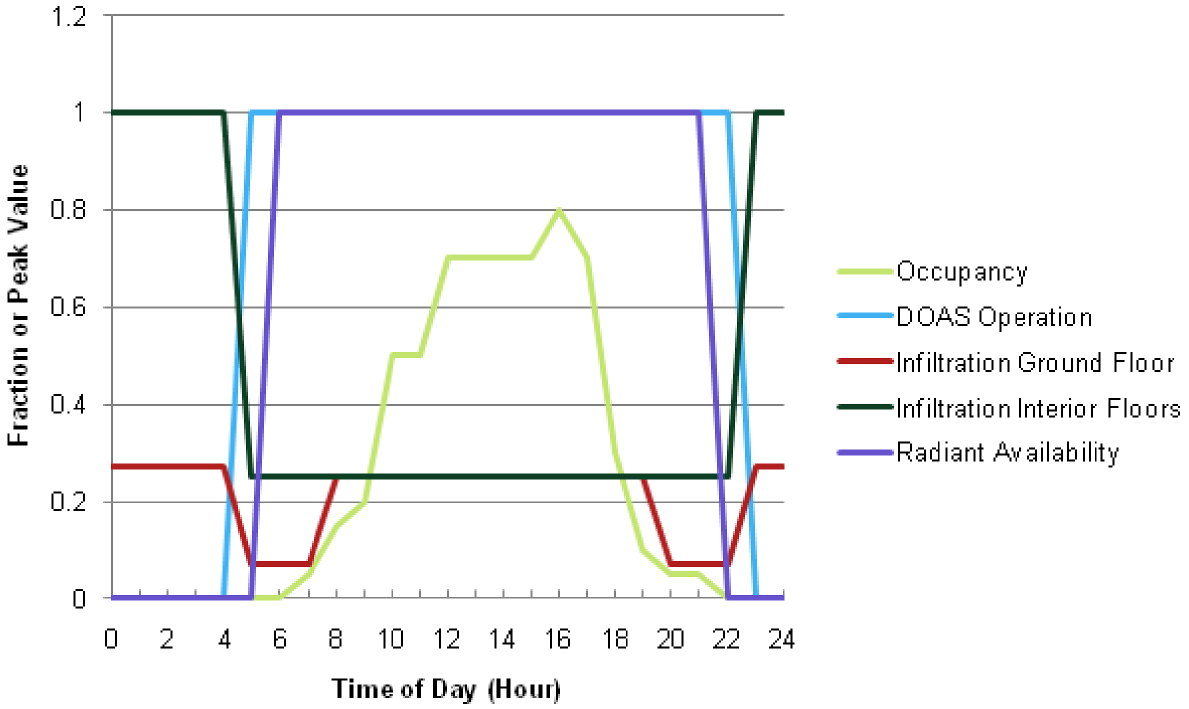

Figure 3-8 Low-energy weekday schedules: occupancy, HVAC operation, and infiltration

The low-energy weekday schedule for the DOAS heating set point, which is measured in operative temperature and includes setback during unoccupied periods, is displayed in Figure 3-9. The low-energy DOAS system does not have a cooling set point during daytime operation; when heating is not required during daytime operation, the DOAS supplies air at 55.0ºF (12.8ºC). At night when the radiant cooling system is unavailable, the DOAS has a dry bulb setup temperature of 87ºF (30.6ºC). Radiant heating and cooling set points are 70ºF (21ºC) and 75ºF (24ºC), measured in operative temperature; radiant set point temperatures apply any time the radiant system is available for operation. (See Section 3.4.4.5 for details on low-energy HVAC operation.)

For the full set of low-energy schedules, see Appendix C.

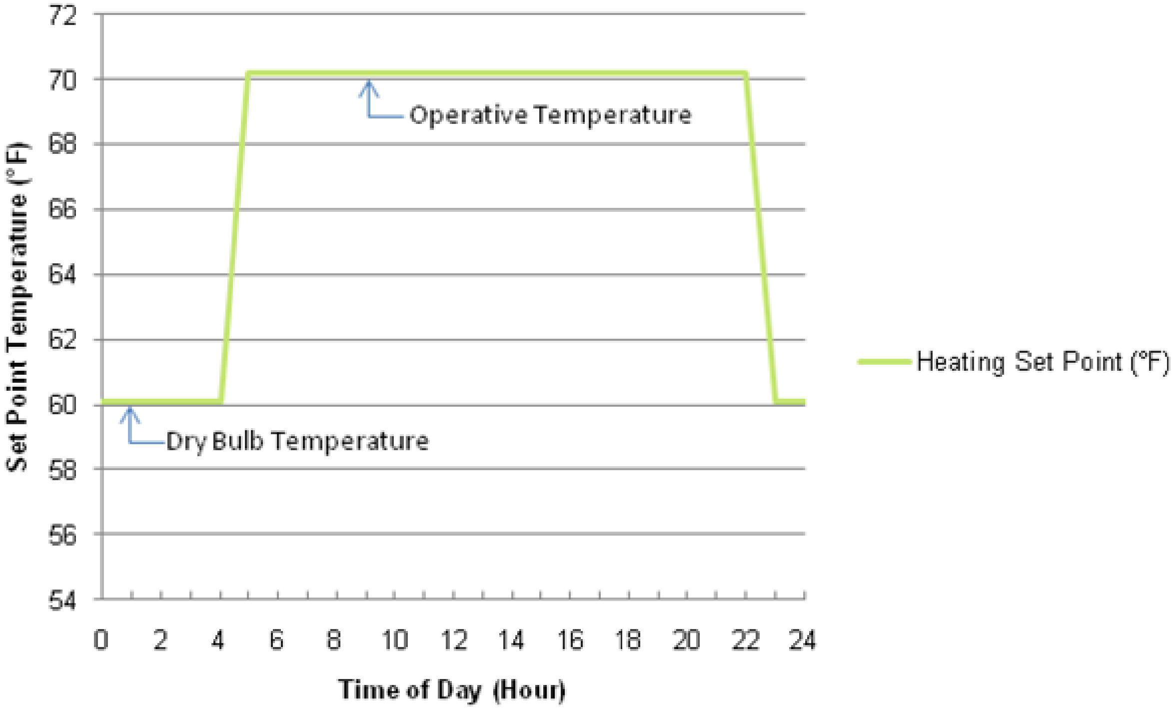

Figure 3-9 Low-energy weekday schedules: DOAS heating set point

3.4.2 Form

3.4.2.1 Fenestration

Three values for WWR were made available for selection: 20%, 30%, and 40%. The lower bound of 20% was based on industry feedback (personal communication with David Okada of Stantec) for the minimum allowable office building WWR, the 40% value represents the maximum allowed by Appendix G of ASHRAE 90.1-2004, and the 30% value represents an intermediate case. WWR was fixed in the common practice high-rise low-energy case at the baseline value of 69%. Varying WWR ratio has a number of implications for whole-building integration, including altering the levels of exterior envelope insulation, admitted solar gain, and the amount of visible light available for the facilitation of daylighting. We did not consider toplighting because of the presence of the radiant ceiling slabs (see Section 3.4.4.5).

This EEM has no inherent cost. It affects cost indirectly by substituting exterior wall constructions for glazing constructions. Its effect on overall building cost depends on the difference in cost between the relevant exterior wall and glazing constructions. The sill height (4.9 ft [1.5 m]) for this EEM was raised above that for the baseline building (3.6 ft [1.1 m]) to ensure façade fenestration (which is shorter than baseline for 20% and 30% WWRs) would be placed so occupants can view the outdoors and daylight can enter.

3.4.2.2 Exterior Shading Devices

An EEM that adds overhangs to shade glazed surfaces was made available for application to the low-rise case; we assumed installation difficulties and other practical considerations (window washing, for example) would preclude shaded overhangs in the high-rise case. For this EEM we assumed a 0.82-ft (0.25-m) offset between the top of each window and the overhang. Projection factors of 0.5, 1.0, and 1.5 were selectable. The size of each overhang was determined by using the height of the window, the offset, and the projection factor. For example, a 3-ft (0.91-m) wide, 2-ft (0.61-m) tall window with a 0.82-ft (0.25-m) offset and a projection factor of 0.5 would yield a 1.41-ft (0.43-m) deep by 3-ft (0.91-m) wide overhang. Costs are based on total overhang area and estimated at \$28.75/ft^2 (\$309.45/m^2) (Priebe 2010).

3.4.2.3 Aspect Ratio

For the low-rise case, building aspect ratio was allowed to vary between 1.5 and 15 (with selectable values of 1.5, 3, 5, 10, and 15) to explore the energy and cost trade-offs associated with reducing the depth of the cross section. Increasing aspect ratio increases the surface area to volume ratio, which increases capital costs and the effect of outdoor conditions on energy use via thermal conductance. It also increases the possible effectiveness of passive strategies such as daylighting, natural ventilation, and load shifting via thermal storage in the building's internal mass. The upper limit value corresponds roughly with the RSF design, which has an aspect ratio of approximately 13. We assume very high aspect ratio buildings would need to be designed with multiple wings to allow for a practical overall footprint. We restricted aspect ratio for the high-rise case because of typical footprint limitations for high-rise construction sites; accordingly, it was fixed at the baseline value of 1.5 for the high-rise case.

No explicit cost is associated with this EEM; the effect varying aspect ratio has on capital cost is determined by the changes in envelope and HVAC costs that result from elongating the building.

3.4.3 Fabric

3.4.3.1 Exterior Walls

This section details the EEM exterior wall constructions for the low-rise and high-rise large office models. In both cases, EEM exterior wall construction layups are the same as those for the corresponding baseline exterior wall construction; in the EEM case, increased insulation thicknesses were considered to allow for superior thermal insulation.

The precast concrete wall EEMs for the low-rise large office building are shown in Table 3-28 (see Table D-13 for metric units) along with capital costs provided by The Abo Group (Priebe 2010). The construction layup (which has a thicker interior concrete layer than exterior concrete layer) maximizes the internal thermal mass available to the low-energy radiant heating and cooling system for thermal storage to facilitate load shifting. The low-rise exterior wall EEM layers are equivalent to those for the baseline exterior wall sandwich panels and are:

- Exterior air film (calculated by EnergyPlus)
- 3-in. (7.6-cm) solid heavyweight concrete, 140 lb/ft^3 (2,240 kg/m^3)
- Rigid isocyanurate insulation (R-value varies)
- 6-in. (15.2-cm) solid heavyweight concrete, 140 lb/ft^3 (2,240 kg/m^3)
- Interior air film (calculated by EnergyPlus).

Table 3-28 Low-Rise Exterior Wall EEMs

Insulation R-Value, Nominal	Assembly U-Factor (Btu/h·ft^2·°F)	Capital Cost ($/ft^2)
R-5.7 c.i.	0.173	$44.05
R-9.5 c.i.	0.114	$44.75
R-13.3 c.i.	0.086	$45.45
R-15.0 c.i.	0.077	$45.95
R-19.5 c.i.	0.061	$46.25
R-22.5 c.i.	0.053	$46.60
R-28.5 c.i.	0.043	$46.95

The spandrel glass wall EEMs for the code-compliant high-rise large office case are shown in Table 3-29 (see Table D-14 for metric units), along with capital costs from Priebe (2010). Exterior wall construction was fixed in the common practice high-rise low-energy case at the specified baseline construction to provide an approximate wall assembly insulation level of R-3. The high-rise (code-compliant case) exterior wall EEM layers are equivalent to those for the baseline exterior wall spandrel panels and are:

- Exterior air film (calculated by EnergyPlus)
- 0.25-in. (0.64-cm) exterior spandrel glass, 113 lb/ft^3 (1,810 kg/m^3)
- Rigid isocyanurate insulation (R-value varies by climate)
- 0.5-in. (1.3-cm)-thick gypsum board, 49 lb/ft^3 (785 kg/m^3).

Table 3-29 High-Rise Exterior Wall EEMs

Insulation R-Value, Nominal	Assembly U-Factor (Btu/h·ft^2·°F)	Capital Cost ($/ft^2)
R-13.0	0.139	$35.75
R-13.0 + R-3.8 c.i.	0.091	$36.65
R-13.0 + R-7.5 c.i.	0.068	$37.15
R-22.5 c.i.	0.043	$39.85
R-28.5 c.i.	0.034	$40.75

3.4.3.2 Roofs

The insulation-above-deck roof EEMs for the low-rise large office case are shown in Table 3-30 (see Table D-15 for metric units) along with capital costs from Priebe (2010). The construction of the EEM roofs in the EnergyPlus models is identical to that of the baseline roofs, except for the amount of c.i.; the roof EEM layers are:

- A 60-mil (0.15-cm) thick, mechanically fastened ethylene propylene diene monomer single-ply membrane

- Polyisocyanurate insulation, including a tapered drainage piece finished with 7/16-in. (1.11-cm) strand board
- 0.05-in. (0.13-cm) base flashing and edging around the perimeter of the roof.

Table 3-30 Low-Rise Roof EEMs

EEM Key	U-Factor (Btu/h·ft^2·°F)	Capital Cost ($/ft^2)
R-20 c.i.	0.050	$9.59
R-30 c.i.	0.033	$10.47
R-40 c.i.	0.023	$11.36
R-60 c.i.	0.016	$13.12

We omitted high albedo roof membranes from consideration to reduce optimization simulation time and because they were not selected during optimization in past TSD work (Hale, Leach et al. 2009; Leach, Hale et al. 2009) in any climate zones.

3.4.3.3 View Glass

Table 3-31 and Table 3-32 (see Table D-16 and Table D-17 for metric units) list the window EEMs for the low-rise and high-rise (code-compliant) cases, respectively, including a short description, performance data, and cost data. The set was selected from a list of glazing systems compiled by The Abo Group to provide a good mix of available performances (Priebe 2006). Window construction was fixed in the common practice high-rise low-energy case at the specified baseline construction to provide an approximate wall assembly insulation level of R-3. Cost data were updated to 2010 dollars (Priebe 2010).

Table 3-31 Low-Rise Fenestration Construction EEMs

EEM Key	SHGC	VLT	U-Factor (Btu/h·ft^2·°F)	Capital Cost ($/ft^2)	Fixed O&M Cost ($/ft^2·yr)
Single pane with clear glass	0.810	0.881	1.08	$37.30	$0.21
Single pane with pyrolytic low-e	0.710	0.811	0.745	$41.80	$0.21
Double pane with low-e and argon	0.564	0.745	0.264	$50.70	$0.21
Double pane with low-e2 and argon	0.416	0.750	0.235	$52.70	$0.21
Triple layer with low-e polyester film	0.355	0.535	0.215	$72.80	$0.21
Quadruple layer with low-e polyester films and krypton	0.461	0.624	0.136	$93.70	$0.21

Table 3-32 High-Rise Fenestration Construction EEMs

EEM Key	SHGC	VLT	U-Factor (Btu/h·ft^2·°F)	Capital Cost ($/ft^2)	Fixed O&M Cost ($/ft^2·yr)
Single pane with clear glass	0.810	0.881	1.08	$67.65	$0.21
Single pane with tinted glass	0.567	0.431	1.08	$69.64	$0.21
Single pane with pyrolytic low-e	0.710	0.811	0.745	$70.45	$0.21
Double pane with low-e and argon	0.564	0.745	0.264	$76.05	$0.21
Double pane with reflective coating and tinted glass	0.24	0.44	0.518	$76.60	$0.21
Double pane with low-e2 and argon	0.416	0.750	0.235	$78.25	$0.21
Double pane with low-e2 and tinted glass	0.282	0.55	0.288	$78.25	$0.21

Capital costs assume punched-hole constructions for the low-rise case and glass curtain constructions for the high-rise case. Constructions for the high-rise case were limited to single- and double-pane assemblies, based on industry feedback about installation feasibility. Because there is no window shading EEM for the high-rise case, tinted and reflective constructions were considered to reduce solar gain. The high-rise fenestration construction EEMs applied only to the code-compliant case; fenestration constructions were fixed at their baselines for low-energy common practice high-rise models.

3.4.3.4 Infiltration

The infiltration reduction EEMs reduced the baseline infiltration rate by applying an envelope air barrier and entrance vestibules. The air barrier was assumed to reduce envelope infiltration from 0.244 to 0.054 ACH for the low-rise case and from 0.213 to 0.047 for the high-rise case, based on the assumption that it would result in building envelope tightness equivalent to specifications for best construction practice according to CIBSE (2000). Its cost was estimated at \$1.40/ft^2 (\$15.07/m^2) of exterior wall area (Emmerich, McDowell et al. 2005). Vestibules were assumed to reduce the front door infiltration from 0.075 to 0.037 ACH (whole building), based on the door opening model of Yuill et al. (2000). Infiltration from doors being opened was not modeled for the high-rise case, because it included only an interior floor; however, infiltration reduction EEM costs include the cost of adding vestibules, based on the assumption that these would be included in a low-energy, high-rise construction. The cost of this EEM (based on adding one vestibule to each façade) was assumed to be that of adding four sets of two, 7-ft (2.13-m) tall swinging doors with a total surface area of 168 ft^2 (15.61 m^2) and adding 120 linear feet (36.6 m) of interior walls, based on a 15-ft. (4.6-m) deep vestibule), and corresponding to an additional interior wall area of 1080 ft^2 (100.34 m^2). The cost associated with adding vestibules is thus $10,786 (Waier 2008).

3.4.4 Equipment

3.4.4.1 Daylighting Controls and Equipment

The daylighting EEM adds light sensors and dimming controls to zones with windows (perimeter zones). It does not add windows; rather, the EEM performance impact and cost depend on how many windows are installed. The perimeter zones were limited to a depth of 20 ft (6.1 m) to ensure quality sidelighting.

To model daylighting, one light sensor is placed in each zone in the center of the zone at a height of 2.95 ft (0.90 m) from the floor. The dimming controls are continuous; they start dimming when the lighting set point is exceeded, linearly decreasing until the lighting set point is met or the input power decreases to 30% of its maximum (where the light output is 20% of its maximum), whichever comes first.

Based on industry feedback, we chose a daylighting set point of 27.9 fc (300 lux). The cost of a continuous dimming daylighting system for a building larger than 100,000 ft^2 (9,290 m^2) is estimated at \$0.55/ft^2 (\$5.92/m^2) of daylit area (RMH Group 2010b).

The recommended design packages include radiant heated and cooled ceiling slabs above the occupied spaces, precluding skylights for daylighting of core spaces.

3.4.4.2 Electric Lighting

A whole-building LPD reduction EEM of 42% was considered. For the low rise case, this corresponds to a building-average LPD of 0.63 W/ft^2 (6.8 W/m^2), which is the designed LPD for the RSF and representative of best practice for low-rise large office lighting design; for the high-rise case, it corresponds to 0.61 W/ft^2 (6.6 W/m^2). This reduction can be achieved by decreasing the number of fixtures (by 27%), replacing baseline lighting equipment (32-W T8 lamps) with 25-W T8 lamps, and adding task lights to work spaces. The T8 lamps provide ambient light with an average horizontal illuminance of 25 fc (270 lux); the task lights bring the average horizontal illuminance at the workstations to higher than 40 fc (430 lux). The T8 lamps require 0.61 W/ft^2 (6.6 W/m^2) in the low-rise case; the task lights add 3–9 W per workstation. For the workstation distribution in the RSF, this corresponds to an LPD of 0.015–0.045 W/ft^2 (0.16–0.48 W/m^2). Assuming a total LPD of 0.63 W/ft^2 (6.8 W/m^2) for the low-rise case to match that of the RSF, this corresponds to 4 W per task light.

For the electric lighting EEM configuration, we assumed a fixture spacing of 80 ft^2 (7.4 m^2) of floor area per fixture (based on the interior lighting design in the RSF). The baseline lighting configuration assumed a fixture spacing of one fixture for every 58 ft^2 (5.4 m^2) of floor area.

The LPD EEM includes an additional 9.6% overall LPD reduction, based on including occupancy sensors in all space types where such equipment is not already considered baseline. Savings estimates from occupancy sensors are based on Thornton, Wang et al. (2009). Occupancy sensors are considered standard equipment for conference and break rooms; accordingly, no credit is taken for energy savings for installing occupancy sensors in those zones. See Table 3-33 and Table 3-34 (for low-rise and high-rise, respectively) for detailed breakdowns of occupancy sensor LPD reductions by space type and for the buildings as a whole (see Table D-18 and Table D-19 for metric units).

Table 3-33 Low-Rise Occupancy Sensor LPD Reductions

Space Type	Baseline LPD (W/ft^2)	Reduced LPD (W/ft^2)	LPD Reduction
Office-open	1.1	1.08	1.4%
Office-enclosed	1.1	1.04	5.7%
Conference	1.3	1.30	0.0%
Break room	0.90	0.90	0.0%
Elevator	0.00	0.00	0.0%
Restroom	0.90	0.90	0.5%
Stairs	0.60	0.60	0.0%
Mechanical/ electrical room	1.50	1.47	2.0%
Total	1.09	0.99	9.6%

Table 3-34 High-Rise Occupancy Sensor LPD Reductions

Space Type	Baseline LPD (W/ft^2)	Reduced LPD (W/ft^2)	LPD Reduction
Office-open	1.1	1.08	1.4%
Office-enclosed	1.1	1.04	5.7%
Conference	1.3	1.30	0.0%
Break room	0.90	0.90	0.0%
Elevator	0.00	0.00	0.0%
Restroom	0.90	0.90	0.5%
Stairs	0.60	0.60	0.0%
Mechanical/ electrical room	1.50	1.47	2.0%
Total	1.06	0.96	9.6%

The cost of one occupancy sensor is $150.00, including materials and labor (Greene 2008). The cost of a power pack, which powers the occupancy sensors and activates the lighting control relay, is $63.50. Two sensors and one power pack are required for every 1000 ft^2 (93 m^2) (Roth, Westphalen et al. 2005), so the approximate cost of this EEM is \$0.36/ft^2 (\$3.88/m^2).

The capital cost of the baseline lighting system for both cases was modeled as \$10.36/ft^2 (\$111.51/m^2). The cost of the baseline lighting fixture (with 32-W T8 lamps), installed, was estimated at $366 per fixture. For a spacing of one fixture for every 58 ft^2 (5.4 m^2) of floor area, this amounts to a per area cost of \$6.29/ft^2 (\$67.70/m^2). The cost of the EEM lighting fixture (with 25-W T8 lamps) was estimated at $566 per fixture. With one fixture for every 80 ft^2 (7.4 m^2) of floor area, this amounts to \$7.08/ft^2 (\$76.15/m^2). Assuming other costs associated with the lighting system scale evenly for the baseline and EEM cases, and accounting for the addition of occupancy sensors, the overall cost for the lighting configuration representative of the 42% LPD reduction EEM was calculated at \$11.51/ft^2 (\$123.90/m^2), an 11% increase over the cost for the baseline lighting system. We assumed maintenance costs for the baseline and EEM lighting systems to be equivalent when measured vis-a-vis lighting power installed.

In Opt-E-Plus, lighting costs are expressed in dollars per installed kilowatt. The LPD EEM results in fewer installed kilowatts, so the baseline and marginal costs are summed on a whole-building basis, and then divided by the actual installed kilowatts to arrive at the EEM cost. The resulting EEM LPDs and costs are shown in Table 3-35 (see Table D-20 for metric units).

The LPD EEM inputs assume an 80/20 distribution of open floor plan and enclosed office spaces.

Table 3-35 Lighting Power Density EEMs

EEM Key	LPD (W/ft^2)	Capital Cost ($/kW)	Capital Cost ($/$ft^2$)	Fixed O&M Cost ($/kW·yr)	Fixed O&M Cost ($/$ft^2$·yr)
Baseline	1.1	$9,418	$10.36	$77.24	$0.08
42% LPD reduction	0.63	$18,270	$11.51	$77.24	$0.05

3.4.4.3 Plug and Process Loads

We developed a plug load reduction EEM according to RSF design specifications and ENERGY STAR® recommendations. Plug load density reduction includes:

- Replacing a number of desktop computers with laptop computers
- Using ENERGY STAR equipment where possible
- Implementing control strategies such as occupancy sensors at workstations, on vending machines, on break room equipment, etc.

The computing component of the plug load reduction EEM consists of replacing desktop computers with laptop computers and purchasing high efficiency monitors. During operation, a typical desktop computer consumes between 100 W and 200 W. A laptop providing equivalent computing power consumes 30 W. CRT monitors, as well as older LCD monitors, are replaced with LED backlit LCD monitors. Current LCD monitor technology provides 24-in. monitors that consume as little as 18 W, compared to CRT monitors that consume as much as 70 W. We modeled occupants as using laptop computers and separate monitors.

The plug and process load EEM accounts for additional savings from the specification of ENERGY STAR equipment and other nonrated but energy-efficiency equipment. Fluorescent task lights (35 W each) are replaced with efficient LED task lights (6 W each). All-in-one print machines replace individual printers, copiers, and fax machines. Break room equipment is replaced with the most efficient equipment available. The vending machines are either de-lamped entirely, or equipped with LED display lighting controlled by motion sensors. Drinking fountains without coolers replace cooler equipped units. Conventional phones are replaced with VOIP phones. See Table 3-36 for a summary of the plug load reduction strategies.

Table 3-36 Plug Load Reduction Strategies

Plug Loads	Baseline	Low Energy
Elevators	Hydraulic design with uncontrolled fluorescent lighting	Traction design with controlled fluorescent lighting
Break room	Approximately 20 users per, non-Energy Star equipment	Approximately 30-50 users per, Energy Star equipment
Task lights	35 W fluorescent task lights	6 W LED task lights
Phones	15 W conventional phones	2 W VOIP phones
Printers and copiers	Single-function devices, occupants with personal devices, approximately 15 users per shared device	Multi-function devices, no occupants with personal devices, approximately 30-50 users per shared device
Computers	200 W desktop computers using screen savers	30 W Laptop Computers using standby mode

A third aspect of the plug and process load EEM implements control strategies to reduce plug and process loads during unoccupied hours. Cubicles are implemented with power strips that turn off equipment and eliminate parasitic losses while they are unoccupied. Computers and monitors are configured to go into standby when unused rather than sitting idle or running screen savers. Personal printers are reduced in number, or eliminated entirely, and replace by all-in-one machines. The number of occupants who use each all-in-one machine is maximized to limit the number of machines required. The number of occupants who use each all-in-one machine is maximized. The number of occupants per break room is also maximized.

For a new construction case specified with the most efficient electrical equipment and equipment operational schedules, we assumed that the described plug and process load reductions could be achieved without increasing equipment costs with respect to the baseline plug and process load configuration.

Load densities for the plug and process load EEM are shown in Table 3-37.

Table 3-37 Low-Energy Peak Plug Loads

Space Type	Low-Rise		High-Rise	
	Plug Load Density (W/ft^2)	Plug Load Density (W/m^2)	Plug Load Density (W/ft^2)	Plug Load Density (W/m^2)
Office	0.31	3.34	0.31	3.34
Conference	0.31	3.34	0.31	3.34
Break room	2.60	27.99	2.60	27.99
Elevator	0.00	0.00	0.00	0.00
Restroom	0.10	1.08	0.10	1.08
Stairs	0.00	0.00	0.00	0.00
Mechanical/electrical room	0.00	0.00	0.00	0.00
Average	0.32	3.44	0.31	3.33

3.4.4.4 Data Center

Data center energy savings are achieved by replacing standard servers with blade servers and by improving the design of the data center's HVAC system. Installing blade servers decreases the equipment load for the data center from the baseline value of 65 W per person to 48 W per person. Employing hot and cold aisle containment in the data center allows data center supply air temperatures to be increased, reducing the need for mechanical cooling. Additionally, effective cable management reduces airflow restrictions and lowers fan energy consumption. These strategies allow for an overall reduction in PUE from 1.9 for the baseline case to 1.2 for the low-energy case; see Table 3-38 for details.

Table 3-38 Low-Energy Data Center Load per Person

	Low-Rise	High-Rise
PUE	1.20	1.20
IT equipment (W/person)	48.00	48.00
HVAC and lighting equipment (W/person)	9.60	9.60

Table 3-39 (see Table D-21 for metric units) presents the overall energy usage numbers for the low-energy data center, which indicate 53.9% energy savings with respect to the baseline configuration (see Table 3-21 for comparison). Again note that data center energy usage was not explicitly modeled using EnergyPlus; it was added to the building end uses and overall energy consumption in postprocessing.

Table 3-39 Low-Energy Data Center EUIs

	Low-Rise	High-Rise
IT equipment (kBtu/ft^2·yr)	10.76	10.76
HVAC and lighting equipment (kBtu/ft^2·yr)	2.15	2.15
Total data center (kBtu/ft^2·yr)	12.91	12.91

3.4.4.5 HVAC Systems and Components

For all low-energy building models, the baseline hydronic VAV system was replaced with high thermal mass, radiantly heated and cooled concrete ceilings, and DOAS for ventilation. DOAS design was location specific based on climatic considerations.

The radiant concrete ceiling construction includes the following layers, from top to bottom:

- 3-in. (7.6-cm) heavyweight concrete slab, 140 lb/ft^3 (2240 kg/m^3)
- 5/8-in. (1.6-cm) inner diameter radiant tubing, spaced 6 in. (15.2 cm) on center
- 1-in. (2.5-cm) heavyweight concrete slab, 140 lb/ft^3 (2240 kg/m^3).

The tubing was specified to be as near to the underside of the ceiling slab as possible to reduce the system response time. See Figure 3-10 for a visual of the slab construction.

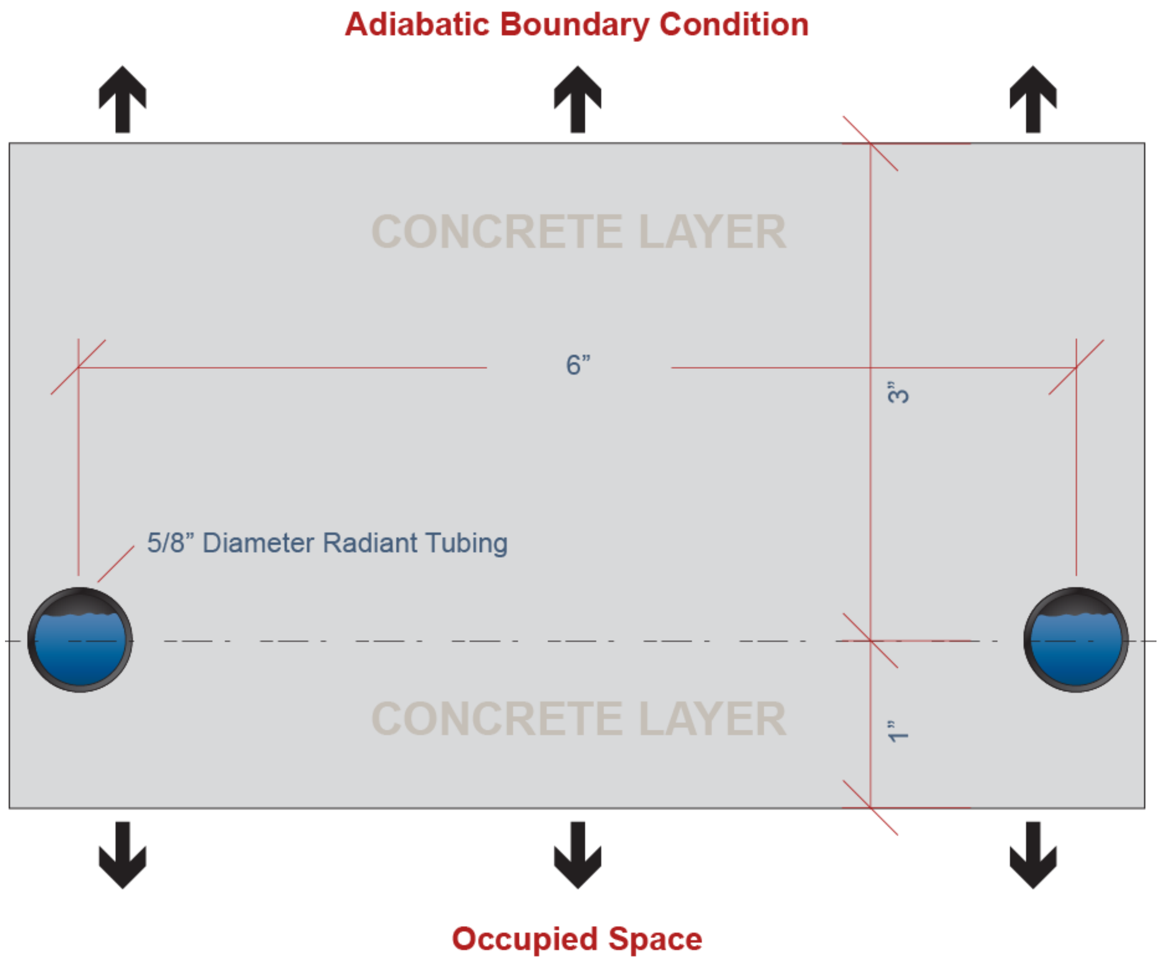

Figure 3-10 Radiant slab ceiling construction

We did not consider airside economizing because of the nature of DOAS design, but waterside economizing was included as an EEM option (see Section 3.4.4.5.7).

3.4.4.5.1 Radiant Heating and Cooling with DOAS: System Control

The ability of a radiant-based heating and cooling system to deliver energy savings depends largely on the algorithms that control it. Accordingly, we put considerable effort into implementing and testing our control logic.

First, we established temperature control dead bands appropriate for a radiant heating and cooling system. One benefit of a radiant conditioning system is that, because it can influence mean radiant temperature (MRT), it allows for a wider dry bulb dead band than does an air-conditioning system. For the low-energy system with radiantly heated and cooled ceilings, we can achieve the same comfort levels as with the baseline VAV system with a daytime dry bulb range of 68º–78ºF (20º–25.6ºC). See Table 3-40 (Table D-22 for metric units) for details. For proper control of the radiant system and to ensure the comfort levels defined in Table 3-40 are maintained, we control the radiant system based on operative temperature (the average of MRT and dry bulb temperature); we defined the heating set point at an operative temperature of 70ºF (21ºC) and the cooling set point at an operative temperature of 75ºF (24ºC).

Table 3-40 Baseline and Low-Energy HVAC System Comfort Comparison

Control Set Point	Baseline VAV System			Low Energy Radiant System with DOAS		
	Air Temperature (ºF)	MRT (ºF)	PMV	Air Temperature (ºF)	MRT (ºF)	PMV
Heating	70	70	–0.17	68	73	–0.17
Cooling	75	75	0.12	78	70	0.12

Second, we devised a radiant heating and cooling water mass flow control strategy with the goal of mitigating response time issues related to the high thermal mass of the radiant ceiling. Typically, the thermally massive concrete ceiling slab in which the radiant tubes are installed would create much slower response times for the radiant heating and cooling system than for a typical air system. As such, we devised our water mass flow control using a proactive approach to mitigate possible response time issues. Our version of a proactive radiant heating and cooling water mass flow control scheme is based on the work of Doebber (2010) and can be visualized as a "trickle and ramp" approach (Figure 3-11). The idea is to "charge" the thermally massive slab gradually as its temperature begins to trend toward the edges of the dead band, which eliminates situations in which the slab's long response time prevents it from providing space operative temperatures within the desired dead band and provides the potential to shift load outside periods of peak demand by "charging" or storing thermal energy inside the slab. It also reduces overall pumping energy via reduced pump power consumption during part-load operation.

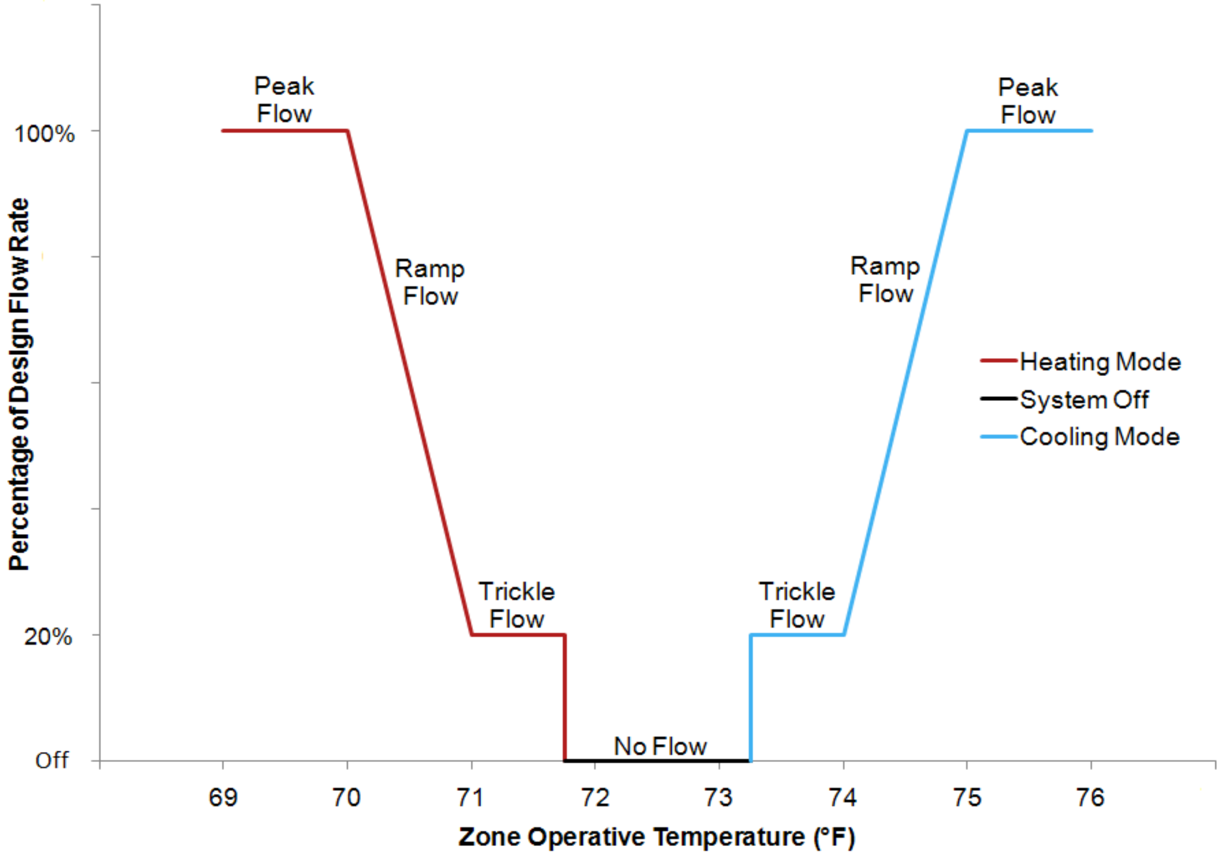

Figure 3-11 "Trickle and ramp" radiant flow control

In simulation, our radiant heating and cooling model operated most efficiently with a minimal "ramp" period and with no "trickle" period. This is likely due to shorter-than-expected response times; with only 4-in. (10.2-cm) thick slabs and radiant tubing placed only 1 in. (2.5 cm) from the ceiling surfaces, the system could quickly adjust the operative temperature. Accordingly, controlling with larger "trickle" and "ramp" periods increased energy consumption by reducing the operative temperature dead band within which the system operated. By specifying a radiant heating and cooling system with low effective thermal mass, response time can be shortened to allow for a more reactive control approach. By specifying a radiant heating and cooling system with high thermal mass (by using a thicker slab and placing the radiant tubing farther from the radiant surface, for example), response time is lengthened, allowing for more sophisticated load shifting strategies with properly designed proactive control. We would like to explore these tradeoffs more in the future (see Section 5.2). As currently specified, our radiant system begins to operate at 20% flow capacity when operative temperature comes to within 0.16ºF (0.09ºC) of the heating or cooling set point and ramps up to 100% flow capacity at the heating and cooling set points.

Third, we designed an air system to help the radiant system meet load requirements and to ensure temperature set points are met when the radiant system cannot meet them alone. The air system's primary function is to provide ventilation. The DOAS is operated as a 100% OA system that is sized to meet the ventilation requirements. The averaged ventilation approach obscures intricacies in how variations in ventilation requirements between zones would influence the interaction between the DOAS and the radiant slab (see Section 5.2). Because office buildings have high internal loads and are typically core dominated (high core to perimeter area ratio), they tend to be cooling-dominated spaces. We set up our DOAS control strategy accordingly: the DOAS supplies ventilation air at 55ºF (12.8ºC) unless core zone operative temperature drops below 70.2ºF (21.2ºC), in which case ventilation supply temperature is ramped up to reach 85ºF (29.4ºC) at a core zone operative temperature of 69.4ºF (20.8ºC) (see Figure 3-12 for a visual). DOAS heating control was designed such that the DOAS supplies 68ºF (20ºC) air at the heating set point. Additional heating is delivered by heating coils at the zone level to bring the ventilation air up to the desired supply temperature. Heating coils are installed only in the perimeter zones. We assume the additional (booster) heat is unnecessary in the core zone. If the core zone needs its ventilation air heated to help the radiant system meet the heating load, the DOAS supply temperature control algorithm (as previously stated) was designed to comply. None of the zones have secondary zone-level cooling equipment; accordingly, although the DOAS meets a significant portion of the cooling load, the burden is placed on the radiant cooling system to perform all load trimming in cooling.

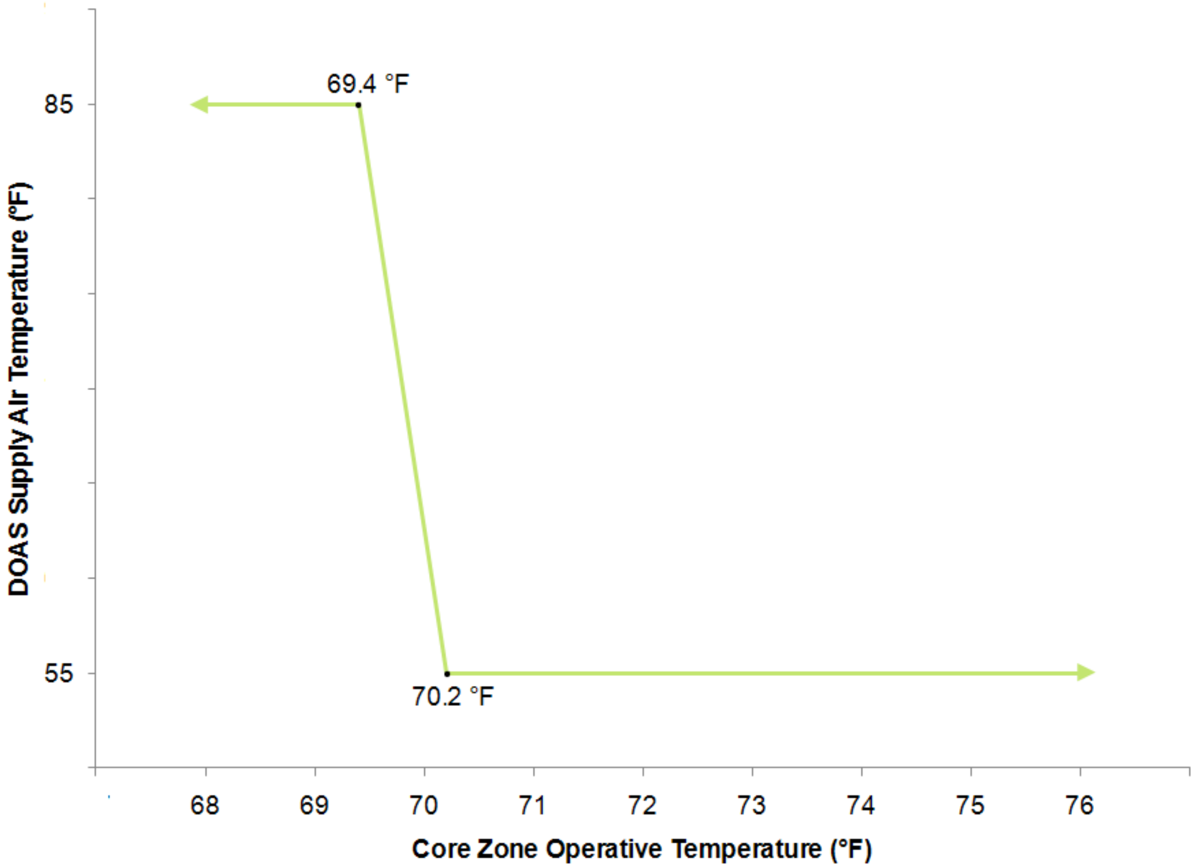

Figure 3-12 DOAS supply air temperature control

The assumption of core dominance is based on the baseline low-rise and high-rise building configurations, which have aspect ratios of 1.5. As aspect ratios are increased (up to 15), this assumption becomes less and less valid.

We also implemented nighttime humidity control. The control scheme is identical to that for the baseline VAV system, except that the heating set point during dehumidification is lowered from 70ºF (21ºC) to 68ºF (20ºC) to reflect the differences in daytime operational dry bulb dead bands between the baseline and low-energy HVAC systems.

3.4.4.5.2 Radiant Heating and Cooling with DOAS: System Sizing

After establishing the requirements of the radiant heating and cooling system, the next step was to ensure such a system could reasonably be designed and implemented. Considerations for this process included both system capacity and occupant comfort. The first step was to determine the boiler and chiller output temperatures that would be required to maintain the desired comfort level (PMV) at the heating and cooling set points. At a dry bulb temperature of 68ºF (20ºC), the radiant heating system is required to provide an MRT of 73ºF (22.8ºC) to maintain a comfort level (PMV of –0.17) equivalent to that for the baseline VAV system at its heating set point. At a dry bulb temperature of 78ºF (25.6ºC), the radiant cooling system is required to provide an MRT of 70.2ºF (21.2ºC) to maintain a comfort level (PMV of 0.12) equivalent to that for the baseline VAV system at its cooling set point.

A single-zone EnergyPlus model was used to solve for the ceiling surface temperatures and radiant tube temperatures required to produce these MRTs at the specified dry bulb conditions (see Table 3-41; Table D-23 for metric units). By fixing the dry bulb temperature in the zone and the surface temperature on the topside of the 1-in. (2.5-cm) thick concrete slab layer between the radiant tubing and the zone and by specifying an adiabatic boundary condition on the other external surfaces to the zone, we were able to calculate the resulting temperature on the underside of the 1-in. (2.5-cm) thick concrete layer (the radiant surface temperature) and the MRT within the zone (see Figure 3-10 for a visualization of the surface layup). This was an iterative process in which the specified topside concrete temperature was adjusted until the desired MRT was reached. For this analysis, the conductivity of the ceiling slab was adjusted such that the uniform temperature boundary condition imposed on the topside of the 1-in. (2.5-cm) thick concrete layer was representative of the radiant tube surface temperature (conductivity was reduced to account for temperature gradients through the concrete).

Radiant tube surface temperature was used to calculate supply water temperatures (hot water supply temperature for heating, cold water supply temperature for cooling) using the following assumptions:

- Supply water temperature is roughly equivalent to the surface temperature of the radiant tubing.
- Temperature differences across the radiant loop are 10ºF (5.6ºC) for heating and 7ºF (3.9ºC) for cooling (Olesen 2008).
- Supply water temperature is specified to meet an average radiant tube surface temperature throughout the loop.

Table 3-41 Radiant System Temperatures Required for Baseline Equivalent Comfort

Control Set Point	Air Temperature (ºF)	Mean Radiant Temperature (ºF)	Supply Water Temperature (ºF)	Radiant Tube Temperature (ºF)	Radiant Surface Temperature (ºF)
Heating	68	73	84	79	77
Cooling	78	70.2	57.3	60.8	65

For a radiant ceiling, maximum and minimum allowable surface temperatures for comfort are estimated at 80.6ºF (27ºC) and 62.6ºF (17ºC) (Olesen 2008). The radiant surface temperatures fall within this range; accordingly, it is feasible to design a radiant heated and cooled ceiling to meet the comfort requirements we specified.

To maximize cooling capacity (and thus minimize pumping energy), a radiant system can be designed to the limits of the allowable comfort range; we chose to so model our radiant system to ascertain its maximum effectiveness, and to maximize the range of loading requirements for which it can satisfy the desired comfort range. The single-zone EnergyPlus model was used to characterize the system operation. See Table 3-42 (Table D-24 for metric units) for details.

Table 3-42 Radiant System Temperatures Required for Maximum Capacity

Control Set Point	Air Temperature (ºF)	Mean Radiant Temperature (ºF)	Supply Water Temperature (ºF)	Radiant Tube Temperature (ºF)	Radiant Surface Temperature (ºF)
Heating	68	75.5	88.8	83.8	80.6
Cooling	78	68.8	54.1	57.6	62.6

The total average heat exchange coefficients for a radiant ceiling are 1.0 Btu/h·ft^2·F (6 W/m^2·K) in heating and 1.9 Btu/h·ft^2·F (11 W/m^2·K) in cooling (Olesen 2008). For the temperature differences between zone air and radiant surface for maximum radiant system conditioning capacity at the heating and cooling set points, we calculated heating and cooling capacities of 13.3 Btu/h·ft^2 (42 W/m^2) and 29.8 Btu/h·ft^2 (94 W/m^2), respectively. For 6 in. (0.15 m) on center radiant tube spacing and loop temperature drops of 10ºF (5.6ºC) for heating and 7ºF (3.9ºC) for cooling, we calculated peak per floor water volumetric flow rates for heating and cooling for the low-rise and high-rise large office layouts (Table 3-43 [Table D-25 for metric units]). Larger values for the low-rise case reflect the larger floor area (by a factor of three).

Table 3-43 Radiant System Peak Volumetric Flow Rates per Floor

Low-Rise Building		High-Rise Building	
Maximum Heating Flow (cfm)	Maximum Cooling Flow (cfm)	Maximum Heating Flow (cfm)	Maximum Cooling Flow (cfm)
40.9	130.9	13.6	43.6

3.4.4.5.3 Climate-Specific DOAS Configurations

To reach the aggressive 50% savings goal, we tailored HVAC equipment to each climate type separately. The radiant system design is climate independent; only DOAS was configured based on climate. For cold and marine climates (4C and 7) where latent loads are generally low, DOAS should be outfitted with sensible heat recovery equipment (sensible wheels). For humid climates (1A and 5A), latent loads are an important consideration; accordingly, both sensible and latent heat recovery equipment (enthalpy wheels) are beneficial. For dry climates (3B-NV and 5B), DOAS with IDEC that can be adapted to a low-efficiency sensible heat exchanger during the winter is an efficient way to condition OA.

Because of the condensation concerns associated with radiantly cooled surfaces, direct evaporative cooling was not considered, even in dry climates. In all climates, humidity is monitored and radiant cooling is temporarily halted when condensation on the radiant surface would otherwise occur.

3.4.4.5.4 Cooling Efficiency

A cooling efficiency EEM increases the chiller COP from 6.1 to 7.0 and replaces the baseline two-speed cooling tower fan with a variable-speed model. We estimated the cost of this EEM as a 10% increase in chiller cost, and assumed its cost is factored into the overall low-energy HVAC system costs (see Section 3.4.4.5.8) (RMH Group 2010a).

3.4.4.5.5 Boiler Efficiency

A boiler EEM replaces the baseline boiler with a high-efficiency condensing boiler. Condensing boiler efficiency depends on water supply temperature: a high efficiency boiler providing heat to a DOAS, for which boiler outlet temperature is near 167 ºF (75 ºC), has an efficiency range between 88% and 97%; a high efficiency boiler providing heat for radiant heating, for which boiler outlet temperature is near 104 ºF (40 ºC), has an efficiency range between 92% and 98%. See Figure 3-13 for a graphical comparison between the baseline and EEM boiler efficiency curves. We estimated the cost of this EEM as a 20% increase in boiler cost, and assumed its cost is factored into the overall low-energy HVAC system costs (see Section 3.4.4.5.8) (RMH Group 2010a).

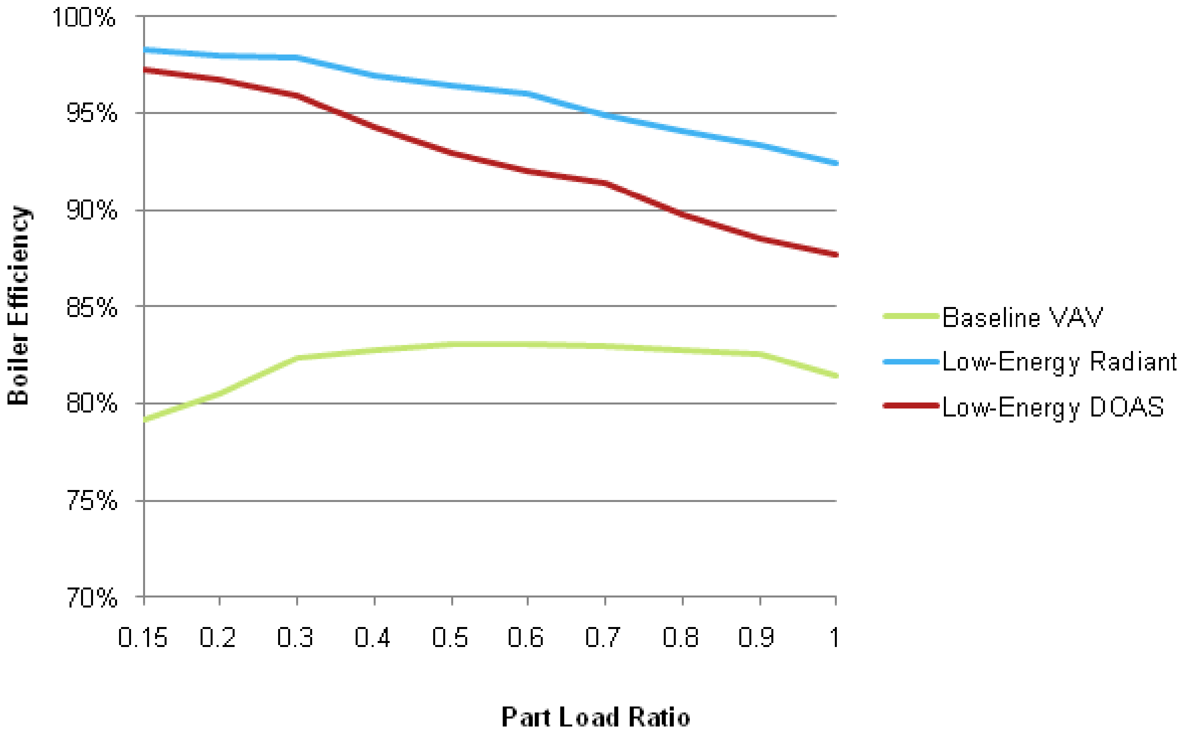

Figure 3-13 Boiler efficiency curves for the baseline and low-energy boilers

3.4.4.5.6 Higher Efficiency Fans

Baseline fan efficiency for the RTUs and AHUs in the baseline VAV systems was set to 52.1% and 50.1% for the low-rise and high-rise cases, respectively, as per the requirements of Appendix G.3.1.2.9 of ASHRAE 90.1-2004 (ASHRAE 2004c). We set our EEM fan efficiency to 75% (total fan efficiency of 69%, including motor efficiency), corresponding to a housed, centrifugal airfoil configuration.

For the DOAS, we assumed a nominal 3.5 in. w.c. (875 Pa) of static pressure drop for the supply air path and 1.5 in. w.c. (375 Pa) of static pressure drop for the return air path (which is required with the inclusion of energy recovery equipment), for a total nominal static pressure drop of 5.0 in. w.c. (1250 Pa). We reduced nominal static pressure based on DOAS configuration (to account for flow required for building pressurization and/or 6 ACH of restroom exhaust) to obtain effective operating static pressure drops; see Section 3.4.4.6.2 for details. We modeled static pressure reset to 0.5 in. w.c. (125 Pa) (PG&E 2007).

We estimated the cost of this EEM as a 10% increase in the cost of the air distribution units (RTUs or AHUs), and assumed its cost is factored into the overall low-energy HVAC system costs (see Section 3.4.4.5.8) (Priebe 2010).

3.4.4.5.7 Economizers

An EEM for waterside economizing was made available. Costs to install and operate economizers were assumed to be included as part of the low-energy HVAC system costs.

Airside economizing was applied to the baseline HVAC system where required by ASHRAE 90.1-2004, but was not considered as an EEM because it is incompatible with DOAS. DOAS reduces the size of the air system to what is required for ventilation; oversizing it to allow for airside economizing defeats that purpose.

3.4.4.5.8 Radiant Heating and Cooling with DOAS: Summary and Costs

HVAC cost estimates for the low-rise and high-rise radiant heating and cooling with DOAS system were provided by the RMH Group based on the average sizing results from a preliminary set of low-energy model simulations (Table 3-44 and Table 3-45; Table D-26 and Table D-27 for metric units); the equipment breakdowns upon which their estimates were based are presented in Table 3-46 (RMH Group 2010a). In all low-energy models, radiant boiler and chiller capacities were hard-sized as needed to achieve the maximum heating and cooling capacities defined by Table 3-42 and Table 3-43 (Table D-24 and Table D-25 for metric units).

Table 3-44 Low-Rise Low-Energy Radiant With DOAS HVAC System Cost Estimation Sizes

Climate	Low-Rise Low-Energy				
	DOAS Boiler (kBtu/h)	DOAS Chiller (tons)	DOAS Fan (cfm)	Radiant Boiler (kBtu/h)	Radiant Chiller (tons)
Average	3839	177	56574	4623	867

Table 3-45 High-Rise Low-Energy Radiant with DOAS HVAC System Cost Estimation Sizes

Climate	High-Rise Low-Energy: Code Compliant					High-Rise Low Energy: Common Practice				
	DOAS Boiler (kBtu/h)	DOAS Chiller (tons)	DOAS Fan (cfm)	Radiant Boiler (kBtu/h)	Radiant Chiller (tons)	DOAS Boiler (kBtu/h)	DOAS Chiller (tons)	DOAS Fan (cfm)	Radiant Boiler (kBtu/h)	Radiant Chiller (tons)
Average	7438	175	55091	6149	1145	7438	175	55091	6149	1145

Table 3-46 Low-Energy HVAC System Cost Estimate Equipment Breakdown

HVAC Component	Radiant Heating and Cooling With DOAS, Low-Rise	Radiant Heating and Cooling With DOAS, High-Rise
Chillers and cooling tower (#)	3	3
Boilers (#)	5	5
Air distribution units (#)	2	4
Perimeter heating coils (#)	64	120
Pumps (#)	11	11

The cost of the low-energy HVAC system was estimated at \$22.07/ft^2 (\$237.56/m^2) for the low-rise case and at \$22.51/ft^2 (\$242.30/m^2) for the high-rise case (see Table 3-47; Table D-28 for metric units). For the equipment sizes in Table 3-44 and Table 3-45, capacity-based costs of \$9,741.25/ton of cooling (\$2,769.76/kW) and \$7,858.77/ton of cooling (\$2,234.51/kW) for the low-rise and high-rise cases, respectively, were calculated and applied to simulations to allow for cost variation based on differences in required system capacities for different climate zones. The low-rise estimate assumes the use of RTUs for the air distribution system; the high-rise estimate assumes air distribution via AHUs (one unit per every three floors), which is more practical from a ducting standpoint for a high-rise building.

Table 3-47 Low-Energy HVAC System Cost Estimate Breakdown

HVAC Input	Radiant Heating and Cooling With DOAS, Low-Rise	Radiant Heating and Cooling With DOAS, High-Rise
Chillers and cooling tower (\$/ft^2)	\$1.52	\$1.52
Boilers (\$/ft^2)	\$0.60	\$0.60
Radiant heating and cooling (\$/ft^2)	\$10.89	\$10.81
Air distribution units (\$/ft^2)	\$1.00	\$1.09
Perimeter heating coils (\$/ft^2)	\$0.11	\$0.21
Pumps (\$/ft^2)	\$0.39	\$0.39
Ductwork (\$/ft^2)	\$3.69	\$4.61
Air system water distribution (\$/ft^2)	\$2.61	\$2.03
Life Safety (\$/ft^2)	\$0.09	\$0.09
Air and water balance (\$/ft^2)	\$0.18	\$0.18
Temperature controls (\$/ft^2)	\$1.00	\$1.00
Total (\$/ft^2)	\$22.07	\$22.51

3.4.4.6 Outside Air

We considered three options beyond code minimum for reducing OA loads: carbon dioxide (CO_2) DCV, energy recovery from exhaust air, and natural ventilation.

3.4.4.6.1 Demand Control Ventilation

DCV was not made available as an EEM because it provides only minimal energy savings in an office building, which has a low per-person ventilation requirement (5 cfm/person [2.36 L/s·person]) that amounts to roughly 0.04 cfm/ft^2 (0.20 L/s·m^2). Extensive changes would need to be made to implement the DOAS (replacing a constant volume ventilation system with a VAV system, installing CO_2 sensors, etc.) It would be cost prohibitive based on the high implementation costs.

3.4.4.6.2 Energy Recovery

Where appropriate by climate, energy recovery equipment is incorporated into DOAS design such that exhaust air can be used to precondition ventilation air. Humid climates can be equipped with sensible and latent energy recovery equipment (enthalpy wheels). Cold and marine climates can be equipped with sensible energy recovery equipment (sensible wheels). Dry climates can be equipped with an IDEC that can be converted to a low-efficiency sensible heat exchanger during winter months. Costs for energy recovery were assumed to be included as part of the cost of the high-efficiency DOAS in the low-energy HVAC system cost breakdown.

An enthalpy wheel with nominal sensible effectiveness of 60% and latent effectiveness of 50% was available as an EEM in climate zones 1A (Miami) and 5A (Chicago). We assumed the pressure drop through one side of the enthalpy wheel at 0.7 in. w.c. (175 Pa) (Murphy and Bradley 2008). Because air passes through the wheel twice (once when it enters the building as unconditioned OA and once when it leaves the building as conditioned return air), an overall pressure drop of 1.4 in. w.c. (350 Pa) was applied to the implementation of an enthalpy wheel.

A sensible recovery wheel with nominal sensible effectiveness of 60% was available as an EEM in climate zones 4C (Seattle) and 7 (Duluth). Sensible heat recovery wheels (which have a latent effectiveness of zero) have lower pressure drops than enthalpy wheels because they do not have to transfer moisture. We modeled our sensible wheel as having a total added pressure drop of 1 in. w.c. (250 Pa), assuming 0.5 in. w.c. (125 Pa) pressure drop through each side (Murphy and Bradley 2008).

For dry climates (3B-NV [Las Vegas] and 5B [Boulder]), a hybrid IDEC/sensible heat recovery system was available as an EEM. We assumed the evaporative media could theoretically be dried during the winter so the IDEC unit could serve as a low effectiveness sensible heat exchanger. We modeled our IDEC unit with a maximum nominal wet bulb effectiveness of 75% and a high-efficiency (69% total efficiency) secondary (return) air stream fan that adds a total of 1.0 in. w.c. (250 Pa) of pressure drop (0.5 in. w.c. [125 Pa] to the primary air stream and 0.5 in. w.c. [125 Pa] to the secondary air stream). During the winter, when the unit converts to a sensible heat exchanger, we assumed a nominal sensible effectiveness of 40%; this estimate was based on the unit operating as a low-effectiveness version of a fixed-plate heat exchanger, for which a typical effectiveness is 60%–70% (Murphy and Bradley 2008).

Nominal efficiencies needed to be decreased to account for flow reduction of the return air stream caused by building pressurization and/or restroom exhaust. We assumed 10% of the OA is required to pressurize the building (and reduce infiltration by 75%) during HVAC operation, and that the remaining 90% is available for energy recovery. For enthalpy and sensible wheels, leakage can occur between the entering and leaving air streams such that contamination concerns prevent restroom exhaust from being used for energy recovery; accordingly, we reduced the return air stream flow available for energy recovery by 6 ACH of restroom exhaust for DOAS equipped with enthalpy or sensible wheels. For IDEC, the primary and secondary air streams are isolated from each other such that restroom exhaust can be used for energy recovery. For the resulting return air to supply air flow ratios of 0.71 for DOAS with energy recovery wheels and 0.9 for DOAS with IDEC, we calculated the following operational efficiencies: for enthalpy wheels, 51% sensible effectiveness, 42% latent effectiveness; for sensible wheels, 51% sensible effectiveness; and for IDEC, 72% maximum wet bulb effectiveness. We also used the return air to supply air flow ratios to reduce fan static pressure drop (as mentioned in Section 3.4.4.5.6); see Table 3-48 (Table D-29 for metric units) for details.

Table 3-48 Low-Energy HVAC System Operational Static Pressure Breakdown

Building Type	Low-Rise Low-Energy (in. w.c.)			High-Rise Low-Energy: Code Compliant (in. w.c.)			High-Rise Low Energy: Common Practice (in. w.c.)		
	Enthalpy Wheel	Sensible Wheel	IDEC	Enthalpy Wheel	Sensible Wheel	IDEC	Enthalpy Wheel	Sensible Wheel	IDEC
Supply and return fans	4.58	4.58	4.85	4.57	4.57	4.85	4.57	4.57	4.85
Energy recovery	1.40	1.00	1.00	1.40	1.00	1.00	1.40	1.00	1.00
Total	5.98	5.58	5.85	5.97	5.57	5.84	5.97	5.57	5.84

3.4.4.6.3 Natural Ventilation

Natural ventilation was not available as an EEM because accurately capturing its effects through simulation is difficult. Achieving energy savings by implementing natural ventilation (in an actual building or a simulation model) requires accurate inputs and sophisticated control. Preliminary modeling indicates more efforts are necessary to validate this EEM.

3.4.4.7 Service Water Heating

An SWH EEM increases thermal efficiency from 80% to 90%. We assigned no incremental cost specifically to this EEM, because we assumed SWH costs are included in our whole-building area-normalized capital costs.

3.4.4.8 Photovoltaic Panels

We ignore any electricity tariff changes associated with varying amounts of PV, as 5-TLCC and the amount of electricity generated by the PV panels vary linearly with panel area. We thus include a single PV EEM, then use a postprocessing step to determine the PV panel area needed to reach 50% energy savings (for cases where PV is selected and required to achieve the goal).

We assumed the following in all cases:

- The panels are 13% efficient.
- The direct current to alternating current inverters are 96% efficient.
- The panels are installed flat on the roof.
- The PV efficiency does not degrade with increasing temperature.
- The panels do not shade the roof.
- The cost is $4.00 per installed Watt for panels of this efficiency based on data collected through an internal PV study.

The EEM used by Opt-E-Plus covers up to 60% of the roof area with PV panels and is sized assuming 1000 W/m^2 incident solar radiation.

4.0 Results

This section presents the results of the energy modeling performed for this report. Section 4.1 includes the baseline model economic and energy use results, both for the ASHRAE 90.1-2004 (ASHRAE 2004c) compliant baselines that serve as the standard for our percent energy savings calculations and ASHRAE 90.1-2007 (ASHRAE 2007b) compliant baselines that are provided for reference. Section 4.2 describes the selected low-energy model results (both the preliminary low-energy models and the selected low-energy models from the subsequent optimizations) for each climate zone and compares them to the baseline results. The EEMs selected for the low-energy models in each climate zone are also listed.

In this section, the following metrics are used to report performance:

- **Net site EUI** (MJ/m^2·yr or kBtu/ft^2·yr). The whole-building net site yearly energy use (Section 2.2.1.1) divided by the building floor area.
- **Net source EUI** (MJ/m^2·yr or kBtu/ft^2·yr). The whole-building net source yearly energy use (Section 2.2.1.1) divided by the building floor area.
- **Energy cost intensity** (\$/m^2·yr or \$/ft^2·yr). The cost of the yearly electrical and natural gas consumption divided by the building floor area.
- **Energy emissions intensity** (kgCO$_2$/ m^2·yr or lbCO$_2$/ ft^2·yr). The yearly quantity of CO$_2$ emissions generated by the building divided by the building floor area.
- **5-TLCC intensity** (\$/m^2 or \$/ft^2). The 5-TLCC divided by the building floor area. It represents the total cost of the building for a five-year analysis period (see Section 3.1.2.6).
- **Electricity intensity** (kWh/m^2·yr or kWh/ft^2·yr). The yearly electrical consumption divided by the building floor area.
- **Natural gas intensity** (kWh/m^2·yr or therms/ft^2·yr). The yearly natural gas consumption divided by the building floor area.
- **Capital cost intensity** (\$/m^2 or \$/ft^2). The total cost for materials, installation, fees, and commissioning divided by the building floor area.
- **Peak monthly electricity demand** (kW). The maximum 15-minute net electrical demand, taking credit for electricity produced by PV, computed for each month of the annual simulation.

4.1 Baseline Models

This section summarizes the energy and economic performance of the baseline models described in Section 3.3.

4.1.1 ASHRAE 90.1-2004 Baseline Models: Performance

The energy and cost intensities of the ASHRAE 90.1-2004 baseline models are displayed in Figure 4-1 and Figure 4-2 for the low-rise and high-rise cases, respectively and summarized in Table 4-1 and Table 4–2 (Table D-30 and Table D-31 for metric units) for the low-rise case, in Table 4-3 and Table 4-4 (Table D-32 and Table D-33 for metric units) for the code-compliant high-rise case, and in Table 4-5 and Table 4-6 (Table D-34 and Table D-35 for metric units) for the common practice high-rise case.

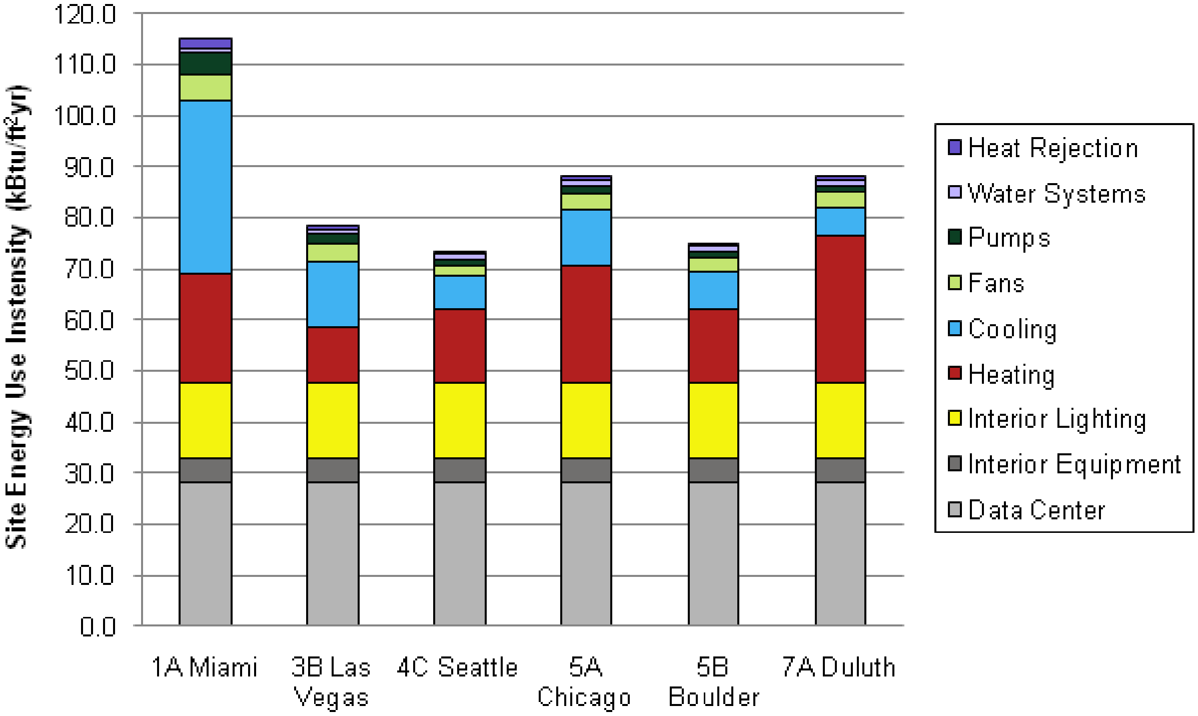

Figure 4-1 Low-rise EUI by end use for baseline energy models

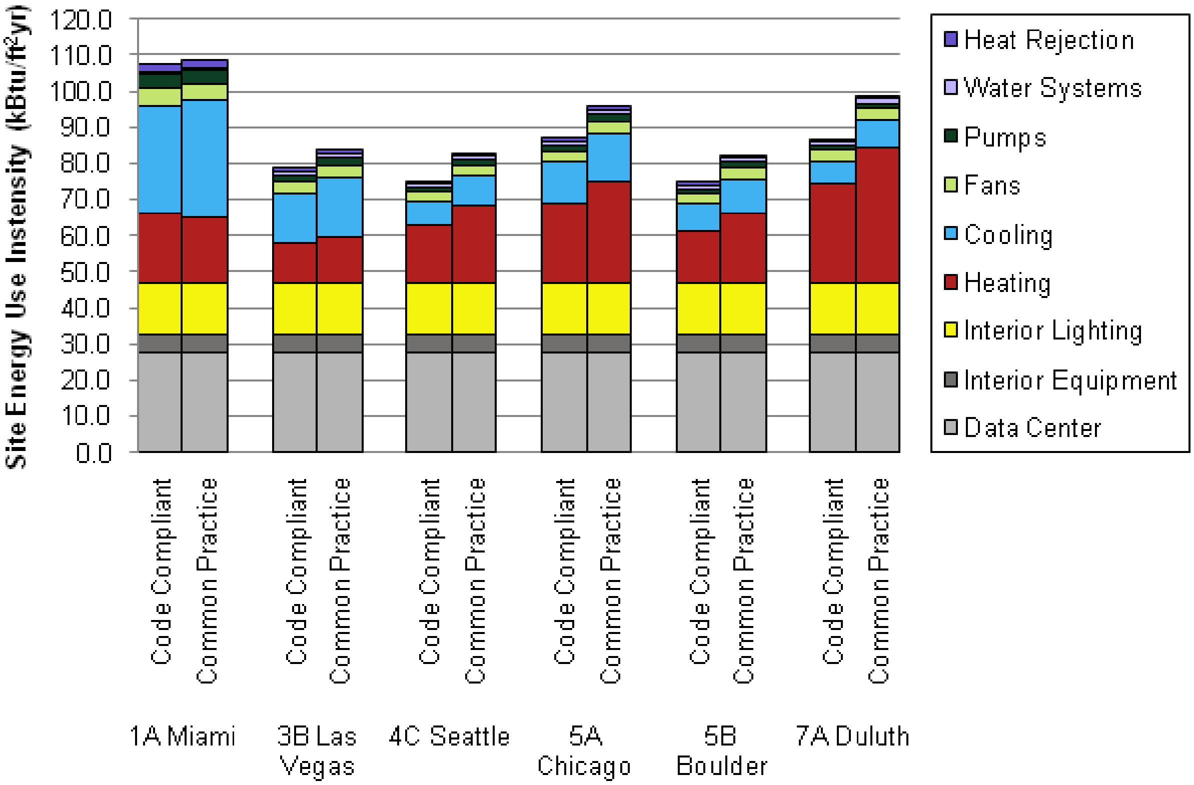

Figure 4-2 High-rise EUI by end use for baseline energy models

Table 4-1 ASHRAE 90.1-2004 Low-Rise Baseline Model Energy Performance

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Site EUI (kBtu/ft^2·yr)	115.2	78.5	73.4	88.2	74.9	88.0
Source EUI (kBtu/ft^2·yr)	337.4	238.1	211.8	242.3	216.9	227.6
Energy emissions intensity (lbCO$_2$/ ft^2·yr)	45.6	32.3	28.6	32.5	29.3	30.3
Electricity intensity (kWh/ft^2·yr)	27.3	19.6	17.0	18.8	17.4	16.9
Natural gas intensity (therms/ft^2·yr)	0.221	0.115	0.154	0.239	0.155	0.301
Peak demand (kW)	1984	1750	1721	1908	1690	1818

Table 4-2 ASHRAE 90.1-2004 Low-Rise Baseline Model Costs

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
5-TLCC intensity ($\$/ft^2$)	$139.07	$128.90	$126.46	$134.81	$124.75	$130.66
Capital cost intensity ($\$/ft^2$)	$119.51	$114.68	$113.43	$118.93	$111.99	$116.07
Annual energy cost intensity ($\$/ft^2\cdot yr$)	$2.60	$1.84	$1.67	$1.93	$1.70	$1.83
Annual electricity cost intensity ($\$/ft^2\cdot yr$)	$2.32	$1.70	$1.48	$1.64	$1.51	$1.47
Annual natural gas cost intensity ($\$/ft^2\cdot yr$)	$0.27	$0.14	$0.19	$0.30	$0.19	$0.37

Table 4-3 ASHRAE 90.1-2004 Code-Compliant High-Rise Baseline Model Energy Performance

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Site EUI ($kBtu/ft^2\cdot yr$)	107.3	78.8	74.9	86.9	74.7	86.6
Source EUI ($kBtu/ft^2\cdot yr$)	315.7	238.2	213.3	239.3	216.6	225.2
Energy emissions intensity ($lbCO_2/ft^2\cdot yr$)	42.7	32.3	28.7	32.1	29.2	30.0
Electricity intensity ($kWh/ft^2\cdot yr$)	25.6	19.6	16.9	18.6	17.4	16.8
Natural gas intensity ($therms/ft^2\cdot yr$)	0.200	0.118	0.170	0.233	0.153	0.291
Peak demand (kW)	1940	1758	1746	1925	1717	1872

Table 4-4 ASHRAE 90.1-2004 Code-Compliant High-Rise Baseline Model Costs

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
5-TLCC intensity ($\$/ft^2$)	$144.56	$137.40	$135.54	$142.35	$134.29	$139.48
Capital cost intensity ($\$/ft^2$)	$127.17	$123.91	$122.99	$127.49	$122.01	$125.58
Annual energy cost intensity ($\$/ft^2\cdot yr$)	$2.44	$1.85	$1.69	$1.91	$1.71	$1.82
Annual electricity cost intensity ($\$/ft^2\cdot yr$)	$2.19	$1.70	$1.48	$1.63	$1.52	$1.46
Annual natural gas cost intensity ($\$/ft^2\cdot yr$)	$0.25	$0.15	$0.21	$0.29	$0.19	$0.36

Table 4-5 ASHRAE 90.1-2004 Common Practice High-Rise Baseline Model Energy Performance

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Site EUI (kBtu/ft^2·yr)	108.7	83.8	82.8	95.8	82.3	98.5
Source EUI (kBtu/ft^2·yr)	322.2	250.7	226.8	255.0	230.6	242.9
Energy emissions intensity (kgCO$_2$/ft^2·yr)	43.6	34.0	30.4	34.1	31.0	32.2
Electricity intensity (kWh/ft^2·yr)	26.2	20.5	17.6	19.4	18.1	17.4
Natural gas intensity (therms/ft^2·yr)	0.191	0.138	0.227	0.296	0.205	0.390
Peak demand (kW)	1999	1868	1879	2066	1850	2036

Table 4-6 ASHRAE 90.1-2004 Common Practice High-Rise Baseline Model Costs

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
5-TLCC intensity ($/ft^2)	$150.65	$145.69	$144.13	$151.04	$142.60	$149.03
Capital cost intensity ($/ft^2)	$132.51	$130.84	$129.96	$134.43	$128.71	$133.11
Annual energy cost intensity ($/ft^2·yr)	$2.49	$1.96	$1.83	$2.07	$1.85	$2.00
Annual electricity cost intensity ($/ft^2·yr)	$2.25	$1.79	$1.55	$1.70	$1.60	$1.53
Annual natural gas cost intensity ($/ft^2·yr)	$0.24	$0.17	$0.28	$0.36	$0.25	$0.48

A detailed end use breakdown of energy consumption for the ASHRAE 90.1-2004 baseline models is presented in Table 4-7 to Table 4-9 for the low-rise, code-compliant high-rise, and common practice high-rise cases, respectively (Table D-36 to Table D-38 for metric units). For each end use and for the building as a whole, EUIs corresponding to 50% net site energy savings are defined. The 50% savings value for each end use is provided as a reference for comparison with low-energy results; we do not imply that the low-energy models need to achieve 50% net site energy savings for each end use. The 50% savings goals for the high-rise cases are defined with respect to the code-compliant baseline case, as our goal is to find designs that achieve 50% net site energy savings with respect to ASHRAE 90.1-2004 and ASHRAE 62.1-2004. Thus, the common practice high-rise cases need to achieve larger than 50% net site EUI savings to achieve the low-energy savings target.

Table 4-7 Comparison of Low-Rise EUI by End Use Between Baseline and 50% Savings Target

EDM Key	1A Miami		3B Las Vegas		4C Seattle		5A Chicago		5B Boulder		7 Duluth	
	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings
Heating	21.4	10.7	10.7	5.4	14.4	7.2	22.8	11.4	14.4	7.2	28.8	14.4
Cooling	33.9	17.0	13.2	6.6	6.5	3.3	11.0	5.5	7.3	3.6	5.6	2.8
Interior lighting	14.8	7.4	14.8	7.4	14.8	7.4	14.8	7.4	14.8	7.4	14.8	7.4
Interior equipment	4.8	2.4	4.8	2.4	4.8	2.4	4.8	2.4	4.8	2.4	4.8	2.4
Fans	5.2	2.6	3.2	1.6	2.1	1.0	3.0	1.5	2.8	1.4	3.0	1.5
Pumps	4.1	2.1	1.9	1.0	1.1	0.6	1.7	0.9	1.2	0.6	1.2	0.6
Heat rejection	2.3	1.1	1.1	0.5	0.6	0.3	0.8	0.4	0.6	0.3	0.5	0.2
Water systems	0.7	0.3	0.8	0.4	1.1	0.5	1.1	0.6	1.1	0.6	1.3	0.7
Data center	28.0	14.0	28.0	14.0	28.0	14.0	28.0	14.0	28.0	14.0	28.0	14.0
Total end uses	115.2	57.6	78.5	39.3	73.4	36.7	88.2	44.1	74.9	37.5	88.0	44.0

Table 4-8 Comparison of Code-Compliant High-Rise EUI by End Use Between Baseline and 50% Savings Target

EDM Key	1A Miami		3B Las Vegas		4C Seattle		5A Chicago		5B Boulder		7 Duluth	
	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings
Heating	19.3	9.7	11.0	5.5	15.9	8.0	22.2	11.1	14.2	7.1	27.8	13.9
Cooling	30.1	15.0	13.9	7.0	7.0	3.5	11.3	5.6	7.9	3.9	6.1	3.0
Interior lighting	14.4	7.2	14.4	7.2	14.4	7.2	14.4	7.2	14.4	7.2	14.4	7.2
Interior equipment	4.7	2.3	4.7	2.3	4.7	2.3	4.7	2.3	4.7	2.3	4.7	2.3
Fans	4.9	2.4	3.2	1.6	2.2	1.1	3.0	1.5	2.9	1.5	3.0	1.5
Pumps	3.6	1.8	2.0	1.0	1.2	0.6	1.7	0.9	1.2	0.6	1.2	0.6
Heat rejection	2.0	1.0	1.1	0.6	0.6	0.3	0.8	0.4	0.6	0.3	0.5	0.2
Water systems	0.7	0.3	0.8	0.4	1.1	0.5	1.1	0.6	1.1	0.6	1.3	0.7
Data center	27.7	13.8	27.7	13.8	27.7	13.8	27.7	13.8	27.7	13.8	27.7	13.8
Total end uses	107.3	53.7	78.8	39.4	74.9	37.4	86.9	43.4	74.7	37.4	86.6	43.3

Table 4-9 Comparison of Common Practice High-Rise EUI by End Use Between Baseline and 50% Savings Target

EDM Key	1A Miami		3B Las Vegas		4C Seattle		5A Chicago		5B Boulder		7 Duluth	
	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings
Heating	18.5	9.7	13.0	5.5	21.7	8.0	28.5	11.1	19.4	7.1	37.7	13.9
Cooling	32.2	15.0	16.1	7.0	8.4	3.5	13.2	5.6	9.5	3.9	7.3	3.0
Interior lighting	14.4	7.2	14.4	7.2	14.4	7.2	14.4	7.2	14.4	7.2	14.4	7.2
Interior equipment	4.7	2.3	4.7	2.3	4.7	2.3	4.7	2.3	4.7	2.3	4.7	2.3
Fans	4.6	2.4	3.5	1.6	2.7	1.1	3.3	1.5	3.5	1.5	3.5	1.5
Pumps	3.8	1.8	2.3	1.0	1.4	0.6	2.0	0.9	1.5	0.6	1.4	0.6
Heat rejection	2.1	1.0	1.3	0.6	0.7	0.3	1.0	0.4	0.7	0.3	0.6	0.2
Water systems	0.7	0.3	0.8	0.4	1.1	0.5	1.1	0.6	1.1	0.6	1.3	0.7
Data center	27.7	13.8	27.7	13.8	27.7	13.8	27.7	13.8	27.7	13.8	27.7	13.8
Total end uses	108.7	53.7	83.8	39.4	82.8	37.4	95.8	43.4	82.3	37.4	98.5	43.3

4.1.2 ASHRAE 90.1-2007 Baseline Models: Performance

To analyze the impact of energy code changes on energy savings, baseline models were constructed that minimally satisfy ASHRAE 90.1-2007. Relevant differences between the ASHRAE 90.1-2004 and ASHRAE 90.1-2007 baselines are the window, wall, and roof performance requirements. Ventilation requirements are consistent between the ASHRAE 90.1-2004 and ASHRAE 90.1-2007 baselines because ASHRAE 62.1-2004 is used as the ventilation Standard in both cases.

For completeness, the 90.1-2007 baseline windows, walls, and roofs are summarized in Table 4-10 to Table 4-14 (Table D-39 to Table D-43 for metric units). To compare to the 90.1-2004 values, see Table 3-9 to Table 3-16 (Table D-2 to Table D-9 for metric units).

Table 4-10 ASHRAE 90.1-2007 Low-Rise Baseline Exterior Wall Constructions

Properties	Climate Zone 1A	Climate Zone 3B-NV	Climate Zone 4C	Climate Zones 5A, and 5B	Climate Zone 7
Key	**Baseline Wall Construction No c.i.**	**Baseline Wall Construction R-7.6 c.i.**	**Baseline Wall Construction R-9.5 c.i.**	**Baseline Wall Construction R-11.4 c.i.**	**Baseline Wall Construction R-15.2 c.i.**
Assembly U-factor (Btu/h·ft^2·°F)	1.010	0.137	0.114	0.097	0.076
Capital cost ($/ft^2)	$36.15	$44.40	$44.75	$45.10	$45.80

Table 4-11 ASHRAE 90.1-2007 High-Rise Baseline Exterior Wall Constructions

Properties	Climate Zone 1A	Climate Zone 3B-NV	Climate Zones 4C, 5A, 5B, and 7
Key	**Baseline Wall Construction R-13.0**	**Baseline Wall Construction R-13.0 + R-3.8 c.i.**	**Baseline Wall Construction R-13.0 + R-7.5 c.i.**
Assembly U-factor (Btu/ h·ft^2·°F)	0.139	0.091	0.068
Capital cost ($/ft^2)	$35.75	$36.65	$37.15

Table 4-12 ASHRAE 90.1-2007 Baseline Roof Constructions

Properties	Climate Zone 1A	Climate Zones 3B-NV, 4C, 5A, 5B, and 7
Key	**Baseline Roof Construction R-15.0 c.i.**	**Baseline Roof Construction R-20.0 c.i.**
Assembly U-factor (Btu/h·ft^2·°F)	0.066	0.050
Capital cost ($/ft^2)	$9.15	$9.59

Table 4-13 ASHRAE 90.1-2007 Low-Rise Baseline Window Constructions

Properties	Climate Zone 1A	Climate Zones 3B-NV	Climate Zones 4C, 5A, and 5B	Climate Zone 7
Key	Baseline Window Construction	Baseline Window Construction	Baseline Window Construction	Baseline Window Construction
SHGC	0.250	0.250	0.400	0.450
VLT	0.250	0.318	0.508	0.450
U-factor (Btu/h·ft^2·°F)	1.200	0.650	0.550	0.450
Capital cost (\$/ft^2)	\$49.67	\$52.40	\$47.57	\$47.23
Fixed O&M cost (\$/ft^2)	\$0.22	\$0.22	\$0.22	\$0.22

Table 4-14 ASHRAE 90.1-2007 High-Rise Baseline Window Constructions

Properties	Climate Zone 1A	Climate Zones 3B-NV	Climate Zones 4C, 5A, and 5B	Climate Zone 7
Key	Baseline Window Construction	Baseline Window Construction	Baseline Window Construction	Baseline Window Construction
SHGC	0.250	0.250	0.400	0.450
VLT	0.250	0.318	0.508	0.450
U-factor (Btu/h·ft^2·°F)	1.200	0.650	0.550	0.450
Capital cost (\$/ft^2)	\$76.68	\$79.41	\$74.58	\$74.24
Fixed O&M cost (\$/ft^2)	\$0.22	\$0.22	\$0.22	\$0.22

The performance of the ASHRAE 90.1-2007 baseline models is summarized in Table 4-17 and Table 4-18 (Table D-46 and Table D-47 for metric units) for the low-rise case, in Table 4-19 and Table 4-20 (Table D-48 and Table D-49 for metric units) for the code compliant high-rise case, and in Table 4-21 and Table 4-22 (Table D-50 and Table D-51 for metric units) for the common practice high-rise case. Table 4-15 and Table 4-16 (Table D-44 and Table D-45 for metric units) present performance comparisons between the ASHRAE 90.1-2004 and ASHRAE 90.1-2007 baselines for the low-rise and high-rise cases, respectively.

Table 4-15 Low-Rise EUI Comparison Between 90.1-2004 and 90.1-2007 Baselines

Climate Zone	ASHRAE 90.1-2004 Baseline Site Energy Use (kBtu/ft^2·yr)	ASHRAE 90.1-2007 Baseline Site Energy Use (kBtu/ft^2·yr)
1A Miami	115.2	116.0
3B Las Vegas	78.5	78.6
4C Seattle	73.4	72.6
5A Chicago	88.2	87.3
5B Denver	74.9	74.1
7 Duluth	88.0	85.5

Table 4-16 High-Rise EUI Comparison Between 90.1-2004 and 90.1-2007 Baselines

Climate Zone	ASHRAE 90.1-2004 Baseline Site Energy Use (kBtu/ft^2·yr)		ASHRAE 90.1-2007 Baseline Site Energy Use (kBtu/ft^2·yr)	
	Code Compliant	Common Practice	Code Compliant	Common Practice
1A Miami	107.3	108.7	107.9	108.6
3B Las Vegas	78.8	83.8	78.8	84.7
4C Seattle	74.9	82.8	73.3	82.8
5A Chicago	86.9	95.8	86.1	95.4
5B Denver	74.7	82.3	73.9	82.1
7 Duluth	86.6	98.5	84.3	94.5

Table 4-17 ASHRAE 90.1-2007 Low-Rise Baseline Model Energy Performance

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Site EUI (kBtu/ft^2·yr)	116.0	78.6	72.6	87.3	74.1	85.5
Source EUI (kBtu/ft^2·yr)	339.1	237.9	211.1	241.5	216.0	224.8
Energy emissions (lbCO$_2$/ ft^2·yr)	45.8	32.3	28.5	32.4	29.2	30.0
Electricity intensity (kWh/ft^2·yr)	27.4	19.6	17.0	18.8	17.4	16.9
Natural gas intensity (therms/ft^2·yr)	0.226	0.116	0.145	0.229	0.146	0.277
Peak demand (kW)	1982	1747	1726	1908	1693	1813

Table 4-18 ASHRAE 90.1-2007 Low-Rise Baseline Model Costs

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
5-TLCC intensity ($\$/ft^2$)	$139.31	$129.24	$129.24	$134.89	$124.93	$130.56
Capital cost intensity ($\$/ft^2$)	$119.72	$115.06	$115.06	$119.06	$112.19	$116.16
Annual energy cost intensity ($\$/ft^2\cdot yr$)	$2.61	$1.84	$1.66	$1.92	$1.69	$1.80
Annual electricity cost intensity ($\$/ft^2\cdot yr$)	$2.33	$1.70	$1.48	$1.64	$1.51	$1.46
Annual natural gas cost intensity ($\$/ft^2\cdot yr$)	$0.28	$0.14	$0.18	$0.28	$0.18	$0.34

Table 4-19 ASHRAE 90.1-2007 Code-Compliant High-Rise Baseline Model Energy Performance

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Site EUI ($kBtu/ft^2\cdot yr$)	107.9	78.8	73.3	86.1	73.9	84.3
Source EUI ($kBtu/ft^2\cdot yr$)	316.1	238.2	211.9	238.6	216.0	222.4
Energy emissions intensity ($lbCO_2/ft^2\cdot yr$)	42.7	32.3	28.6	32.0	29.2	29.7
Electricity intensity ($kWh/ft^2\cdot yr$)	25.6	19.6	17.0	18.6	17.4	16.8
Natural gas intensity ($therms/ft^2\cdot yr$)	0.206	0.118	0.153	0.224	0.144	0.269
Peak demand (kW)	1934	1757	1755	1930	1723	1862

Table 4-20 ASHRAE 90.1-2007 Code-Compliant High-Rise Baseline Model Costs

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
5-TLCC intensity ($\$/ft^2$)	$144.87	$138.15	$136.10	$142.63	$134.60	$139.31
Capital cost intensity ($\$/ft^2$)	$127.51	$124.66	$123.57	$127.78	$122.32	$125.63
Annual energy cost intensity ($\$/ft^2\cdot yr$)	$2.44	$1.85	$1.67	$1.90	$1.70	$1.79
Annual electricity cost intensity ($\$/ft^2\cdot yr$)	$2.18	$1.70	$1.49	$1.63	$1.52	$1.46
Annual natural gas cost intensity ($\$/ft^2\cdot yr$)	$0.26	$0.15	$0.19	$0.28	$0.18	$0.33

Table 4-21 ASHRAE 90.1-2007 Common Practice High-Rise Baseline Model Energy Performance

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Site EUI (kBtu/ft^2·yr)	108.6	84.7	82.8	95.4	82.1	94.5
Source EUI (kBtu/ft^2·yr)	322.2	252.4	227.5	255.2	231.0	238.2
Energy emissions intensity (lbCO$_2$/ ft^2·yr)	43.6	34.2	30.5	34.1	31.1	31.6
Electricity intensity (kWh/ft^2·yr)	26.2	20.6	17.7	19.5	18.2	17.4
Natural gas intensity (therms/ft^2·yr)	0.191	0.144	0.224	0.289	0.199	0.350
Peak demand (kW)	2000	1879	1898	2082	1866	2028

Table 4-22 ASHRAE 90.1-2007 Common Practice High-Rise Baseline Model Costs

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
5-TLCC intensity ($/ft^2)	$151.50	$146.75	$144.80	$151.58	$143.16	$148.55
Capital cost intensity ($/ft^2)	$133.35	$131.74	$130.47	$134.87	$129.15	$132.92
Annual energy cost intensity ($/ft^2·yr)	$2.48	$1.98	$1.84	$2.07	$1.85	$1.95
Annual electricity cost intensity ($/ft^2·yr)	$2.25	$1.80	$1.56	$1.71	$1.61	$1.52
Annual natural gas cost intensity ($/ft^2·yr)	$0.24	$0.18	$0.28	$0.36	$0.24	$0.43

4.1.3 Discussion

EUIs for the ASHRAE 90.1-2004 baselines are similar for the low-rise (88.3 kBtu/ft^2·yr [1002 MJ/m^2·yr] on average) and code-compliant high-rise (88.5 kBtu/ft^2·yr [1004 MJ/m^2·yr] on average) cases, but larger for the less insulated common practice high-rise case (97.8 kBtu/ft^2·yr [1110 MJ/m^2·yr] on average), as one would expect. This is especially the case in more severe climates where already large heating or cooling loads are further magnified by a less insulated envelope. In all cases the data center is responsible for a significant fraction (averaging 28%–32%) of total building energy consumption.

The ASHRAE 90.1-2007 baseline energy models perform similarly to the ASHRAE 90.1-2004 baseline models. In all but the coldest climate zone (7), EUI changed by less than 1.3% when replacing ASHRAE 90.1-2004 with ASHRAE 90.1-2007. In climate zone 7, ASHRAE 90.1-2007 baselines saved 3.1%–4.6% in EUI compared to their ASHRAE 90.1-2004 counterparts. Capital cost and 5-TLCC values are similar between the corresponding ASHRAE 90.1-2007 and ASHRAE 90.1-2004 baseline models. Capital costs are slightly higher for the ASHRAE 90.1-2007 baseline models because of the slightly more stringent envelope insulation requirements of ASHRAE 90.1-2007 compared to ASHRAE 90.1-2004; 5-TLCC costs are slightly higher except in climate zone 7, where slightly more significant energy savings for the ASHRAE 90.1-2007 baselines were enough to offset increased capital costs during the five-year analysis period.

4.2 Selected Low-Energy Models

The models described in this section meet the 50% energy savings goal over ASHRAE 90.1-2004 and ASHRAE 62.1-2004 (see Section 2.2). The models were assembled according to the procedure outlined in Section 2.4: first, we applied packages of the EEMs described in Section 3.4 to the baseline models described in Section 3.3 to identify a set of preliminary low-energy models aimed at achieving 50% net site energy savings; then we used the preliminary low-energy models as starting points for optimizations that refined the package of EEM selections to achieve the best possible combination of net site energy savings and 5-TLCC (see Section 3.1.2.6).

4.2.1 Preliminary Low-Energy Models: Selection

We assembled the preliminary low-energy models according to the procedure outlined in Section 2.4.2. We used the design of the RSF and the results from Thornton, Wang et al. (2009) as a basis to define our low-energy HVAC system as a radiant heated and cooled system with DOAS. To mitigate concerns about condensation with radiant cooling, we minimized infiltration by installing an envelope air barrier and entrance vestibules. We applied climate-specific energy recovery strategies and then used the results from Hale, Leach et al. (2009) and Leach, Hale et al. (2009) and industry feedback to make the remaining EEM selections. Preliminary low-energy DOAS design was climate specific (see Section 3.4.4.6.2). Waterside economizing was implemented for all but the humid climates (Miami [1A] and Chicago [5A]), where opportunities for wet bulb depression are limited. Specific EEM selections are presented in Table 4-23 to Table 4-25 for the low-rise, code-compliant high-rise, and common practice high-rise cases, respectively.

Table 4-23 Preliminary Low-Rise Low-Energy Model EEM Selections

Form	Subcategory	EEM Type	Climate Zones					
			1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Form	Aspect ratio	Aspect ratio	1.5	1.5	1.5	1.5	1.5	1.5
	Fenestration	Facade window fraction	20% WWR	20% WWR	20% WWR	20% WWR	20% WWR	20% WWR
	Shading	Shading depth	None	None	None	None	None	None
Fabric	Fenestration	Windows	Double pane with low-e and argon	Double pane with low-e and argon	Double pane with low-e and argon	Double pane with low-e and argon	Double pane with low-e and argon	Double pane with low-e and argon
	Infiltration	Infiltration	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule
	Opaque constructions	Walls	R-22.5 c.i. mass walls	R-22.5 c.i. mass walls	R-22.5 c.i. mass walls	R-22.5 c.i. mass walls	R-22.5 c.i. mass walls	R-22.5 c.i. mass walls
		Roof	R-15 c.i. Insulation above deck	R-15 c.i. Insulation above deck	R-15 c.i. Insulation above deck	R-15 c.i. Insulation above deck	R-15 c.i. Insulation above deck	R-15 c.i. Insulation above deck
Equipment	Energy generation	PV	None	None	None	None	None	None
	HVAC system	System	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS
	Lighting	Daylighting Controls	300 lux set point	300 lux set point	300 lux set point	300 lux set point	300 lux set point	300 lux set point
		LPD	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors
	Outdoor air	ERV	Enthalpy wheel	IDEC with conversion to sensible heat recovery	Sensible wheel	Enthalpy wheel	IDEC with conversion to sensible heat recovery	Sensible wheel
	Economizer	Waterside economizer	No	Yes	Yes	No	Yes	Yes

Table 4-24 Preliminary Code Compliant High-Rise Low-Energy Model EEM Selections

Form	Subcategory	EEM Type	Climate Zones					
			1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Form	Aspect ratio	Aspect ratio	1.5	1.5	1.5	1.5	1.5	1.5
	Fenestration	Facade window fraction	20% WWR	20% WWR	20% WWR	20% WWR	20% WWR	20% WWR
	Shading	Shading depth	Not modeled	Not modeled	Not modeled	Not modeled	Not modeled	Not modeled
Fabric	Fenestration	Windows	Double pane with low-e and argon	Double pane with low-e and argon	Double pane with low-e and argon	Double pane with low-e and argon	Double pane with low-e and argon	Double pane with low-e and argon
	Infiltration	Infiltration	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule
	Opaque constructions	Walls	R-22.5 c.i. spandrel walls	R-22.5 c.i. spandrel walls	R-22.5 c.i. spandrel walls	R-22.5 c.i. spandrel walls	R-22.5 c.i. spandrel walls	R-22.5 c.i. spandrel walls
		Roof	Not modeled	Not modeled	Not modeled	Not modeled	Not modeled	Not modeled
Equipment	Energy generation	PV	None	None	None	None	None	None
	HVAC system	System	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS
	Lighting	Daylighting controls	300 lux set point	300 lux set point	300 lux set point	300 lux set point	300 lux set point	300 lux set point
		LPD	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors
	Outdoor air	ERV	Enthalpy wheel	IDEC with conversion to sensible heat recovery	Sensible wheel	Enthalpy wheel	IDEC with conversion to sensible heat recovery	Sensible wheel
	Economizer	Waterside economizer	No	Yes	Yes	No	Yes	No

Table 4-25 Preliminary Common Practice High-rise Low-Energy Model EEM Selections

Form	Subcategory	EEM Type	Climate Zones 1A Miami	 3B Las Vegas	 4C Seattle	 5A Chicago	 5B Boulder	 7 Duluth
Form	Aspect ratio	Aspect ratio	1.5	1.5	1.5	1.5	1.5	1.5
	Fenestration	Facade window fraction	69% WWR	69% WWR	69% WWR	69% WWR	69% WWR	69% WWR
	Shading	Shading depth	Not modeled	Not modeled	Not modeled	Not modeled	Not modeled	Not modeled
Fabric	Fenestration	Windows	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
	Infiltration	Infiltration	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule
	Opaque constructions	Walls	Assembly R-5.8 c.i. spandrel walls	Assembly R-5.8 c.i. spandrel walls	Assembly R-5.8 c.i. spandrel walls	Assembly R-5.8 c.i. spandrel walls	Assembly R-5.8 c.i. spandrel walls	Assembly R-5.8 c.i. spandrel walls
		Roof	Not modeled	Not modeled	Not modeled	Not modeled	Not modeled	Not modeled
Equipment	Energy generation	PV	None	None	None	None	None	None
	HVAC System	System	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS
	Lighting	Daylighting controls	300 lux set point	300 lux set point	300 lux set point	300 lux set point	300 lux set point	300 lux set point
		LPD	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors
	Outdoor air	ERV	Enthalpy wheel	IDEC with conversion to sensible heat recovery	Sensible wheel	Enthalpy wheel	IDEC with conversion to sensible heat recovery	Sensible wheel
	Economizer	Waterside economizer	No	Yes	Yes	No	Yes	No

4.2.2 Preliminary Low-Energy Models: Performance

For the low-rise and code-compliant high-rise cases, the preliminary low-energy models achieved greater than 50% net site energy savings in all climates. This was not the case for the common practice high-rise preliminary low-energy models, for which the envelope restrictions (high WWR, low insulation wall and window constructions) were too severe to achieve that goal. Table 4-26 shows the preliminary low-energy model savings.

Table 4-26 Preliminary Low-Energy Model Net Site Energy Savings

Climate Zone	Low-Rise	Code-Compliant High-Rise	Common Practice High-Rise
1A Miami	57.2%	54.4%	45.2%
3B Las Vegas	56.3%	57.0%	40.6%
4C Seattle	54.0%	56.9%	34.3%
5A Chicago	53.7%	54.4%	33.1%
5B Denver	55.4%	57.6%	34.4%
7 Duluth	54.7%	57.3%	33.8%

4.2.3 Optimized Low-Energy Models: Selection

After the preliminary low-energy modeling process was complete, we used the resulting low-energy models as the starting points for Opt-E-Plus optimizations to improve energy savings and/or reduce 5-TLCC compared to the starting configuration. For the optimizations, we allowed only EEMs related to envelope (roof construction, exterior wall construction, window construction, WWR, and shaded overhang fraction) and PV roof coverage to vary. All others were fixed at their preliminary low-energy model configuration settings because we were confident we needed to maintain those settings to achieve the 50% net site energy savings goal and minimize 5-TLCC. That confidence was provided by the results of Hale, Leach et al. (2009) and Leach, Hale et al. (2009). For the common practice high-rise case, for which all envelope-related EEMs are fixed by definition, this optimization framework allows only PV to be applied as a means of achieving additional energy savings with respect to the preliminary low-energy models.

In each case, the EEM package resulting in the building configuration representing the minimum cost point of the Pareto front was selected; the resulting EEM selections are summarized for each climate zone in Table 4-27 to Table 4-29 for the low-rise, code-compliant high-rise, and common practice high-rise cases, respectively.

4.2.3.1 Optimization Trends

We identified the following trends for the optimization results (excluding the common practice high-rise case):

- 20% WWR was selected in all cases, likely because of the capital cost decrease associated with replacing glazing with exterior opaque wall construction and because overall envelope insulation levels improve with lower WWR. These factors outweighed the decrease in lighting energy that might accompany larger WWR.
- In all cases, exterior wall insulation was reduced to or near baseline insulation levels (except in climate zone 7) and window assembly R-value was increased (with respect to preliminary low-energy model envelope insulation selection values).

- Roof insulation was not increased above the preliminary low-energy model selection value (R-15 c.i.) in any case.
- Overhangs to shade glazing, when available as an EEM, were only selected in Seattle (4C).
- Increasing aspect ratio was not selected as a cost-effective measure in any low-rise cases. However, additional analysis of high aspect ratio designs is required to reach any definite conclusions (see Section 5.2).

Table 4-27 Optimized Low-Rise Low-Energy Model EEM Selections

Form	Subcategory	EEM Type	Climate Zones					
			1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Form	Aspect ratio	Aspect ratio	1.5	1.5	1.5	1.5	1.5	1.5
	Fenestration	Facade window fraction	20% WWR	20% WWR	20% WWR	20% WWR	20% WWR	20% WWR
	Shading	Shading depth	None	None	Shaded overhangs with a 0.5 projection factor	None	None	None
Fabric	Fenestration	Windows	Double pane with low-e2 and argon	Double pane with low-e2 and argon	Double pane with low-e2 and argon	Double pane with low-e2 and argon	Double pane with low-e2 and argon	Double pane with low-e2 and argon
	Infiltration	Infiltration	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule
	Opaque constructions	Walls	R-5.7 walls	R-9.5 walls	R-9.5 walls	R-13.3 walls	R-13.3 walls	R-19.5 walls
		Roof	R-15 c.i. insulation above deck	R-15 c.i. insulation above deck	R-15 c.i. insulation above deck	R-15 c.i. insulation above deck	R-15 c.i. insulation above deck	R-15 c.i. insulation above deck
Equipment	Energy generation	PV	None	None	None	None	None	None
	HVAC system	System	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS
	Lighting	Daylighting controls	300 lux set point	300 lux set point	300 lux set point	300 lux set point	300 lux set point	300 lux set point
		LPD	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors
	Outdoor Air	ERV	Enthalpy wheel	IDEC with conversion to sensible heat recovery	Sensible wheel	Enthalpy wheel	IDEC with conversion to sensible heat recovery	Sensible wheel
	Economizer	Waterside economizer	No	Yes	Yes	No	Yes	Yes

Table 4-28 Optimized Code Compliant High-Rise Low-Energy Models

Form	Subcategory	EEM Type	Climate Zones					
			1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Form	Aspect ratio	Aspect ratio	Fixed at 1.5	Fixed at 1.5	Fixed at 1.5	Fixed at 1.5	Fixed at 1.5	Fixed at 1.5
	Fenestration	Facade window fraction	20% WWR	20% WWR	20% WWR	20% WWR	20% WWR	20% WWR
	Shading	Shading depth	Not modeled	Not modeled	Not modeled	Not modeled	Not modeled	Not modeled
Fabric	Fenestration	Windows	Double pane with low-e2 and tinted glass	Double pane with low-e2 and tinted glass	Double pane with low-e2 and tinted glass	Double pane with low-e2 and tinted glass	Double pane with low-e2 and tinted glass	Double pane with low-e2 and tinted glass
	Infiltration	Infiltration	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule
	Opaque constructions	Walls	R-13.0 spandrel Walls	R-13.0 spandrel Walls	R-13.0 + R-7.5 c.i. spandrel Walls	R-13.0 + R-3.8 c.i. spandrel Walls	R-13.0 + R-7.5 c.i. spandrel Walls	R-22.5 c.i. spandrel Walls
		Roof	Not modeled	Not modeled	Not modeled	Not modeled	Not modeled	Not modeled
Equipment	Energy generation	PV	None	None	None	None	None	None
	HVAC system	System	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS
	Lighting	Daylighting Controls	300 lux set point	300 lux set point	300 lux set point	300 lux set point	300 lux set point	300 lux set point
		LPD	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors
	Outdoor air	ERV	Enthalpy wheel	IDEC with conversion to sensible heat recovery	Sensible wheel	Enthalpy wheel	IDEC with conversion to sensible heat recovery	Sensible wheel
	Economizer	Waterside economizer	No	Yes	Yes	No	Yes	Yes

Table 4-29 Optimized Common Practice High-Rise Low-Energy Model EEM Selections

Form	Subcategory	EEM Type	Climate Zones					
			1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Form	Aspect ratio	Aspect ratio	Fixed at 1.5	Fixed at 1.5	Fixed at 1.5	Fixed at 1.5	Fixed at 1.5	Fixed at 1.5
	Fenestration	Facade window fraction	69% WWR	69% WWR	69% WWR	69% WWR	69% WWR	69% WWR
	Shading	Shading depth	Not modeled	Not modeled	Not modeled	Not modeled	Not modeled	Not modeled
Fabric	Fenestration	Windows	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
	Infiltration	Infiltration	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule	Tighter envelope and front door vestibule
	Opaque constructions	Walls	Assembly R-5.8 c.i. spandrel walls	Assembly R-5.8 c.i. spandrel walls	Assembly R-5.8 c.i. spandrel walls	Assembly R-5.8 c.i. spandrel walls	Assembly R-5.8 c.i. spandrel walls	Assembly R-5.8 c.i. spandrel walls
		Roof	Not modeled	Not modeled	Not modeled	Not modeled	Not modeled	Not modeled
Equipment	Energy generation	PV	60% roof coverage	60% roof coverage	60% roof coverage	60% roof coverage	60% roof coverage	60% roof coverage
	HVAC System	System	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS	Radiant heated and cooled ceilings and DOAS
	Lighting	Daylighting controls	300 lux set point	300 lux set point	300 lux set point	300 lux set point	300 lux set point	300 lux set point
		LPD	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors	42% LPD reduction and occupancy sensors
	Outdoor air	ERV	Enthalpy wheel	IDEC with conversion to sensible heat recovery	Sensible wheel	Enthalpy wheel	IDEC with conversion to sensible heat recovery	Sensible wheel
	Economizer	Waterside economizer	No	Yes	Yes	No	Yes	No

4.2.4 Optimized Low-Energy Models: Performance

The energy performance of the optimized low-energy models is depicted in Figure 4-3 through Figure 4-5 and summarized in Table 4-30 through Table 4-35 (Table D-52 through Table D-57 for metric units). The economic performance of the optimized low-energy models is summarized in Table 4-36 through Table 4-41 (Table D-58 through Table D-63 for metric units).

Table 4-42 presents a comparison between the energy savings achievable in the common practice high-rise case with and without the installation of PV. Table 4-43 through Table 4-45 present simple payback results for each of the optimized low-energy models (Table D-64 through Table D-66 for metric units). Note that common practice high-rise low-energy cases are measured against the corresponding code-compliant high-rise baselines for purposes of computing energy and cost percent savings performance; as mentioned in Section 4.1.1, it is the goal of this study to seek out designs that achieve 50% net site energy savings with respect to ASHRAE 90.1-2004 and ASHRAE 62.1-2004.

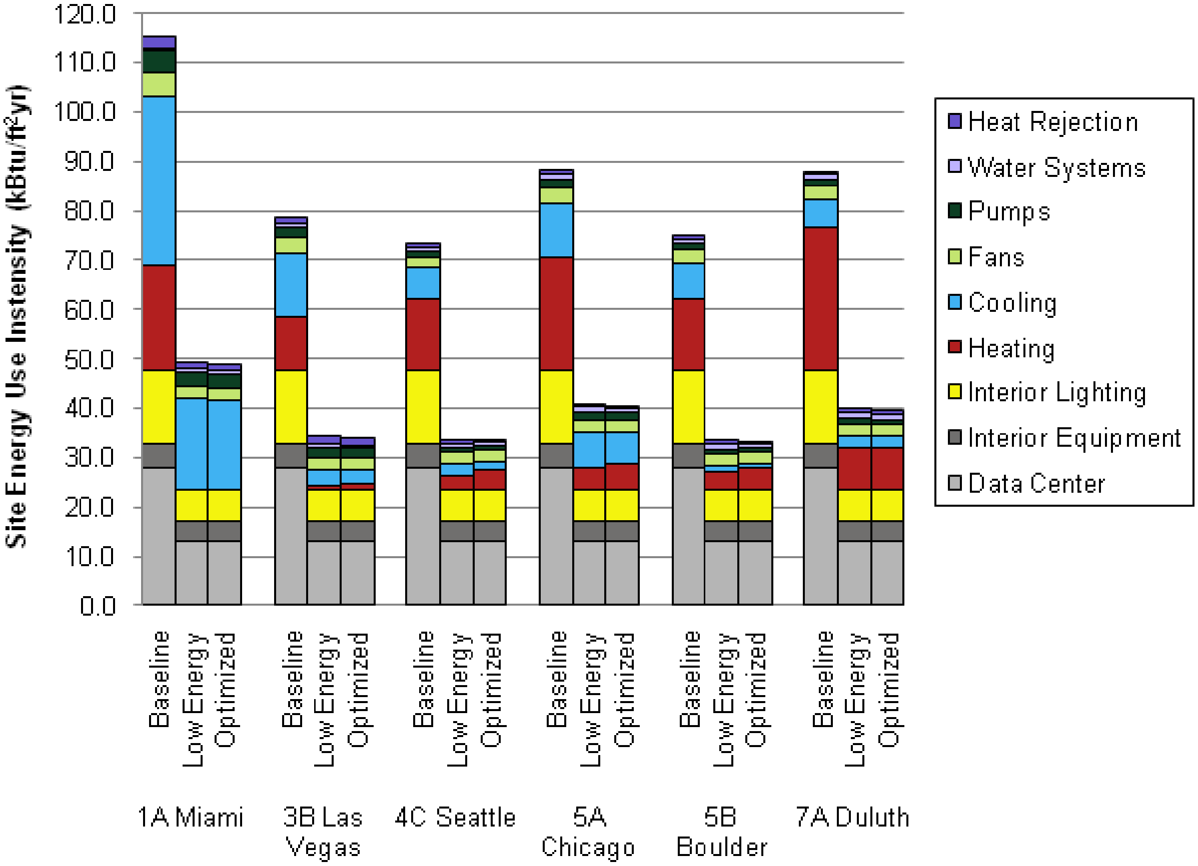

Figure 4-3 Low-rise EUI by end use for low-energy models

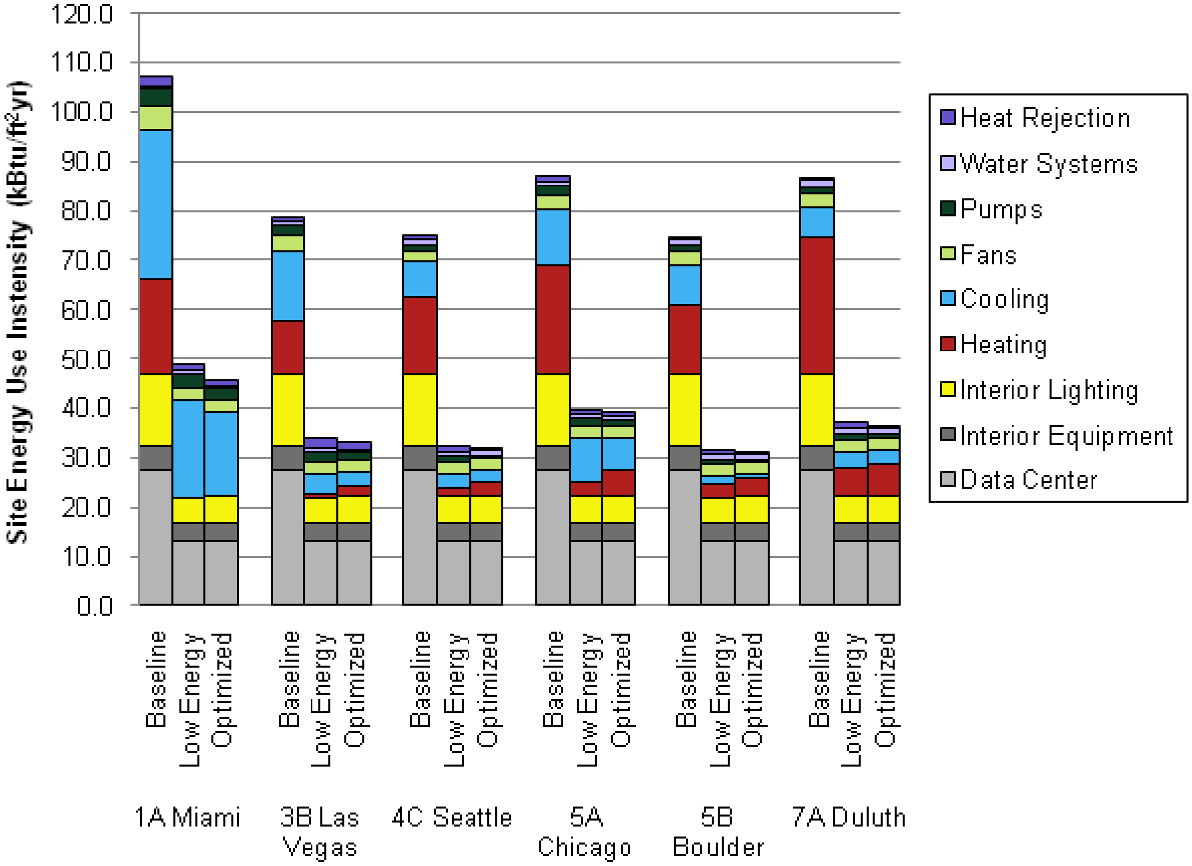

Figure 4-4 High-rise EUI by end use for code-compliant low-energy models

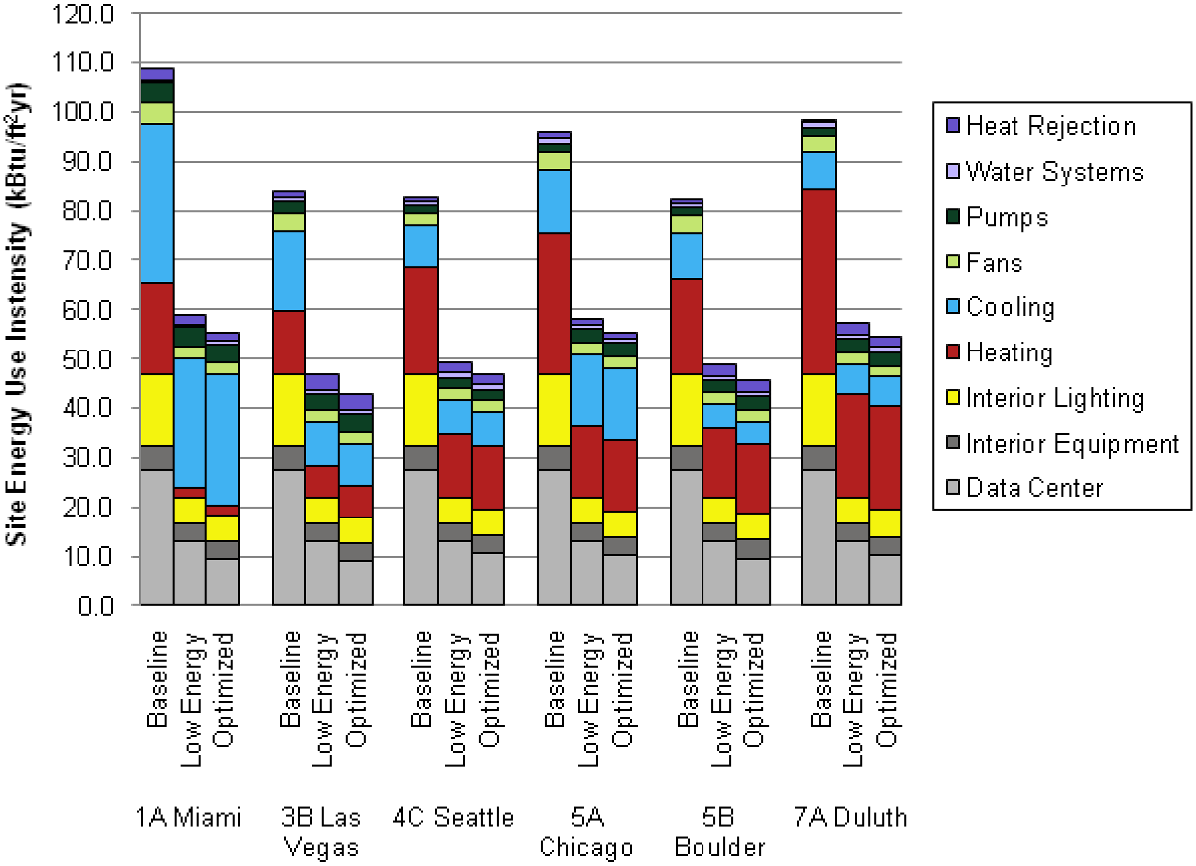

Figure 4-5 High-rise EUI by end use for common practice low-energy models

The reductions in EUI between the preliminary low-energy cases and the optimized low-energy cases shown in Figure 4-5 are due to the addition of PV. 60% roof coverage by PV is modeled. The energy generated by PV is used to offset the electrical EUI of the data center.

Table 4-30 Low-rise Optimized Low-Energy Model Energy Performance: Warm Climates

Metric	Climate Zones								
	1A Miami			3B Las Vegas			4C Seattle		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
Site EUI (kBtu/ft^2·yr)	115.2	48.8	57.6%	78.5	34.0	56.7%	73.4	33.7	54.1%
Source EUI (kBtu/ft^2·yr)	337.4	162.9	51.7%	238.1	109.9	53.8%	211.8	102.1	51.8%
Energy Emissions Intensity (lbCO$_2$/ft^2·yr)	45.6	22.3	51.1%	32.3	15.0	53.5%	28.6	13.8	51.6%
Electricity Intensity (kWh/ft^2·yr)	27.3	14.1	48.2%	19.6	9.4	52.2%	17.0	8.4	50.4%
Natural Gas Intensity (Therms/ft^2·yr)	0.221	0.007	97.0%	0.115	0.020	82.8%	0.154	0.049	68.0%
Peak Demand (kW)	1984	1822	8.2%	1750	1630	6.9%	1721	1385	19.5%

Table 4-31 Low-rise Optimized Low-Energy Model Energy Performance: Cold Climates

Metric	Climate Zones								
	5A Chicago			5B Boulder			7 Duluth		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
Site EUI (kBtu/ft^2·yr)	88.2	40.6	54.0%	74.9	33.3	55.5%	88.0	39.6	55.0%
Source EUI (kBtu/ft^2·yr)	242.3	122.5	49.5%	216.9	100.1	53.9%	227.6	110.8	51.3%
Energy Emissions Intensity (lbCO$_2$/ft^2·yr)	32.5	16.6	48.9%	29.3	13.6	53.7%	30.3	14.9	50.9%
Electricity Intensity (kWh/ft^2·yr)	18.8	10.1	46.5%	17.4	8.2	52.8%	16.9	8.7	48.6%
Natural Gas Intensity (Therms/ft^2·yr)	0.239	0.062	74.2%	0.155	0.053	65.6%	0.301	0.098	67.3%
Peak Demand (kW)	1908	1680	11.9%	1690	1496	11.5%	1818	1704	6.3%

Table 4-32 Code Compliant High-rise Optimized Low-Energy Model Energy Performance: Warm Climates

Metric	Climate Zones								
	1A Miami			3B Las Vegas			4C Seattle		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
Site EUI (kBtu/ft^2·yr)	107.3	45.6	57.5%	78.8	33.0	58.2%	74.9	32.1	57.1%
Source EUI (kBtu/ft^2·yr)	315.7	152.0	51.9%	238.2	105.0	55.9%	213.3	99.4	53.4%
Energy Emissions Intensity (lbCO$_2$/ft^2·yr)	42.7	20.8	51.3%	32.3	14.3	55.7%	28.7	13.5	53.0%
Electricity Intensity (kWh/ft^2·yr)	25.6	13.2	48.5%	19.6	8.9	54.7%	16.9	8.3	51.0%
Natural Gas Intensity (Therms/ft^2·yr)	0.200	0.007	96.5%	0.118	0.026	77.9%	0.170	0.037	77.9%
Peak Demand (kW)	1940	1804	7.0%	1758	1587	9.7%	1746	1608	7.9%

Table 4-33 Code Compliant High-rise Optimized Low-Energy Model Energy Performance: Cold Climates

Metric	Climate Zones								
	5A Chicago			5B Boulder			7 Duluth		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
Site EUI (kBtu/ft2·yr)	86.9	39.0	55.1%	74.7	31.2	58.3%	86.6	36.6	57.8%
Source EUI (kBtu/ft^2·yr)	239.3	117.5	50.9%	216.6	94.7	56.3%	225.2	105.4	53.2%
Energy Emissions Intensity (lbCO$_2$/ft^2·yr)	32.1	15.9	50.4%	29.2	12.8	56.1%	30.0	14.2	52.7%
Electricity Intensity (kWh/ft^2·yr)	18.6	9.6	48.2%	17.4	7.8	55.1%	16.8	8.4	49.9%
Natural Gas Intensity (Therms/ft^2·yr)	0.233	0.061	73.9%	0.153	0.045	70.5%	0.291	0.078	73.3%
Peak Demand (kW)	1925	1665	13.5%	1717	1528	11.0%	1872	1729	7.6%

Table 4-34 Common Practice High-rise Optimized Low-Energy Model Energy Performance: Warm Climates

Metric	Climate Zones								
	1A Miami			3B Las Vegas			4C Seattle		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
Site EUI (kBtu/ft2·yr)	107.3	55.3	48.5%	78.8	42.7	45.8%	74.9	46.8	37.5%
Source EUI (kBtu/ft^2·yr)	315.7	180.6	42.8%	238.2	127.2	46.6%	213.3	126.0	40.9%
Energy Emissions Intensity (lbCO_2/ft^2·yr)	42.7	24.7	42.2%	32.3	17.2	46.7%	28.7	16.9	41.3%
Electricity Intensity (kWh/ft^2·yr)	25.6	15.5	39.4%	19.6	10.4	47.0%	16.9	9.6	43.1%
Natural Gas Intensity (Therms/ft^2·yr)	0.200	0.024	87.9%	0.118	0.072	39.0%	0.170	0.138	18.7%
Peak Demand (kW)	1940	1563	19.4%	1758	1351	23.1%	1746	1378	21.0%

Table 4-35 Common Practice High-rise Optimized Low-Energy Model Energy Performance: Cold Climates

Metric	Climate Zones								
	5A Chicago			5B Boulder			7 Duluth		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
Site EUI (kBtu/ft2·yr)	86.9	55.3	36.3%	74.7	45.7	38.9%	86.6	54.6	36.9%
Source EUI (kBtu/ft^2·yr)	239.3	151.5	36.7%	216.6	119.3	44.9%	225.2	133.6	40.7%
Energy Emissions Intensity (lbCO_2/ft^2·yr)	32.1	20.3	36.7%	29.2	15.9	45.6%	30.0	17.7	41.1%
Electricity Intensity (kWh/ft^2·yr)	18.6	11.7	36.9%	17.4	8.9	48.6%	16.8	9.5	43.4%
Natural Gas Intensity (Therms/ft^2·yr)	0.233	0.153	34.5%	0.153	0.151	1.0%	0.291	0.221	24.0%
Peak Demand (kW)	1925	1454	24.5%	1717	1274	25.8%	1872	1509	19.4%

The energy savings results shown in Table 4-34 and Table 4-35 are in part due to the installation of a PV array that covers 60% of the roof area.

Table 4-36 Low-rise Optimized Low-Energy Model Cost Performance: Warm Climates

Metric	Climate Zones								
	1A Miami			3B Las Vegas			4C Seattle		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
5-TLCC Intensity ($/ft^2)	$139.07	$155.23	-11.6%	$128.90	$137.71	-6.8%	$126.46	$139.75	-10.5%
Capital Cost Intensity ($/ft^2)	$119.51	$136.64	-14.3%	$114.68	$124.68	-8.7%	$113.43	$126.67	-11.7%
Annual Energy Cost Intensity ($/ft^2·yr)	$2.60	$1.35	47.9%	$1.84	$0.91	50.8%	$1.67	$0.82	51.0%
Annual Electricity Cost Intensity ($/ft^2·yr)	$2.32	$1.35	42.1%	$1.70	$0.88	48.1%	$1.48	$0.76	48.8%
Annual Natural Gas Cost Intensity ($/ft^2·yr)	$0.27	$0.01	97.1%	$0.14	$0.02	83.1%	$0.19	$0.06	68.1%

Table 4-37 Low-rise Optimized Low-Energy Model Cost Performance: Cold Climates

Metric	Climate Zones								
	5A Chicago			5B Boulder			7 Duluth		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
5-TLCC Intensity ($/ft^2)	$134.81	$149.00	-10.5%	$124.75	$134.82	-8.1%	$130.66	$145.05	-11.0%
Capital Cost Intensity ($/ft^2)	$118.93	$133.10	-11.9%	$111.99	$122.79	-9.6%	$116.07	$130.46	-12.4%
Annual Energy Cost Intensity ($/ft^2·yr)	$1.93	$1.02	47.4%	$1.70	$0.82	52.0%	$1.83	$0.91	50.5%
Annual Electricity Cost Intensity ($/ft^2·yr)	$1.64	$0.94	42.6%	$1.51	$0.75	50.2%	$1.47	$0.79	46.2%
Annual Natural Gas Cost Intensity ($/ft^2·yr)	$0.30	$0.08	74.5%	$0.19	$0.07	65.9%	$0.37	$0.12	67.5%

Table 4-38 Code Compliant High-rise Optimized Low-Energy Model Cost Performance: Warm Climates

Metric	Climate Zones								
	1A Miami			3B Las Vegas			4C Seattle		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
5-TLCC Intensity ($/ft^2)	$144.56	$154.02	-6.5%	$137.40	$139.19	-1.3%	$135.54	$142.28	-5.0%
Capital Cost Intensity ($/ft^2)	$127.17	$137.71	-8.3%	$123.91	$127.73	-3.1%	$122.99	$130.48	-6.1%
Annual Energy Cost Intensity ($/ft^2·yr)	$2.44	$1.29	47.0%	$1.85	$0.88	52.3%	$1.69	$0.81	52.0%
Annual Electricity Cost Intensity ($/ft^2·yr)	$2.19	$1.28	41.4%	$1.70	$0.85	50.0%	$1.48	$0.77	48.3%
Annual Natural Gas Cost Intensity ($/ft^2·yr)	$0.25	$0.01	96.6%	$0.15	$0.03	78.1%	$0.21	$0.05	78.0%

Table 4-39 Code Compliant High-rise Optimized Low-Energy Model Cost Performance: Cold Climates

Metric	Climate Zones								
	5A Chicago			5B Boulder			7 Duluth		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
5-TLCC Intensity ($/ft^2)	$142.35	$149.10	-4.7%	$134.29	$137.72	-2.6%	$139.48	$147.03	-5.4%
Capital Cost Intensity ($/ft^2)	$127.49	$135.01	-5.9%	$122.01	$127.01	-4.1%	$125.58	$134.11	-6.8%
Annual Energy Cost Intensity ($/ft^2·yr)	$1.91	$1.00	47.6%	$1.71	$0.79	53.4%	$1.82	$0.87	52.1%
Annual Electricity Cost Intensity ($/ft^2·yr)	$1.63	$0.93	42.9%	$1.52	$0.74	51.3%	$1.46	$0.77	47.0%
Annual Natural Gas Cost Intensity ($/ft^2·yr)	$0.29	$0.07	74.1%	$0.19	$0.06	70.7%	$0.36	$0.09	73.4%

Table 4-40 Common Practice High-rise Optimized Low-Energy Model Cost Performance: Warm Climates

Metric	Climate Zones								
	1A Miami			3B Las Vegas			4C Seattle		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
5-TLCC Intensity ($/ft^2)	$144.56	$165.16	-14.2%	$137.40	$150.99	-9.9%	$135.54	$154.47	-14.0%
Capital Cost Intensity ($/ft^2)	$127.17	$147.64	-16.1%	$123.91	$138.32	-11.6%	$122.99	$140.80	-14.5%
Annual Energy Cost Intensity ($/ft^2·yr)	$2.44	$1.48	39.4%	$1.85	$1.07	42.2%	$1.69	$1.10	34.8%
Annual Electricity Cost Intensity ($/ft^2·yr)	$2.19	$1.45	33.8%	$1.70	$0.98	42.4%	$1.48	$0.93	37.1%
Annual Natural Gas Cost Intensity ($/ft^2·yr)	$0.25	$0.03	88.1%	$0.15	$0.09	39.5%	$0.21	$0.17	18.6%

Table 4-41 Common Practice High-rise Optimized Low-Energy Model Cost Performance: Cold Climates

Metric	Climate Zones								
	5A Chicago			5B Boulder			7 Duluth		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
5-TLCC Intensity ($/ft^2)	$142.35	$161.66	-13.6%	$134.29	$148.86	-10.8%	$139.48	$158.16	-13.4%
Capital Cost Intensity ($/ft^2)	$127.49	$145.59	-14.2%	$122.01	$136.76	-12.1%	$125.58	$143.29	-14.1%
Annual Energy Cost Intensity ($/ft^2·yr)	$1.91	$1.31	31.3%	$1.71	$1.03	39.4%	$1.82	$1.18	35.2%
Annual Electricity Cost Intensity ($/ft^2·yr)	$1.63	$1.13	30.6%	$1.52	$0.85	44.1%	$1.46	$0.91	37.9%
Annual Natural Gas Cost Intensity ($/ft^2·yr)	$0.29	$0.19	34.8%	$0.19	$0.19	1.0%	$0.36	$0.27	24.0%

Table 4-42 Common Practice High-rise PV Comparison

Climate Zone	Energy Savings	Energy Savings without PV	PV Roof Coverage	PV Roof Coverage to Achieve 50% Savings
1A Miami	48.5%	45.2%	60.0%	88.3%
3B Las Vegas	45.8%	40.6%	60.0%	108.4%
4C Seattle	37.5%	34.3%	60.0%	294.0%
5A Chicago	36.3%	33.1%	60.0%	314.1%
5B Denver	38.9%	34.4%	60.0%	210.7%
7 Duluth	36.9%	33.8%	60.0%	316.2%

Table 4-43 Low-rise Simple Payback Results

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Capital Cost Increase ($/ft^2)	$17.13	$10.00	$13.24	$14.17	$10.80	$14.39
Capital Cost Increase (%)	14.3	8.7	11.7	11.9	9.6	12.4
Annual Energy Cost Savings ($/ft^2·yr)	$1.25	$0.93	$0.85	$0.91	$0.88	$0.92
Simple Payback Period (yr)	13.7	10.8	15.6	15.6	12.3	15.6

Table 4-44 Code Compliant High-rise Simple Payback Results

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Capital Cost Increase ($/ft^2)	$10.54	$3.82	$7.49	$7.52	$5.00	$8.53
Capital Cost Increase (%)	8.3	3.1	6.1	5.9	4.1	6.8
Annual Energy Cost Savings ($/ft^2·yr)	$1.15	$0.97	$0.88	$0.91	$0.92	$0.95
Simple Payback Period (yr)	9.2	3.9	8.5	8.3	5.4	9.0

Table 4-45 Common Practice High-rise Simple Payback Results

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Capital Cost Increase ($/ft^2)	$20.47	$14.41	$17.81	$18.10	$14.75	$17.71
Capital Cost Increase (%)	16.1	11.6	14.5	14.2	12.1	14.1
Annual Energy Cost Savings ($/ft^2·yr)	$0.96	$0.78	$0.59	$0.60	$0.68	$0.64
Simple Payback Period (yr)	21.3	18.5	30.2	30.2	21.7	27.7

4.2.5 Discussion

The optimized low-energy models can achieve 50% net site energy savings more cost effectively (in terms of 5-TLCC) than their corresponding preliminary low-energy models in all instances for the low-rise and code-compliant high-rise cases.

The low-energy models for the common practice high-rise case cannot achieve 50% net site energy savings in any case, even with PV arrays that cover 60% of the roof, the maximum coverage allowed for this study. Table 4-42 indicates that more than 88% roof coverage would be required in all cases (up to a maximum coverage of more than 316%, for the Duluth [7] case) to reach the energy savings goal.

For the low-rise and code-compliant high-rise cases, the optimized low-energy models could also achieve 50% net source energy savings in nearly all cases (except the low-rise, Chicago [5A] case, for which 49.5% net source energy savings were achieved). In all cases, however, net source energy savings were significantly lower than net site energy savings (by 3.6%, on average); this is due to significantly lower electricity intensity savings (50.5% on average) than natural gas intensity savings (77.1% on average) in conjunction with a higher site to source energy conversion factor for electricity (3.37) than for natural gas (1.09).

A higher site to source energy conversion factor for electricity than for natural gas correlates to higher energy emissions and energy cost savings for electricity than for natural gas. Accordingly, the low-rise and code-compliant high-rise low-energy models exhibited energy emissions savings and energy costs savings similar to those for net source energy, and below those for net site energy.

The low-energy building configurations result in significantly less reduction in peak demand (26% maximum) than in net site energy use. So, although such buildings would reduce total energy consumption by 50% or more, they provide much less reduction in capacity requirements for the electricity grid.

Simple payback is longer for the low-rise case (10.8–15.6 years) than for the code-compliant high-rise case (3.9–9.2 years). This is likely because lowering WWR can significantly reduce capital costs in the high-rise case (glass curtain construction is significantly more expensive than spandrel panel construction), but not in the low-rise case (low-rise exterior wall and fenestration construction costs are very similar). Simple payback for the common practice high-rise optimized low-energy models is considerably longer than for the corresponding code-compliant high-rise models (18.5–30.2 years) because PV arrays covered 60% of the roof area in the common practice high-rise models. The payback for the common practice high-rise cases would be even longer (19.5–35.6 years) if additional PV could be added to the roof or other building surfaces to achieve the 50% net site energy savings goal (see Table 4-42). Although it was required for this analysis, a five-year analysis period seems conservative for a large office building; whether or not these payback periods are acceptable in practice will depend on the building owner and the designed use.

Low-rise and code-compliant high-rise optimizations were initiated with EEM packages that produced greater than 50% net site energy savings in all cases (Table 4-26). The optimization algorithm precludes the selection of EEM packages that produce less energy savings than the EEM package with which the optimization is initialized. Accordingly, it is possible that EEM packages exist that would satisfy the energy savings goal at lower 5-TLCCs than the EEM packages selected by our optimizations; however, those packages would result in lower energy savings than the EEM packages with which their respective optimizations were initialized (see Section 5.1).

5.0 Suggestions for Future Work

In this section we outline areas of improvement recommended for the AEDG stage of this analysis.

5.1 Optimization Setup

As mentioned in Section 4.2.5, the setup of our optimizations may have precluded the discovery of additional EEM packages that can create building configurations that reach the 50% net site energy savings goal. By initializing an optimization at an energy savings level beyond the savings goal, all solutions achieving savings between those of the goal and those of the optimization initialization point are precluded from discovery and possible selection as Pareto front points. To remedy this issue, we will ensure that future optimizations are initialized with EEM packages that result in energy savings that fall short of the energy savings goal.

5.2 Energy Modeling

Some EEMs were not included in this study because reliable input data or modeling validation was lacking, or because significantly more simulation time would have been required. Other EEMs were included but need to be reevaluated. Measures we feel deserve increased attention are:

- **Alternative HVAC systems.** Our selected low-energy HVAC system (radiant heated and cooled ceiling slabs with DOAS) represents a new approach in HVAC design in the United States and building owners and designers may wish to reach the 50% net site energy savings goal with more conventional HVAC system types. We plan to consider a low-energy VAV case as a comparison point to out selected low-energy HVAC system configuration as this work progresses, although 50% energy savings was not found to be possible with a VAV approach in the earlier medium office TSD work.
- **Building thermal mass.** Building thermal mass plays an important role in influencing the control of the building's HVAC system by storing energy. Low-rise low-energy exterior wall constructions were designed to maximize their contribution to internal thermal mass; however, we did not allow the internal mass characteristics of the exterior walls, the radiant slabs, or the interior furnishings to vary.
- **Natural ventilation.** We did not include this EEM because accurately capturing its effects in the energy models was not possible within the scope of this project. Achieving energy savings by implementing natural ventilation (in an actual building or a simulation model) requires accurate inputs and sophisticated building controls. Preliminary modeling indicated that more work will be necessary to validate the impact of this EEM.
- **Advanced daylighting strategies.** The current daylighting configuration is based on using a single type of glass for both views and daylighting. More advanced daylighting configurations and equipment may be considered, including: different combinations of view glass and daylighting glass, with function-specific material properties; installation of light redirection devices to allow deeper penetration of daylight.
- **High aspect ratio designs.** We included the ability to vary aspect ratio as part of our low-rise low-energy optimization process in hopes of capturing the possible benefits of high aspect ratio design for reducing building EUI. Although increasing aspect ratio

increases capital costs and the effect of outdoor conditions on energy use via thermal conductance, it also increases the possible effectiveness of passive strategies such as daylighting, natural ventilation, and load shifting through thermal storage in the building's internal mass. Among these strategies, we explored only daylighting in any detail. To reach definite conclusions about the energy efficiency implications of high aspect ratio design, we need to perform more studies about passive strategies. It is recognized, though, that there are benefits of high aspect ratio such as connection of workspaces to the outdoors through proximity to windows and full daylighting of the workspace.

- **Under floor air distribution (UFAD).** A likely pairing of air distribution method with radiant slab ceilings is UFAD in order to avoid obstruction of the radiant surface. Further verification of UFAD modeling with EnergyPlus is required before this EEM can be used with confidence. As this large office work progresses, we would like to identify the inputs that will allow us to model the effects of UFAD on the energy efficiency of an air distribution system.

- **Air flow models.** Our EnergyPlus models currently assume that air masses in different thermal zones are isolated from one another. Modeling air transfers between zones would increase their accuracy and enable us to better study design features such as entrance vestibules and natural ventilation. For vestibules, infiltration through the front entrances is currently divided on an area-weighted basis between the perimeter zones and the central core zone, based on the assumption that the air would pass through the vestibules and into the core of the building. According to that division, half the air infiltrating through the front entrances is applied directly to the core. In reality, vestibules are equipped with dedicated HVAC units that precondition the infiltrated air before it passes through to the rest of the building. With natural ventilation, accurate air flow is required to capture sophisticated scenarios such as cross-ventilation, which is possible with high aspect ratio designs. A more accurate model (EnergyPlus's Airflow Network) would enable us to capture the significance of using the vestibules to precondition infiltrated air.

We also recommend that some model inputs be reevaluated and validated:

- **Radiant heating and cooling flow control.** As mentioned in Section 3.4.4.5.1, we initially planned to control the water flow (in heating and cooling) through the radiant tubing network using a "trickle and ramp" approach Doebber (2010) designed to account for the effect of the high thermal mass of the radiant slab on system response time. During simulation, our radiant system behaved differently than we expected, exhibiting prompt enough response to thermal loads to render the "trickle and ramp" approach almost unnecessary. We believe this indicates the thermal mass characteristics of our design (for exterior walls, interior furnishings, and especially the layup of the radiant slab) and that revised thermal mass inputs will result in more expected system behavior, for which the "trickle and ramp" approach to system control will be more appropriate.

- **Building model zoning.** To allow aspect ratio to vary during our low-rise low-energy optimizations, we modeled our prototypes with simplified geometries and lumped space types. This reduced the ability of our models to capture the intricacies associated with space specific ventilation requirements, including how the interaction between the air system and the radiant system varies (and the resulting effects on system control) with air flow rate (which is defined by the ventilation requirement of the space for a DOAS). In the future, we may attempt to capture these effects through a more realistic breakdown of thermal zones and space type requirements. As a result, aspect ratio will be fixed, not varied, during a given optimization and varied between optimizations.

- **Building pressurization analysis.** The model inputs for infiltration (see Section 3.3.3.4) and ERV (see Section 3.4.4.6.2) depend on a number of assumptions. The EnergyPlus Airflow Network should be used to determine the validity of those assumptions.
- **Infiltration.** The building pressurization analysis through which infiltration inputs were developed was based on driving pressures associated with HVAC pressurization and wind speed. To strengthen the analysis, stack effect should be factored in. Stack effect was omitted from the current analysis because of its strong dependence on building design and ambient temperature, which make it difficult to model accurately in EnergyPlus. Capturing the influence of stack effect on building EUI is especially important for high-rise buildings; accordingly, we plan to devote time to explore this issue further.

6.0 Conclusions

Our results suggest that fifty percent net site energy savings can be achieved in large office buildings (both low-rise and high-rise) in a range of climates spanning of the spectrum of U.S. weather conditions. Low-rise and high-rise buildings with energy efficient envelopes averaged 56.4% net site energy savings; however, large office buildings with non-compliant envelope design (represented here by a high-rise case with floor-to-ceiling glazing and poorly insulated spandrel panels) could not reach the 50% net site energy savings goal without significant renewable energy generation (in this case, an average of 990 kW of installed PV).

EUI for the ASHRAE 90.1-2004 baselines was similar for the integrated design low-rise and high-rise cases, but greater for the high-rise case with poor envelope design (by an average of 11%), as one would expect; this was especially the case in more severe climates where already large heating or cooling loads were exacerbated by a poorly insulated, highly transparent envelope.

The ASHRAE 90.1-2007 baseline energy models performed similarly to the ASHRAE 90.1-2004 baseline models. In climate zone 7 (Duluth), replacing ASHRAE 90.1-2004 with ASHRAE 90.1-2007 as the baseline building standard resulted in enough energy savings (4% average) to offset increased capital costs associated with the implementation of the slightly more stringent envelope insulation requirements of ASHRAE 90.1-2007 and reduce overall 5-TLCC. In all other climates, replacing ASHRAE 90.1-2004 with ASHRAE 90.1-2007 as the baseline building standard resulted in negligible energy savings and slightly increased capital and life cycle costs.

For the EEM combinations that achieve the 50% net site energy savings goal with the minimum increase in life cycle cost, we calculated simple payback periods. Low-energy high-rise large office buildings with energy efficient envelopes demonstrated minimum simple payback periods shorter than 10 years; integrated design low-energy low-rise large office buildings demonstrated minimum simple payback periods of 9–16 years; and low-energy high-rise large office buildings hampered with poor envelope design demonstrated minimum simple payback periods longer than 20 years. Although this study calculated life cycle cost using a five-year period, acceptable payback for large office buildings may be longer and will depend on the building's owner and use.

We defined the energy goal with respect to net site energy, but we also evaluated our selected low-energy buildings with respect to net source energy, energy emissions, and energy cost. Our low-energy solutions (except the poorly insulated high-rise case) resulted in greater natural gas intensity savings (77% average) than electricity intensity savings (51% average). As a result, our low-energy buildings performed less well, although still at or above 50% savings in most cases, with respect to net source energy savings (52.8% average), energy emissions savings (52.4% average), and energy cost (50.3% average) than with respect to net site energy savings (56.4% average). This is because source energy (and also energy emissions and energy cost, which are strongly related to source energy) savings is weighted toward electricity savings due to our using a higher site-to-source multiplier for electricity (3.37) versus natural gas (1.09). If reducing energy emissions and energy cost become the primary energy efficiency criteria, our analysis supports using source energy as the defining metric for future energy efficiency goals. However, using source energy introduces challenges since site-to-source conversion factors vary with both space and time in ways that are difficult to characterize.

The 50% recommendations are intended to serve as starting points for project-specific analyses. They are not meant for specific design guidance on an actual project because of project-specific variations in economic criteria and EEM availability, cost, and performance. Project-specific analyses are also recommended because they can account for site-specific rebate programs that may improve the cost effectiveness of certain efficiency measures.

For sector-wide studies and individual projects, our approach has the advantages that it allows for the efficient exploration of many building design options and explicitly considers economic factors so the most cost-effective solutions can be identified. The design features we explored can be tailored to match a given energy savings target (regardless of the energy metric used) in a particular climate zone.

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Appendix A Prototype Schedules

The following schedules apply to the low-rise and high-rise large office prototypes; they were determined through a combination of industry-validated assumption and schedule set data from the Medium Office TSD (Thornton, Wang et al. 2009) and the Reference Building project (Deru, Field et al. 2010), for which schedules were largely based on the recommendations of ASHRAE Standard 90.1-1989 (ASHRAE 1989). Schedules are presented as fractions of peak, unless otherwise noted. The entries for total hours/day, etc. are the equivalent number of peak hours during the given time period.

A.1 Occupancy

The occupancy schedule for all the prototypes is shown in Table A-1.

Table A-1 Prototype Occupancy Schedule

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	0	0	1	0	0
2	0	0	1	0	0
3	0	0	1	0	0
4	0	0	1	0	0
5	0	0	1	0	0
6	0	0	1	0	0
7	0.05	0	1	0	0
8	0.15	0.05	1	0	0
9	0.2	0.2	1	0	0.05
10	0.5	0.2	1	0	0.05
11	0.5	0.2	1	0	0.05
12	0.7	0.2	1	0	0.05
13	0.7	0.1	1	0	0.05
14	0.7	0.1	1	0	0.05
15	0.7	0.1	1	0	0.05
16	0.8	0.05	1	0	0.05
17	0.7	0.05	1	0	0.05
18	0.3	0.05	1	0	0.05
19	0.1	0.05	1	0	0
20	0.05	0	1	0	0
21	0.05	0	1	0	0
22	0	0	1	0	0
23	0	0	1	0	0
24	0	0	1	0	0
Total Hours/Day	6.20	1.35	24.00	0.00	0.50
Total Hours/Week	32.85				

A.2 Lighting

The lighting schedule for the prototypes is shown in Table A-2.

Table A-2 Prototype Lighting Schedule

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	0.05	0.05	1	0	0.05
2	0.05	0.05	1	0	0.05
3	0.05	0.05	1	0	0.05
4	0.05	0.05	1	0	0.05
5	0.05	0.05	1	0	0.05
6	0.05	0.05	1	0	0.05
7	0.4	0.05	1	0	0.05
8	0.75	0.4	1	0	0.05
9	0.75	0.75	1	0	0.4
10	0.9	0.75	1	0	0.4
11	0.9	0.75	1	0	0.4
12	0.9	0.75	1	0	0.4
13	0.9	0.75	1	0	0.4
14	0.9	0.75	1	0	0.4
15	0.9	0.75	1	0	0.4
16	0.9	0.4	1	0	0.4
17	0.9	0.4	1	0	0.4
18	0.9	0.4	1	0	0.4
19	0.75	0.4	1	0	0.05
20	0.75	0.05	1	0	0.05
21	0.75	0.05	1	0	0.05
22	0.4	0.05	1	0	0.05
23	0.05	0.05	1	0	0.05
24	0.05	0.05	1	0	0.05
Total Hours/Day	13.05	7.85	24.00	0.00	4.70
Total Hours/Week	77.80				

A.3 Plug and Process Loads

The plug and process load schedule for the prototypes is shown in Table A-3.

Table A-3 Prototype Plug and Process Load Schedule

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	0.2	0.15	1	0	0.15
2	0.2	0.15	1	0	0.15
3	0.2	0.15	1	0	0.15
4	0.2	0.15	1	0	0.15
5	0.2	0.15	1	0	0.15
6	0.2	0.15	1	0	0.15
7	0.4	0.15	1	0	0.15
8	0.4	0.35	1	0	0.15
9	0.4	0.35	1	0	0.35
10	0.7	0.35	1	0	0.35
11	0.7	0.35	1	0	0.35
12	0.9	0.35	1	0	0.35
13	0.9	0.35	1	0	0.35
14	0.9	0.35	1	0	0.35
15	0.9	0.35	1	0	0.35
16	0.9	0.35	1	0	0.35
17	0.9	0.35	1	0	0.35
18	0.7	0.35	1	0	0.35
19	0.4	0.35	1	0	0.15
20	0.2	0.15	1	0	0.15
21	0.2	0.15	1	0	0.15
22	0.2	0.15	1	0	0.15
23	0.2	0.15	1	0	0.15
24	0.2	0.15	1	0	0.15
Total Hours/Day	11.30	6.00	24.00	0.00	5.60
Total Hours/Week	68.10				

A.4 Service Water Heating

The SWH schedule is adopted from ASHRAE 90.1-1989 (ASHRAE 1989) and is shown in Table A-4.

Table A-4 Prototype Service Water Heating Schedule

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	0.04	0.11	0.04	0.11	0.07
2	0.05	0.10	0.05	0.10	0.07
3	0.05	0.08	0.05	0.08	0.07
4	0.04	0.06	0.04	0.06	0.06
5	0.04	0.06	0.04	0.06	0.06
6	0.04	0.06	0.04	0.06	0.06
7	0.04	0.07	0.04	0.07	0.07
8	0.15	0.20	0.15	0.20	0.10
9	0.23	0.24	0.23	0.24	0.12
10	0.32	0.27	0.32	0.27	0.14
11	0.41	0.42	0.41	0.42	0.29
12	0.57	0.54	0.57	0.54	0.31
13	0.62	0.59	0.62	0.59	0.36
14	0.61	0.60	0.61	0.60	0.36
15	0.50	0.49	0.50	0.49	0.34
16	0.45	0.48	0.45	0.48	0.35
17	0.46	0.47	0.46	0.47	0.37
18	0.47	0.46	0.47	0.46	0.34
19	0.42	0.44	0.42	0.44	0.25
20	0.34	0.36	0.34	0.36	0.27
21	0.33	0.29	0.33	0.29	0.21
22	0.23	0.22	0.23	0.22	0.16
23	0.13	0.16	0.13	0.16	0.10
24	0.08	0.13	0.08	0.13	0.06
Total Hours/Day	6.62	6.90	6.62	6.90	4.59
Total Hours/Week	44.59				

Appendix B Baseline Model Schedules

The following schedules apply to the low-rise and high-rise large office baseline models; they were determined through a combination of industry-validated assumption and schedule set data from the Medium Office TSD (Thornton, Wang et al. 2009) and the Reference Building project (Deru, Field et al. 2010), for which schedules were largely based on the recommendation of ASHRAE Standard 90.1-1989 (ASHRAE 1989). Schedules are presented as fractions of peak, unless otherwise noted. The entries for total hours/day, etc. are the equivalent number of peak hours during the given time period.

B.1 HVAC

The baseline HVAC schedule is shown in Table B-1.

Table B-1 Baseline HVAC Schedule

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	1	0	1	0	0
7	1	1	1	1	0
8	1	1	1	1	1
9	1	1	1	1	1
10	1	1	1	1	1
11	1	1	1	1	1
12	1	1	1	1	1
13	1	1	1	1	1
14	1	1	1	1	1
15	1	1	1	1	1
16	1	1	1	1	1
17	1	1	1	1	1
18	1	1	1	1	1
19	1	1	1	1	0
20	1	0	1	0	0
21	1	0	1	0	0
22	1	0	1	0	0
23	0	0	0	0	0
24	0	0	0	0	0
Total Hours/Day	17	13	17	13	11
Total Hours/Week	109				

B.2 Infiltration

The baseline infiltration schedule is defined for a ground floor (applies to the ground level of the low-rise baselines) in Table B-2 and for an interior floor (applies to all but the ground floor of the low-rise baselines and to the high-rise baselines) in Table B-3.

Table B-2 Baseline Ground Floor Infiltration Schedule

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	0.45	0.45	0.45	0.45	0.45
2	0.45	0.45	0.45	0.45	0.45
3	0.45	0.45	0.45	0.45	0.45
4	0.45	0.45	0.45	0.45	0.45
5	0.45	0.45	0.45	0.45	0.45
6	0.11	0.45	0.11	0.45	0.45
7	0.11	0.11	0.11	0.11	0.45
8	0.25	0.11	0.25	0.11	0.11
9	0.25	0.25	0.25	0.25	0.11
10	0.25	0.25	0.25	0.25	0.11
11	0.25	0.25	0.25	0.25	0.11
12	0.25	0.25	0.25	0.25	0.11
13	0.25	0.25	0.25	0.25	0.11
14	0.25	0.25	0.25	0.25	0.11
15	0.25	0.25	0.25	0.25	0.11
16	0.25	0.11	0.25	0.11	0.11
17	0.25	0.11	0.25	0.11	0.11
18	0.25	0.11	0.25	0.11	0.11
19	0.25	0.11	0.25	0.11	0.45
20	0.11	0.45	0.11	0.45	0.45
21	0.11	0.45	0.11	0.45	0.45
22	0.11	0.45	0.11	0.45	0.45
23	0.45	0.45	0.45	0.45	0.45
24	0.45	0.45	0.45	0.45	0.45
Total Hours/Day	6.70	7.36	6.70	7.36	7.06
Total Hours/Week	47.92				

Table B-3 Baseline Interior Floor Infiltration Schedule

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	1	1	1	1	1
2	1	1	1	1	1
3	1	1	1	1	1
4	1	1	1	1	1
5	1	1	1	1	1
6	0.25	1	0.25	1	1
7	0.25	0.25	0.25	0.25	1
8	0.25	0.25	0.25	0.25	0.25
9	0.25	0.25	0.25	0.25	0.25
10	0.25	0.25	0.25	0.25	0.25
11	0.25	0.25	0.25	0.25	0.25
12	0.25	0.25	0.25	0.25	0.25
13	0.25	0.25	0.25	0.25	0.25
14	0.25	0.25	0.25	0.25	0.25
15	0.25	0.25	0.25	0.25	0.25
16	0.25	0.25	0.25	0.25	0.25
17	0.25	0.25	0.25	0.25	0.25
18	0.25	0.25	0.25	0.25	0.25
19	0.25	0.25	0.25	0.25	1
20	0.25	1	0.25	1	1
21	0.25	1	0.25	1	1
22	0.25	1	0.25	1	1
23	1	1	1	1	1
24	1	1	1	1	1
Total Hours/Day	11.25	14.25	11.25	14.25	15.75
Total Hours/Week	86.25				

B.3 Thermostat Set Points

The baseline heating and cooling set point schedules are shown in Table B-4 and Table B-5, respectively, which list temperatures in degrees centigrade. The baseline VAV system has dual thermostatic control based on dry bulb temperature in the zones. The thermostat heating set point is 70ºF (21ºC) with a setback temperature of 60.1ºF (15.6ºC). The thermostat cooling set point is 75ºF (24ºC) with a setup temperature of 87ºF (30.6ºC).

Table B-4 Baseline Heating Set Point Schedule (ºC)

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	15.6	15.6	15.6	15.6	15.6
2	15.6	15.6	15.6	15.6	15.6
3	15.6	15.6	15.6	15.6	15.6
4	15.6	15.6	15.6	15.6	15.6
5	15.6	15.6	15.6	15.6	15.6
6	21	15.6	15.6	21	15.6
7	21	21	15.6	21	15.6
8	21	21	15.6	21	21
9	21	21	15.6	21	21
10	21	21	15.6	21	21
11	21	21	15.6	21	21
12	21	21	15.6	21	21
13	21	21	15.6	21	21
14	21	21	15.6	21	21
15	21	21	15.6	21	21
16	21	21	15.6	21	21
17	21	21	15.6	21	21
18	21	21	15.6	21	21
19	21	21	15.6	21	15.6
20	21	15.6	15.6	21	15.6
21	21	15.6	15.6	21	15.6
22	21	15.6	15.6	21	15.6
23	15.6	15.6	15.6	15.6	15.6
24	15.6	15.6	15.6	15.6	15.6

Table B-5 Baseline Cooling Set Point Schedule (ºC)

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	30.6	30.6	30.6	30.6	30.6
2	30.6	30.6	30.6	30.6	30.6
3	30.6	30.6	30.6	30.6	30.6
4	30.6	30.6	30.6	30.6	30.6
5	30.6	30.6	30.6	30.6	30.6
6	24	30.6	24	30.6	30.6
7	24	24	24	30.6	30.6
8	24	24	24	30.6	24
9	24	24	24	30.6	24
10	24	24	24	30.6	24
11	24	24	24	30.6	24
12	24	24	24	30.6	24
13	24	24	24	30.6	24
14	24	24	24	30.6	24
15	24	24	24	30.6	24
16	24	24	24	30.6	24
17	24	24	24	30.6	24
18	24	24	24	30.6	24
19	24	24	24	30.6	30.6
20	24	30.6	24	30.6	30.6
21	24	30.6	24	30.6	30.6
22	24	30.6	24	30.6	30.6
23	30.6	30.6	30.6	30.6	30.6
24	30.6	30.6	30.6	30.6	30.6

Appendix C Low-Energy Model Schedules

The following schedules apply to the low-rise and high-rise large office low-energy models; they were determined through a combination of industry-validated assumption and schedule set data from the Medium Office TSD (Thornton, Wang et al. 2009) and the Reference Building project (Deru, Field et al. 2010), for which schedules were largely based on the recommendation of ASHRAE Standard 90.1-1989 (ASHRAE 1989). Schedules are presented as fractions of peak, unless otherwise noted. The entries for total hours/day, etc. are the equivalent number of peak hours during the given time period.

C.1 HVAC

The low-energy DOAS schedule is shown in Table C-1. The low-energy radiant availability schedule is shown in Table C-2.

Table C-1 Low-Energy DOAS Schedule

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	1	0	1	0	0
6	1	1	1	1	0
7	1	1	1	1	1
8	1	1	1	1	1
9	1	1	1	1	1
10	1	1	1	1	1
11	1	1	1	1	1
12	1	1	1	1	1
13	1	1	1	1	1
14	1	1	1	1	1
15	1	1	1	1	1
16	1	1	1	1	1
17	1	1	1	1	1
18	1	1	1	1	1
19	1	1	1	1	0
20	1	0	1	0	0
21	1	0	1	0	0
22	1	0	1	0	0
23	0	0	0	0	0
24	0	0	0	0	0
Total Hours/Day	18	14	18	14	12
Total Hours/Week	116				

Table C-2 Low-Energy Radiant Availability Schedule

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	1	0	1	0	0
7	1	1	1	1	0
8	1	1	1	1	1
9	1	1	1	1	1
10	1	1	1	1	1
11	1	1	1	1	1
12	1	1	1	1	1
13	1	1	1	1	1
14	1	1	1	1	1
15	1	1	1	1	1
16	1	1	1	1	1
17	1	1	1	1	1
18	1	1	1	1	0
19	1	0	1	0	0
20	1	0	1	0	0
21	1	0	1	0	0
22	0	0	0	0	0
23	0	0	0	0	0
24	0	0	0	0	0
Total Hours/Day	16	12	16	12	10
Total Hours/Week	102				

C.2 Infiltration

The low-energy infiltration schedule is defined for a ground floor (applies to the ground level of the low-rise baselines) in Table C-3 and for an interior floor (applies to all but the ground floor of the low-rise baselines and to the high-rise baselines) in Table C-4.

Table C-3 Low-Energy Ground Floor Infiltration Schedule

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	0.27	0.27	0.27	0.27	0.27
2	0.27	0.27	0.27	0.27	0.27
3	0.27	0.27	0.27	0.27	0.27
4	0.27	0.27	0.27	0.27	0.27
5	0.07	0.27	0.07	0.27	0.27
6	0.07	0.07	0.07	0.07	0.27
7	0.07	0.07	0.07	0.07	0.07
8	0.25	0.07	0.25	0.07	0.07
9	0.25	0.25	0.25	0.25	0.07
10	0.25	0.25	0.25	0.25	0.07
11	0.25	0.25	0.25	0.25	0.07
12	0.25	0.25	0.25	0.25	0.07
13	0.25	0.25	0.25	0.25	0.07
14	0.25	0.25	0.25	0.25	0.07
15	0.25	0.25	0.25	0.25	0.07
16	0.25	0.07	0.25	0.07	0.07
17	0.25	0.07	0.25	0.07	0.07
18	0.25	0.07	0.25	0.07	0.07
19	0.25	0.07	0.25	0.07	0.27
20	0.07	0.27	0.07	0.27	0.27
21	0.07	0.27	0.07	0.27	0.27
22	0.07	0.27	0.07	0.27	0.27
23	0.27	0.27	0.27	0.27	0.27
24	0.27	0.27	0.27	0.27	0.27
Total Hours/Day	5.04	4.94	5.04	4.94	4.08
Total Hours/Week	34.22				

Table C-4 Low-Energy Interior Floor Infiltration Schedule

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	1	1	1	1	1
2	1	1	1	1	1
3	1	1	1	1	1
4	1	1	1	1	1
5	0.25	1	0.25	1	1
6	0.25	0.25	0.25	0.25	1
7	0.25	0.25	0.25	0.25	0.25
8	0.25	0.25	0.25	0.25	0.25
9	0.25	0.25	0.25	0.25	0.25
10	0.25	0.25	0.25	0.25	0.25
11	0.25	0.25	0.25	0.25	0.25
12	0.25	0.25	0.25	0.25	0.25
13	0.25	0.25	0.25	0.25	0.25
14	0.25	0.25	0.25	0.25	0.25
15	0.25	0.25	0.25	0.25	0.25
16	0.25	0.25	0.25	0.25	0.25
17	0.25	0.25	0.25	0.25	0.25
18	0.25	0.25	0.25	0.25	0.25
19	0.25	0.25	0.25	0.25	1
20	0.25	1	0.25	1	1
21	0.25	1	0.25	1	1
22	0.25	1	0.25	1	1
23	1	1	1	1	1
24	1	1	1	1	1
Total Hours/Day	10.50	13.50	10.50	13.50	15.00
Total Hours/Week	81.00				

C.3 Thermostat Set Points

The low-energy heating set point schedule for the DOAS is shown in Table C-5, which lists temperatures in degrees centigrade. The low-energy DOAS system has heating control as described in Section 3.4.4.5.1 based on operative temperature in the zones. The thermostat heating set point is an operative temperature 70.2ºF (21.2ºC) with a dry bulb setback temperature of 60.1ºF (15.6ºC). The DOAS does not have a day time cooling set point; when heating is not required during day time operation, the DOAS supplies air at 55.0ºF (12.8ºC). At night when the radiant cooling system is unavailable, the DOAS has a dry bulb set up temperature of 87ºF (30.6ºC). Radiant heating and cooling set points are 70ºF (21ºC) and 75ºF (24ºC), measured in operative temperature; radiant set point temperatures apply any time the radiant system is available for operation.

Table C-5 Low-Energy Heating Set Point Schedule (ºC)

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	15.6	15.6	15.6	15.6	15.6
2	15.6	15.6	15.6	15.6	15.6
3	15.6	15.6	15.6	15.6	15.6
4	15.6	15.6	15.6	15.6	15.6
5	21.2	15.6	15.6	21.2	15.6
6	21.2	21.2	15.6	21.2	15.6
7	21.2	21.2	15.6	21.2	21.2
8	21.2	21.2	15.6	21.2	21.2
9	21.2	21.2	15.6	21.2	21.2
10	21.2	21.2	15.6	21.2	21.2
11	21.2	21.2	15.6	21.2	21.2
12	21.2	21.2	15.6	21.2	21.2
13	21.2	21.2	15.6	21.2	21.2
14	21.2	21.2	15.6	21.2	21.2
15	21.2	21.2	15.6	21.2	21.2
16	21.2	21.2	15.6	21.2	21.2
17	21.2	21.2	15.6	21.2	21.2
18	21.2	21.2	15.6	21.2	21.2
19	21.2	21.2	15.6	21.2	15.6
20	21.2	15.6	15.6	21.2	15.6
21	21.2	15.6	15.6	21.2	15.6
22	21.2	15.6	15.6	21.2	15.6
23	15.6	15.6	15.6	15.6	15.6
24	15.6	15.6	15.6	15.6	15.6

Appendix D Metric Unit Tables

Table D-1 National Average Natural Gas Tariff and Source Data in $/GJ

Month	Year				Tariff
	2006	2007	2008	2009	
January	–	$10.57	$10.44	$10.46	$10.49
February	–	$10.63	$10.73	$10.12	$10.49
March	–	$11.17	$11.19	$9.57	$10.65
April	$10.97	$10.89	$11.79	–	$11.22
May	$11.00	$10.88	$12.55	–	$11.48
June	$10.51	$11.24	$13.64	–	$11.80
July	$10.41	$11.00	$14.64	–	$12.02
August	$10.62	$10.58	$13.31	–	$11.50
September	$10.58	$10.33	$12.34	–	$11.08
October	$9.53	$10.33	$11.21	–	$10.36
November	$10.47	$10.61	$10.85	–	$10.64
December	$11.00	$10.44	$10.73	–	$10.73

Table D-2 Low-Rise Baseline Exterior Wall Constructions

Properties	Climate Zone 1A	Climate Zones 3B-NV and 4C	Climate Zones 5A and 5B	Climate Zone 7
Key	Baseline Wall Construction No c.i.	Baseline Wall Construction R-5.7 c.i.	Baseline Wall Construction R-7.6 c.i.	Baseline Wall Construction R-11.4 c.i.
Assembly U-factor (W/K·m^2)	5.735	0.982	0.778	0.551
Capital cost ($/m^2)	$389.12	$474.15	$477.92	$485.45

Table D-3 High-Rise Code-Compliant Baseline Exterior Wall Constructions

Properties	Climate Zones 1A, 3B-NV, and 4C	Climate Zones 5A, and 5B	Climate Zone 7
Key	Baseline Wall Construction R-13.0	Baseline Wall Construction R-13.0 + R-3.8 c.i.	Baseline Wall Construction R-13.0 + R-7.5 c.i.
Assembly U-factor (W/K·m^2)	0.789	0.517	0.386
Capital cost ($/m^2)	$384.81	$394.50	$399.88

Table D-4 High-Rise Common Practice Baseline Exterior Wall Construction

Properties	All Climate Zones
Key	Baseline Wall Construction, Whole Wall Assembly R-3.0
U-factor (W/K·m^2)	0.982
Capital cost ($/m^2)	$374.58

Table D-5 Low-Rise Baseline Roof Constructions

Properties	Climate Zones 1–7
Key	**Baseline Roof Construction, R-15 c.i.**
U-factor (W/K·m^2)	0.375
Capital cost (\$/m^2)	\$98.49

Table D-6 Low-Rise Baseline East-, South-, and West-Facing Punched-Hole Window Constructions

Properties	Climate Zone 1A	Climate Zone 3B-NV	Climate Zones 4C, 5A, and 5B	Climate Zone 7
Key	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**
SHGC	0.25	0.25	0.39	0.49
VLT	0.25	0.318	0.495	0.49
U-factor (W/K·m^2)	6.871	3.237	3.237	3.237
Capital cost (\$/m^2)	\$498.26	\$536.15	\$508.49	\$508.49
Fixed O&M cost (\$/m^2)	\$2.37	\$2.37	\$2.37	\$2.37

Table D-7 Low-Rise Baseline North-Facing Punched-Hole Window Constructions

Properties	Climate Zone 1A	Climate Zone 3B-NV	Climate Zones 4C, 5A, and 5B	Climate Zone 7
Key	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**
SHGC	0.44	0.39	0.49	0.64
VLT	0.44	0.622	0.622	0.64
U-factor (W/K·m^2)	6.871	3.237	3.237	3.237
Capital cost (\$/m^2)	\$486.64	\$445.52	\$502.24	\$439.60
Fixed O&M cost (\$/m^2)	\$2.37	\$2.37	\$2.37	\$2.37

Table D-8 High-Rise Baseline East-, South-, and West-Facing Glass Curtain Constructions

Properties	Climate Zone 1A	Climate Zone 3B-NV	Climate Zones 4C, 5A, and 5B	Climate Zone 7
Key	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**
SHGC	0.25	0.25	0.39	0.49
VLT	0.25	0.318	0.495	0.49
U-factor (W/K·m^2)	6.871	3.237	3.237	3.237
Capital cost (\$/m^2)	\$788.99	\$826.88	\$799.22	\$799.22
Fixed O&M cost (\$/m^2)	\$2.37	\$2.37	\$2.37	\$2.37

Table D-9 High-Rise Baseline North-Facing Glass Curtain Constructions

Properties	Climate Zone 1A	Climate Zone 3B-NV	Climate Zones 4C, 5A, and 5B	Climate Zone 7
Key	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**
SHGC	0.44	0.39	0.49	0.64
VLT	0.44	0.622	0.622	0.64
U-factor (W/K·m^2)	6.871	3.237	3.237	3.237
Capital cost (\$/m^2)	\$777.37	\$736.25	\$792.98	\$730.33
Fixed O&M cost (\$/m^2)	\$2.37	\$2.37	\$2.37	\$2.37

Table D-10 Baseline Data Center EUIs

	Low-Rise	High-Rise
IT equipment (MJ/m^2·yr)	167.3	167.3
HVAC and lighting equipment (MJ/m^2·yr)	150.6	150.6
Total data center (MJ/m^2·yr)	317.9	317.9

Table D-11 Baseline HVAC System Cost Estimation Sizes

Climate	Low-Rise Baseline			High-Rise Baseline: Code-Compliant			High-Rise Baseline: Common Practice		
	Boilers (kW)	Chillers (kW)	Fans (m^3/s)	Boilers (kW)	Chillers (kW)	Fans (m^3/s)	Boilers (kW)	Chillers (kW)	Fans (m^3/s)
Average	5002	3253	198	5965	4055	214	7294	5085	256

Table D-12 Baseline HVAC System Cost Breakdown

HVAC Input	ASHRAE 90.1-2004 Baseline Hydronic VAV Low-rise	ASHRAE 90.1-2004 Baseline Hydronic VAV High-Rise
Chillers and cooling tower (\$/m^2)	\$15.07	\$15.07
Boilers (\$/m^2)	\$5.27	\$7.10
Air distribution units (\$/m^2)	\$81.70	\$111.51
VAV terminal boxes (\$/m^2)	\$9.04	\$9.15
Pumps (\$/m^2)	\$4.20	\$4.20
Ductwork (\$/m^2)	\$48.01	\$51.34
Water distribution network (\$/m^2)	\$20.24	\$17.65
Life safety (\$/m^2)	\$3.77	\$1.83
Air and water balance (\$/m^2)	\$2.15	\$2.80
Temperature controls (\$/m^2)	\$10.76	\$10.76
Total (\$/m^2)	\$200.10	\$231.64

Table D-13 Low-Rise Exterior Wall EEMs

Insulation R-value, Nominal	Assembly U-Factor (W/K·m^2)	Capital Cost ($/m^2)
R-5.7 c.i.	0.982	$474.15
R-9.5 c.i.	0.647	$481.68
R-13.3 c.i.	0.488	$489.22
R-15.0 c.i.	0.437	$494.60
R-19.5 c.i.	0.346	$497.83
R-22.5 c.i.	0.301	$501.60
R-28.5 c.i.	0.244	$505.37

Table D-14 High-Rise Exterior Wall EEMs

Insulation R-value, Nominal	Assembly U-Factor (W/K·m^2)	Capital Cost ($/m^2)
R-13.0	0.789	$384.81
R-13.0 + R-3.8 c.i.	0.517	$394.50
R-13.0 + R-7.5 c.i.	0.386	$399.88
R-22.5 c.i.	0.244	$428.94
R-28.5 c.i.	0.193	$438.63

Table D-15 Low-rise Roof EEMs

EEM Key	U-Factor (W/K·m^2)	Capital Cost ($/m^2)
R-20 c.i.	0.284	$103.23
R-30 c.i.	0.187	$112.70
R-40 c.i.	0.131	$122.28
R-60 c.i.	0.091	$141.22

Table D-16 Low-Rise Fenestration Construction EEMs

EEM Key	SHGC	VLT	U-Factor (W/K·m^2)	Capital Cost ($/m^2)	Fixed O&M Cost ($/m^2·yr)
Single pane with clear glass	0.81	0.881	6.133	$401.49	$2.26
Single pane with pyrolytic low-e	0.71	0.811	4.230	$449.93	$2.26
Double pane with low-e and argon	0.564	0.745	1.499	$545.73	$2.26
Double pane with low-e2 and argon	0.416	0.75	1.334	$567.26	$2.26
Triple layer with low-e polyester film	0.355	0.535	1.221	$783.61	$2.26
Quadruple layer with low-e polyester films and krypton	0.461	0.624	0.772	$1,008.58	$2.26

Table D-17 High-Rise Fenestration Construction EEMs

EEM Key	SHGC	VLT	U-Factor (W/K·m^2)	Capital Cost ($/m^2)	Fixed O&M Cost ($/m^2·yr)
Single pane with clear glass	0.81	0.881	6.133	$728.18	$2.26
Single pane with tinted glass	0.567	0.431	6.133	$749.60	$2.26
Single pane with pyrolytic low-e	0.71	0.811	4.230	$758.32	$2.26
Double pane with low-e and argon	0.564	0.745	1.499	$818.60	$2.26
Double pane with reflective coating and tinted glass	0.24	0.44	2.941	$824.52	$2.26
Double pane with low-e2 and argon	0.416	0.75	1.334	$842.28	$2.26
Double pane with low-e2 and tinted glass	0.282	0.55	1.635	$842.28	$2.26

Table D-18 Low-Rise Occupancy Sensor LPD Reductions

Space Type	Baseline LPD (W/m^2)	Reduced LPD (W/m^2)	LPD Reduction (Total %)
Office-open	11.84	11.63	1.40%
Office-enclosed	11.84	11.19	5.70%
Conference	13.99	13.99	0.00%
Break room	9.69	9.69	0.00%
Elevator	0.00	0.00	0.00%
Restroom	9.69	9.69	0.50%
Stairs	6.46	6.46	0.00%
Mechanical/electrical room	16.15	15.82	2.00%
Total	11.73	10.66	9.60%

Table D-19 High-Rise Occupancy Sensor LPD Reductions

Space Type	Baseline LPD (W/m^2)	Reduced LPD (W/m^2)	LPD Reduction (Total %)
Office-open	11.84	11.63	1.40%
Office-enclosed	11.84	11.19	5.70%
Conference	13.99	13.99	0.00%
Break room	9.69	9.69	0.00%
Elevator	0.00	0.00	0.00%
Restroom	9.69	9.69	0.50%
Stairs	6.46	6.46	0.00%
Mechanical/electrical room	16.15	15.82	2.00%
Total	11.41	10.33	9.60%

Table D-20 Lighting Power Density EEMs

EEM Key	LPD (W/m^2)	Capital Cost ($/kW)	Capital Cost ($/m^2)	Fixed O&M Cost ($/kW·yr)	Fixed O&M Cost ($/m^2·yr)
Baseline	11.84	$9,418	$112	$77.24	$0.86
42% LPD reduction	6.78	$18,270	$124	$77.24	$0.54

Table D-21 Low-Energy Data Center EUIs

	Low-Rise	High-Rise
IT equipment (MJ/m^2·yr)	122.1	122.1
HVAC and lighting equipment (MJ/m^2·yr)	24.4	24.4
Total data center (MJ/m^2·yr)	146.5	146.5

Table D-22 Baseline and Low-Energy HVAC System Comfort Comparison

Control Set Point	Baseline VAV System			Low Energy Radiant System With DOAS		
	Air Temperature (ºC)	Mean Radiant Temperature (ºC)	PMV	Air Temperature (ºC)	Mean Radiant Temperature (ºC)	PMV
Heating	21.1	21.1	–0.17	20.0	22.8	–0.17
Cooling	23.9	23.9	0.12	25.6	21.1	0.12

Table D-23 Radiant System Temperatures Required for Baseline Equivalent Comfort

Control Set Point	Air Temperature (ºC)	Mean Radiant Temperature (ºC)	Supply Equipment Outlet Temperature (ºC)	Radiant Tube Temperature (ºC)	Radiant Surface Temperature (ºC)
Heating	20.0	22.8	28.9	26.1	25.0
Cooling	25.6	21.2	14.1	16.0	18.3

Table D-24 Radiant System Temperatures Required for Maximum Capacity

Control Set Point	Air Temperature (ºC)	Mean Radiant Temperature (ºC)	Supply Equipment Outlet Temperature (ºC)	Radiant Tube Temperature (ºC)	Radiant Surface Temperature (ºC)
Heating	20.0	24.2	31.6	28.8	27.0
Cooling	25.6	20.4	12.3	14.2	17.0

Table D-25 Radiant System Peak Volumetric Flow Rates Per Floor

Low-Rise Building		High-Rise Building	
Maximum Heating Flow (m^3/s)	Maximum Cooling Flow (m^3/s)	Maximum Heating Flow (m^3/s)	Maximum Cooling Flow (m^3/s)
0.0193	0.0618	0.0064	0.0206

Table D-26 Low-Rise Low-Energy Radiant With DOAS HVAC System Cost Estimation Sizes

Climate	Low-rise Low-Energy				
	DOAS Boiler (kW)	DOAS Chiller (kW)	DOAS Fan (m^3/s)	Radiant Boiler (kW)	Radiant Chiller (kW)
Average	1125	622	26.7	1355	3049

Table D-27 High-Rise Low-Energy Radiant With DOAS HVAC System Cost Estimation Sizes

Climate	High-Rise Low-Energy: Code-Compliant					High-Rise Low Energy: Common Practice				
	DOAS Boiler (kW)	DOAS Chiller (kW)	DOAS Fan (m^3/s)	Radiant Boiler (kW)	Radiant Chiller (kW)	DOAS Boiler (kW)	DOAS Chiller (kW)	DOAS Fan (m^3/s)	Radiant Boiler (kW)	Radiant Chiller (kW)
Average	2180	615	26	1802	2180	2180	2180	26	1802	2180

Table D-28 Low-Energy HVAC System Cost Estimate Breakdown

HVAC Input	Radiant Heating and Cooling With DOAS, Low-Rise	Radiant Heating and Cooling With DOAS, High-Rise
Chillers and cooling tower ($\$/\mathrm{m}^2$)	\$16.36	\$16.36
Boilers ($\$/\mathrm{m}^2$)	\$6.46	\$6.46
Radiant heating and cooling ($\$/\mathrm{m}^2$)	\$117.22	\$116.36
Air distribution units ($\$/\mathrm{m}^2$)	\$10.76	\$11.73
Perimeter heating coils ($\$/\mathrm{m}^2$)	\$1.18	\$2.26
Pumps ($\$/\mathrm{m}^2$)	\$4.20	\$4.20
Ductwork ($\$/\mathrm{m}^2$)	\$39.72	\$49.62
Air system water distribution ($\$/\mathrm{m}^2$)	\$28.09	\$21.85
Life safety ($\$/\mathrm{m}^2$)	\$0.97	\$0.97
Air and water balance ($\$/\mathrm{m}^2$)	\$1.94	\$1.94
Temperature controls ($\$/\mathrm{m}^2$)	\$10.76	\$10.76
Total ($\$/\mathrm{m}^2$)	\$237.56	\$242.30

Table D-29 Low-Energy HVAC System Operational Static Pressure Breakdown

Building Type	Low-Rise Low-Energy (Pa)			High-Rise Low-Energy: Code-Compliant (Pa)			High-Rise Low Energy: Common Practice (Pa)		
	Enthalpy Wheel	Sensible Wheel	IDEC	Enthalpy Wheel	Sensible Wheel	IDEC	Enthalpy Wheel	Sensible Wheel	IDEC
Supply and return fans	1140.8	1140.8	1208.1	1138.3	1138.3	1208.1	1138.3	1138.3	1208.1
Energy recovery	348.7	249.1	249.1	348.7	249.1	249.1	348.7	249.1	249.1
Total	1489.6	1389.9	1457.2	1487.1	1387.4	1454.7	1487.1	1387.4	1454.7

Table D-30 ASHRAE 90.1-2004 Low-Rise Baseline Model Energy Performance

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Site EUI (MJ/m^2·yr)	1307	891	833	1001	851	998
Source EUI (MJ/m^2·yr)	3829	2702	2404	2750	2461	2583
Energy emissions intensity (kgCO$_2$/m^2·yr)	223	158	140	159	143	148
Electricity intensity (MJ/m^2·yr)	1057	760	658	729	674	657
Natural gas intensity (MJ/m^2·yr)	251	131	175	272	176	342
Peak demand (kW)	1984	1750	1721	1908	1690	1818

Table D-31 ASHRAE 90.1-2004 Low-Rise Baseline Model Costs

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
5-TLCC ($/m^2)	$1,496.92	$1,387.43	$1,361.22	$1,451.06	$1,342.80	$1,406.39
Capital cost ($/m^2)	$1,286.44	$1,234.46	$1,220.95	$1,280.20	$1,205.44	$1,249.34
Annual energy cost intensity ($/m^2·yr)	$27.96	$19.83	$17.94	$20.81	$18.32	$19.75
Annual electricity cost intensity ($/m^2·yr)	$25.00	$18.29	$15.90	$17.64	$16.26	$15.77
Annual natural gas cost intensity ($/m^2·yr)	$2.96	$1.54	$2.04	$3.18	$2.06	$3.97

Table D-32 ASHRAE 90.1-2004 Code-Compliant High-Rise Baseline Model Energy Performance

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Site EUI (MJ/m^2·yr)	1218	894	850	986	848	983
Source EUI (MJ/m^2·yr)	3583	2704	2421	2716	2458	2556
Energy emissions intensity (kgCO$_2$/m^2·yr)	208	158	140	157	143	147
Electricity intensity (MJ/m^2·yr)	991	760	657	721	674	653
Natural gas intensity (MJ/m^2·yr)	227	134	193	265	173	330
Peak demand (kW)	1940	1758	1746	1925	1717	1872

Table D-33 ASHRAE 90.1-2004 Code-Compliant High-Rise Baseline Model Costs

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
5-TLCC ($\$/m^2$)	$1,556.06	$1,478.98	$1,458.92	$1,532.21	$1,445.48	$1,501.32
Capital cost ($\$/m^2$)	$1,368.85	$1,333.73	$1,323.85	$1,372.30	$1,313.34	$1,351.77
Annual energy cost intensity ($\$/m^2 \cdot yr$)	$26.22	$19.88	$18.19	$20.59	$18.35	$19.56
Annual electricity cost intensity ($\$/m^2 \cdot yr$)	$23.55	$18.31	$15.94	$17.49	$16.33	$15.73
Annual natural gas cost intensity ($\$/m^2 \cdot yr$)	$2.67	$1.57	$2.25	$3.09	$2.02	$3.83

Table D-34 ASHRAE 90.1-2004 Common Practice High-Rise Baseline Model Energy Performance

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Site EUI ($MJ/m^2 \cdot yr$)	1234	951	939	1087	934	1118
Source EUI ($MJ/m^2 \cdot yr$)	3657	2845	2574	2894	2616	2757
Energy emissions intensity ($kgCO_2/m^2 \cdot yr$)	213	166	149	166	151	157
Electricity intensity ($MJ/m^2 \cdot yr$)	1016	795	681	751	702	676
Natural gas intensity ($MJ/m^2 \cdot yr$)	217	156	258	336	232	442
Peak demand (kW)	1999	1868	1879	2066	1850	2036

Table D-35 ASHRAE 90.1-2004 Common Practice High-Rise Baseline Model Costs

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
5-TLCC ($\$/m^2$)	$1,621.62	$1,568.21	$1,551.41	$1,625.77	$1,534.98	$1,604.17
Capital cost ($\$/m^2$)	$1,426.30	$1,408.34	$1,398.82	$1,447.02	$1,385.40	$1,432.80
Annual energy cost intensity ($\$/m^2 \cdot yr$)	$26.75	$21.09	$19.69	$22.26	$19.89	$21.57
Annual electricity cost intensity ($\$/m^2 \cdot yr$)	$24.19	$19.26	$16.69	$18.35	$17.19	$16.44
Annual natural gas cost intensity ($\$/m^2 \cdot yr$)	$2.56	$1.82	$3.01	$3.91	$2.70	$5.14

Table D-36 Comparison of Low-Rise EUI in MJ/m^2·yr by End Use Between Baseline and 50% Savings Target

EDM Key	1A Miami		3B Las Vegas		4C Seattle		5A Chicago		5B Boulder		7 Duluth	
	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings
Heating	243.3	121.6	121.7	60.9	162.9	81.5	259.3	129.6	163.9	81.9	326.8	163.4
Cooling	385.0	192.5	149.2	74.6	73.8	36.9	125.0	62.5	82.3	41.1	63.8	31.9
Interior lighting	168.1	84.1	168.1	84.1	168.1	84.1	168.1	84.1	168.1	84.1	168.1	84.1
Interior equipment	54.7	27.3	54.7	27.3	54.7	27.3	54.7	27.3	54.7	27.3	54.7	27.3
Fans	58.6	29.3	36.3	18.1	23.6	11.8	34.4	17.2	31.5	15.7	33.5	16.7
Pumps	46.6	23.3	22.1	11.1	12.8	6.4	19.5	9.7	13.1	6.5	13.4	6.7
Heat rejection	25.6	12.8	12.1	6.0	6.7	3.4	9.5	4.7	6.6	3.3	5.3	2.6
Water systems	7.6	3.8	9.3	4.6	12.3	6.1	12.7	6.3	12.6	6.3	15.0	7.5
Data center	317.9	158.9	317.9	158.9	317.9	158.9	317.9	158.9	317.9	158.9	317.9	158.9
Total end uses	1307.4	653.7	891.4	445.7	832.7	416.4	1000.9	500.5	850.6	425.3	998.4	499.2

Table D-37 Comparison of Code-Compliant High-Rise EUI in MJ/m^2·yr by End Use Between Baseline and 50% Savings Target

EDM Key	1A Miami		3B Las Vegas		4C Seattle		5A Chicago		5B Boulder		7 Duluth	
	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings
Heating	219.2	109.6	124.7	62.4	180.7	90.4	252.3	126.1	160.9	80.4	315.0	157.5
Cooling	341.3	170.6	158.0	79.0	79.9	39.9	127.7	63.9	89.5	44.7	68.9	34.4
Interior lighting	163.5	81.7	163.5	81.7	163.5	81.7	163.5	81.7	163.5	81.7	163.5	81.7
Interior equipment	52.9	26.5	52.9	26.5	52.9	26.5	52.9	26.5	52.9	26.5	52.9	26.5
Fans	55.6	27.8	35.9	17.9	25.5	12.7	33.8	16.9	33.1	16.6	33.7	16.9
Pumps	41.1	20.6	23.0	11.5	13.6	6.8	19.6	9.8	14.1	7.0	13.8	6.9
Heat rejection	22.6	11.3	12.6	6.3	7.1	3.6	9.5	4.8	7.1	3.5	5.6	2.8
Water systems	7.6	3.8	9.3	4.6	12.3	6.1	12.7	6.3	12.6	6.3	15.0	7.5
Data center	314.1	157.1	314.1	157.1	314.1	157.1	314.1	157.1	314.1	157.1	314.1	157.1
Total end uses	1218.0	609.0	894.0	447.0	849.7	424.8	986.1	493.0	847.8	423.9	982.5	491.3

Table D-38 Comparison of Common Practice High-Rise EUI in MJ/m^2·yr by End Use Between Baseline and 50% Savings Target

EDM Key	1A Miami		3B Las Vegas		4C Seattle		5A Chicago		5B Boulder		7 Duluth	
	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings	Baseline	50% Savings
Heating	209.8	104.9	147.0	73.5	245.8	122.9	323.1	161.5	219.6	109.8	427.4	213.7
Cooling	365.2	182.6	183.2	91.6	95.7	47.9	149.3	74.6	107.3	53.6	83.4	41.7
Interior lighting	163.5	81.7	163.5	81.7	163.5	81.7	163.5	81.7	163.5	81.7	163.5	81.7
Interior equipment	52.9	26.5	52.9	26.5	52.9	26.5	52.9	26.5	52.9	26.5	52.9	26.5
Fans	52.7	26.4	40.1	20.1	30.3	15.2	38.0	19.0	39.3	19.7	39.5	19.8
Pumps	43.7	21.8	26.5	13.2	16.1	8.0	22.3	11.1	16.5	8.3	15.6	7.8
Heat rejection	24.0	12.0	14.5	7.2	8.5	4.2	11.0	5.5	8.4	4.2	6.7	3.4
Water systems	7.6	3.8	9.3	4.6	12.3	6.1	12.7	6.3	12.6	6.3	15.0	7.5
Data center	314.1	157.1	314.1	157.1	314.1	157.1	314.1	157.1	314.1	157.1	314.1	157.1
Total end uses	1233.6	616.8	951.1	475.5	939.2	469.6	1086.9	543.4	934.4	467.2	1118.1	559.1

Table D-39 ASHRAE 90.1-2007 Low-Rise Baseline Exterior Wall Constructions

Properties	**Climate Zone 1A**	**Climate Zone 3B-NV**	**Climate Zone 4C**	**Climate Zones 5A, and 5B**	**Climate Zone 7**
Key	**Baseline Wall Construction No c.i.**	**Baseline Wall Construction R-7.6 c.i.**	**Baseline Wall Construction R-9.5 c.i.**	**Baseline Wall Construction R-11.4 c.i.**	**Baseline Wall Construction R-15.2 c.i.**
Assembly U-factor ($W/K{\cdot}m^2$)	5.735	0.778	0.647	0.551	0.432
Capital cost ($\$/m^2$)	$389.12	$477.92	$481.68	$485.45	$492.99

Table D-40 ASHRAE 90.1-2007 High-Rise Baseline Exterior Wall Constructions

Properties	**Climate Zone 1A**	**Climate Zone 3B-NV**	**Climate Zones 4C, 5A, 5B, and 7**
Key	**Baseline Wall Construction R-13.0**	**Baseline Wall Construction R-13.0 + R-3.8 c.i.**	**Baseline Wall Construction R-13.0 + R-7.5 c.i.**
Assembly U-factor ($W/K{\cdot}m^2$)	0.789	0.517	0.386
Capital cost ($\$/m^2$)	$384.81	$394.50	$399.88

Table D-41 ASHRAE 90.1-2007 Baseline Roof Constructions

Properties	**Climate Zone 1A**	**Climate Zones 3B-NV, 4C, 5A, 5B, and 7**
Key	**Baseline Roof Construction R-15.0 c.i.**	**Baseline Roof Construction R-20.0 c.i.**
Assembly U-factor ($W/K{\cdot}m^2$)	0.375	0.284
Capital cost ($\$/m^2$)	$98.49	$103.23

Table D-42 ASHRAE 90.1-2007 Low-Rise Baseline Window Constructions

Properties	**Climate Zone 1A**	**Climate Zones 3B-NV**	**Climate Zones 4C, 5A, and 5B**	**Climate Zone 7**
Key	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**	**Baseline Window Construction**
SHGC	0.25	0.25	0.4	0.45
VLT	0.25	0.318	0.508	0.45
U-factor ($W/K{\cdot}m^2$)	6.814	3.691	3.123	2.555
Capital cost ($\$/m^2$)	$534.64	$564.03	$512.04	$508.38
Fixed O&M cost ($\$/m^2$)	$2.37	$2.37	$2.37	$2.37

Table D-43 ASHRAE 90.1-2007 High-Rise Baseline Window Constructions

Properties	Climate Zone 1A	Climate Zones 3B-NV	Climate Zones 4C, 5A, and 5B	Climate Zone 7
Key	Baseline Window Construction	Baseline Window Construction	Baseline Window Construction	Baseline Window Construction
SHGC	0.25	0.25	0.4	0.45
VLT	0.25	0.318	0.508	0.45
U-factor ($W/K{\cdot}m^2$)	6.814	3.691	3.123	2.555
Capital cost ($\$/m^2$)	$825.38	$854.76	$802.77	$799.11
Fixed O&M cost ($\$/m^2$)	$2.37	$2.37	$2.37	$2.37

Table D-44 Low-Rise EUI Comparison Between 90.1-2004 and 90.1-2007 Baselines

Climate Zone	ASHRAE 90.1-2004 Baseline Site Energy Use ($MJ/m^2{\cdot}yr$)	ASHRAE 90.1-2007 Baseline Site Energy Use ($MJ/m^2{\cdot}yr$)
1A Miami	1307.4	1316.8
3B Las Vegas	891.4	891.8
4C Seattle	832.7	823.5
5A Chicago	1000.9	990.4
5B Denver	850.6	840.5
7 Duluth	998.4	970.7

Table D-45 High-Rise EUI Comparison between 90.1-2004 and 90.1-2007 baselines

Climate Zone	ASHRAE 90.1-2004 Baseline Site Energy Use ($MJ/m^2{\cdot}yr$)		ASHRAE 90.1-2007 Baseline Site Energy Use ($MJ/m^2{\cdot}yr$)	
	Code-Compliant	Common Practice	Code-Compliant	Common Practice
1A Miami	1218.0	1233.6	1224.4	1233.0
3B Las Vegas	894.0	951.1	894.3	961.6
4C Seattle	849.7	939.2	831.8	939.2
5A Chicago	986.1	1086.9	976.7	1082.7
5B Denver	847.8	934.4	838.9	931.4
7 Duluth	982.5	1118.1	956.6	1072.0

Table D-46 ASHRAE 90.1-2007 Low-Rise Baseline Model Energy Performance

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Site EUI ($MJ/m^2{\cdot}yr$)	1317	892	823	990	840	971
Source EUI ($MJ/m^2{\cdot}yr$)	3848	2700	2396	2741	2451	2552
Energy emissions intensity ($kgCO_2/m^2{\cdot}yr$)	224	158	139	158	142	147
Electricity intensity ($MJ/m^2{\cdot}yr$)	1060	760	659	730	675	656
Natural gas intensity ($MJ/m^2{\cdot}yr$)	256	132	165	260	166	314
Peak demand (kW)	1982	1747	1726	1908	1693	1813

Table D-47 ASHRAE 90.1-2007 Low-Rise Baseline Model Costs

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
5-TLCC ($\$/m^2$)	$1,499.52	$1,391.18	$1,391.18	$1,451.91	$1,344.76	$1,405.34
Capital cost ($\$/m^2$)	$1,288.69	$1,238.53	$1,238.53	$1,281.55	$1,207.63	$1,250.31
Annual energy cost intensity ($\$/m^2\cdot yr$)	$28.10	$19.82	$17.85	$20.70	$18.21	$19.42
Annual electricity cost intensity ($\$/m^2\cdot yr$)	$25.08	$18.26	$15.93	$17.66	$16.28	$15.76
Annual natural gas cost intensity ($\$/m^2\cdot yr$)	$3.02	$1.55	$1.93	$3.04	$1.93	$3.66

Table D-48 ASHRAE 90.1-2007 Code-Compliant High-Rise Baseline Model Energy Performance

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Site EUI ($MJ/m^2\cdot yr$)	1224	894	832	977	839	957
Source EUI ($MJ/m^2\cdot yr$)	3588	2704	2405	2708	2451	2524
Energy emissions intensity ($kgCO_2/m^2\cdot yr$)	209	158	140	156	142	145
Electricity intensity ($MJ/m^2\cdot yr$)	990	760	658	722	676	651
Natural gas intensity ($MJ/m^2\cdot yr$)	234	134	173	255	163	306
Peak demand (kW)	1934	1757	1755	1930	1723	1862

Table D-49 ASHRAE 90.1-2007 Code-Compliant High-Rise Baseline Model Costs

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
5-TLCC ($\$/m^2$)	$1,559.36	$1,486.99	$1,464.99	$1,535.23	$1,448.79	$1,499.50
Capital cost ($\$/m^2$)	$1,372.51	$1,341.78	$1,330.11	$1,375.41	$1,316.62	$1,352.22
Annual energy cost intensity ($\$/m^2\cdot yr$)	$26.27	$19.88	$18.01	$20.49	$18.28	$19.23
Annual electricity cost intensity ($\$/m^2\cdot yr$)	$23.51	$18.31	$15.99	$17.52	$16.37	$15.69
Annual natural gas cost intensity ($\$/m^2\cdot yr$)	$2.76	$1.57	$2.02	$2.97	$1.90	$3.55

Table D-50 ASHRAE 90.1-2007 Common Practice High-Rise Baseline Model Energy Performance

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Site EUI ($MJ/m^2\cdot yr$)	1233	962	939	1083	931	1072
Source EUI ($MJ/m^2\cdot yr$)	3656	2865	2582	2897	2622	2703
Energy emissions intensity ($kgCO_2/m^2\cdot yr$)	213	167	149	167	152	154
Electricity intensity ($MJ/m^2\cdot yr$)	1016	798	685	754	706	674
Natural gas intensity ($MJ/m^2\cdot yr$)	217	163	254	328	226	398
Peak demand (kW)	2000	1879	1898	2082	1866	2028

Table D-51 ASHRAE 90.1-2007 Common Practice High-Rise Baseline Model Costs

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
5-TLCC ($/m^2)	$1,630.73	$1,579.57	$1,558.58	$1,631.64	$1,541.00	$1,598.94
Capital cost ($/m^2)	$1,435.40	$1,418.04	$1,404.32	$1,451.74	$1,390.13	$1,430.78
Annual energy cost intensity ($/m^2·yr)	$26.74	$21.26	$19.76	$22.27	$19.93	$21.01
Annual electricity cost intensity ($/m^2·yr)	$24.19	$19.36	$16.80	$18.44	$17.30	$16.40
Annual natural gas cost intensity ($/m^2·yr)	$2.55	$1.90	$2.96	$3.82	$2.63	$4.62

Table D-52 Low-Rise Optimized Low-Energy Model Energy Performance: Warm Climates

Metric	Climate Zones								
	1A Miami			3B Las Vegas			4C Seattle		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
Site EUI (MJ/m^2·yr)	1307	554	57.6%	891	386	56.7%	833	382	54.1%
Source EUI (MJ/m^2·yr)	3829	1848	51.7%	2702	1248	53.8%	2404	1158	51.8%
Energy emissions intensity (kgCO$_2$/m^2·yr)	223	109	51.1%	158	73	53.5%	140	68	51.6%
Electricity intensity (MJ/m^2·yr)	1057	547	48.2%	760	363	52.2%	658	326	50.4%
Natural gas intensity (MJ/m^2·yr)	251	7	97.0%	131	23	82.8%	175	56	68.0%
Peak demand (kW)	1984	1822	8.2%	1750	1630	6.9%	1721	1385	19.5%

Table D-53 Low-Rise Optimized Low-Energy Model Energy Performance: Cold Climates

Metric	Climate Zones								
	5A Chicago			5B Boulder			7 Duluth		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
Site EUI (MJ/m^2·yr)	1001	460	54.0%	851	378	55.5%	998	449	55.0%
Source EUI (MJ/m^2·yr)	2750	1390	49.5%	2461	1136	53.9%	2583	1258	51.3%
Energy emissions intensity (kgCO$_2$/m^2·yr)	159	81	48.9%	143	66	53.7%	148	73	50.9%
Electricity intensity (MJ/m^2·yr)	729	390	46.5%	674	318	52.8%	657	338	48.6%
Natural gas intensity (MJ/m^2·yr)	272	70	74.2%	176	61	65.6%	342	112	67.3%
Peak demand (kW)	1908	1680	11.9%	1690	1496	11.5%	1818	1704	6.3%

Table D-54 Code-Compliant High-Rise Optimized Low-Energy Model Energy Performance: Warm Climates

Metric	Climate Zones								
	1A Miami			3B Las Vegas			4C Seattle		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
Site EUI (MJ/m^2·yr)	1218	518	57.5%	894	374	58.2%	850	364	57.1%
Source EUI (MJ/m^2·yr)	3583	1725	51.9%	2704	1191	55.9%	2421	1129	53.4%
Energy emissions intensity (kgCO$_2$/m^2·yr)	208	102	51.3%	158	70	55.7%	140	66	53.0%
Electricity intensity (MJ/m^2·yr)	991	510	48.5%	760	344	54.7%	657	322	51.0%
Natural gas intensity (MJ/m^2·yr)	227	8	96.5%	134	30	77.9%	193	43	77.9%
Peak demand (kW)	1940	1804	7.0%	1758	1587	9.7%	1746	1608	7.9%

Table D-55 Code-Compliant High-Rise Optimized Low-Energy Model Energy Performance: Cold Climates

Metric	Climate Zones								
	5A Chicago			5B Boulder			7 Duluth		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
Site EUI (MJ/m^2·yr)	986	443	55.1%	848	354	58.3%	983	415	57.8%
Source EUI (MJ/m^2·yr)	2716	1333	50.9%	2458	1074	56.3%	2556	1196	53.2%
Energy emissions intensity (kgCO$_2$/m^2·yr)	157	78	50.4%	143	63	56.1%	147	69	52.7%
Electricity intensity (MJ/m^2·yr)	721	374	48.2%	674	303	55.1%	653	327	49.9%
Natural gas intensity (MJ/m^2·yr)	265	69	73.9%	173	51	70.5%	330	88	73.3%
Peak demand (kW)	1925	1665	13.5%	1717	1528	11.0%	1872	1729	7.6%

Table D-56 Common Practice High-Rise Optimized Low-Energy Model Energy Performance: Warm Climates

Metric	Climate Zones								
	1A Miami			3B Las Vegas			4C Seattle		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
Site EUI (MJ/m^2·yr)	1218	628	48.5%	894	484	45.8%	850	531	37.5%
Source EUI (MJ/m^2·yr)	3583	2050	42.8%	2704	1444	46.6%	2421	1429	40.9%
Energy emissions intensity (kgCO$_2$/m^2·yr)	208	120	42.2%	158	84	46.7%	140	82	41.3%
Electricity intensity (MJ/m^2·yr)	991	600	39.4%	760	403	47.0%	657	374	43.1%
Natural gas intensity (MJ/m^2·yr)	227	27	87.9%	134	82	39.0%	193	157	18.7%
Peak demand (kW)	1940	1563	19.4%	1758	1351	23.1%	1746	1378	21.0%

Table D-57 Common Practice High-Rise Optimized Low-Energy Model Energy Performance: Cold Climates

Metric	Climate Zones								
	5A Chicago			5B Boulder			7 Duluth		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
Site EUI (MJ/m^2·yr)	986	628	36.3%	848	518	38.9%	983	620	36.9%
Source EUI (MJ/m^2·yr)	2716	1719	36.7%	2458	1354	44.9%	2556	1517	40.7%
Energy emissions intensity (kgCO$_2$/m^2·yr)	157	99	36.7%	143	78	45.6%	147	86	41.1%
Electricity intensity (MJ/m^2·yr)	721	455	36.9%	674	347	48.6%	653	369	43.4%
Natural gas intensity (MJ/m^2·yr)	265	173	34.5%	173	172	1.0%	330	251	24.0%
Peak demand (kW)	1925	1454	24.5%	1717	1274	25.8%	1872	1509	19.4%

Table D-58 Low-Rise Optimized Low-Energy Model Cost Performance: Warm Climates

Metric	Climate Zones								
	1A Miami			3B Las Vegas			4C Seattle		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
5-TLCC ($\$/m^2$)	$1,496.92	$1,670.85	–11.6%	$1,387.43	$1,482.28	–6.8%	$1,361.22	$1,504.28	–10.5%
Capital cost ($\$/m^2$)	$1,286.44	$1,470.79	–14.3%	$1,234.46	$1,342.07	–8.7%	$1,220.95	$1,363.42	–11.7%
Annual energy cost intensity ($\$/m^2\cdot yr$)	$27.96	$14.57	47.9%	$19.83	$9.75	50.8%	$17.94	$8.79	51.0%
Annual electricity cost intensity ($\$/m^2\cdot yr$)	$25.00	$14.48	42.1%	$18.29	$9.49	48.1%	$15.90	$8.14	48.8%
Annual natural gas cost intensity ($\$/m^2\cdot yr$)	$2.96	$0.09	97.1%	$1.54	$0.26	83.1%	$2.04	$0.65	68.1%

Table D-59 Low-Rise Optimized Low-Energy Model Cost Performance: Cold Climates

Metric	Climate Zones								
	5A Chicago			5B Boulder			7 Duluth		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
5-TLCC ($\$/m^2$)	$1,451.06	$1,603.81	–10.5%	$1,342.80	$1,451.21	–8.1%	$1,406.39	$1,561.34	–11.0%
Capital cost ($\$/m^2$)	$1,280.20	$1,432.63	–11.9%	$1,205.44	$1,321.68	–9.6%	$1,249.34	$1,404.21	–12.4%
Annual energy cost intensity ($\$/m^2\cdot yr$)	$20.81	$10.94	47.4%	$18.32	$8.80	52.0%	$19.75	$9.77	50.5%
Annual electricity cost intensity ($\$/m^2\cdot yr$)	$17.64	$10.13	42.6%	$16.26	$8.10	50.2%	$15.77	$8.48	46.2%
Annual natural gas cost intensity ($\$/m^2\cdot yr$)	$3.18	$0.81	74.5%	$2.06	$0.70	65.9%	$3.97	$1.29	67.5%

Table D-60 Code-Compliant High-rise Optimized Low-Energy Model Cost Performance: Warm Climates

Metric	Climate Zones								
	1A Miami			3B Las Vegas			4C Seattle		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
5-TLCC ($/m^2)	$1,556.06	$1,657.89	-6.5%	$1,478.98	$1,498.23	-1.3%	$1,458.92	$1,531.48	-5.0%
Capital cost ($/m^2)	$1,368.85	$1,482.30	-8.3%	$1,333.73	$1,374.90	-3.1%	$1,323.85	$1,404.43	-6.1%
Annual energy cost intensity ($/m^2·yr)	$26.22	$13.88	47.0%	$19.88	$9.49	52.3%	$18.19	$8.73	52.0%
Annual electricity cost intensity ($/m^2·yr)	$23.55	$13.79	41.4%	$18.31	$9.15	50.0%	$15.94	$8.24	48.3%
Annual natural gas cost intensity ($/m^2·yr)	$2.67	$0.09	96.6%	$1.57	$0.34	78.1%	$2.25	$0.50	78.0%

Table D-61 Code-Compliant High-Rise Optimized Low-Energy Model Cost Performance: Cold Climates

Metric	Climate Zones								
	5A Chicago			5B Boulder			7 Duluth		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
5-TLCC ($/m^2)	$1,532.21	$1,604.86	-4.7%	$1,445.48	$1,482.45	-2.6%	$1,501.32	$1,582.63	-5.4%
Capital cost ($/m^2)	$1,372.30	$1,453.28	-5.9%	$1,313.34	$1,367.15	-4.1%	$1,351.77	$1,443.58	-6.8%
Annual energy cost intensity ($/m^2·yr)	$20.59	$10.79	47.6%	$18.35	$8.55	53.4%	$19.56	$9.36	52.1%
Annual electricity cost intensity ($/m^2·yr)	$17.49	$9.99	42.9%	$16.33	$7.95	51.3%	$15.73	$8.34	47.0%
Annual natural gas cost intensity ($/m^2·yr)	$3.09	$0.80	74.1%	$2.02	$0.59	70.7%	$3.83	$1.02	73.4%

Table D-62 Common Practice High-Rise Optimized Low-Energy Model Cost Performance: Warm Climates

Metric	Climate Zones								
	1A Miami			3B Las Vegas			4C Seattle		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
5-TLCC $(\$/m^2)$	$1,556.06	$1,777.80	-14.2%	$1,478.98	$1,625.28	-9.9%	$1,458.92	$1,662.68	-14.0%
Capital cost $(\$/m^2)$	$1,368.85	$1,589.23	-16.1%	$1,333.73	$1,488.91	-11.6%	$1,323.85	$1,515.60	-14.5%
Annual energy cost intensity $(\$/m^2\cdot yr)$	$26.22	$15.90	39.4%	$19.88	$11.49	42.2%	$18.19	$11.86	34.8%
Annual electricity cost intensity $(\$/m^2\cdot yr)$	$23.55	$15.58	33.8%	$18.31	$10.54	42.4%	$15.94	$10.03	37.1%
Annual natural gas cost intensity $(\$/m^2\cdot yr)$	$2.67	$0.32	88.1%	$1.57	$0.95	39.5%	$2.25	$1.83	18.6%

Table D-63 Common Practice High-Rise Optimized Low-Energy Model Cost Performance: Cold Climates

Metric	Climate Zones								
	5A Chicago			5B Boulder			7 Duluth		
	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings	Baseline	Low-Energy	Percent Savings
5-TLCC $(\$/m^2)$	$1,532.21	$1,740.09	-13.6%	$1,445.48	$1,602.31	-10.8%	$1,501.32	$1,702.42	-13.4%
Capital cost $(\$/m^2)$	$1,372.30	$1,567.13	-14.2%	$1,313.34	$1,472.03	-12.1%	$1,351.77	$1,542.32	-14.1%
Annual energy cost intensity $(\$/m^2\cdot yr)$	$20.59	$14.15	31.3%	$18.35	$11.13	39.4%	$19.56	$12.68	35.2%
Annual electricity cost intensity $(\$/m^2\cdot yr)$	$17.49	$12.14	30.6%	$16.33	$9.13	44.1%	$15.73	$9.77	37.9%
Annual natural gas cost intensity $(\$/m^2\cdot yr)$	$3.09	$2.01	34.8%	$2.02	$2.00	1.0%	$3.83	$2.91	24.0%

Table D-64 Low-Rise Simple Payback Results

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Capital cost increase ($\$/m^2$)	$184.39	$107.64	$142.51	$152.52	$116.25	$154.89
Capital cost increase (%)	14.3	8.7	11.7	11.9	9.6	12.4
Annual energy cost savings ($\$/m^2\cdot yr$)	$13.45	$10.01	$9.15	$9.80	$9.47	$9.90
Simple payback period (yr)	13.7	10.8	15.6	15.6	12.3	15.6

Table D-65 Code-Compliant High-Rise Simple Payback Results

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Capital cost increase ($\$/m^2$)	$113.45	$41.12	$80.62	$80.94	$53.82	$91.82
Capital cost increase (%)	8.3	3.1	6.1	5.9	4.1	6.8
Annual energy cost savings ($\$/m^2\cdot yr$)	$12.38	$10.44	$9.47	$9.80	$9.90	$10.23
Simple payback period (yr)	9.2	3.9	8.5	8.3	5.4	9

Table D-66 Common Practice High-Rise Simple Payback Results

Metric	Climate Zones					
	1A Miami	3B Las Vegas	4C Seattle	5A Chicago	5B Boulder	7 Duluth
Capital cost increase ($\$/m^2$)	$220.34	$155.11	$191.71	$194.83	$158.77	$190.63
Capital cost increase (%)	16.1	11.6	14.5	14.2	12.1	14.1
Annual energy cost savings ($\$/m^2\cdot yr$)	$10.33	$8.40	$6.35	$6.46	$7.32	$6.89
Simple payback period (yr)	21.3	18.5	30.2	30.2	21.7	27.7

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14. **ABSTRACT** *(Maximum 200 Words)*

This Technical Support Document (TSD) documents technical analysis that informs design guidance for designing and constructing large office buildings that achieve 50% net site energy savings over baseline buildings defined by minimal compliance with respect to ANSI/ASHRAE/IESNA Standard 90.1-2004. This report also represents a step toward developing a methodology for using energy modeling in the design process to achieve aggressive energy savings targets. This report documents the modeling and analysis methods used to identify design recommendations for six climate zones that capture the range of U.S. climate variability; demonstrates how energy savings change between ASHRAE Standard 90.1-2007 and Standard 90.1-2004 to determine baseline energy use; uses a four-story “low-rise” prototype to analyze the effect of building aspect ratio on energy use intensity; explores comparisons between baseline and low-energy building energy use for alternate energy metrics (net source energy, energy emissions, and energy cost); and examines the extent to which glass curtain construction limits achieve energy savings by using a 12-story “high-rise” prototype.

15. **SUBJECT TERMS**
technical support document; tsd; energy modeling; climate zone; energy use intensity; eui; aspect ratio; glass curtain; large office

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