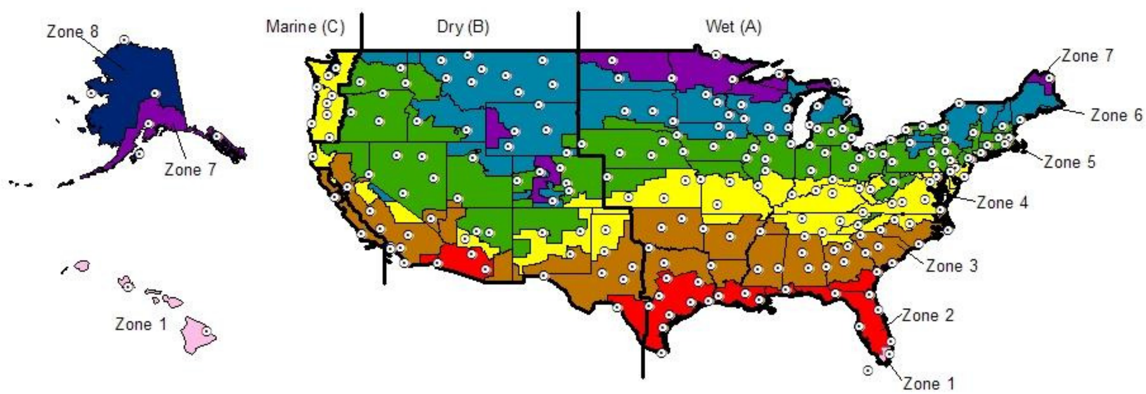
NIST Technical Note 1732

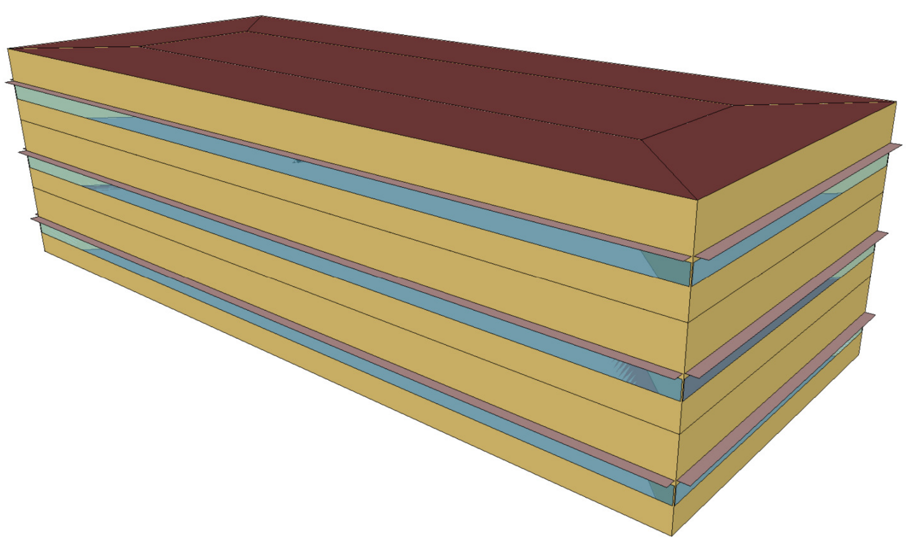
U.S. Department of Commerce
National Institute of Standards and Technology

Applied Economics Office
Engineering Laboratory
Gaithersburg, Maryland 20899

Prototype Commercial Buildings for Energy and Sustainability Assessment: Design Specification, Life-Cycle Costing and Carbon Assessment

Joshua D. Kneifel





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U.S. DEPARTMENT OF COMMERCE

John Bryson, Secretary

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

Dr. Patrick D. Gallagher, Under Secretary of Commerce for Standards and Technology and Director

Abstract

Energy efficiency requirements in current commercial building energy codes vary across states, and most states have not yet adopted the newest energy standards. Current state energy code adoptions range across all editions of the *ASHRAE 90.1 Standard* (*-1999, -2001, -2004,* and *-2007*). Some states do not have a code requirement for energy efficiency, leaving it up to the locality or jurisdiction to set its own requirement. The ability for states to quantify the relative costs and benefits of past or future code adoptions can inform policymakers with respect to the outcomes from their decisions.

The Engineering Laboratory's Applied Economics Office has developed an extensive database, known as the Building Industry Reporting and Design for Sustainability (BIRDS) database, which allows the comparison of the energy efficiency and sustainability of alternative building designs based on different editions of *ASHRAE Standard 90.1*. The expansive database is a compilation of multiple data sources, including results from 13 680 whole building energy simulations for 12 commercial building prototypes in 228 cities across all U.S. states, building construction costs from RS Means and Whitestone databases, energy cost data collected from the Energy Information Administration, and emissions data collected from the Environmental Protection Agency. This report documents the prototype building designs and the life-cycle costing and carbon assessment data and approaches implemented in the BIRDS building energy efficiency and sustainability database.

Keywords

Building economics; economic analysis; life-cycle costing; carbon assessment; energy efficiency; commercial buildings

Preface

The research documented in this report was conducted by the Applied Economics Office in the Engineering Laboratory (EL) at the National Institute of Standards and Technology (NIST). This document is the second of a series of reports on the BIRDS database, the first being NIST Technical Note 1716 – "Prototype Commercial Buildings for Energy and Sustainability Assessment: Whole Building Energy Simulation Design" that documents the whole building energy simulation designs. The report is designed to document the data sources, assumptions, and approaches implemented in developing the energy, life-cycle cost, and carbon assessments for new commercial buildings. The intended audience is the National Institute of Standards and Technology, researchers in the commercial building sector, and any other government or private research group that is concerned with energy efficiency in commercial building designs.

Disclaimers

Certain trade names and company products are mentioned in the text in order to adequately specify the technical procedures and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

The policy of the National Institute of Standards and Technology is to use metric units in all of its published materials. Because this report is intended for the U.S. construction industry that uses U.S. customary units, it is more practical and less confusing to include U.S. customary units as well as metric units. Measurement values in this report are therefore stated in metric units first, followed by the corresponding values in U.S. customary units within parentheses.

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List of Acronyms

Acronym	Definition
AEDG	Advanced Energy Design Guide
AEO	Applied Economics Office
AFUE	Annual Fuel Utilization Efficiency
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BEES	Building for Environmental and Economic Sustainability
BIM	Building Information Model
BIRDS	Building Industry Reporting and Design for Sustainability
CBECS	Commercial Building Energy Consumption Survey
CH4	Methane
ci	continuous insulation
CO2	Carbon Dioxide
CO2e	Carbon Dioxide Equivalent
COP	Coefficienct of Performance
DOE	Department of Energy
DSIRE	Database of State Incentives for Renewables & Efficiency
EEFG	EnergyPlus Example File Generator
EER	Energy Efficiency Ratio
eGRID	Emissions and Generation Resource Integrated Database
EIA	Energy Information Administration
EL	Engineering Laboaratory
EPA	Environmental Protection Agency
EPS	Expanded Polystyrene
ERDC	Engineer Research and Development Center
FEMP	Federal Energy Management Program
FERC	Federal Energy Regulatory Commission
GWP	Global Warming Potential
HVAC	Heating, Ventilating, and Air Conditioning
I-P	Inch-Pounds (Customary Units)
IEAD	Insulation Entirely Above Deck
IECC	International Energy Conservation Code

Acronym	Definition
ISO	International Organization for Standardization
LCA	Life-Cycle Assessment
LCC	Life-Cycle Cost
LEC	Low Energy Case
MRR	Maintenance, Repair, and Replacement
N2O	Nitrous Oxide
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
S-I	System International (Metric Units)
SEER	Seasonal Energy Efficiency Ratio
SFCE	Square Foot Cost Estimator
SHGC	Solar Heat Gain Coefficient
SPV	Single Present Value
TN	Technical Note
USACE	United States Army Corp of Engineers
UPV*	Uniform Present Value Factor Modified for Fuel Price Escalation
VT	Visual Transmittance
XPS	Extruded Polystyrene

1 Introduction

1.1 Background and Purpose

Energy efficiency requirements in current commercial building energy codes vary across states, and most states have not yet adopted the newest energy standards. Current state energy code adoptions range across all editions of the *ASHRAE 90.1 Standard* (*-1999, -2001, -2004,* and *-2007*). Some states do not have a code requirement for energy efficiency, leaving it up to the locality or jurisdiction to set its own requirement. There may be significant energy and cost savings to be realized by states if they were to adopt more energy efficient commercial building energy standards.

The purpose of this report is to document the prototype building designs and the life-cycle costing and carbon assessment approaches implemented in the Building Industry Reporting and Design for Sustainability (BIRDS) database. Future analysis of the database results will be able to cite this documentation, allowing the research to focus on the results instead of repeatedly documenting the assumptions and approaches.

1.2 Literature Review

The National Renewable Energy Laboratory (NREL) has documented 16 commercial prototypical buildings for 16 different climate zones.[1] These 256 reference commercial buildings are based on the Commercial Building Energy Consumption Survey (CBECS) database and the *American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 90.1 Standard*, and represent greater than 70 % of the U.S. building stock. These prototypes have become the basis for significant research in the analysis of energy efficiency measures in commercial buildings. In a similar manner, this report will define prototypical buildings that can be used to research energy efficiency in commercial buildings.

No study has attempted to document the framework, assumptions, data sources, and approaches necessary to connect whole building energy simulation results to both life-cycle cost and carbon assessment analysis. This report fills the gap in an effort to enable whole building sustainability analysis.

1.3 Approach

The prototype commercial building designs are based on a compilation of sources, including the *EnergyPlus Example File Generator* (*EEFG*), *ASHRAE 90.1*, CBECS, and the RS Means *Square Foot Cost Estimator (SFCE)*, and represent a significant portion of the U.S. commercial building stock. The whole building energy simulations are generated

[1] Field, Deru, and Studer (2010)

by the *EnergyPlus EEFG*. The *EEFG* narrows down a building's description into simple, high-level characteristics: building geometry, orientation, number of floors, floor height, building type, wall and roof construction type, window-to-wall ratio, and location. The remaining building parameters are defined based on the chosen edition of the *ASHRAE 90.1* building energy standard and some default values based on the building type. This report will describe simulation parameters that relate to building cost estimates.[2]

Whole building sustainability is analyzed on the basis of operating energy use, its resultant carbon emissions, and building life-cycle costs. Building construction and operating cost data are based on RS Means *CostWorks* databases and Energy Information Administration (EIA) energy cost data while the life-cycle costing approach is based on American Society for Testing and Materials (ASTM) Standards for Building Economics. The initial cost of constructing a building is estimated using the RS Means *SFCE*. RS Means CostWorks databases are used to adjust the building costs to match *ASHRAE 90.1*-compliant building designs. Carbon assessment for operating energy-related greenhouse gas emissions is based on data originating from the Environmental Protection Agency (EPA) Emissions and Generation Resource Integrated Database (eGRID) and the *Building for Environmental and Economic Sustainability* (*BEES*) database. The carbon assessment approach is based on International Organization for Standardization (ISO) life-cycle assessment standards.

[2] See NIST Technical Note (TN) 1716 – "Prototype Commercial Buildings for Energy and Sustainability Assessment: Whole Building Energy Simulation Design" for energy simulation details.

2 Commercial Building Prototypes

The prototype buildings in this study are defined by two aspects: building types and building designs. Twelve building types are selected to represent about half of the existing building stock in the United States. Five building designs, based on different editions of *ASHRAE 90.1*, are created for each building type to compare different energy efficiency performance levels.

2.1 Building Types

The building characteristics in Table 2-1 describe the 12 building types used in this study, which include 2 dormitories, 2 apartment buildings, 1 hotel, 3 office buildings, 2 schools, 1 retail store, and 1 restaurant, and represent 46 % of the U.S. commercial building stock floor space.[3] The prototype buildings range in size from 465 m^2 (5000 ft^2) to 41 806 m^2 (450 000 ft^2).[4] The building abbreviations given in the second column of Table 2-1 are used to represent the building types in tables throughout this study.

Table 2-1 Building Characteristics

Building Type	Bldg. Abbr.	Floors	Floor Height m (ft)	Wall	Roof†	Pct. Glazing	Building Size m^2 (ft^2)	CBECS Occupancy Type	U.S. Floor Space (%)
Dormitory	DORMI04	4	3.66 (12)	Mass	IEAD	20 %	3097 (33 333)	Lodging	7.1 %
Dormitory	DORMI06	6	3.66 (12)	Steel	IEAD	20 %	7897 (85 000)		
Hotel	HOTEL15	15	3.05 (10)	Steel	IEAD	100 %	41 806 (450 000)		
Apartment	APART04	4	3.05 (10)	Mass	IEAD	12 %	2787 (30 000)		
Apartment	APART06	6	3.15 (10)	Steel	IEAD	14 %	5574 (60 000)		
School, Elem.	ELEMS01	1	4.57 (15)	Mass	IEAD	25 %	4181 (45 000)	Education	13.8 %
School, High	HIGHS02	2	4.57 (15)	Mass	IEAD	25 %	12 077 (130 000)		
Office	OFFIC03	3	3.66 (12)	Mass	IEAD	20 %	1858 (20 000)	Office	17.0 %
Office	OFFIC08	8	3.66 (12)	Mass	IEAD	20 %	7432 (80 000)		
Office	OFFIC16	16	3.05 (10)	Steel	IEAD	100 %	24 155 (260 000)		
Retail Store	RETAIL1	1	4.27 (14)	Mass	IEAD	10 %	743 (8000)	Mercantile*	6.0 %
Restaurant	RSTRNT1	1	3.66 (12)	Wood	IEAD	30 %	465 (5000)	Food Service	2.3 %

*Only includes non-mall floor area.
†IEAD = Insulation Entirely Above Deck

2.2 Building Designs

Current state energy codes are based on different iterations of the *International Energy Conservation Code (IECC)* or *ASHRAE 90.1 Standards*, which have requirements that

[3] Based on the Commercial Building Energy Consumption Survey (CBECS) database

[4] The 12 prototype buildings used in this study are different than the NREL prototype buildings.

vary based on a building's characteristics and the climate zone of the location. For this study, the *ASHRAE Standard*-equivalent design is used to meet current state energy codes and to define the alternative building designs.

Table 2-2 shows that current commercial building energy codes vary by state.[5] In a few instances, local jurisdictions have adopted energy standards that are more stringent than the state energy codes.[6] These cities are also included in Table 2-2.

Table 2-2 Energy Code by State and City Exceptions

Location	Energy Code	Location	Energy Code	Location	Energy Code
AK	**None**	**IN**	**2007**	**NV**	**2004**
AL	**None**	**KS**	**None**	**NY**	**2007**
Huntsville	2001	**KY**	**2007**	**OH**	**2007**
AR	**2001**	**LA**	**2007**	**OK**	**None**
AZ	**None**	**MA**	**2007**	**OR**	**2007**
Flagstaff	2004	**MD**	**2007**	**PA**	**2007**
Phoenix	2004	**ME**	**None**	**RI**	**2007**
Tucson	2004	**MI**	**2007**	**SC**	**2004**
CA	**2007**	**MN**	**2004**	**SD**	**None**
CO	**2001**	**MO**	**None**	Huron	2001
Grand Junction	2004	St Louis	2001	**TN**	**2004**
CT	**2004**	**MS**	**None**	**TX**	**2007**
DE	**2007**	**MT**	**2007**	**UT**	**2007**
FL	**2007**	**NC**	**2007**	**VA**	**2007**
GA	**2007**	**ND**	**None**	**VT**	**2007**
HI	**2004**	**NE**	**2007**	**WA**	**2007**
IA	**2007**	**NH**	**2007**	**WI**	**2007**
ID	**2007**	**NJ**	**2007**	**WV**	**2001**
IL	**2007**	**NM**	**2007**	**WY**	**None**

Note: Some city ordinances require energy codes that exceed state energy codes.
Note: State codes as of December 1, 2010.

State energy codes vary from no statewide code to *ASHRAE 90.1-2007* with some regional trends shown in Figure 2-1. The states in the central U.S. tend to wait longer to adopt newer editions of *ASHRAE 90.1*. However, there are many cases in which energy codes of neighboring states vary drastically. For example, Illinois, Iowa, and Nebraska have adopted *ASHRAE 90.1-2007* while Kansas, Missouri, and Oklahoma do not have any energy code, Arkansas has adopted *ASHRAE 90.1-2001*, and Tennessee has adopted *ASHRAE 90.1-2004*.

[5] State energy codes as of December 1, 2011 according to the DOE Building Technologies Program.

[6] Local and jurisdictional requirements are obtained from the Database of State Incentives for Renewables and Efficiency (DSIRE). State energy code requirements targeting only public buildings and green standards are ignored in this study.

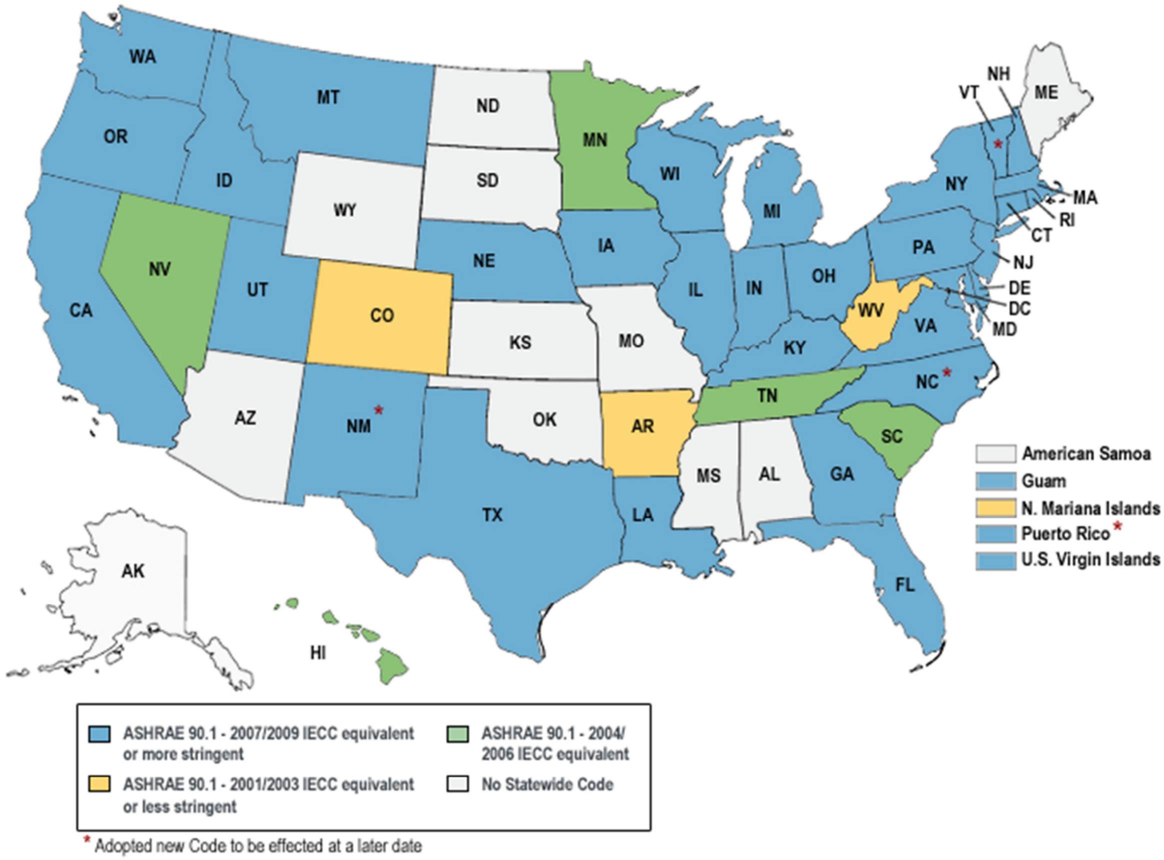

Figure 2-1 State Commercial Energy Codes[7]

The prototype buildings are designed to meet the requirements for each of the editions of *ASHRAE 90.1* (*-1999, -2001, -2004,* and *-2007*) and an additional building design option defined as the "Low Energy Case" (LEC), which goes beyond *ASHRAE 90.1-2007* in a number of ways. The LEC design increases the thermal efficiency of insulation and windows beyond *ASHRAE 90.1-2007*, reduces the lighting power density, and adds daylighting and window overhangs. The LEC design assumes the same HVAC equipment efficiency as required by *ASHRAE 90.1-2007*. For this study, *ASHRAE 90.1-1999* is assumed to be "common practice," and is used for the building design requirements in states with no statewide energy code.

Table B-1 in Appendix B lists the cities included in the BIRDS database and their current *ASHRAE* climate zones. The 228 cities and current *ASHRAE* climate zones for the U.S. are mapped in Figure 2-2. These cities are selected for three reasons. First, the cities are spread out to represent the entire United States, and represent as many climate zones in each state as possible. Second, the locations cover all the major population centers in the

[7] Obtained from the DOE Building Technologies Program in October 2011.

country. Third, multiple locations for a climate zone within a state are included to allow building costs to vary for each building design.

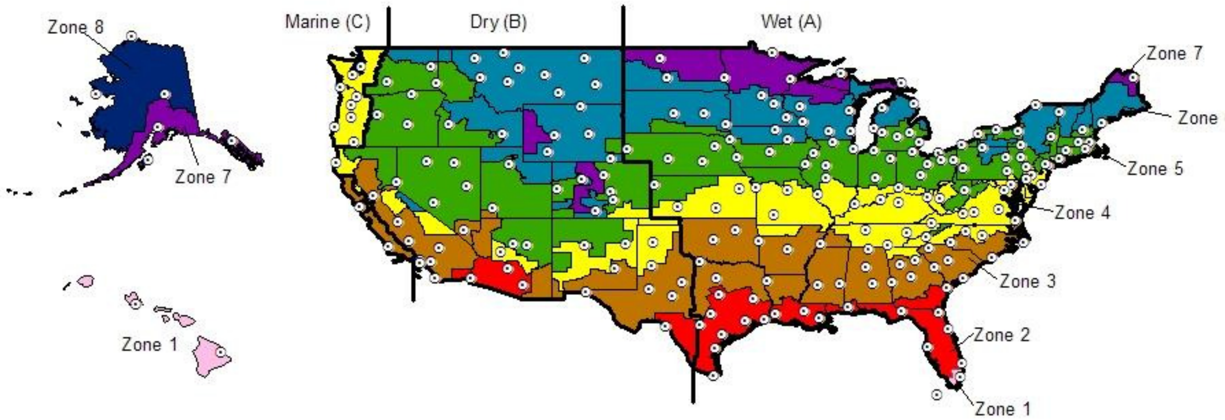

Figure 2-2 Cities and *ASHRAE-2004/2007* Climate Zones

The *ASHRAE*-defined climate zones were consolidated from the 26 climate zones shown in Table 2-3 for *ASHRAE 90.1-1999* and *90.1-2001* into 8 climate zones in *ASHRAE 90.1-2004* and *90.1-2007*. The consolidation is more complex than simply grouping the *90.1-2001* climate zones together. The zones in Table 2-3 are based on a city's cooling degree days at a base of 10 °C (50 °F) (CDD50) and heating degree days at a base of 18 °C (65 °F) (HDD65) while the zones in Figure 2-2 are based on a county's cooling and heating degree days. The generalization results in some cities located in the same climate zone in *ASHRAE 90.1-2001* being located in a different climate zone in *ASHRAE 90.1-2004*. The new climate zones are further separated into subzones, "wet," "dry," and "marine," as shown in Figure 2-2, for a total of 16 subzones.

Table 2-3 *ASHRAE 90.1-1999/2001* Climate Zone Definitions

CDD50	Climate Zone											
10801+	1											
9001-10800	2											
7201-9000	3	5										
5401-7200	4	6	8	10								
3601-5400		7	9	11	13	16						
1801-3600				12	14	17	19	21				
0-1800					15	18	20	22	23	24	25	26
HDD65	0-900	901-1800	1801-2700	2701-3600	3601-5400	5401-7200	7201-9000	9001-10800	10801-12600	12601-16200	16201-19800	19801+
CDD50 = Cooling Degree Days base 10°C (50°F) HDD65 = Heating Degree Days base 18°C (65°F)												

Occupancy types for the prototype buildings are based on the 1999 Commercial Building Energy Consumption Survey (CBECS) "principal building activity" categories. The principal building activity determines the maximum people density, electrical plug density, and lighting power density, and the correlating density schedules. Table 2-4 summarizes each building type's maximum densities. The maximum number of occupants varies between 1 person per 7.0 m^2 (75 ft^2) to 1 person per 27.9 m^2 (300 ft^2). The maximum interior lighting density and daily schedule varies based on the occupancy type and the edition of *ASHRAE 90.1* or Low Energy Case (LEC) building design. All building types are assumed to have zero external lighting loads. The maximum electrical equipment load varies between 1.08 W/m^2 (0.10 W/ft^2) to 8.07 W/m^2 (0.75 W/ft^2).[8]

Table 2-4 Occupancy, Lighting, and Equipment

Bldg. Abbr.	ASHRAE 90.1 Occupancy Type	Max. Occ.	m^2 (ft^2) Per Occupant	Lighting W/m^2 (ft^2)	Equipment W/m^2 (ft^2)
DORMI04	Dormitory	99	23.2 (250)	8.6 to 16.1 (0.8 to 1.5)	2.69 (0.25)
DORMI06	Dormitory	342	23.2 (250)	8.6 to 16.1 (0.8 to 1.5)	2.69 (0.25)
HOTEL15	Hotel	1800	23.2 (250)	8.6 to 18.3 (0.8 to 1.7)	2.69 (0.25)
APART04	Dormitory	90	23.2 (250)	8.6 to 18.3 (0.8 to 1.7)	2.69 (0.25)
APART06	Dormitory	240	23.2 (250)	8.6 to 18.3 (0.8 to 1.7)	2.69 (0.25)
ELEMS01	School	602	7.0 (75)	10.8 to 16.1 (1.0 to 1.5)	5.38 (0.50)
HIGHS02	School	1740	7.0 (75)	10.8 to 16.1 (1.0 to 1.5)	5.38 (0.50)
OFFIC03	Office	72	25.5 (275)	8.6 to 14.0 (0.8 to 1.3)	8.07 (0.75)
OFFIC08	Office	288	25.5 (275)	8.6 to 14.0 (0.8 to 1.3)	8.07 (0.75)
OFFIC16	Office	944	25.5 (275)	8.6 to 14.0 (0.8 to 1.3)	8.07 (0.75)
RETAIL1	Retail	27	27.9 (300)	16.1 to 20.5 (1.5 to 1.9)	2.69 (0.25)
RSTRNT1	Dining: Fast Food	50	9.3 (100)	14.0 to 19.4 (1.3 to 1.8)	1.08 (0.10)

The square footage, number of floors, floor height, wall type, roof type, percent glazing, and heating, ventilation, and air conditioning (HVAC) system for each building type are based on the RS Means *Square Foot Cost Estimator* (*SFCE*) default prototype specifications. The cooling system is assumed to run on electricity while the heating system is assumed to run on natural gas. Table 2-5 identifies the heating and cooling equipment for each building type.

[8] See NIST Technical Note (TN) 1716 – "Prototype Commercial Buildings for Energy and Sustainability Assessment: Whole Building Energy Simulation Design" for additional details regarding the energy simulation design.

Table 2-5 HVAC Equipment by Building Type

Building Type	Cooling Equipment	Heating Equipment
DORMI04	Rooftop Packaged Unit	Furnace
DORMI06	Air-Cooled Chiller	Hot Water Boiler
HOTEL15	Water-Cooled Chiller	Hot Water Boiler
APART04	Air-Cooled Chiller	Hot Water Boiler
APART06	Air-Cooled Chiller	Hot Water Boiler
ELEMS01	Split System with Condensing Unit	Hot Water Boiler
HIGHS02	Water-Cooled Chiller	Hot Water Boiler
OFFIC03	Rooftop Packaged Unit	Furnace
OFFIC08	Rooftop Packaged Unit	Furnace
OFFIC16	Water-Cooled Chiller	Hot Water Boiler
RETAIL1	Rooftop Packaged Unit	Furnace
RSTRNT1	Rooftop Packaged Unit	Furnace

3 Building Construction Costs

The cost data collected to estimate building life-cycle costs originates from multiple sources, including RS Means *CostWorks* databases, Whitestone (2008), and the Energy Information Administration (EIA). Categories of cost include initial building construction costs, maintenance, repair, and replacement costs, energy costs, and building residual value. Each of these cost categories and associated costing approaches are described in detail in this chapter.

Building construction costs are obtained from the RS Means *CostWorks* online databases. The costs of a baseline building are estimated by the RS Means *CostWorks SFCE* to obtain the total baseline costs and the baseline costs for each building component for each building type. The RS Means *SFCE* baseline building is then adjusted to create a building that is compliant with each of the five energy efficiency design alternatives: *ASHRAE 90.1-1999*, *ASHRAE 90.1-2001*, *ASHRAE 90.1-2004*, *ASHRAE 90.1-2007*, and the higher efficiency "Low Energy Case" (LEC) design.

Designing to the standards is accomplished by adjusting five cost components – roof insulation, wall insulation, windows, lighting, and HVAC. A summary of the minimum requirement ranges for each building design is given in Table 3-1.

Table 3-1 Energy Efficiency Component Requirements for Alternative Building Designs

Design Component	Parameter	Units	ASHRAE 90.1-1999	ASHRAE 90.1-2001	ASHRAE 90.1-2004	ASHRAE 90.1-2007	Low Energy Case*
Roof Insulation	R-Value	m^2·K/W (ft^2·°F·h/Btu)	1.7 to 4.4 (10.0 to 25.0)	1.7 to 4.4 (10.0 to 25.0)	2.6 to 3.5 (15.0 to 20.0)	2.6 to 3.5 (15.0 to 20.0)	4.4 to 6.2 (25.0 to 35.0)
Wall Insulation	R-Value	m^2*K/W (ft^2·°F·h/Btu)	0.0 to 3.8 (0.0 to 21.6)	0.0 to 3.8 (0.0 to 21.6)	0.0 to 2.7 (0.0 to 15.2)	0.0 to 2.7 (0.0 to 15.2)	0.7 to 5.5 (3.8 to 31.3)
Windows	U-Value	W/(m2·K) (Btu/(h·ft^2·°F))	1.42 to 7.21 (0.25 to 1.27)	1.42 to 7.21 (0.25 to 1.27)	1.99 to 6.47 (0.35 to 1.14)	2.50 to 6.47 (0.44 to 1.14)	1.97 to 6.42 (0.35 to 1.13)
	SHGC	Fraction	0.14 to NR†	0.14 to NR†	0.17 to NR†	0.25 to NR	0.25 to 0.47
Lighting	Power Density	W/m^2 (W/ft^2)	14.0 to 20.5 (1.3 to 1.9)	14.0 to 20.5 (1.3 to 1.9)	10.8 to 16.1 (1.0 to 1.5)	10.8 to 16.1 (1.0 to 1.5)	8.6 to 16.1 (0.8 to 1.5)
Overhangs			None	None	None	None	Zones 1 to 5
Daylighting			None	None	None	None	Zones 1 to 8

†North facing SHGC requirements are less restrictive than the requirements for the other 3 orientations.
* Low Energy Case design requirements are taken from the EnergyPlus simulations.
NR = No Requirement for one or more climate zones. The value of SHGC cannot exceed 1.0.

The LEC design increases the thermal efficiency of insulation and windows beyond *ASHRAE 90.1-2007* and adds daylighting and window overhangs. The LEC design adds rigid insulation to the wall exterior to increase the R-value of the *ASHRAE 90.1-2007* design. Roof deck insulation is increased for all climate zones by at least an R-value of 0.88 m^2·K/W (5 ft^2·°F·h/Btu). The LEC design also adds daylighting controls and overhangs for window shading based on the *EEFG* recommendations. Daylighting is included for all building types and climate zones. See Section 3.4 for minimum illumination levels for natural lighting utilization. Overhangs are placed on the east, west, and south sides of the building for each floor in Climate Zone 1 through Climate Zone 5 because warmer climates benefit from blocking solar radiation.

The HVAC system size varies across the five building designs because changing the thermal characteristics of the building envelope alters the heating and cooling loads of the building. The E*nergyPlus V6.0* whole building energy simulations "autosize" the HVAC system to determine the appropriate system size to efficiently maintain the thermal comfort and ventilation requirements. As the thermal performance of the building envelope is improved, a smaller HVAC system is required to meet the HVAC loads. Smaller HVAC systems cost less to purchase and install, which offset some or all of the additional costs from other measures used to increase the building's thermal performance. For each building design, the baseline HVAC cost is replaced with the cost of the "autosized" HVAC system.

HVAC efficiency varies across editions of *ASHRAE 90.1* and equipment sizes (as shown in Table 3-2). The RS Means baseline building design is assumed to meet *ASHRAE 90.1-1999* requirements. The LEC design is assumed to have the same efficiency as *ASHRAE 90.1-2007* for all system types and system sizes.

Table 3-2 HVAC Energy Efficiency Requirements for Alternative Building Designs

HVAC Type	Equipment Type	Unit	ASHRAE 90.1-1999	ASHRAE 90.1-2001	ASHRAE 90.1-2004	ASHRAE 90.1-2007	LEC
Cooling	Rooftop Packaged Unit	EER	8.2 to 9.0	9.0 to 9.9	9.2 to 10.1	9.5 to 13.0	9.5 to 13.0
	Air-Cooled Chiller	COP	2.5 to 2.7	2.8	2.8	2.8	2.8
	Water-Cooled Chiller	COP	3.80 to 5.20	4.45 to 5.50	4.45 to 5.50	4.45 to 5.50	4.45 to 5.50
	Split System with Condensing Unit	EER	8.7 to 9.9	9.9 to 10.1	10.1	10.1	10.1
Heating	Hot Water Boiler	E_t	75% to 80%	75% to 80%	75% to 80%	75% to 80%	75% to 80%
	Furnace	E_t	80%	75% to 80%	75% to 80%	75% to 80%	75% to 80%

Assume that E_c = 75% E_t and AFUE = E_t, where E_c = combustion efficiency; E_t = thermal efficiency; AFUE = Annual Fuel Utilization Efficiency
EER = Energy Efficiency Ratio
COP = Coefficient of Performance

The details of the building construction costs are described below, beginning with the baseline building cost estimate followed by the cost adjustments for HVAC, building envelope, and lighting components required by the prototype building designs.

3.1 Baseline Building Design

The *RS Means SFCE* is used to determine the baseline building design, including the construction materials. An example of the input and output from the RS Means *SFCE* is shown in Figure A-1 and Figure A-2, respectively in Appendix A. The user chooses the values for 13 inputs, shown in Table 3-3, that the *SFCE* uses to estimate total baseline construction costs.

Table 3-3 RS Means Square Foot Cost Estimator Inputs and Default Values

Input Category	Inputs	Unit	Default Values
General Assumptions	Labor Type	Union or Open Shop	Standard Union
	Data Release	Year	2009
	Location	City/State	National Average
	Building Type	No Unit	Varies
	Wall/Framing Type	No Unit	Varies
Building Parameters	Area	Floor Area	Varies
	Perimeter	Linear Distance	Varies
	Stories	No Unit	Varies
	Contractor Fees	Percentage Mark-up	25.0 %
	Architectural Fees	Percentage Mark-up	7.0 %
	User Fees	Percentage Mark-up	0.0 %
	Include Basement	Yes/No	No

Note: The RS Means SFCE also allows for "Building Additives" such as appliances, elevators, and safety equipment.
Note: Some default values vary by building type and size.

The default values are used for all inputs, given the selected building type and number of stories.[9] All building types use the 2009 national average construction costs, which include material costs and labor costs based on standard union labor rates. The mark-up values are assumed to be 25.0 % for contractors and 7.0 % for architects. All building types are assumed to be slab-on-grade construction with insulation entirely above the roof deck (IEAD). The default wall construction and the associated *ASHRAE 90.1*-defined wall construction category for each building type are shown in Table 3-4.

[9] The only exception is the square footage for the 4-story apartment building and 4-story dormitory, which are based on the default values for the 3-story apartment building and 3-story dormitory. An additional floor is added to these two building types to exclude them from the low-rise residential classification.

Table 3-4 Baseline Building Envelope Construction - Walls

Building	Baseline Wall Construction	ASHRAE-Defined Construction
DORMI04	Brick veneer, concrete block, concrete frame	Mass
DORMI06	Decorative concrete block, steel frame	Steel
HOTEL15	Curtain wall, steel framing	Steel
APART04	Brick veneer, concrete block, steel joists	Mass
APART06	Brick veneer, concrete block, steel joists	Mass
ELEMS01	Brick-faced, concrete block back-up/bearing walls	Mass
HIGHS02	Brick-faced, concrete block back-up, concrete frame	Mass
OFFIC03	Precast concrete façade, steel framing	Steel
OFFIC08	Brick-faced façade, concrete block back-up, steel joists	Mass
OFFIC16	Plate glass panels, steel framing	Steel
RETAIL1	Concrete block, steel joists	Mass
RSTRNT1	Wood frame	Wood

To match the baseline building design to the energy simulation design, the HVAC, building envelope, and lighting costs are adjusted.[10] The remainder of this section will describe these adjustments in detail.

3.2 HVAC

There are three types of HVAC systems in the prototype buildings: heating systems, cooling systems, and packaged units. The approaches used to cost each of these systems are similar. The system(s) and the related costs in the baseline building are broken down into fixed costs and variable costs.

The fixed costs are based on the size of the building, and include all costs that are indifferent to the thermal load capacity requirement for the system. The cost for the system is linearly adjusted based on the size of the building. For example, if the system is priced for an 1858 m^2 (20 000 ft^2) building, but the size of the prototype building is 2323 m^2 (25 000 ft^2), then the fixed costs are inflated by 25 % relative to the baseline costs.[11]

The variable costs are the costs determined by the thermal load capacity of the system, such as installed costs from boilers, furnaces, chillers, cooling towers, condensers, and fan coils. A cost function, based on costs in the RS Means *CostWorks* database, is

[10] Both the baseline construction costs and the component cost adjustments initially are based on national average data, then indexed for local material and labor costs for life-cycle cost analysis.

[11] The fixed costs for the HVAC system in 10 of the 12 prototype buildings are not adjusted because the prototype building and baseline building are the same size. Only the 4-story apartment building and 4-story dormitory are adjusted because the baseline building is based on a 3-story building.

developed for each particular system type in the RS Means baseline buildings, and is dependent on the system capacity size determined by the whole building energy simulation. This cost function is used to estimate the variable system costs for the prototype building. For example, a baseline building cost estimate may report costs for a 100 ton air-cooled chiller. Meanwhile, the energy simulation determines that the prototype building requires an 80 ton system. The function for the air-cooled chiller is used to calculate costs for the 80 ton system. The change in HVAC costs is the difference between the costs for an 80 ton system and the baseline 100 ton system.

3.2.1 HVAC Efficiency

The efficiency of an HVAC system component has a significant impact on the energy performance and construction cost of a building. The baseline building assumes HVAC equipment efficiency that will meet *ASHRAE 90.1-1999* because, as in previous studies, this standard edition is assumed to require the equipment installed under "common practices" across the United States.[12] The efficiency requirement for an HVAC system is determined based on the equipment type, size of the equipment, and the edition of *ASHRAE 90.1* to which the building is designed. The efficiency requirements are indifferent to the climate zone in which the building is located. The energy simulations are run for the design day conditions to determine the necessary capacity of the equipment. The equipment type and size combination is then used to find the efficiency requirement associated with the building design, as shown in Table 3-5. The derived HVAC efficiency parameter is then adjusted in the energy simulation model, and the annual energy simulation is run to estimate the building's energy use.

[12] Source: Kneifel (2010) and Pacific Northwest National Laboratory (2009).

Table 3-5 HVAC Efficiency Design Requirement by Equipment Size - COP

HVAC Component	Equipment Type	System Size			Standard					Max Efficiency Increase
		kW	MBH	Tons	1999	2001	2004	2007	LEC	
Cooling (COP)	Rooftop Packaged Unit*	19 to 40	65 to 135	5 to 11	2.55	2.96	2.96	2.96	2.96	16 %
		40 to 70	135 to 240	11 to 20	2.43	2.78	2.78	2.78	2.78	14 %
		70 to 223	240 to 760	20 to 63	2.43	2.73	2.73	2.73	2.73	12 %
		223+	760+	63+	2.34	2.64	2.64	2.64	2.64	13 %
	Air-Cooled Chiller	<527	<1800	<150	2.70	2.80	2.80	2.80	2.80	4 %
		>527	>1800	>150	2.50	2.80	2.80	2.80	2.80	12 %
	Water-Cooled Chiller	<264	<900	<75	3.80	4.45	4.45	4.45	4.45	17 %
		264 to 527	900 to 1800	75 to 150	3.80	4.45	4.45	4.45	4.45	17 %
		527 to 1054	1800 to 3600	150 to 300	4.20	4.90	4.90	4.90	4.90	17 %
		1054+	>3600	>300	5.20	5.50	5.50	5.50	5.50	6 %
	Split System w/ Condensing Unit*	19 to 40	65 to 135	5 to 11	2.55	2.96	2.96	2.96	2.96	16 %
		40+	>135	>11	2.90	2.96	2.96	2.96	2.96	2 %
Heating (E_t)	Gas-Fired Boiler	<88	<300	<25	80 %**	80 %**	80 %**	80 %**	80 %**	0 %
		88 to 732	300 to 2500	25 to 208	75 % †	75 %	75 %	75 %	75 %	0 %
		>732	>2500	>208	75 % †	75 % †	75 % †	75 % †	75 % †	0 %
	Gas Warm Air Furnace	<66	<225	<19	80 %	80 %	80 %	80 %	80 %	0 %
		>66	>225	>19	80 %	75 % †	75 % †	75 % †	75 % †	0 %

* No system is autosized smaller than 65 MBH (5 tons) by EnergyPlus. Efficiency requirements for these smaller sizes are excluded from this analysis.
** AFUE assumed equivalent to E_t
† 80 % E_c assumed equivalent to 75 % E_t

The cost of the HVAC equipment for the prototype building design is the baseline building's HVAC fixed costs plus the prototype building's variable costs adjusted for the change in efficiency. The equipment costs are adjusted using a multiplier that controls for the increasing costs of greater efficiency, which is based on RS Means *CostWorks* data and advice from HVAC engineers. The *ASHRAE 90.1* efficiency requirement for the prototype building is compared to the *ASHRAE 90.1-1999* requirement to determine the adjustment in efficiency, in percentage terms, which must be priced into the system. Heating equipment efficiency requirements do not increase across newer editions of the standard, which makes it unnecessary to adjust the equipment costs.

The costs of the initial incremental increase in efficiency for cooling equipment is based on the cost difference of installing a Seasonal Energy Efficiency Ratio (SEER) 14 rooftop packaged unit relative to a SEER 13 unit, which is a fixed percentage cost increase for the unit (20 % increase in material costs). The efficiency is converted from a SEER rating to Coefficient of Performance (COP) rating based on the following equation:

$$COP = \frac{(-0.02 * SEER^2 + 1.12 * SEER)}{3.412}$$

The change in efficiency from a SEER 13 to a SEER 14 is 0.17 COP, which is a 5.2 % increase in efficiency. An increase in efficiency of a cooling system by 5.2 % increases installed costs by 20 % of initial material costs. There are decreasing returns to efficiency gains, which makes each incremental improvement in efficiency more expensive than the previous. To control for these diminishing returns, the cost of each additional efficiency improvement is assumed to increase by an additional 20 % above the previous efficiency level costs. Table 3-6 shows the data used to generate the efficiency multiplier function in Figure 3-1. Based on the efficiency design requirements in Table 3-5, the largest cost multiplier that is implemented in the database is approximately 1.75 times equipment material cost for baseline building system for a 17 % increase in efficiency.

Table 3-6 Material Cost Adjustments for HVAC Equipment Efficiency Improvements

Efficiency Increase*	Cost Multiplier	Incremental Cost
0.0 %	1.00	0.0 %
5.2 %	1.20	20.0 %
10.4 %	1.44	24.0 %
15.6 %	1.73	28.8 %
20.8 %	2.07	34.6 %
26.0 %	2.49	41.5 %

* Percentage improvement relative to baseline building system efficiency

The HVAC efficiency cost multiplier is derived based on a simplistic approach using minimal data. The database is designed to allow for adjusting this multiplier as more precise data becomes available.

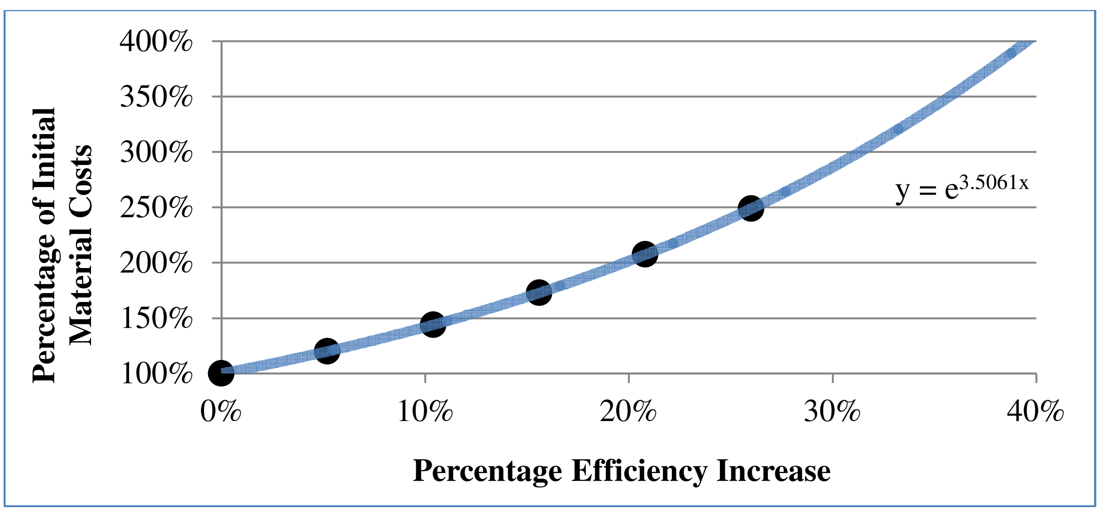

Figure 3-1 HVAC Efficiency Cost Multiplier Function

The change in HVAC costs (ΔC_{HVAC}) is the sum of fixed and variable HVAC costs for the prototype building design minus the baseline building HVAC costs, each adjusted by the appropriate efficiency multiplier. Each of the three system cost calculations is described in detail below.

3.2.2 Heating Systems

Heating systems are divided into one of two RS Means categories, "energy supply" and "heat generating system." The costing approach is similar for both of these component categories. The energy supply costs, given the size of the building, are broken down into fixed (floor area-dependent) costs and variable (thermal load-dependent). The fixed costs are constant across all building designs for a building type regardless of the variation in the thermal load of the buildings. The variable costs are assumed to be the cost of the boiler. The boiler size is adjusted to meet the thermal load of the building.

The cost data from the RS Means *CostWorks* database for gas-fired hot water boilers are assumed to represent equipment that meet the minimum efficiency requirements defined in *ASHRAE 90.1-1999*. For all building types and climate zones, the efficiency is constant across all building designs, which make it unnecessary to adjust the boiler costs for any efficiency improvement.

For energy supply systems, the cost of the boiler in the baseline building design is used to determine an average cost per unit of energy. The boiler capacity calculated by the energy simulation model is multiplied by the average cost per unit of boiler capacity to estimate the total boiler costs for the "energy supply" system.

For "heat generating systems," the cost of the boiler is calculated in a different manner. An exponential function based on RS Means *CostWorks* cost data for 10 hot water boiler capacities is used to estimate the average cost per unit of boiler capacity. The functional form assumes the average cost per unit of capacity decreases as the system increases in capacity. The boiler capacity calculated by the energy simulation model is multiplied by the average cost per unit of capacity to estimate the total boiler costs for the heat generating system.

3.2.3 Cooling Systems

The prototype buildings may use air-cooled scroll chillers or water-cooled screw chillers. The 6-story dormitory, 3-story apartment building, and 6-story apartment building use air-cooled scroll chillers. The 3 prototype buildings with the most total floor area, 15-story hotel, 16-story office building, and 2-story high school, use water-cooled screw chillers. The costing approach for both system types is similar. Air-cooled chiller system costs are divided into variable costs (chiller costs and fan coil costs) and fixed costs. Water-cooled chiller system costs are also divided into variable costs (chiller, cooling tower, and fan coils) and fixed costs. The average variable cost per ton of capacity for each component is calculated by using an exponential function based on RS Means *CostWorks* data. The average variable cost per unit of capacity is multiplied by the cooling capacity calculated in the energy simulation model to estimate the total variable costs for each component.

3.2.4 Packaged Units

Some prototype buildings use rooftop packaged units with electric air conditioning and gas heating. The system costs are determined by making two cost calculations, one based on the air conditioning load requirement and the other based on the heating load requirement from the energy simulation. The greater of the two cost estimates is selected as the system cost estimate because the equipment must meet both cooling and heating loads. The estimates are made using a linear cost function based on RS Means *CostWorks* data.

3.3 Exterior Building Envelope

Four components of the building envelope in the baseline building are adjusted to match the *ASHRAE 90.1*-compliant prototype building designs: exterior wall insulation, exterior roof insulation, exterior window thermal efficiency performance, and window overhangs.

3.3.1 Exterior Wall Insulation

Exterior wall insulation efficiency levels are based on the *ASHRAE 90.1* requirements, which vary depending on the wall construction type and climate zone. Table 3-7 defines the continuous insulation (ci) added to either the interior or exterior of the wall construction to meet the standard requirement.

Table 3-7 Building Envelope Construction – Wall Insulation R-Value (ci)

Building	Wall Construction	Units	90.1-1999/2001	90.1-2004/2007	LEC
DORMI04	Mass	m^2·K/W (ft^2·°F·h/Btu)	0.0 to 2.7 (0.0 to 15.2)	1.0 to 2.7 (5.7 to 15.2)	1.3 to 5.5 (7.6 to 31.3)
DORMI06	Steel**	m^2·K/W (ft^2·°F·h/Btu)	0.0 to 3.8 (0.0 to 21.6)	0.0 to 1.7 (0.0 to 10.0)	0.9 to 1.7 (5.0 to 10.0)
HOTEL15	Steel**	m^2·K/W (ft^2·°F·h/Btu)	0.0 to 3.8 (0.0 to 21.6)	0.0 to 1.7 (0.0 to 10.0)	0.9 to 1.7 (5.0 to 10.0)
APART04	Mass	m^2·K/W (ft^2·°F·h/Btu)	0.0 to 2.7 (0.0 to 15.2)	1.0 to 2.7 (5.7 to 15.2)	1.3 to 5.5 (7.6 to 31.3)
APART06	Steel**	m^2·K/W (ft^2·°F·h/Btu)	0.0 to 3.8 (0.0 to 21.6)	0.0 to 1.7 (0.0 to 10.0)	0.9 to 1.7 (5.0 to 10.0)
ELEMS01	Mass	m^2·K/W (ft^2·°F·h/Btu)	0.0 to 2.7 (0.0 to 15.2)	0.0 to 2.3 (0.0 to 13.3)	1.3 to 5.5 (7.6 to 31.3)
HIGHS02	Mass	m^2·K/W (ft^2·°F·h/Btu)	0.0 to 2.7 (0.0 to 15.2)	0.0 to 2.3 (0.0 to 13.3)	1.3 to 5.5 (7.6 to 31.3)
OFFIC03	Mass	m^2·K/W (ft^2·°F·h/Btu)	0.0 to 2.7 (0.0 to 15.2)	0.0 to 2.3 (0.0 to 13.3)	1.3 to 5.5 (7.6 to 31.3)
OFFIC08	Mass	m^2·K/W (ft^2·°F·h/Btu)	0.0 to 2.7 (0.0 to 15.2)	0.0 to 2.3 (0.0 to 13.3)	1.3 to 5.5 (7.6 to 31.3)
OFFIC16	Steel**	m^2·K/W (ft^2·°F·h/Btu)	0.0 to 1.7 (0.0 to 10.0)	0.0 to 1.7 (0.0 to 7.5)	0.9 to 1.7 (5.0 to 10.0)
RETAIL1	Mass	m^2·K/W (ft^2·°F·h/Btu)	0.0 to 2.7 (0.0 to 15.2)	0.0 to 2.3 (0.0 to 13.3)	1.3 to 5.5 (7.6 to 31.3)
RSTRNT1	Wood*	m^2·K/W (ft^2·°F·h/Btu)	0.0 to 1.7 (0.0 to 7.5)	0.0 to 1.7 (0.0 to 7.5)	0.7 to 1.7 (3.8 to 10.0)

*Wood frame requires R-13 plus the continuous insulation in this table
**Steel frame requires R-13 plus the continuous insulation in this table

The costs of increasing the thermal performance of rigid wall insulation cannot be estimated in a continuous nature because it is installed in increments, and requires incremental increases per unit of insulated area. The amount and type of insulation is therefore adjusted to meet the requirements in Table 3-7. The thermal performance for baseline building insulation is defined in the RS Means *SFCE* as R-0 for all building types. Extruded polystyrene (XPS) rigid insulation is added to the wall construction in 2.5 cm (1 in) increments until the continuous insulation R-value requirements are met for each building design based on the data in Table 3-8.

Table 3-8 Rigid Insulation Thickness and Thermal Performance

Insulation Type	Thickness cm (in)	R-Value (ci) $m^2 \cdot K/W$ ($ft^2 \cdot °F \cdot h/Btu$)
XPS	2.5 (1.0)	0.9 (5.0)
	5.1 (2.0)	1.7 (10.0)
	7.6 (3.0)	2.6 (15.0)

XPS = Extruded polystyrene

The cost of insulation is estimated using the RS Means *CostWorks* databases, which define rigid insulation costs based on the coverage area and insulation thickness. For any insulation thickness requirement greater than 7.6 cm (3 in), combinations of 2.5 cm to 7.6 cm (1 in to 3 in) are used. To estimate the cost of continuous insulation requirements greater than 3.5 $m^2 \cdot K/W$ (20 $ft^2 \cdot °F \cdot h/Btu$), combinations of insulation board are used. For example, to get aan R-value of 4.4 $m^2 \cdot K/W$ (25 $ft^2 \cdot °F \cdot h/Btu$), a 7.6 cm (3 in) XPS and 5.1 cm (2 in) XPS board are layered. Table 3-9 shows the different XPS thicknesses necessary to meet the R-value requirements in Table 3-7.

Table 3-9 Building Envelope Construction –Wall Insulation Thickness

Building	Wall Construction	Baseline cm (in)	90.1-1999/2001 cm (in)	90.1-2004/2007 cm (in)	Low Energy Case cm (in)
DORMI04	Mass	0.0 (0.0)	0.0 to 10.2 (0.0 to 4.0)	5.1 to 10.2 (2.0 to 4.0)	5.1 to 17.8 (2.0 to 7.0)
DORMI06	Steel**	0.0 (0.0)	0.0 to 12.7 (0.0 to 5.0)	0.0 to 5.1 (0.0 to 2.0)	2.5 to 5.1 (1.0 to 2.0)
HOTEL15	Steel**	0.0 (0.0)	0.0 to 12.7 (0.0 to 5.0)	0.0 to 5.1 (0.0 to 2.0)	2.5 to 5.1 (1.0 to 2.0)
APART04	Mass	0.0 (0.0)	0.0 to 10.2 (0.0 to 4.0)	5.1 to 10.2 (2.0 to 4.0)	5.1 to 17.8 (2.0 to 7.0)
APART06	Steel**	0.0 (0.0)	0.0 to 12.7 (0.0 to 5.0)	0.0 to 5.1 (0.0 to 2.0)	2.5 to 5.1 (1.0 to 2.0)
ELEMS01	Mass	0.0 (0.0)	0.0 to 10.2 (0.0 to 4.0)	0.0 to 7.6 (0.0 to 3.0)	5.1 to 17.8 (2.0 to 7.0)
HIGHS02	Mass	0.0 (0.0)	0.0 to 10.2 (0.0 to 4.0)	0.0 to 7.6 (0.0 to 3.0)	5.1 to 17.8 (2.0 to 7.0)
OFFIC03	Mass	0.0 (0.0)	0.0 to 10.2 (0.0 to 4.0)	0.0 to 7.6 (0.0 to 3.0)	5.1 to 17.8 (2.0 to 7.0)
OFFIC08	Mass	0.0 (0.0)	0.0 to 10.2 (0.0 to 4.0)	0.0 to 7.6 (0.0 to 3.0)	5.1 to 17.8 (2.0 to 7.0)
OFFIC16	Steel**	0.0 (0.0)	0.0 to 5.1 (0.0 to 2.0)	0.0 to 5.1 (0.0 to 2.0)	2.5 to 5.1 (1.0 to 2.0)
RETAIL1	Mass	0.0 (0.0)	0.0 to 10.2 (0.0 to 4.0)	0.0 to 7.6 (0.0 to 3.0)	5.1 to 17.8 (2.0 to 7.0)
RSTRNT1	Wood*	0.0 (0.0)	0.0 to 5.1 (0.0 to 2.0)	0.0 to 5.1 (0.0 to 2.0)	2.5 to 5.1 (1.0 to 2.0)

*Wood frame uses 2.3 $m^2 \cdot K/W$ (13 $ft^2 \cdot °F \cdot h/Btu$) batt roll insulation plus the continuous insulation in this table
**Steel frame uses 2.3 $m^2 \cdot K/W$ (13 $ft^2 \cdot °F \cdot h/Btu$) batt roll insulation plus the continuous insulation in this table
All building types use extruded polystyrene (XPS) insulation

The change in wall insulation costs (C_{Wall}) is the difference between the design compliant insulation costs and the baseline insulation costs.

3.3.2 Roof Insulation

Exterior roof insulation efficiency levels are based on the *ASHRAE 90.1* requirements, which vary depending on the roof construction type and climate zone. All prototype buildings are assumed to have insulation entirely above the roof deck (IEAD). The requirements are the same for both non-residential and mid-rise or high-rise residential buildings for all climate zones in each of the *90.1-2004*, *90.1-2007*, and LEC designs. However, the requirements are different for non-residential and mid-rise and high-rise residential buildings for some of the 26 climate zones in both *90.1-1999* and *90.1-2001*.

Table 3-10 shows the insulation requirements for the different building designs for each building type. The condensing of climate zones starting in *90.1-2004* results in a reduction in the range of R-value requirements across building types. The LEC design increases the R-value requirement beyond the *90.1-2007* requirements for all building types and climate zones.

Table 3-10 Building Envelope Construction – Roof Insulation R-Value (ci)

Building Category	Building	Units	Baseline	90.1-1999/2001	90.1-2004/2007	LEC
Residential	DORMI04	m^2·K/W (ft^2·°F·h/Btu)	1.8 (10.5)	2.6 to 3.5 (15 to 20)	2.6 to 3.5 (15 to 20)	4.4 to 6.2 (25 to 35)
	DORMI06	m^2·K/W (ft^2·°F·h/Btu)	1.8 (10.5)	2.6 to 3.5 (15 to 20)	2.6 to 3.5 (15 to 20)	4.4 to 6.2 (25 to 35)
	HOTEL15	m^2·K/W (ft^2·°F·h/Btu)	1.8 (10.5)	2.6 to 3.5 (15 to 20)	2.6 to 3.5 (15 to 20)	4.4 to 6.2 (25 to 35)
	APART04	m^2·K/W (ft^2·°F·h/Btu)	1.8 (10.5)	2.6 to 3.5 (15 to 20)	2.6 to 3.5 (15 to 20)	4.4 to 6.2 (25 to 35)
	APART06	m^2·K/W (ft^2·°F·h/Btu)	1.8 (10.5)	2.6 to 3.5 (15 to 20)	2.6 to 3.5 (15 to 20)	4.4 to 6.2 (25 to 35)
Commercial	ELEMS01	m^2·K/W (ft^2·°F·h/Btu)	2.0 (11.1)	1.7 to 4.4 (10 to 25)	2.6 to 3.5 (15 to 20)	4.4 to 6.2 (25 to 35)
	HIGHS02	m^2·K/W (ft^2·°F·h/Btu)	2.0 (11.1)	1.7 to 4.4 (10 to 25)	2.6 to 3.5 (15 to 20)	4.4 to 6.2 (25 to 35)
	OFFIC03	m^2·K/W (ft^2·°F·h/Btu)	1.8 (10.5)	1.7 to 4.4 (10 to 25)	2.6 to 3.5 (15 to 20)	4.4 to 6.2 (25 to 35)
	OFFIC08	m^2·K/W (ft^2·°F·h/Btu)	1.8 (10.5)	1.7 to 4.4 (10 to 25)	2.6 to 3.5 (15 to 20)	4.4 to 6.2 (25 to 35)
	OFFIC16	m^2·K/W (ft^2·°F·h/Btu)	1.8 (10.5)	1.7 to 4.4 (10 to 25)	2.6 to 3.5 (15 to 20)	4.4 to 6.2 (25 to 35)
	RETAIL1	m^2·K/W (ft^2·°F·h/Btu)	1.8 (10.5)	1.7 to 4.4 (10 to 25)	2.6 to 3.5 (15 to 20)	4.4 to 6.2 (25 to 35)
	RSTRNT1	m^2·K/W (ft^2·°F·h/Btu)	0.7 (3.7)	1.7 to 4.4 (10 to 25)	2.6 to 3.5 (15 to 20)	4.4 to 6.2 (25 to 35)

ci = continuous insulation

The costs of increasing the thermal performance of roof deck insulation cannot be estimated in a continuous nature because it is installed in increments, and require incremental increases per unit of insulated area. The amount and type of insulation is adjusted to meet the requirements in Table 3-10. The baseline building roof deck insulation as defined in the RS Means *SFCE* for all building types, except for both schools and the restaurant, is 5.1 cm (2 in) expanded polystyrene (EPS), 2.5 cm (1 in) perlite composite board, which has a thermal performance of 1.8 $m^2 \cdot K/W$ (10.5 $ft^2 \cdot °F \cdot h/Btu$). This rigid insulation is replaced with extruded polystyrene (XPS), which is increased at 2.5 cm (1 in) increments until the R-value requirements are met for each building design. The baseline building roof deck insulation for both elementary schools and high schools is 5.1 cm (2 in) of polyisocyanurate, which has a thermal performance of 2.0 $m^2 \cdot K/W$ (11.1 $ft^2 \cdot °F \cdot h/Btu$). For schools, the thickness of the roof deck insulation is increased at 1.3 cm (0.5 in) increments until the R-value requirements are met for each building design. For the restaurant, the baseline building roof deck insulation is 2.4 cm (0.9 in) rigid fiberglass insulation, which has a thermal performance of 0.7 $m^2 \cdot K/W$ (3.7 $ft^2 \cdot °F \cdot h/Btu$). This insulation is replaced with the thickness of XPS, in 2.5 cm (1 in) increments, required to meet the R-value requirements for each building design. The R-values by thickness for XPS and polyisocyanurate are defined in Table 3-11.

Table 3-11 Rigid Insulation Thickness and Thermal Performance

Insulation Type	Thickness cm (in)	R-Value (ci) $m^2 \cdot K/W$ ($ft^2 \cdot °F \cdot h/Btu$)
XPS	2.5 (1.0)	0.9 (5.0)
	5.1 (2.0)	1.7 (10.0)
	7.6 (3.0)	2.6 (15.0)
	10.2 (4.0)	3.5 (20.0)
ISO	1.9 (0.75)	0.9 (5.1)
	2.5 (1.0)	1.2 (7.1)
	3.8 (1.5)	1.9 (10.9)
	5.1 (2.0)	2.5 (14.3)
	6.4 (2.5)	2.9 (16.7)
	7.6 (3.0)	3.8 (21.7)
	8.9 (3.5)	4.4 (25.0)

XPS = Extruded polystyrene
ISO = Polyisocyanurate

The cost of roof insulation is estimated using the RS Means *CostWorks* databases, which define rigid insulation costs based on the coverage area and insulation thickness. For insulation thicknesses greater than 10.2 cm (4.0 in) XPS or 8.9 cm (3.5 in) polyisocyanurate, combinations of insulation board are used to estimate the costs. Table 3-12 shows the different XPS and polyisocyanurate thicknesses necessary to meet the R-value requirements in Table 3-10. The change in roof insulation costs (ΔC_{Roof}) is the difference between the design compliant insulation costs and the baseline insulation costs.

Table 3-12 Building Envelope Construction – Roof Insulation Thickness

Building Category	Building	Insulation Type	90.1-1999/2001	90.1-2004/2007	Low Energy Case
Residential	DORMI04	XPS	7.6 to 10.2 (3.0 to 4.0)	7.6 to 10.2 (3.0 to 4.0)	12.7 to 17.8 (5.0 to 7.0)
	DORMI06	XPS	7.6 to 10.2 (3.0 to 4.0)	7.6 to 10.2 (3.0 to 4.0)	12.7 to 17.8 (5.0 to 7.0)
	HOTEL15	XPS	7.6 to 10.2 (3.0 to 4.0)	7.6 to 10.2 (3.0 to 4.0)	12.7 to 17.8 (5.0 to 7.0)
	APART04	XPS	7.6 to 10.2 (3.0 to 4.0)	7.6 to 10.2 (3.0 to 4.0)	12.7 to 17.8 (5.0 to 7.0)
	APART06	XPS	7.6 to 10.2 (3.0 to 4.0)	7.6 to 10.2 (3.0 to 4.0)	12.7 to 17.8 (5.0 to 7.0)
Commercial	ELEMS01	ISO	3.8 to 8.9 (1.5 to 3.5)	6.4 to 7.6 (2.5 to 3.0)	8.9 to 12.7 (3.5 to 5.0)
	HIGHS02	ISO	3.8 to 8.9 (1.5 to 3.5)	6.4 to 7.6 (2.5 to 3.0)	8.9 to 12.7 (3.5 to 5.0)
	OFFIC03	XPS	5.1 to 12.7 (2.0 to 5.0)	7.6 to 10.2 (3.0 to 4.0)	12.7 to 17.8 (5.0 to 7.0)
	OFFIC08	XPS	5.1 to 12.7 (2.0 to 5.0)	7.6 to 10.2 (3.0 to 4.0)	12.7 to 17.8 (5.0 to 7.0)
	OFFIC16	XPS	5.1 to 12.7 (2.0 to 5.0)	7.6 to 10.2 (3.0 to 4.0)	12.7 to 17.8 (5.0 to 7.0)
	RETAIL1	XPS	5.1 to 12.7 (2.0 to 5.0)	7.6 to 10.2 (3.0 to 4.0)	12.7 to 17.8 (5.0 to 7.0)
	RSTRNT1	XPS	5.1 to 12.7 (2.0 to 5.0)	7.6 to 10.2 (3.0 to 4.0)	12.7 to 17.8 (5.0 to 7.0)

XPS = Extruded polystyrene
ISO = Polyisocyanurate
All baseline building types use 5.1 cm (2 in) EPS, 2.5 cm (1 in) Perlite composite board

3.3.3 Exterior Windows

The windows specified for the baseline building are used to determine the baseline window costs. The baseline building windows are listed in Table 3-13.

Table 3-13 Baseline Building Envelope Construction – Window Characteristics

Building	RS Means Description	Operability	Frame	Thermal Break	Panes	Tint	Low-E*
DORMI04	Awning, aluminum frame	Operable	Aluminum	No	1	None	None
DORMI06	Sliding, aluminum frame	Operable	Aluminum	No	1	None	None
HOTEL15	Glazing panel, aluminum frame	Curtain Wall	Aluminum	No	1	None	None
APART04	Sliding, aluminum frame	Operable	Aluminum	No	1	None	None
APART06	Sliding, aluminum frame	Operable	Aluminum	No	1	None	None
ELEMS01	Awning, double-paned, aluminum frame	Operable	Aluminum	No	2	None	None
HIGHS02	Fixed glazing panels, aluminum w/ thermal break	Fixed	Aluminum	Yes	1	None	None
OFFIC03	Sliding, double paned, aluminum frame	Operable	Aluminum	No	2	None	None
OFFIC08	Awning, double-paned, aluminum frame	Operable	Aluminum	No	2	None	None
OFFIC16	Double-paned, tinted, glazing panels	Curtain Wall	Aluminum	No	2	Yes	None
RETAIL1	Glazing panel, aluminum frame	Fixed	Aluminum	No	1	None	None
RSTRNT1	Glazing panel, aluminum frame	Fixed	Aluminum	No	1	None	None

*Low-E = low emissivity

The exterior window performance characteristics of the prototype building are defined by *ASHRAE 90.1* requirements. The *ASHRAE* Fundamentals Handbook defines the performance characteristics of 911 different windows based on combinations of operability, frames, number of glass panes, low-emissivity coatings, and colors or tints.

The *ASHRAE 90.1*-compliant window characteristics, U-factor and solar heat gain coefficient (SHGC), are used to select the window that best matches those characteristics from these 911 window options.

Table 3-14 shows that U-factor and SHGC vary by climate zone within and across building designs for each building type. North facing fenestration has less restrictive requirements than the other 3 orientations for *ASHRAE 90.1-1999*, *-2001*, and *-2004*. This variation is eliminated in *ASHRAE 90.1-2007*. There is also variation across building types due to the operability of the windows and the glazing percentage of the wall area.

Table 3-14 Window Specifications from Simulations

Building	ASHRAE Category: Glazing Percentage	Window Operability	Baseline		90.1-1999/2001		90.1-2004/2007		LEC	
			U	SHGC	U	SHGC†	U	SHGC †	U	SHGC
DORMI04	10.1 % to 20.0 %	Operable	6.98 (1.23)	0.78	2.04 to 7.21 (0.36 to 1.27)	0.25 to NR	2.67 to 7.21 (0.47 to 1.27)	0.25 to NR	1.97 to 6.42 (0.35 to 1.13)	0.25 to 0.47
DORMI06	10.1 % to 20.0 %	Operable	6.98 (1.23)	0.78	2.04 to 7.21 (0.36 to 1.27)	0.25 to NR	2.67 to 7.21 (0.47 to 1.27)	0.25 to NR	1.97 to 6.42 (0.35 to 1.13)	0.25 to 0.47
HOTEL15	40.1 % to 50.0 %	Curtain Wall	6.87 (1.21)	0.79	1.42 to 6.93 (0.25 to 1.22)	0.19 to NR	1.97 to 6.93 (0.35 to 1.22)	0.19 to NR	1.97 to 6.42 (0.35 to 1.13)	0.25 to 0.47
APART04	10.1 % to 20.0 %	Operable	6.98 (1.23)	0.78	2.04 to 7.21 (0.36 to 1.27)	0.25 to NR	2.67 to 7.21 (0.47 to 1.27)	0.25 to NR	1.97 to 6.42 (0.35 to 1.13)	0.25 to 0.47
APART06	10.1 % to 20.0 %	Operable	6.98 (1.23)	0.78	2.04 to 7.21 (0.36 to 1.27)	0.25 to NR	2.67 to 7.21 (0.47 to 1.27)	0.25 to NR	1.97 to 6.42 (0.35 to 1.13)	0.25 to 0.47
ELEMS01	20.1 % to 30.0 %	Operable	4.60 (0.81)	0.69	2.04 to 7.21 (0.36 to 1.27)	0.19 to NR	2.67 to 7.21 (0.47 to 1.27)	0.25 to NR	1.97 to 6.42 (0.35 to 1.13)	0.25 to 0.47
HIGHS02	20.1 % to 30.0 %	Fixed	6.08 (1.07)	0.79	1.82 to 6.93 (0.32 to 1.22)	0.19 to NR	2.61 to 6.93 (0.46 to 1.22)	0.25 to NR	1.97 to 6.42 (0.35 to 1.13)	0.25 to 0.47
OFFIC03	10.1 % to 20.0 %	Operable	4.60 (0.81)	0.69	2.04 to 7.21 (0.36 to 1.27)	0.19 to NR	2.67 to 7.21 (0.47 to 1.27)	0.25 to NR	1.97 to 6.42 (0.35 to 1.13)	0.25 to 0.47
OFFIC08	10.1 % to 20.0 %	Operable	4.60 (0.81)	0.69	2.04 to 7.21 (0.36 to 1.27)	0.19 to NR	2.67 to 7.21 (0.47 to 1.27)	0.25 to NR	1.97 to 6.42 (0.35 to 1.13)	0.25 to 0.47
OFFIC16	40.1 % to 50.0 %	Curtain Wall	4.37 (0.77)	0.55	1.42 to 6.93 (0.25 to 1.22)	0.14 to NR	1.97 to 6.93 (0.35 to 1.22)	0.19 to NR	1.97 to 6.42 (0.35 to 1.13)	0.25 to 0.47
RETAIL1	0.0 % to 10.0 %	Fixed	6.36 (1.12)	0.79	1.82 to 6.93 (0.32 to 1.22)	0.19 to NR	2.61 to 6.93 (0.46 to 1.22)	0.25 to NR	1.97 to 6.42 (0.35 to 1.13)	0.25 to 0.47
RSTRNT1	20.1 % to 30.0 %	Fixed	6.36 (1.12)	0.79	1.82 to 6.93 (0.32 to 1.22)	0.19 to NR	2.61 to 6.93 (0.46 to 1.22)	0.25 to NR	1.97 to 6.42 (0.35 to 1.13)	0.25 to 0.47

U = U-factor
U-factor units = W/m²·K (Btu/h·ft²·°F)
SHGC = Solar Heat Gain Coefficient
† North Facing windows have less restrictive requirements than the other 3 orientations for *ASHRAE 90.1-1999*, *-2001*, and *-2004*.
NR = No Requirement for one or more climate zones. The value of SHGC cannot exceed 1.0.

A hedonic costing approach is used to adjust the cost of windows. The cost of windows on each wall is estimated separately to allow for variation in standard requirements for the north-facing fenestration. Based on RS Means data, a defined cost per unit of area is applied for each tint, coating, framing thermal break, and glazing layer. The change in window costs ($\Delta C_{Windows}$) is the difference between the window costs in the prototype building and the baseline building.

3.3.4 Overhangs

Overhangs are used in the LEC designs, and placed on the west, south, and east sides of the building for buildings in Climate Zone 1 through Zone 5. Table 3-15 shows the width of the overhangs as defined by the *EEFG*. Widths vary by building type at approximately 75 % the height of the window.

Table 3-15 Overhangs by Building Type

Building	Glazing	Floor Height m (ft)	Window Height m (ft)	Overhang Width m (ft)	Overhang Area m^2 (ft^2)
DORMI04	20 %	3.66 (12)	0.7 (2.4)	0.5 (1.5)	1167.02
DORMI06	20 %	3.66 (12)	0.7 (2.4)	0.5 (1.5)	3032.19
HOTEL15	100 %	3.05 (10)	3.0 (10.0)	1.9 (6.2)	46044.70
APART04	12 %	3.05 (10)	0.4 (1.2)	0.2 (0.8)	563.17
APART06	14 %	3.15 (10)	0.4 (1.4)	0.3 (0.9)	6510.65
ELEMS01	25 %	4.57 (15)	1.1 (3.8)	0.7 (2.3)	1921.57
HIGHS02	25 %	4.57 (15)	1.1 (3.8)	0.7 (2.3)	4969.91
OFFIC03	20 %	3.66 (12)	0.7 (2.4)	0.5 (1.5)	1045.28
OFFIC08	20 %	3.66 (12)	0.7 (2.4)	0.5 (1.5)	3398.81
OFFIC16	100 %	3.05 (10)	3.0 (10.0)	1.9 (6.2)	35469.20
RETAIL1	10 %	4.27 (14)	0.4 (1.4)	0.2 (0.8)	227.76
RSTRNT1	30 %	3.66 (12)	1.1 (3.6)	0.8 (2.7)	450.36

RS Means *CostWorks* database does not have costs for overhang construction. The cost of overhangs originates from Winiarski et al. (2003). The change in overhang costs ($\Delta C_{Overhang}$) is the difference between the baseline overhang costs ($0) and the overhang costs for the building design, which is $0 for all building designs except for the LEC design for locations in Climate Zone 1 through Climate Zone 5. The cost calculation for overhangs is shown in the following equation:

$$C_{Overhang} = c_{overhang} * (0.75 * W_H) * (L_S + L_W + L_E)$$

Where $c_{overhang}$ = cost per unit of overhang area
W_H = Window height
L_S = Length of south wall
L_W = Length of west wall
L_E = Length of east wall

3.4 Lighting

The final cost component adjusted for *ASHRAE 90.1* design compliance is lighting. The baseline building interior lighting cost is adjusted to match the lighting density required by each edition of *ASHRAE 90.1*. The lighting density for each building type and building design are listed in Table 3-16. Depending on the building type and building design, the interior lighting costs may increase or decrease relative to the baseline building because the baseline lighting density may be either smaller or larger than the design-compliant density requirement. The lighting density requirement is the same or lower for newer editions of the standard. The LEC design requires lighting densities that are lower than *90.1-2007* requirements for all but one building type, the retail store.

Lighting costs are estimated using a linear function based on lighting density data from the RS Means CostWorks database. The change in lighting costs ($\Delta C_{Lighting}$) is the difference between the prototype building lighting costs and the baseline building lighting costs.

Table 3-16 Building Lighting Density – W/m^2 (W/ft^2)

Building	Baseline	90.1-1999	90.1-2001	90.1-2004	90.1-2007	LEC
DORMI04	12.9 (1.2)	16.1 (1.5)	16.1 (1.5)	10.8 (1.0)	10.8 (1.0)	8.6 (0.8)
DORMI06	12.9 (1.2)	16.1 (1.5)	16.1 (1.5)	10.8 (1.0)	10.8 (1.0)	8.6 (0.8)
HOTEL15	8.6 (0.8)	18.3 (1.7)	18.3 (1.7)	10.8 (1.0)	10.8 (1.0)	8.6 (0.8)
APART04	12.9 (1.2)	18.3 (1.7)	18.3 (1.7)	10.8 (1.0)	10.8 (1.0)	8.6 (0.8)
APART06	12.9 (1.2)	18.3 (1.7)	18.3 (1.7)	10.8 (1.0)	10.8 (1.0)	8.6 (0.8)
ELEMS01	17.2 (1.6)	16.1 (1.5)	16.1 (1.5)	12.9 (1.2)	12.9 (1.2)	10.3 (1.0)
HIGHS02	21.5 (2.0)	16.1 (1.5)	16.1 (1.5)	12.9 (1.2)	12.9 (1.2)	8.6 (0.8)
OFFIC03	17.2 (1.6)	14.0 (1.3)	14.0 (1.3)	10.8 (1.0)	10.8 (1.0)	8.6 (0.8)
OFFIC08	17.2 (1.6)	14.0 (1.3)	14.0 (1.3)	10.8 (1.0)	10.8 (1.0)	8.6 (0.8)
OFFIC16	17.2 (1.6)	14.0 (1.3)	14.0 (1.3)	10.8 (1.0)	10.8 (1.0)	8.6 (0.8)
RETAIL1	21.5 (2.0)	20.4 (1.9)	20.4 (1.9)	16.1 (1.5)	16.1 (1.5)	16.1 (1.5)
RSTRNT1	21.5 (2.0)	19.4 (1.8)	19.4 (1.8)	15.1 (1.4)	15.1 (1.4)	13.6 (1.3)

The LEC design includes daylighting controls that automatically dim the interior lighting given enough natural light to maintain the necessary illumination in the zone. The minimum illumination level is 400 lux (400 lumens/m^2) for all building types and locations for the LEC design. The change in cost from adding a daylighting system ($\Delta C_{Daylighting}$) is based on the RS Means CostWorks database, and is currently based on the baseline lighting system density for lack of more precise data.

4 Building Maintenance, Repair, and Replacement Costs and Rates

In order to maintain the performance of a building, each component of the building must be maintained, repaired, and replaced as needed to keep the building in excellent operating condition for the entire study period. The costs associated with the future building maintenance, repair, and replacement (MRR) activities are calculated using component and building lifetimes and component repair requirements based on data from Whitestone (2008).

Building service lifetimes shown in Table 4-1 are assumed constant across climate zones: apartments last for 65 years; dormitories for 44 years; and hotels, schools, office buildings, retail stores, and restaurants for 41 years. Whitestone (2008) does not have an estimated service life for stand-alone retail stores and sit-down restaurants. The most common service life, 41 years, is assumed for these two building types.

Table 4-1 Building Service Life by Building Type

Building Type	Service Life
DORMI04	44
DORMI06	44
HOTEL15	41
APART04	65
APART06	65
ELEMS01	41
HIGHS02	41
OFFIC03	41
OFFIC08	41
OFFIC16	41
RETAIL1	41
RSTRNT1	41

Insulation and windows are assumed to have lifespans greater than 40 years for all building types. Building component MRR rates, which indicate the frequency of occurrence of these activities, are based on Whitestone (2008). Insulation is assumed to have no maintenance and repair requirements. Windows are assumed to have no maintenance requirements, but have repair requirements of 1% of window panes annually. The heating and cooling units have different repair rates and lifespans based on climate, ranging from 4 to 33 years for repairs and 13 to 50 years for replacements. Figure A-3 shows the HVAC climate zone boundaries as defined in Whitestone (2008).

Table 4-2 illustrates the sensitivity to heating and cooling loads of HVAC repair and replacement rates. A gas boiler is assumed to be repaired once every 19 years and replaced once every 50 years in southern Florida (Zone 1). The same system is repaired once every 4 years and replaced once every 18 years in Alaska (Zone 11). On the other hand, a rooftop air conditioner is repaired once every 9 years and replaced once every 13 years in southern Florida. The same air conditioner is repaired once every 33 years and replaced once every 50 years in Alaska.

Table 4-2 HVAC Repair and Replacement Rate Example

HVAC Equipment		HVAC Zone										
		1	2	3	4	5	6	7	8	9	10	11
Gas Boiler, 586 W (2000 Mbh)	Repair Rate (yrs)	19	11	9	8	7	7	5	5	5	4	4
	Replacement Rate (yrs)	>50	49	36	33	28	30	23	23	20	18	18
Rooftop, Multizone Air Conditioner, 17.6 kW (5 ton)	Repair Rate (yrs)	9	10	15	15	16	10	20	23	23	29	33
	Replacement Rate (yrs)	13	14	23	22	29	15	32	46	46	>50	>50

Maintenance, repair, and replacement (MRR) costs are collected from two sources. Total maintenance and repair costs per square foot of conditioned floor area (excluding HVAC maintenance and repair costs) represent the baseline MRR costs, which occur for a building type regardless of the energy efficiency measures incorporated into the design. These data are collected from Whitestone (2008), which reports average maintenance and repair costs per unit of floor area by building component for each year of service life for each building type. An example of this data is shown in Table B-2 ($\$/m^2$) and Table B-3 ($\$/ft^2$) in Appendix B. The building types in Whitestone do not match exactly to the 12 building types selected for this study, and the most comparable profile is selected. For example, the profile most comparable to the 3-story prototypical office building analyzed in this study is for the 2-story office building in Whitestone (2008).

RS Means *CostWorks* is the source of MRR costs for the individual components for which MRR costs change across alternative building designs, which in this analysis are the HVAC system and windows. Windows have an assumed annual repair cost equal to replacing 1 % of all window panes, with costs that vary depending on the required window specifications. The HVAC system size varies based on the thermal performance of the alternative building design, which results in varying MRR costs because smaller systems are relatively cheaper to maintain, repair, and replace.

Maintenance costs and repair costs for HVAC equipment both vary by the capacity of the equipment. Each piece of equipment is grouped into two to four capacity ranges depending on the available data. Each capacity range has an associated annual maintenance cost (split systems, packaged units, and boilers) or maintenance cost per unit of capacity (chillers). Similarly, each capacity range has an associated repair cost per unit of capacity. Replacement costs are assumed to be the same as initial system installed costs because RS Means *CostWorks* replacement cost data does not appropriately match the systems in the baseline building design. The only exception is for the replacement of the heating component of a packaged unit, which is based on the costs of replacing a furnace of the same heating capacity.

MRR costs for a given year ($C_{MRR,i}$) is the sum of all maintenance, repair, and replacement costs for year "i" adjusted for local material and labor costs, including the baseline MRR costs, HVAC MRR costs, and window repair costs. Baseline MRR costs, HVAC maintenance costs, and window repair costs occur annually while HVAC repair and replacement costs occur based on the location's repair and replacement rates. Baseline MRR costs are indexed using the Whitestone *Local Maintenance Cost Indexes* while the window and HVAC MRR costs are indexed using the RS Means *CostWorks* "component" cost indexes.

5 Energy Costs

Annual energy costs are estimated by multiplying annual electricity and natural gas use predicted by the whole building energy simulation by the average state retail electricity and natural gas prices, respectively. Average state commercial electricity and natural gas prices for 2009 are collected from the Energy Information Administration (EIA) Electric Power Annual State Data Tables and Natural Gas Navigator, respectively. The average electricity prices are the total electricity revenue in a state divided by total electricity retail sales in a state for the commercial sector based on data from Form EIA-861, "Electric Power Monthly." Revenues include state and local taxes, energy or demand charges, customer service charges, environmental surcharges, franchise fees, fuel adjustments, and other miscellaneous charges.[13] Commercial sector natural gas prices are based on two monthly EIA surveys.[14]

Table 5-1 shows the data used for electricity and natural gas prices. Hawaii has the highest prices for electricity, 21.86¢/kWh, and natural gas, $\$849.50/m^3$ ($\$30.00/kft^3$), due to its isolation from the mainland United States. For the contiguous U.S., electricity prices range from 6.49¢/kWh in Idaho to 16.86¢/kWh in Connecticut while natural gas prices range from $\$209.83/m^3$ ($\$7.41/kft^3$) in North Dakota to $\$449.39/m^3$ ($\$15.87/kft^3$) in Delaware. Price variation is a result of a number of factors, including accessibility and affordability of fossil fuels (coal and natural gas) and alternative energy sources (hydroelectric and nuclear power).

[13] Not included in revenue are deferred charges, credits, or other adjustments.

[14] The two EIA surveys are Form EIA-857, "Monthly Report of Natural Gas Purchases and Deliveries to Consumers" and Form EIA-910, "Monthly Natural Gas Marketer Survey."

Table 5-1 Energy Cost Data by State

State	Electricity	Natural Gas	
	¢/kWh	$/m³	$/kft³
AK	14.46	269.29	9.51
AL	10.05	422.77	14.93
AR	7.56	303.27	10.71
AZ	9.35	344.05	12.15
CA	13.42	219.46	7.75
CO	8.15	214.08	7.56
CT	16.86	280.90	9.92
DE	11.98	449.39	15.87
FL	10.77	314.03	11.09
GA	8.94	331.31	11.70
HI	21.86	849.50	30.00
IA	7.55	223.14	7.88
ID	6.49	276.66	9.77
IL	11.31	244.94	8.65
IN	8.32	259.95	9.18
KS	7.87	283.45	10.01
KY	7.63	308.37	10.89
LA	7.69	296.19	10.46
MA	15.37	363.87	12.85
MD	11.97	307.80	10.87
ME	12.55	394.74	13.94
MI	9.24	265.61	9.38
MN	7.92	225.40	7.96
MO	6.96	305.82	10.80
MS	9.5	268.44	9.48
MT	8.32	266.46	9.41
NC	7.98	329.32	11.63
ND	6.81	209.83	7.41
NE	7.33	210.68	7.44
NH	14.55	406.91	14.37
NJ	13.83	288.83	10.20
NM	8.40	212.94	7.52
NV	10.64	309.22	10.92
NY	15.51	303.56	10.72
OH	9.65	294.78	10.41
OK	6.76	300.16	10.60
OR	7.49	335.84	11.86
PA	9.54	334.99	11.83
RI	13.67	428.72	15.14
SC	8.74	316.02	11.16
SD	7.14	210.11	7.42
TN	9.61	302.14	10.67
TX	9.66	231.07	8.16
UT	6.96	214.36	7.57
VA	8.06	291.95	10.31
VT	12.93	366.99	12.96
WA	6.96	347.16	12.26
WI	9.57	253.44	8.95
WV	6.77	403.23	14.24
WY	7.28	226.82	8.01

6 Life-Cycle Costing Approach

Life-cycle cost (LCC) analysis takes into account all relevant costs (in present value terms) throughout the chosen study period, including initial construction costs, maintenance, repair, and replacement costs, energy costs, and residual values. The study period is the investment time horizon, which will vary depending on the type of investor. The database currently generates results for study periods of 1, 5, 10, 15, 20, 25, 30, 35, and 40 years to give a wide range of options to the user. A cost's present value (PV) is calculated by discounting its future value into 2009 dollars based on the year the cost occurs and the assumed discount rate. The formulas and discount factors used to calculate the present values will vary depending on the type of cost. The different cost types and the related formulas and discount factors are described below.

6.1 First Cost

The first costs of a building are the total costs of constructing a building in a particular city. First costs include costs for labor, materials, equipment, overhead, and profit. The construction costs for a prototype building are estimated by summing the costs of the baseline building (C_{NatAvg}) and the changes in costs required to meet the prototype building design (ΔC_x), adjusted for location-related cost variation as well as contractor and architectural profits. Both the baseline building costs and component cost estimates are based on national average construction cost data, and must be adjusted with the 2009 RS Means *CostWorks City Indexes* to control for local material and labor price variations in the 228 locations for which energy simulations are run. The "weighted average" city construction cost index (I_{WAvg}) is used to adjust the costs for the baseline prototypical building while "component" city indexes (I_x) are used to adjust the costs for the change in component designs. The formula below shows the indexed construction cost (C_{Index}) calculation.

$$C_{Index} = \left(C_{NatAvg} * I_{WAvg}\right) + \left(\Delta C_{HVAC} * I_H\right) + \left(\Delta C_{Wall} + \Delta C_{Roof}\right) * I_T + \left(\Delta C_{Light} + \Delta C_{Daylight}\right) * I_E + \left(\Delta C_{Window} + \Delta C_{Overhang}\right) * I_O$$

Where C_{Index} = Indexed construction costs
C_{NatAvg} = National average construction costs
ΔC_{HVAC} = Change in HVAC costs
ΔC_{Wall} = Change in wall insulation costs
ΔC_{Roof} = Change in roof insulation costs
ΔC_{Light} = Change in lighting costs
$\Delta C_{Daylight}$ = Change in daylighting system costs
ΔC_{Window} = Change in window costs
$\Delta C_{Overhang}$ = Change in overhang costs
I_H = "Fire Suppression, Plumbing, & HVAC" cost index
I_T = "Thermal and Moisture Protection" cost index
I_E = "Electrical, Communications, & Utilities" cost index

I_O = "Openings" cost index

Once the indexed construction costs of the building are calculated, it is necessary to adjust for the contractor and architect profits by multiplying the costs by the contractor "mark-up" rate (I_M), assumed to be 25 %, and then the architectural fees rate (I_A), assumed to be 7 %, as shown in the following equation.

$$C_{First} = \left(C_{Indexed} * (1 + I_M)\right) * (1 + I_A)$$

These mark-up rates are based on the default values used by the RS Means *SFCE*. The marked-up, indexed construction costs are the first costs of constructing the prototype building in the particular city (C_{First}).

6.2 Future Costs

Maintenance, repair, and replacement (MRR) costs are discounted to equivalent present values using the Single Present Value (SPV) factors for future non-fuel costs reported in Rushing and Lippiatt (2009). These factors are calculated using the DOE Federal Energy Management Program (FEMP) 2009 real discount rate for energy conservation projects (3 %). Table 6-1 reports the SPV factors used in this study. The MRR costs for each year ($C_{MRR,i}$) are multiplied by the SPV for that year and then summed and indexed to determine the total present value MRR costs (C_{MRR}).

Table 6-1 2009 SPV Discount Factors for Future Non-Fuel Costs, 3 % Real Discount Rate

Yrs	SPV Factor	Yrs	SPV Factor	Yrs	SPV Factor	Yrs	SPV Factor
1	0.971	11	0.722	21	0.538	31	0.400
2	0.943	12	0.701	22	0.522	32	0.388
3	0.915	13	0.681	23	0.507	33	0.377
4	0.888	14	0.661	24	0.492	34	0.366
5	0.863	15	0.642	25	0.478	35	0.355
6	0.837	16	0.623	26	0.464	36	0.345
7	0.813	17	0.605	27	0.450	37	0.335
8	0.789	18	0.587	28	0.437	38	0.325
9	0.766	19	0.570	29	0.424	39	0.316
10	0.744	20	0.554	30	0.412	40	0.307

The electricity and natural gas use predicted by the energy simulation is used as the annual energy use of the building for each year of the selected study period. Electricity and natural gas prices are assumed to change over time according to EIA forecasts from 2009 to 2039. These forecasts are embodied in the FEMP Modified Uniform Present Value Discount Factors for energy price estimates (UPV*) reported in Rushing and Lippiatt (2009).[15] Multiplying the annual electricity costs and natural gas costs by the

[15] The escalation rates for years 31-40 are assumed to be the same as for year 30.

associated UPV* value for the study period of interest estimates the present value total electricity costs (C_{Elect}) and natural gas costs (C_{Gas}). The discount factors vary by Census region, end use, and fuel type. See Table B-4 in Appendix B for commercial sector UPV* factors, and Figure 6-1 for a map of states in each Census Region.

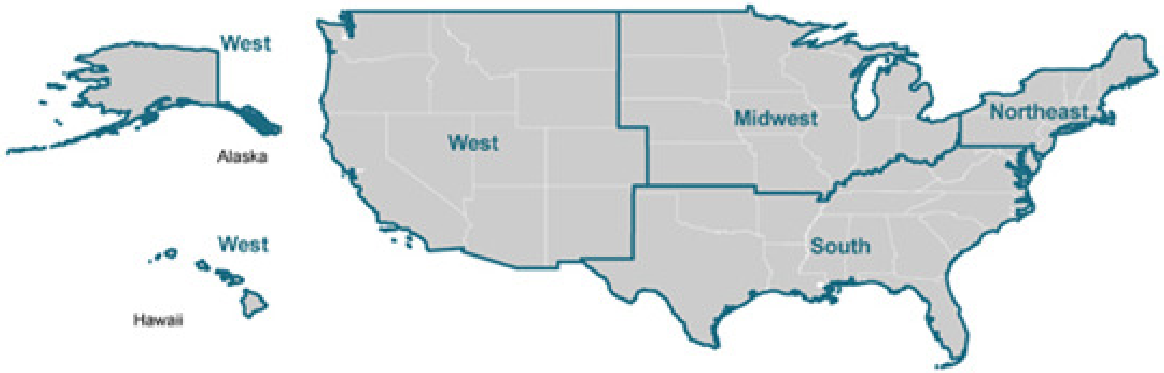

Figure 6-1 U.S. Census Regions[16]

Total present value future costs (C_{Future}) is the sum of present value location-indexed MRR costs and present value energy costs, as shown in the following equation:

$$C_{Future} = C_{MRR} + C_{Elect} + C_{Gas}$$

6.3 Building Residual Value

A building's residual value is its value at the end of the study period. It is estimated in two parts, for the building (excluding HVAC) and the HVAC system, based on the approach defined in Fuller et al. (1996). The building's residual value is assumed to be equal to the building's location-indexed first cost multiplied by one minus the ratio of the study period to the service life of the building, and discounted from the end of the study period. For example, if a building has first costs (excluding HVAC) of $1 million, a 41 year service life, and the study period length is 10 years, the residual value of the building in year 10 (excluding the HVAC system) is $\$1\,000\,000 * \left(1 - \frac{10}{41}\right) = \$756\,098$. The value must then be discounted into present value terms.

Residual values for the HVAC system components, which have different lifespans across locations, are computed for each location in a similar manner. The remaining "life" of the HVAC equipment is determined by taking its service life minus the number of years

[16] Source: National Oceanic and Atmospheric Administration (NOAA)

since its last installation (as of the end of the study period), whether it occurred during building construction or replacement. The ratio of remaining life to service life is multiplied by the location-indexed installed cost of the system and discounted from the end of the study period. For example, assume an HVAC system's installed costs are \$100 000 with a service life in the selected location of 8 years, and a 10-year study period length. After one replacement, the system is 2 years old at the end of the study period, leaving 6 years remaining in its service life. The residual value in year 10 is $\$100\,000 * \frac{6}{8} = \$75\,000$. The total nominal residual value of the building and the HVAC system multiplied by the year 10 SPV factor estimates the present value residual value ($C_{Residual}$).

6.4 Life-Cycle Cost Analysis

The total life-cycle cost of a prototype building (C_{LCC}) is the sum of the present values of first cost and future costs minus the residual value as shown in the following equation:

$$C_{LCC} = C_{First} + C_{Future} - C_{Residual}$$

LCC analysis of buildings typically compares the LCC for a "base case" building design to the costs for alternative, more energy efficient building design(s) to determine if future operational savings justify higher initial investments.[17] For this database total life-cycle costs are calculated as described above for all building design options for all study periods. The user of the database has the option to select any of the building designs as the "base case," and compare it to any of the alternative designs for a selected study period.

Two metrics are used to analyze changes in life-cycle costs: net LCC savings and net LCC savings as a percentage of base case LCC. Net LCC savings (*NS*) is the difference between the base case LCC (C_{Base}) and alternative design LCC (C_{Alt}) as shown in the following equation:

$$NS = C_{Base} - C_{Alt}$$

Net LCC savings as a percentage of base case LCC (*PNS*) is the net LCC savings divided by the base case LCC. This metric, shown in the equation below, allows for comparisons across building types that vary significantly in terms of floor area.

$$PNS = \frac{NS}{C_{Base}}$$

[17] All life-cycle cost calculations are based on ASTM Standards on Building Economics (2007).

7 Carbon Assessment Approach

Estimates of greenhouse gas emissions from operational energy use are derived from two sources. The state-level average emissions rates per GWh (MBtu) of electricity generated, for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are obtained from the 2007 Emissions and Generation Resource Integrated Database (eGRID), which is a collection of data from the EIA, Federal Energy Regulatory Commission (FERC), and the EPA. Table B-5 in Appendix A shows the variation in the emissions rates by state, which results from differing fuel mixes used for electricity generation.

The natural gas emissions data shown in Table 7-1 is collected from Lippiatt (2007). National average emissions rates are used because the consumption of natural gas will create the same amount of emissions regardless of where it is consumed.

Table 7-1 CO_2, CH_4, and N_2O Emissions Rates for Natural Gas

Carbon Dioxide tons/GWh (lb/MBtu)	Methane tons/GWh (lb/MBtu)	Nitrous Oxide kg/GWh (lb/MBtu)
13.75 (8.88)	1.05 (0.676)	0.186 (0.000119)

These environmental flows are converted into a common unit of measure called carbon dioxide equivalents (CO_2e) using equivalency factors in Table 7-2, which represent the global warming potential (GWP) of a unit of an environmental flow relative to that of one unit of carbon dioxide. One unit of methane has 23 times the GWP as one unit of carbon dioxide, and nitrous oxide has 296 times the GWP as carbon dioxide. The aggregate CO_2e is calculated by taking the amount of each flow multiplied by its CO_2e factor, and summing the three CO_2 equivalencies for a unit of energy. The results are analyzed in metric tons of CO_2e emissions.

Table 7-2 CO_2, CH_4, and N_2O Global Warming Potentials

Environmental Flow	CO_2 Equivalent Factor
Carbon Dioxide (CO_2)	1
Methane (CH_4)	23
Nitrous Oxide (N_2O)	296

The carbon assessment of energy-related greenhouse gas emissions considers CO_2, CH_4, and N_2O generated by consumption of two types of energy, electricity and natural gas.

The total CO_2e emissions (E_T) for the study period are calculated using the following equation.[18]

$$E_T = U_{Elect} * F_{Elect} + U_{Gas} * F_{Gas}$$

Total electricity-related CO_2e emissions are estimated using the total CO_2e per unit of electricity for the state (F_{Elect}) multiplied by the total electricity use over the study period (U_{Elect}). Total natural gas-related CO_2e emissions are estimated using the total CO_2e per unit of natural gas (F_{Gas}) multiplied by the total natural gas use over the study period (U_{Gas}).

[18] While carbon assessment of the materials used in building construction, repair, and replacement is currently excluded from the analysis, it is currently under development and will be included in future versions of this work.

8 Summary

This report documents the prototype building designs and the life-cycle costing and carbon assessment data and approaches implemented in the BIRDS building energy efficiency and sustainability database. It is the second in a series of reports on the BIRDS database, the first of which documents the design of the whole building energy simulations used to predict annual operating energy for prototype buildings (Kneifel 2011b). The BIRDS database in its current state is particularly useful for commercial building energy efficiency researchers, and has been designed for near-future use by the building sustainability community at large.

8.1 BIRDS Database Uses

The current BIRDS database will be publicly available in 2012. There are a multitude of uses for the sustainability database depending on the user. Users could estimate the benefits and costs from either a prior energy code adoption or a potential future adoption of a more efficient energy code. The analysis could include the incremental benefits and costs, in both percentage and total value terms, across multiple editions of the *ASHRAE 90.1 Standard* at the building, local, state, regional, or national levels.

Results may be compared for different locations and building types. The BIRDS database may be used to find the length of the investor time horizon – or the value of the discount rate – at which future benefits begin to outweigh initial investment costs. With the wide range of energy efficiencies represented in the BIRDS database – from the ASHRAE 90.1-1999 designs to the Low Energy Case designs – users can benchmark building energy, cost, and carbon performance against “worst-in-class” and “best-in-class” performance. The influence of local fuel prices and the fuel mix for a region’s electricity grids can be seen in the future energy costs and carbon emissions reported for different regions of the country.

These are only a few options for analysis of the BIRDS database. Public availability allows for interested researchers to pursue other areas of interest, even those not considered by its developers.

8.2 BIRDS Database Enhancement and Expansion

Research is well underway to expand the sustainability dimension of the BIRDS database beyond carbon emissions generated by operating energy to include energy and materials sustainability across a wide array of environmental impacts. A comprehensive life-cycle assessment (LCA) dataset will be added to BIRDS in 2013 that evaluates the sustainability of the materials and energy used in construction, operation, maintenance, repair, and replacement for the prototype building designs documented in this report. These whole building LCAs will be keyed to building type and energy efficiency design, and will assess environmental impacts across all life-cycle stages, including raw materials acquisition, manufacturing, transportation, installation, use, and replacement. The whole building LCAs will evaluate prototype building performance across a comprehensive range of 12 environmental impacts including global warming, embodied energy, ecological toxicity, land use, and water use. The BIRDS LCA data will be documented in a third report in this series.

The BIRDS database can be expanded in a number of ways. First, additional prototype building types could be built into the database, such as the 16 NREL Benchmark buildings or the United States Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC) Common Building Information Modeling (BIM) Files (apartment, medical clinic, and office buildings), to better represent the U.S. commercial building stock and expand the research footprint for the database. Second, additional building designs could be included in the database, both designs representing the existing U.S. building stock as well as designs that meet *ASHRAE 90.1-2010*, *ASHRAE 189.1*, or DOE *Advanced Energy Design Guides* (*AEDG*s) requirements. Third, DOE minimum HVAC efficiency requirements can be included in the database. The current database compares editions of *ASHRAE 90.1* without considering federal regulations that set minimum HVAC efficiency requirements. Current DOE regulation requires some new HVAC equipment to meet *ASHRAE 90.1-2007* regardless of the energy code status in a state. Incorporating this federal requirement will enhance the results estimations for states that currently have adopted the *ASHRAE 90.1-2004* edition or older. Fourth, new and existing residential prototype buildings and the associated residential construction costs could be incorporated into the database to add the residential sector to the database scope. Fifth, there are several areas in which more precise or reliable data could enhance the database. In particular, finding more reliable cost data for increasing the efficiency of an HVAC component could lead to more accurate results. Increasing precision of energy cost data, such as incorporating utility-level costing schedules, could improve precision of the relative energy cost savings results.

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A Selected File Input and Output Formats and HVAC Climate Zones

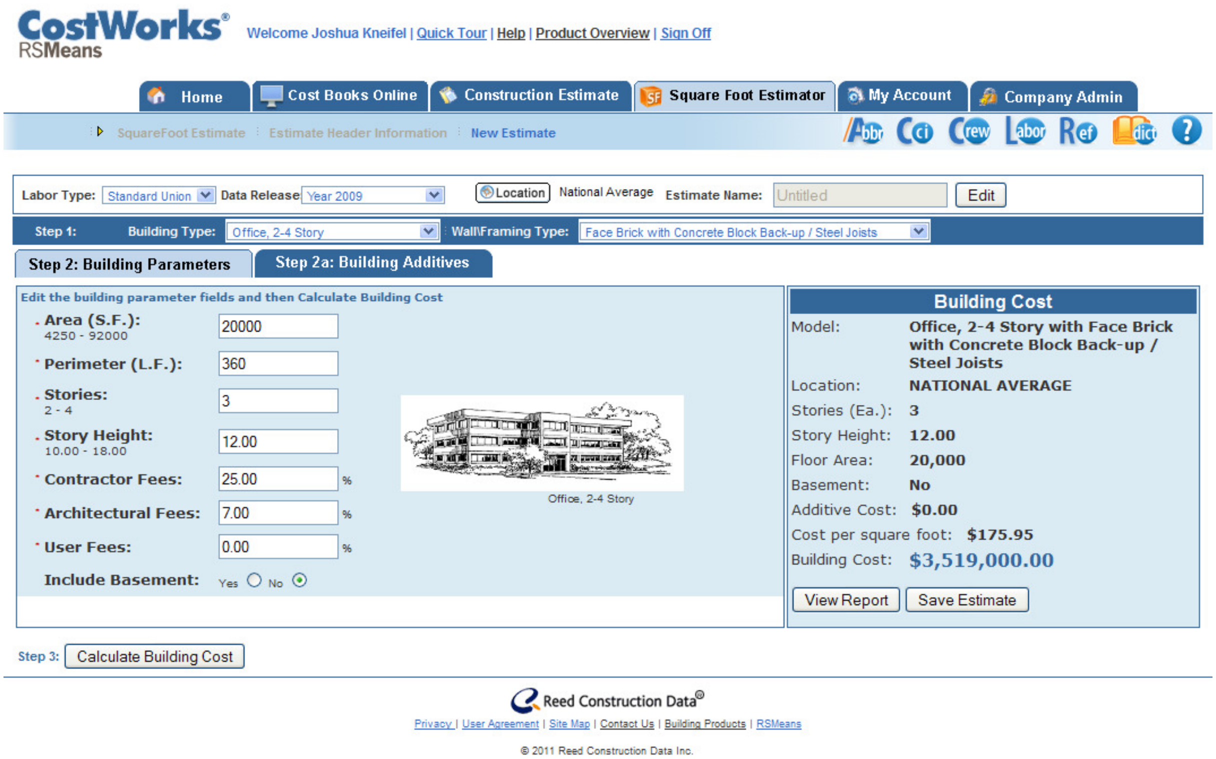

Figure A-1 RS Means CostWorks Square Foot Cost Estimator Web Interface Input

CostWorks RSMeans

Square Foot Cost Estimate Report Back Print Export

Estimate Name: **Untitled**

Building Type:	**Office, 2-4 Story with Face Brick with Concrete Block Back-up / Steel Joists**
Location:	**National Average**
Stories:	**3**
Story Height (L.F.):	**12.00**
Floor Area (S.F.):	**20000**
Labor Type:	**Union**
Basement Included:	**No**
Data Release:	**Year 2009**
Cost Per Square Foot:	
Building Cost:	

Costs are derived from a building model with basic components. Scope differences and market conditions can cause costs to vary significantly.

			% of Total	Cost Per S.F.	Cost
A Substructure			**4.4%**		
A1010	**Standard Foundations**				
	Strip footing, concrete, reinforced, load 11.1 KLF, soil bearing capacity 6 KSF, 12" deep x 24" wide				
	Spread footings, 3000 PSI concrete, load 200K, soil bearing capacity 6 KSF, 6' - 0" square x 20" deep				
	Spread footings, 3000 PSI concrete, load 300K, soil bearing capacity 6 KSF, 7' - 6" square x 25" deep				
A1030	**Slab on Grade**				
	Slab on grade, 4" thick, non industrial, reinforced				
A2010	**Basement Excavation**				
	Excavate and fill, 30,000 SF, 4' deep, sand, gravel, or common earth, on site storage				
A2020	**Basement Walls**				
	Foundation wall, CIP, 4' wall height, direct chute, .099 CY/LF, 4.8 PLF, 8" thick				
	Foundation wall, CIP, 4' wall height, direct chute, .148 CY/LF, 7.2 PLF, 12" thick				
B Shell			**29.6%**		
B1010	**Floor Construction**				
	Floor, concrete, slab form, open web bar joist @ 2' OC, on W beam and wall, 25'x25' bay, 26" deep, 75 PSF superimposed load, 120 PSF total load				
	Floor, concrete, slab form, open web bar joist @ 2' OC, on W beam and wall, 25'x25' bay, 26" deep, 75 PSF superimposed load, 120 PSF total load, for columns add				
	Fireproofing, gypsum board, fire rated, 2 layer, 1" thick, 14" steel column, 3 hour rating, 22 PLF				
B1020	**Roof Construction**				
	Floor, steel joists, beams, 1.5" 22 ga metal deck, on columns and bearing wall, 25'x25' bay, 20" deep, 40 PSF superimposed load, 60 PSF total load				
	Floor, steel joists, beams, 1.5" 22 ga metal deck, on columns and bearing wall, 25'x25' bay, 20" deep, 40 PSF superimposed load, 60 PSF total load, add for column				
B2010	**Exterior Walls**				
	Brick wall, composite double wythe, standard face/CMU back-up, 8" thick, perlite core fill				
B2020	**Exterior Windows**				
	Windows, aluminum, awning, insulated glass, 4'-5" x 5'-3"				

Figure A-2 RS Means CostWorks Square Foot Cost Estimator Web Interface Output

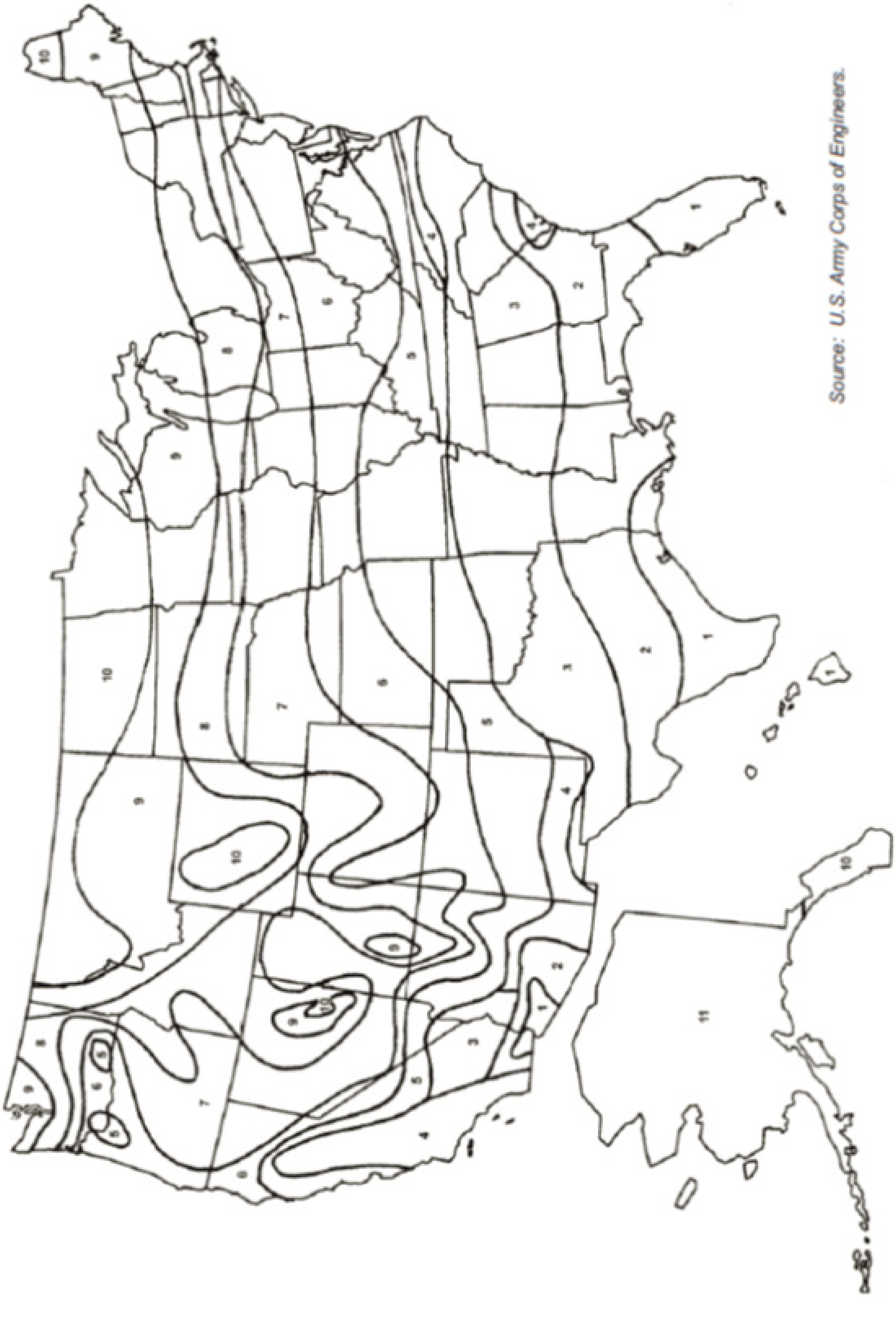

Figure A-3 Whitestone HVAC Climate Zones

B Selected Tabular Information

Table B-1 List of Cities in the BIRDS database

State	City	State	City	State	City	State	City
AK	Anchorage	IA	Waterloo	MT	Missoula	PA	Wilkes-Barre
AK	Barrow	ID	Boise	NC	Asheville	PA	Williamsport
AK	Fairbanks	ID	Lewiston	NC	Charlotte	RI	Providence
AK	Juneau	ID	Pocatello	NC	Greensboro	SC	Charleston
AK	Kodiak	IL	Chicago	NC	Hatteras	SC	Columbia
AK	Nome	IL	Moline	NC	Raleigh	SC	Greenville
AL	Birmingham	IL	Peoria	NC	Wilmington	SD	Huron
AL	Huntsville	IL	Rockford	ND	Bismarck	SD	Pierre
AL	Mobile	IL	Springfield	ND	Fargo	SD	Sioux Falls
AL	Montgomery	IN	Evansville	ND	Minot	TN	Bristol
AR	Fort Smith	IN	Fort Wayne	NE	Grand Island	TN	Chattanooga
AR	Little Rock	IN	Indianapolis	NE	Norfolk	TN	Knoxville
AZ	Flagstaff	IN	South Bend	NE	North Platte	TN	Memphis
AZ	Phoenix	KS	Dodge City	NE	Omaha	TN	Nashville
AZ	Prescott	KS	Goodland	NE	Scottsbluff	TX	Abilene
AZ	Tucson	KS	Topeka	NH	Concord	TX	Amarillo
AZ	Winslow	KS	Wichita	NJ	Atlantic City	TX	Austin
AZ	Yuma	KY	Covington	NJ	Newark	TX	Brownsville
CA	Arcata	KY	Lexington-Fayette	NM	Albuquerque	TX	Corpus Christi
CA	Bakersfield	KY	Louisville	NM	Roswell	TX	Del Rio
CA	Daggett	LA	Baton Rouge	NM	Tucumcari	TX	El Paso
CA	Fresno	LA	Lake Charles	NV	Elko	TX	Fort Worth
CA	Long Beach	LA	New Orleans	NV	Ely	TX	Houston
CA	Los Angeles	LA	Shreveport	NV	Las Vegas	TX	Lubbock
CA	Riverside	MA	Boston	NV	Reno	TX	Lufkin
CA	Sacramento	MA	Worcester	NV	Tonopah	TX	Midland
CA	San Diego	MD	Baltimore	NV	Winnemucca	TX	Port Arthur
CA	San Francisco	ME	Caribou	NY	Albany	TX	San Angelo
CA	Santa Maria	ME	Portland	NY	Binghamton	TX	San Antonio
CO	Alamosa	MI	Alpena	NY	Buffalo	TX	Victoria
CO	Boulder	MI	Detroit	NY	Massena	TX	Waco
CO	Colorado Springs	MI	Flint	NY	New York	TX	Wichita Falls
CO	Eagle	MI	Grand Rapids	NY	Rochester	UT	Cedar City
CO	Grand Junction	MI	Houghton	NY	Syracuse	UT	Salt Lake City
CO	Pueblo	MI	Lansing	OH	Akron	VA	Lynchburg
CT	Bridgeport	MI	Muskegon	OH	Cleveland	VA	Norfolk
CT	Hartford	MI	Sault Sainte Marie	OH	Columbus	VA	Richmond
DE	Wilmington	MI	Traverse City	OH	Mansfield	VA	Roanoke
FL	Daytona Beach	MN	Duluth	OH	Toledo	VT	Burlington
FL	Jacksonville	MN	International Falls	OH	Youngstown	WA	Olympia
FL	Key West	MN	Minneapolis	OK	Oklahoma City	WA	Quillayute
FL	Miami	MN	Rochester	OK	Tulsa	WA	Seattle
FL	Tallahassee	MN	Saint Cloud	OR	Astoria	WA	Spokane
FL	Tampa	MO	Columbia	OR	Burns	WA	Yakima
FL	West Palm Beach	MO	Kansas City	OR	Eugene	WI	Eau Claire
GA	Athens	MO	Saint Louis	OR	Medford	WI	Green Bay
GA	Atlanta	MO	Springfield	OR	North Bend	WI	La Crosse
GA	Augusta	MS	Jackson	OR	Pendleton	WI	Madison
GA	Columbus	MS	Meridian	OR	Portland	WI	Milwaukee
GA	Macon	MT	Billings	OR	Redmond	WV	Charleston

GA	Savannah	MT	Cut Bank	OR	Salem	WV	Elkins
HI	Hilo	MT	Glasgow	PA	Allentown	WV	Huntington
HI	Honolulu	MT	Great Falls	PA	Bradford	WY	Casper
IA	Burlington	MT	Helena	PA	Erie	WY	Cheyenne
IA	Des Moines	MT	Kalispell	PA	Harrisburg	WY	Lander
IA	Mason City	MT	Lewistown	PA	Philadelphia	WY	Rock Springs
IA	Sioux City	MT	Miles City	PA	Pittsburgh	WY	Sheridan

Table B-2 Average Maintenance, Repair, and Replacement Costs, 2-Story Office Building (S-I)

$/m² by Year and Component													
Building Age	Exterior Enclosure	Roofing	Interior Construction	Stairways	Interior Finishes	Conveying Systems	Plumbing	HVAC Systems	Fire Protection	Electrical	Equipment	Total	Total (No HVAC)
1		1.08				1.08	0.65	4.09	0.43	1.94	0.11	9.36	5.27
2		1.08				1.08	1.40	4.09	0.43	1.94	0.11	10.12	6.03
3		1.08				1.08	0.65	4.09	0.43	2.69	0.11	10.12	6.03
4		1.08	0.65		9.58	1.08	1.40	4.09	0.43	1.94	0.11	20.34	16.25
5	0.22	1.83	2.37		0.97	1.08	0.97	4.31	0.65	2.80	0.11	15.28	10.98
6		1.08				1.08	1.40	4.09	0.43	2.69	0.11	10.87	6.78
7		1.08				1.08	1.08	4.63	0.43	1.94	0.11	10.33	5.70
8		1.08	0.65		9.58	1.08	1.40	4.09	0.43	1.94	0.11	20.34	16.25
9		1.08			0.54	1.08	0.65	4.09	0.43	2.69	0.11	10.66	6.57
10	18.84	17.44	9.69		1.72	1.08	4.52	16.47	3.66	28.31	0.86	102.80	86.33
11		1.08				1.08	0.65	4.09	0.43	1.94	0.11	9.36	5.27
12		1.08	0.65		9.58	1.08	2.26	4.20	1.94	2.69	0.11	23.57	19.38
13		1.08				1.08	0.65	4.09	0.43	1.94	0.11	9.36	5.27
14		1.08				1.08	1.72	4.74	0.43	1.94	0.11	11.19	6.46
15	1.08	1.83	2.37		49.41	1.08	0.86	47.15	0.86	9.36	0.11	114.10	66.95
16		1.08	0.65		9.58	1.08	1.40	4.09	0.43	1.94	0.11	20.34	16.25
17		1.08				1.08	0.65	4.09	0.43	1.94	0.11	9.69	5.60
18		1.08			1.18	1.08	1.40	4.09	0.65	5.06	0.11	14.42	10.33
19		1.08				1.08	0.65	4.09	0.43	1.94	0.11	9.36	5.27
20	18.84	42.95	13.89		11.84	1.08	5.81	33.80	3.44	39.72	0.86	172.65	138.85
21		1.08				1.08	1.08	4.63	0.43	2.69	0.11	11.09	6.46
22		1.08				1.08	1.40	4.09	0.65	1.94	0.11	10.44	6.35
23		1.08				14.75	0.65	4.09	0.43	1.94	0.11	9.36	5.27
24		1.08	0.65		9.58	1.08	2.26	4.20	1.94	2.69	0.11	23.57	19.38
25	10.33	1.83	2.37		4.20	1.08	7.97	7.53	0.43	8.50	0.11	57.91	50.38
26		1.08				1.08	1.40	4.09	0.43	1.94	0.11	10.12	6.03
27		1.08			0.54	1.08	0.65	4.09	0.43	2.69	0.11	10.66	6.57
28		1.08	0.65		9.58	1.08	1.72	4.74	0.43	1.94	0.11	21.31	16.58
29		1.08				1.08	0.65	4.09	0.65	1.94	0.11	9.69	5.60
30	19.70	17.44	9.69		52.42	1.08	4.63	67.49	3.88	42.41	0.86	219.69	152.20
31		1.08				1.08	0.65	4.09	0.43	1.94	0.11	9.36	5.27
32		1.08	0.65		9.58	1.08	1.40	4.09	0.43	1.94	0.11	20.34	16.25
33		1.08				1.08	0.65	4.09	0.43	2.69	0.11	10.12	6.03
34		1.08				1.08	1.40	4.09	0.65	1.94	0.11	10.44	6.35
35	0.22	1.83	2.37		0.97	1.08	7.97	4.31	0.43	2.80	0.11	22.07	17.76
36		1.08	0.65		10.76	1.08	1.61	4.20	1.94	5.06	0.11	26.48	22.28
37		1.08				1.08	1.18	4.63	0.43	1.94	0.11	10.55	5.92
38		1.08				1.08	0.75	4.09	0.43	1.94	0.11	9.47	5.38
39		1.08				1.08	1.18	4.09	0.43	2.69	0.11	10.76	6.67
40	18.84	42.95	33.37	0.22	11.84	1.08	4.20	37.03	3.44	45.53	0.86	199.46	162.43

Table B-3 Average Maintenance, Repair, and Replacement Costs, 2-Story Office Building (I-P)

	$/ft^2 by Year and Component												
Building Age	Exterior Enclosure	Roofing	Interior Construction	Stairways	Interior Finishes	Conveying Systems	Plumbing	HVAC Systems	Fire Protection	Electrical	Equipment	Total	Total (No HVAC)
1		0.10				0.10	0.06	0.38	0.04	0.18	0.01	0.87	0.49
2		0.10				0.10	0.13	0.38	0.04	0.18	0.01	0.94	0.56
3		0.10				0.10	0.06	0.38	0.04	0.25	0.01	0.94	0.56
4		0.10	0.06		0.89	0.10	0.13	0.38	0.04	0.18	0.01	1.89	1.51
5	0.02	0.17	0.22		0.09	0.10	0.09	0.40	0.06	0.26	0.01	1.42	1.02
6		0.10				0.10	0.13	0.38	0.04	0.25	0.01	1.01	0.63
7		0.10				0.10	0.10	0.43	0.04	0.18	0.01	0.96	0.53
8		0.10	0.06		0.89	0.10	0.13	0.38	0.04	0.18	0.01	1.89	1.51
9		0.10			0.05	0.10	0.06	0.38	0.04	0.25	0.01	0.99	0.61
10	1.75	1.62	0.90		0.16	0.10	0.42	1.53	0.34	2.63	0.08	9.55	8.02
11		0.10				0.10	0.06	0.38	0.04	0.18	0.01	0.87	0.49
12		0.10	0.06		0.89	0.10	0.21	0.39	0.18	0.25	0.01	2.19	1.80
13		0.10				0.10	0.06	0.38	0.04	0.18	0.01	0.87	0.49
14		0.10				0.10	0.16	0.44	0.04	0.18	0.01	1.04	0.60
15	0.10	0.17	0.22		4.59	0.10	0.08	4.38	0.08	0.87	0.01	10.60	6.22
16		0.10	0.06		0.89	0.10	0.13	0.38	0.04	0.18	0.01	1.89	1.51
17		0.10				0.10	0.06	0.38	0.04	0.18	0.01	0.90	0.52
18		0.10			0.11	0.10	0.13	0.38	0.06	0.47	0.01	1.34	0.96
19		0.10				0.10	0.06	0.38	0.04	0.18	0.01	0.87	0.49
20	1.75	3.99	1.29		1.10	0.10	0.54	3.14	0.32	3.69	0.08	16.04	12.90
21		0.10				0.10	0.10	0.43	0.04	0.25	0.01	1.03	0.60
22		0.10				0.10	0.13	0.38	0.06	0.18	0.01	0.97	0.59
23		0.10				1.37	0.06	0.38	0.04	0.18	0.01	0.87	0.49
24		0.10	0.06		0.89	0.10	0.21	0.39	0.18	0.25	0.01	2.19	1.80
25	0.96	0.17	0.22		0.39	0.10	0.74	0.70	0.04	0.79	0.01	5.38	4.68
26		0.10				0.10	0.13	0.38	0.04	0.18	0.01	0.94	0.56
27		0.10			0.05	0.10	0.06	0.38	0.04	0.25	0.01	0.99	0.61
28		0.10	0.06		0.89	0.10	0.16	0.44	0.04	0.18	0.01	1.98	1.54
29		0.10				0.10	0.06	0.38	0.06	0.18	0.01	0.90	0.52
30	1.83	1.62	0.90		4.87	0.10	0.43	6.27	0.36	3.94	0.08	20.41	14.14
31		0.10				0.10	0.06	0.38	0.04	0.18	0.01	0.87	0.49
32		0.10	0.06		0.89	0.10	0.13	0.38	0.04	0.18	0.01	1.89	1.51
33		0.10				0.10	0.06	0.38	0.04	0.25	0.01	0.94	0.56
34		0.10				0.10	0.13	0.38	0.06	0.18	0.01	0.97	0.59
35	0.02	0.17	0.22		0.09	0.10	0.74	0.40	0.04	0.26	0.01	2.05	1.65
36		0.10	0.06		1.00	0.10	0.15	0.39	0.18	0.47	0.01	2.46	2.07
37		0.10				0.10	0.11	0.43	0.04	0.18	0.01	0.98	0.55
38		0.10				0.10	0.07	0.38	0.04	0.18	0.01	0.88	0.50
39		0.10				0.10	0.11	0.38	0.04	0.25	0.01	1.00	0.62
40	1.75	3.99	3.10	0.02	1.10	0.10	0.39	3.44	0.32	4.23	0.08	18.53	15.09

Table B-4 2009 UPV* Factors for Commercial Electricity and Natural Gas Use, by Census Region (3 % Discount Rate)

	Electricity					Natural Gas			
Year	Northeast	Midwest	South	West	Year	Northeast	Midwest	South	West
1	0.83	0.90	0.88	0.92	1	0.94	0.96	0.96	0.96
2	1.65	1.78	1.74	1.81	2	1.89	1.92	1.94	1.91
3	2.44	2.63	2.57	2.66	3	2.83	2.86	2.91	2.84
4	3.21	3.46	3.38	3.49	4	3.72	3.75	3.85	3.73
5	3.97	4.27	4.18	4.28	5	4.60	4.63	4.78	4.59
6	4.72	5.06	4.96	5.04	6	5.44	5.50	5.68	5.43
7	5.46	5.84	5.72	5.78	7	6.28	6.35	6.58	6.28
8	6.19	6.62	6.47	6.51	8	7.11	7.19	7.46	7.12
9	6.93	7.38	7.21	7.21	9	7.93	8.03	8.33	7.97
10	7.66	8.13	7.93	7.90	10	8.74	8.86	9.20	8.80
11	8.38	8.86	8.64	8.58	11	9.55	9.70	10.08	9.64
12	9.10	9.59	9.34	9.24	12	10.35	10.53	10.95	10.47
13	9.80	10.31	10.04	9.88	13	11.13	11.35	11.81	11.28
14	10.49	11.00	10.71	10.49	14	11.88	12.13	12.64	12.05
15	11.16	11.68	11.37	11.09	15	12.62	12.89	13.44	12.79
16	11.81	12.33	12.00	11.67	16	13.32	13.62	14.21	13.51
17	12.44	12.97	12.62	12.23	17	14.01	14.34	14.97	14.23
18	13.05	13.58	13.22	12.78	18	14.70	15.06	15.72	14.94
19	13.66	14.19	13.82	13.32	19	15.38	15.77	16.47	15.65
20	14.26	14.79	14.42	13.86	20	16.06	16.48	17.22	16.36
21	14.86	15.37	15.00	14.39	21	16.73	17.19	17.96	17.06
22	15.44	15.95	15.57	14.90	22	17.39	17.89	18.69	17.76
23	16.02	16.50	16.12	15.40	23	18.05	18.58	19.41	18.44
24	16.58	17.05	16.67	15.89	24	18.69	19.25	20.12	19.11
25	17.13	17.58	17.20	16.37	25	19.33	19.93	20.82	19.78
26	17.67	18.10	17.73	16.83	26	19.95	20.59	21.51	20.43
27	18.20	18.61	18.24	17.28	27	20.57	21.24	22.18	21.08
28	18.72	19.11	18.73	17.72	28	21.18	21.89	22.85	21.72
29	19.23	19.60	19.22	18.15	29	21.77	22.53	23.50	22.35
30	19.73	20.07	19.70	18.57	30	22.37	23.15	24.15	22.97
31	20.21	20.53	20.16	18.98	31	22.94	23.76	24.78	23.57
32	20.68	20.98	20.62	19.37	32	23.50	24.35	25.39	24.16
33	21.14	21.41	21.05	19.76	33	24.05	24.92	25.98	24.73
34	21.58	21.83	21.48	20.13	34	24.57	25.48	26.55	25.28
35	22.01	22.24	21.89	20.49	35	25.08	26.02	27.11	25.82
36	22.43	22.64	22.29	20.85	36	25.58	26.55	27.65	26.34
37	22.83	23.02	22.68	21.19	37	26.06	27.05	28.18	26.84
38	23.23	23.40	23.06	21.52	38	26.53	27.55	28.69	27.34
39	23.61	23.76	23.42	21.84	39	26.99	28.03	29.19	27.81
40	23.98	24.11	23.78	22.15	40	27.43	28.49	29.67	28.28

Table B-5 CO_2, CH_4, and N_2O Emissions from Electricity Generation by State

State	CO_2 (tons/GWh)	CH_4 (kg/GWh)	N_2O (kg/GWh)
AK	494.32	11.19	2.74
AL	608.05	11.39	10.47
AR	557.57	14.51	10.12
AZ	525.52	7.04	7.23
CA	244.97	13.88	2.04
CO	866.76	10.65	13.27
CT	364.65	30.75	6.18
DE	915.37	16.55	12.03
FL	608.06	20.74	8.02
GA	636.18	9.99	10.85
HI	785.17	75.02	13.59
IA	865.11	10.15	14.34
ID	60.66	8.69	1.56
IL	510.74	5.96	8.39
IN	946.99	11.13	15.77
KS	859.52	10.55	14.20
KY	933.24	10.95	15.83
LA	533.19	11.54	6.09
MA	572.85	31.03	7.82
MD	613.38	15.69	10.31
ME	335.50	103.88	14.74
MI	611.24	13.45	10.73
MN	723.33	17.56	12.92
MO	837.75	9.67	13.93
MS	556.00	12.02	7.90
MT	722.14	8.95	12.34
NC	555.64	8.99	9.67
ND	1054.67	11.39	16.94
NE	728.42	8.43	12.11
NH	357.56	27.67	6.81
NJ	325.94	13.71	4.89
NM	878.11	10.56	13.85
NV	653.53	9.08	8.10
NY	375.72	16.76	4.72
OH	803.69	9.52	13.56
OK	708.86	9.83	9.27
OR	182.09	7.70	2.18
PA	564.50	11.53	9.50
RI	437.59	8.71	0.90
SC	405.45	6.77	6.88
SD	535.90	6.33	8.63
TN	571.10	7.44	9.84
TX	614.80	8.96	6.96
UT	953.89	10.95	15.96
VA	542.52	18.59	9.65
VT	2.11	40.19	5.37
WA	150.19	7.44	2.74
WI	780.24	11.58	12.83
WV	874.58	9.93	14.84
WY	1021.24	11.65	16.89