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Grocery Store 50% Energy Savings Technical Support Document

Matthew Leach, Elaine Hale, Adam Hirsch, and Paul Torcellini

Technical Report
NREL/TP-550-46101
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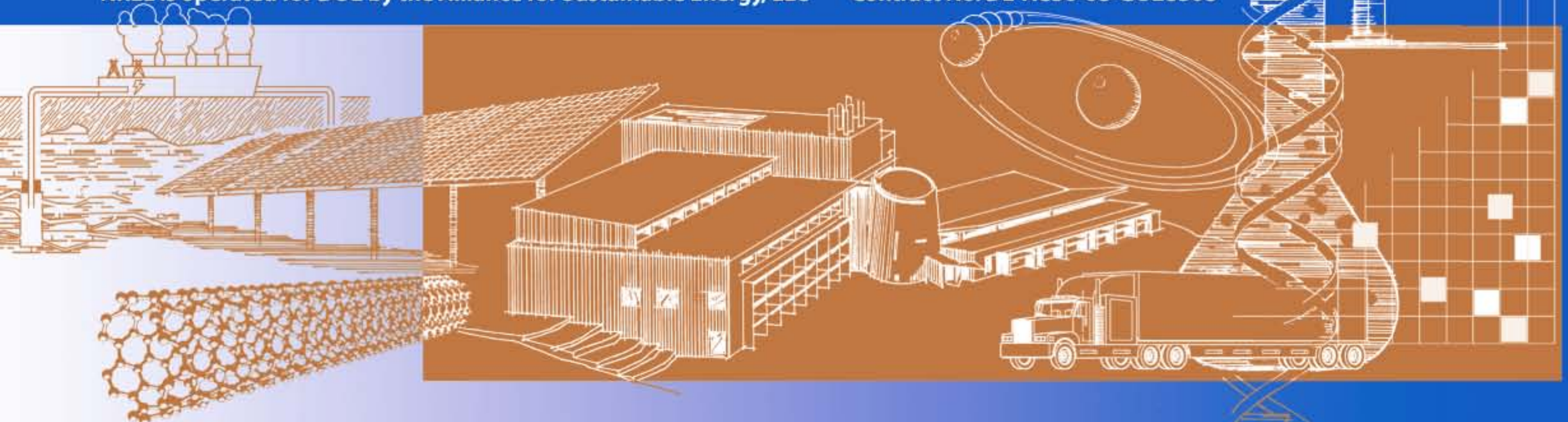

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We are indebted to a number of retailers and building industry professionals for taking the time to review our analysis assumptions and earlier versions of this report. Jim Kirk of A&P Grocery Stores, Kathy Loftus of Whole Foods, and Scott Williams of Target, all members of the Retailer Energy Alliance, commented on our prototype and energy design measure (EDM) model assumptions based on their companies' experiences and standard practices. Don Zerrip, Ben Butler, and H. J. Enck of CxGBS; Tim A. Speller of Speller Energy Consulting; and Thomas H. Phoenix of Moser Mayer Phoenix Associates reviewed an earlier draft of this report.

We extend our thanks to our colleagues Larry Brackney and Kristin Field for conducting formal internal reviews of this document, and to Stefanie Woodward for editing assistance.

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Tens of thousands of EnergyPlus simulations were run for this report. This would not have been possible without the support of the NREL High Performance Computing Center managed by Wesley Jones and Jim Albin.

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Executive Summary

This Technical Support Document (TSD) was developed by the Commercial Buildings Group at NREL, under the direction of the DOE Building Technologies Program. It documents technical analysis and design guidance for grocery stores to achieve whole-building energy savings of at least 50% over ASHRAE Standard 90.1-2004 and represents a step toward determining how to provide design guidance for aggressive energy savings targets.

This report:

- Documents the modeling and integrated analysis methods used to identify cost-effective sets of recommendations for different locations.
- Demonstrates sets of recommendations that meet, or exceed, the 50% goal. There are 16 sets of recommendations, one for each climate zone location.
- Establishes methodology for providing a family of solutions, as opposed to a single solution, that meet the 50% goal as a means of exploring the relative importance of specific design strategies.
- Demonstrates the energy efficiency, and, to a lesser extent, cost implications, of using ASHRAE Standard 90.1-2007 instead of Standard 90.1-2004.

This report, along with a sister document for general merchandise stores (Hale et al. 2009), also evaluates the possibility of compiling a 50% *Advanced Energy Design Guide* (AEDG) in the tradition of the 30% AEDGs available through the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and developed by an interorganizational committee structure.

Methodology

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

The following steps were used to determine 50% savings:

1. Define architectural-program characteristics (design features not addressed by ASHRAE 90.1-2004) for typical grocery stores, thereby defining a prototype model.
2. Create baseline energy models for each climate zone that are elaborations of the prototype models and are minimally compliant with ASHRAE 90.1-2004.
3. Create a list of energy design measures (EDMs) that can be applied to the baseline models to create candidate low-energy models.
4. Use industry feedback to strengthen inputs for baseline energy models and EDMs.

5. Simulate and select low-energy models for each climate zone that achieve 50% energy savings (or more). Give preference to those models that have low five-year total life cycle cost.

The simulations supporting this work were managed with the NREL commercial building energy analysis platform, Opt-E-Plus. Opt-E-Plus employs an iterative search technique to find EDM combinations that best balance percent energy savings with total life cycle cost for a given building in a given location. The primary advantages of the analysis platform are its abilities to (1) transform high-level building parameters (building area, internal gains per zone, HVAC system configuration, etc.) into a fully parameterized input file for EnergyPlus; (2) conduct automated searches to optimize multiple criteria; and (3) manage distributed EnergyPlus simulations on the local CPU and a Linux cluster. In all, 78,355 EnergyPlus models were run. The economic criterion used to filter the recommendations is five-year total life cycle cost (using the January 2008 OMB real discount rate, 2.3%). The five-year analysis period was established in our statement of work and is assumed acceptable to a majority of developers and owners.

The bulk of this report (Section 3.0) documents prototype building characteristics, baseline building model inputs, and modeling inputs for each EDM. The prototypes are 45,000 ft^2 (4,181 m^2), one-story rectangular buildings with a 1.5 aspect ratio. We assume 1,400 ft^2 (130 m^2) of glazing on the façade, which gives a 27% window-to-wall ratio for that wall, and an 8% window-to-wall ratio for the whole building. The prototype building has masonry wall construction and a roof with all insulation above deck. HVAC equipment consists of 10-ton packaged rooftop units with natural gas furnaces for heating, and electric direct-expansion coils with air-cooled condensers for cooling. The nominal refrigerated case and walk-in cooler load is 973 kBtu/h (274 kW), split 78%/22% between medium and low temperature compressor racks, respectively. The EDMs considered in this work fall into the following categories:

- **Lighting technologies**. Reduced lighting power density, occupancy controls, and daylighting controls.
- **Fenestration**. Amounts and types of façade glazing and skylights; overhangs.
- **Envelope**. Opaque envelope insulation, air barriers, and vestibules.
- **HVAC Equipment**. Higher efficiency equipment and fans, economizers, demand control ventilation (DCV), and energy recovery ventilators (ERVs).
- **Refrigeration Equipment**. Higher efficiency refrigerated cases, and evaporatively cooled condensers.
- **Generation**. Photovoltaic (PV) electricity generation.

Findings

The results show that 50% net site energy savings can be achieved cost-effectively in grocery stores. On-site generation technology (in this case, PV) was not necessary to meet the energy goal in any climate zone. Specific recommendations for achieving the 50% goal are tabulated for all climate zones. The following EDMs are recommended in all locations:

- Reduce lighting power density by 47%, and install occupancy sensors in the active storage, mechanical room, restroom, and office zones.
- Add a vestibule to the front entrance to reduce infiltration.

- Equip rooftop HVAC units with high efficiency fans.
- Install daylighting sensors tuned to a 46.5 fc (500 lux) set point.
- Replace baseline frozen food and ice cream refrigerated cases with efficient, vertical models with doors and hot gas defrost.
- Replace open multi-deck dairy/deli refrigerated cases with efficient, vertical models with doors
- Replace baseline meat display cases with models that have efficient fans, anti-sweat heater controls, electric defrost, and sliding doors.
- Reduce south façade window-to-wall ratio by 50%.

Two EDMs were not chosen for any location:

- Shaded overhangs above the windows on the south façade.
- Replacing the refrigeration system's air-cooled condensers with evaporative condensers.

In general, EDM selection trends were as expected:

- Skylights were selected in warm and hot climates where there is ample sunlight for daylighting.
- More highly insulated opaque envelope constructions were selected in extreme climates (better insulated walls in hot climates and a better insulated roof in the coldest climate).
- High coefficient of performance (a 20% increase over baseline) HVAC rooftop units were selected in all but the coldest climate, which has a very low cooling load.
- Infiltration reduction measures (front entrance vestibule and envelope air barrier) were almost universally selected, especially in humid and cold climates.
- Economizers were not selected in humid or cold climates.
- ERVs played an important role in achieving the energy savings goal, especially in humid and cold climates.

A comparison of baseline models that satisfy ASHRAE 90.1-2004 and ASHRAE 90.1-2007 demonstrates that the newest standard does save energy, but at the expense of increased capital and lifetime costs (except in climate zone 8, where a five year analysis period is sufficient for the energy savings to balance out increased capital expenditures).

A novel post-processing methodology designed to identify multiple designs that reach the energy savings goal while simultaneously answering questions like, "Is daylighting required to meet the goal?" was developed and applied to five climate zones. It identified ten to twelve additional designs per climate zone, and demonstrated that the energy used by baseline multi-deck dairy/deli refrigerated cases must be addressed if one intends to build a 50% energy savings grocery store. The successful designs are significantly different from each other in both composition and performance across several criteria of interest, including capital cost, lifetime cost, and maximum electricity demand. Perturbation information is also extracted and used to calculate the amount of PV required to replicate the energy savings associated with the EDMs used in the original low-energy model.

A number of modeling errors skewed the results of our original optimizations over the complete set of EDMs. The original results indicated that the low-energy models would require a larger initial capital investment than the corresponding baseline models and that the climate zone 1A and 2A stores would not be able to save enough energy to offset those higher capital costs within the five-year analysis period. By correcting the modeling errors and performing abbreviated optimization runs to determine which of ERV, DCV, and PV should actually be included in each low-energy model, we were able to show that 50% energy savings can be achieved cost effectively in terms of both lifetime and capital cost.

Although this TSD is fairly comprehensive and describes design packages that achieve the 50% energy savings goal cost effectively, future analyses may benefit from adopting some of the recommendations outlined in Section 5.0. For instance, EDMs we feel are deserving of increased attention, but omitted because of modeling constraints, are:

- Alternative HVAC systems such as ground source heat pumps, packaged variable air volume systems, and radiant heating and cooling
- Solar thermal technologies for service water heating and space conditioning
- Direct and indirect evaporative cooling
- Decreased pressure drop via improved duct design
- Advanced humidity control
- Strategies to use waste heat from the refrigeration equipment
- Secondary loop refrigeration
- Multiple compressor types
- Under-case HVAC return air

Nomenclature

5-TLCC	five-year total life cycle cost
AEDG	Advanced Energy Design Guide
AIA	American Institute of Architects
ARI	Air-Conditioning and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CBECS	Commercial Buildings Energy Consumption Survey
CDD	cooling degree day
c.i.	continuous insulation
CO_2	carbon dioxide
COP	coefficient of performance
DEA	dedicated exhaust air
DOE	U.S. Department of Energy
DX	direct expansion
EA	exfiltrated air
EER	energy efficiency ratio
ERV	energy recovery ventilator
EUI	energy use intensity
HDD	heating degree day
HVAC	heating, ventilation, and air conditioning
IECC	International Energy Conservation Code
IESNA	Illuminating Engineering Society of North America
LEED	Leadership in Energy and Environmental Design
LPD	lighting power density
NREL	National Renewable Energy Laboratory
OA	outside air
O&M	operations and maintenance
RTU	rooftop unit
PSZ	A package single zone DX rooftop unit
SHGC	solar heat gain coefficient
5-TLCC	total life cycle cost
TSD	Technical Support Document
USGBC	U.S. Green Building Council
VAV	variable air volume
VLT	visible light transmittance
w.c.	water column
XML	extensible markup language

Contents

Figures and Tables

Figures

Tables

1.0 Introduction

This report is often referred to as a *Technical Support Document*, or TSD, because it is a detailed compilation of the modeling assumptions, analysis techniques, and results that provide the technical basis for recommending building design packages that achieve a desired level of net energy savings as compared to a baseline grocery store model. Historically, there have been a series of TSDs for different building types and different energy savings levels, some of which have led to the production of volumes in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Advanced Energy Design Guide (AEDG) series. The AEDGs are user-friendly books containing the design recommendations of the TSDs plus relevant case studies and best practice tips.

The TSDs and AEDGs are part of an inter-organizational effort to progressively facilitate the design, construction, and operation of more efficient buildings, with the eventual goal of achieving net zero energy buildings (Torcellini et al. 2006). The first phase concentrated on achieving 30% energy savings over ANSI/ASHRAE/IESNA Standard 90.1-2004 (ASHRAE). The study presented here is part of the second phase of this effort as it provides design guidance that architects, designers, contractors, developers, owners and lessees of grocery stores can use to achieve whole-building net site energy savings of at least 50% compared to the minimum requirements of Standard 90.1-2004. The recommendations are given by climate zone, and address building envelope (including infiltration through walls and doors), fenestration quantities and types, electrical lighting systems, daylighting, HVAC systems, outside air (OA) quantity and treatment, refrigerated cases, refrigeration system condensers, and photovoltaic (PV) systems. In all cases, the recommendations are not part of a code or a standard, and should be used as starting points for project-specific analyses.

This TSD belongs to a first set of studies aimed at the 50% milestone on the path toward Zero Energy Buildings (ZEBs), which generate or purchase an amount of renewable energy equivalent to or greater than the fossil fuel-derived energy they purchase over the course of a year. A number of public, private, and nongovernmental organizations have adopted ZEB goals. Directly relevant to this report is this statement by the U.S. Department of Energy (DOE) Efficiency and Renewable Energy Building Technologies Program (DOE 2005):

> By 2025, the Building Technologies Program will create technologies and design approaches that enable the construction of net-zero energy buildings at low incremental cost. A net-zero energy building is a residential or commercial building with greatly reduced needs for energy through efficiency gains, with the balance of energy needs supplied by renewable technologies.

The interorganizational AEDG effort is one pathway being pursued to help reach these goals. We hope that this TSD will result in the production of a Grocery Store 50% AEDG, in support of the ASHRAE Vision 2020 Committee and AEDG Scoping Committee goals to enable interested parties to achieve 50% energy savings by 2010 (Jarnagin et al. 2007; Mitchell et al. 2006). This work will also reach its intended audience of architects, designers, contractors, developers, owners, and lessees of grocery stores through the DOE-sponsored Retailer Energy Alliance (REA) (DOE 2008a).

This TSD was developed by the Commercial Buildings Section at the National Renewable Energy Laboratory (NREL), under the direction of the DOE Building Technologies Program, and in parallel with a sister TSD for general merchandise stores (Hale et al. 2009). It builds on previous work (Hale et al. 2008a; Hale et al. 2008b) that established a basic methodology for finding building designs that achieve 50% energy savings over ASHRAE 90.1-2004. These analyses improve on the earlier work in that (1) the analysis assumptions were reviewed by external experts; (2) an extended methodology for determining alternative 50% designs was developed; and (3) the extended methodology was applied to select climate zones.

1.1 Objectives

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

- **Develop recommendations that meet a numeric goal**. The energy savings goal is a hard value, not an approximate target. All recommendation sets have been verified to give at least 50% net site energy savings compared with Standard 90.1-2004. The savings are calculated on a whole-building energy consumption basis, which includes non-regulated loads.
- **Develop recommendations that can assist a range of interested parties**. Multiple designs that meet the 50% goal are provided in select climate zones (1A, 3B-NV, 4C, 5A, and 8). The method for producing those design packages also provides guidance as to whether particular strategies (types of design measures) or combinations of strategies are necessary to reach the target.
- **Investigate and communicate the benefits of integrated design.** An EnergyPlus-based building optimization tool, Opt-E-Plus, is used to find complementary combinations of efficiency measures that economically achieve the desired level of energy savings. The resulting recommendations demonstrate and quantify the benefits of considering the energy and economic implications of every design decision on a whole-building basis.
- **Incorporate review of modeling assumptions by industry representatives.** A condensed compilation of baseline and energy design measure (EDM) cost and performance assumptions was circulated to the REA to assess their validity. Several collaborating engineering firms reviewed an earlier draft of this document. Many of their comments were incorporated into this study or taken into consideration for future study.
- **Compare ASHRAE 90.1-2004 to ASHRAE 90.1-2007 as they apply to grocery stores.** We report the energy use and approximate cost difference between baseline grocery stores that prescriptively satisfy ASHRAE 90.1-2004 and ASHRAE 90.1-2007 so interested parties can evaluate the progression of Standard 90.1.

1.2 Scope

This document provides recommendations and design assistance to designers, developers, and owners of grocery stores that will encourage steady progress toward net zero energy buildings. To ease the burden of designing and constructing energy-efficient grocery stores, we describe a set of designs that reach the 50% energy savings target for each climate zone. The recommendations and discussion apply to grocery stores of 25,000 ft^2 to 65,000 ft^2 (2,323 m^2 to 6,039 m^2), with about 750 ft (229 m) of refrigerated cases and 500 ft (152 m) of walk-in coolers and freezers.

This TSD is not intended to substitute for rating systems or other references that address the full range of sustainable issues, such as acoustics, productivity, indoor environmental quality, water efficiency, landscaping, and transportation, except as they relate to operational energy consumption. It is also not a design text—we leave detailed design to the experts working on particular projects. Our results are intended to demonstrate the advantages of integrated whole-building design, and to suggest sets of design features that seem to work well together in each climate zone.

1.3 Report Organization

This report is organized into four sections. The introduction, **Section 1.0**, gives background, overview and scope information. **Section 2.0** describes our modeling methodology, including definitions, analysis framework, post-processing of results, and external review. S**ection 3.0** documents all our modeling assumptions: (1) overall assumptions including economic methodology; (2) the prototype model, that is, programmatic, floor plan, and equipment type information that remains constant throughout the study; (3) detailed cost and performance data for climate-specific baseline buildings; and (4) EDMs, which are design perturbations that may provide energy savings in one or more climates. **Section 4.0** contains the results of the modeling study, including cost and energy use intensity (EUI) of baseline and low-energy models, the EDMs chosen in different climate zones to reach the energy saving goal, and post-processing results showing alternative paths to 50% energy savings. We also show how the baseline energy use changes when using ASHRAE Standard 90.1-2007 instead of Standard 90.1-2004 and compare baseline results with the Commercial Buildings Energy Consumption Survey (CBECS) dataset.

2.0 Methodology

This chapter describes the methodology and assumptions used to develop early stage building designs that achieve 50% energy savings. We begin with the overall approach of the study to modeling energy savings in grocery stores, including the energy and economic metrics used and the scope of EDMs that are considered in the analysis. We proceed to describe how we found models that meet the 50% energy savings goal, and conclude with a summary of our solicitations for retailer and engineering review and the results of that activity.

2.1 Guiding Principles

Our objective is to find grocery store designs that achieve 50% energy savings over ASHRAE 90.1-2004. We also seek designs that are cost effective over a five-year analysis period. These objectives lead us to examine the *Percent Net Site Energy Savings* and the *Five-Year Total Life Cycle Cost* (5-TLCC) of candidate buildings. Of course, other objectives could be used; this choice best fits the mandate for this project.

Achieving 50% savings cost effectively requires integrated building design--a design approach that analyzes buildings as holistic systems, rather than as disconnected collections of individually engineered subsystems. Indeed, accounting for and taking advantage of interactions between subsystems is a paramount concern. As an example, a reduction in installed lighting power density (LPD) can often be accompanied by a smaller HVAC system, but only if an integrated design process allows for it. (In one instance, we found that the capacity of the HVAC system could be reduced by 0.7 tons cooling for every kilowatt reduction in installed lighting power.)

Candidate designs are chosen by applying one or more perturbations to a baseline building. The perturbations are called *Energy Design Measures* (EDMs) to reflect that they are meant to have an impact on energy use. We used the following guiding principles to develop a list of prospective EDMs:

- We recommend off-the-shelf technologies that are available from multiple sources, as opposed to technologies or techniques that are available only in limited quantities or from one manufacturer.
- The EDMs are limited to technologies that can be modeled using EnergyPlus and the NREL Opt-E-Plus platform.

The methodology for developing candidate integrated designs is discussed in Sections 2.4 and 2.5. That the recommended low-energy designs achieve 50% energy savings is verified during the process of model development and simulation. The recommended designs are also expected to be reasonably cost effective, but not necessarily the most cost effective, given the difficulty of obtaining accurate and timely cost data on all the technologies required to reach 50% savings in all climate zones.

2.2 Definitions

This section specifies how we calculate building energy use and percent energy savings relative to ASHRAE 90.1-2004. This description includes the site boundary used to calculate net site energy use, how we deal with energy demands not treated by the ASHRAE Standards, and how Appendix G of ASHRAE 90.1 is applied.

2.2.1 Energy Use

Building energy use can be calculated a number of ways based on where the energy is assumed to originate, and on which loads are included in the calculation. The assumptions used in this TSD follow.

2.2.1.1 Net Site Energy Use

The percent energy savings goal is based on net site energy use: the amount of energy delivered to a building by the utility (typically in the form of electricity or natural gas) minus any renewable energy generated within its footprint. Other metrics, such as energy cost savings, source energy savings, and carbon savings, could be used (Torcellini et al. 2006). Each metric has advantages and disadvantages in calculation and interpretation, and each favors different technologies and fuel types. This TSD uses net site energy savings to retain consistency with the previous AEDGs, and to serve as a milestone on the path to the DOE goal of zero net site energy.

2.2.1.2 Whole Building Energy Use

Historically, energy savings have been expressed in two ways: for regulated loads only and for all loads (the whole building). Regulated loads metrics do not include plug and process loads that are not code regulated. Whole-building energy savings calculations, on the other hand, include all loads, whether regulated or not. In general, whole-building savings are more challenging than regulated loads savings given the same numerical target, but more accurately represent a building's impact on the national energy system.

We use the whole-building energy savings method to determine 50% energy savings, in line with the current ASHRAE and Leadership in Energy and Environmental Design (LEED) practices specified in Appendix G of ASHRAE 90.1-2004 and in LEED 2.2. However, we do not limit our recommendations to the regulated loads, as was done in the 30% AEDGs.

2.2.2 Percent Energy Savings

Percent energy savings are based on the notion of a minimally code-compliant building as described in Appendix G of ASHRAE 90.1-2004 (ASHRAE 2004a). The following steps were used to determine 50% savings:

1. Define architectural-program characteristics (design aspects not addressed by ASHRAE 90.1-2004) for typical grocery stores, thereby defining prototype models.
2. Create baseline energy models for each climate zone that are elaborations of the prototype models and are minimally compliant with ASHRAE 90.1-2004.
3. Create a list of EDMs that can be applied to the baseline models to create candidate low-energy models.
4. Select low-energy models for each climate zone that achieve 50% energy savings as compared to the baseline models, giving preference to those models that have low 5-TLCC.

2.2.3 ASHRAE 90.1-2004 Baseline

The 50% level of savings achieved by each low-energy building model is demonstrated in comparison with a baseline model that minimally satisfies the requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004 (ASHRAE 2004a). The baseline models are constructed in a manner similar to what was used in the previous *TSD*s (Hale et al. 2008a; Hale et al. 2008b; Jarnagin et al. 2006; Liu et al. 2006; Pless et al. 2007), and in compliance with

Appendix G of Standard 90.1-2004 when appropriate. Notable deviations from Standard 90.1-2004 Appendix G include:

- Glazing amounts (window area and skylight area) are allowed to vary between the baseline and low-energy models. We thereby demonstrate the effects of optimizing window and skylight areas for daylighting and thermal considerations.
- Fan efficiencies are set slightly higher than code-minimum[1] to represent a more realistic split of energy efficiency ratio (EER) between the supply fan and the compressor/condenser system in a packaged rooftop direct expansion HVAC unit.
- Net site energy use, rather than energy cost, is used to calculate savings.
- Mass walls are modeled in the baseline and low-energy models to ensure that our baseline accurately reflects typical design practice.

2.3 Building Energy Modeling Methodology

2.3.1 EnergyPlus

EnergyPlus Version 3.1 (DOE 2009), a publicly available building simulation engine, is used for all energy analyses. The simulations are managed with the NREL analysis platform, Opt-E-Plus, which transforms user-specified, high-level building parameters (building area, internal gains per zone, HVAC system configuration, etc.) stored in XML files into an input file for EnergyPlus. Opt-E-Plus can automatically generate the XML files, or it can manage XML files that have been assembled or modified elsewhere. Working with the XML files is much faster than modifying EnergyPlus input files directly, because a single XML parameter usually maps to multiple EnergyPlus inputs.

We selected EnergyPlus because it is a detailed DOE simulation tool that computes building energy use based on the interactions between climate, building form and fabric, internal gains, HVAC systems, and renewable energy systems. The simulations were run with EnergyPlus Version 3.1 compiled on local personal computers (PCs), and a 64-bit cluster computer at NREL. EnergyPlus is a heavily tested program with formal BESTEST validation efforts repeated for every release (Judkoff and Neymark 1995).

2.3.2 Climate Zones

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

[1] We use the code-minimum EER value with a typical value for the compressor/condenser coefficient of performance (COP) and the total static pressure to calculate fan power. The resulting horsepower per 1000 cfm is lower than code-maximum.

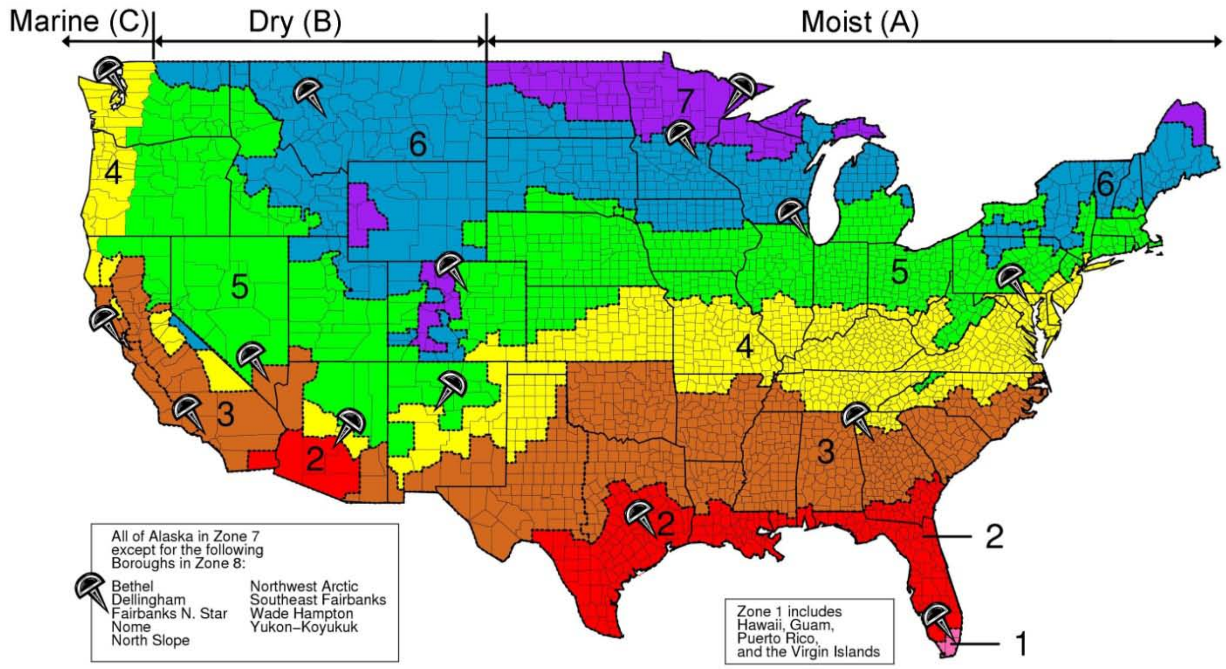

Figure 2-1 DOE climate zones and representative cities

To provide a concrete basis for analysis, the 16 specific locations (cities) used in the Benchmark Project (Deru et al. 2008) are designated as representatives of their climate zones. The cities are marked in Figure 2-1 and listed below. Larger cities were chosen, as their weather and utility data directly apply to a large fraction of building floor area. Two cities are provided for Zone 3B to account for the microclimate effects in California. Climate zone-specific recommendations were validated by running baseline and low-energy model simulations with the same weather file (one set of simulations for each city).

Zone 1A: Miami, Florida (hot, humid)

Zone 2A: Houston, Texas (hot, humid)

Zone 2B: Phoenix, Arizona (hot, dry)

Zone 3A: Atlanta, Georgia (hot, humid)

Zone 3B: Las Vegas, Nevada (hot, dry) and Los Angeles, California (warm, dry)

Zone 3C: San Francisco, California (marine)

Zone 4A: Baltimore, Maryland (mild, humid)

Zone 4B: Albuquerque, New Mexico (mild, dry)

Zone 4C: Seattle, Washington (marine)

Zone 5A: Chicago, Illinois (cold, humid)

Zone 5B: Denver, Colorado (cold, dry)

Zone 6A: Minneapolis, Minnesota (cold, humid)

Zone 6B: Helena, Montana (cold, dry)

Zone 7: Duluth, Minnesota (very cold)

Zone 8: Fairbanks, Alaska (extremely cold)

2.4 Integrated Design Methodology

We used Opt-E-Plus, an internal NREL building energy and cost optimization research tool, to determine combinations of EDMs that best balance two objective functions: net site energy savings and Five-Year Total Life Cycle Cost (5-TLCC, see Section 3.1.2.6). After the user specifies these functions, a baseline building, and a list of EDMs, Opt-E-Plus generates new building models, manages EnergyPlus simulations, and algorithmically determines optimal combinations of EDMs. The building models are first specified in high-level eXtensible Markup Language (XML) files. The NREL preprocessor then translates them into EnergyPlus input files (IDFs). The output of the optimization is a 5-TLCC versus Percent Energy Savings graph, see Figure 2-2, that includes one point for each building, and a curve that connects the minimum cost buildings starting at 0% savings (the baseline building) and proceeding to the building with maximum percent savings.

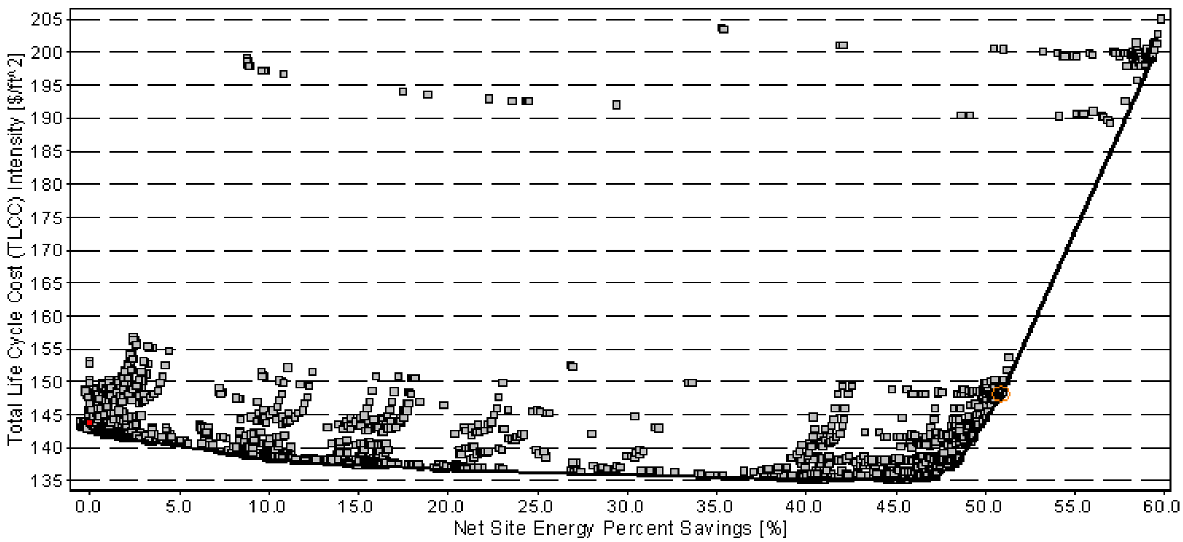

Figure 2-2 Example Opt-E-Plus output: Climate zone 4C (Seattle, Washington)

The buildings along the portion of this curve, which starts at the minimum cost building (5-TLCC intensity of ~135 $/ft^2 and percent energy savings of ~45%) and continues toward higher percent energy savings, are called *Pareto Points*. For such buildings, if one objective is improved, the other must deteriorate. For instance, for a given Pareto point, moving to a less expensive building necessitates that it will have a lower level of energy savings, and moving to a more energy-efficient building necessitates higher total life cycle costs. The set of Pareto Points determines a Pareto Front, which in general is a curve that represents the most cost-effective pathway to achieving low-energy buildings (given the limitations of our input data and search algorithm). This is the portion of the black curve in Figure 2-2 from about 45% savings to 60% savings.

2.4.1 Initialization

To set up the analysis, we apply methods to a custom defined high-level building model to create a code-compliant building for each desired location. These location-sensitive methods apply code minimum building constructions and other values specified by ASHRAE 90.1-2004 and ASHRAE 62-1999 (ASHRAE 1999; ASHRAE 2004a). Economizers are manually added to the baseline buildings in climate zones 3B, 3C, 4B, 4C, 5B, and 6B (see Section 2.3.2 for climate zone definitions). All the EDMs described in Section 3.4 are available in all climate zones.

Although climate considerations could have allowed us, for instance, to eliminate the highest levels of insulation in Miami, all measures were retained to simplify the initialization procedures, and to ensure that all potentially useful measures were included.

2.4.2 Execution

Opt-E-Plus searches for lowest cost designs starting from the baseline model at 0% energy savings, and proceeds to designs with higher and higher predicted energy savings. An iterative search algorithm is used to avoid an exhaustive search of all possible EDM combinations. Each iteration starts at the most recently found Pareto point, and then creates, simulates and analyzes all of the models that are single-EDM perturbations of that point. The algorithm stops when it cannot find additional Pareto points. Cost is measured in terms of 5-TLCC, which is described in Section 3.1.2.6, and is calculated using the economic data in Sections 3.1.2, 3.3, and 3.4.

Even with the sequential search algorithm, an Opt-E-Plus search often requires numerous simulations. For this study, each optimization required 2,500 to 4,000 simulations, each of which took 9 to 21 minutes of computer time to complete. Such computational effort requires distributed computing. Opt-E-Plus manages two pools of simulations: local simulations (if the PC contains multiple cores) and those sent to a Linux cluster. The Linux cluster can, on average, run 64 simulations simultaneously. When the simulations are complete, the Opt-E-Plus database run manager specifies the next batch of simulations and distributes them based on the available resources.

2.5 Post-Processing Methodology

2.5.1 Basic

Once the search for the lowest cost designs is complete, we select a point along the Pareto front that satisfies our percent energy savings goal. All the EDMs besides photovoltaic (PV) panels are treated as discrete design choices that are either applied or not. The number of roof-mounted PV panels, on the other hand, is automatically selected to just reach the 50% energy savings goal, subject to a cap on the allowable roof coverage (see Section 3.4.3.6).

Figure 2-2 shows an example Opt-E-Plus search with the selected building identified by an orange circle. In this case, PV was not needed to reach the target and the selected point was simulated during the normal course of running the search algorithm. The percent savings goal is exceeded by about 1%.

When PV is required to reach the 50% energy savings goal, the first Pareto front point beyond 50% is used to determine exactly how much PV is needed to just reach the goal. The resulting model with reduced PV is run, and shows up on the Opt-E-Plus plot as a '+' (see Figure 2-3). The selected point (again, identified by an orange circle), is identical to the first Pareto point after the long straight segment associated with adding PV at maximum roof coverage (near 58% energy savings in the figure), except that the PV coverage has been scaled back to achieve 50% energy savings.

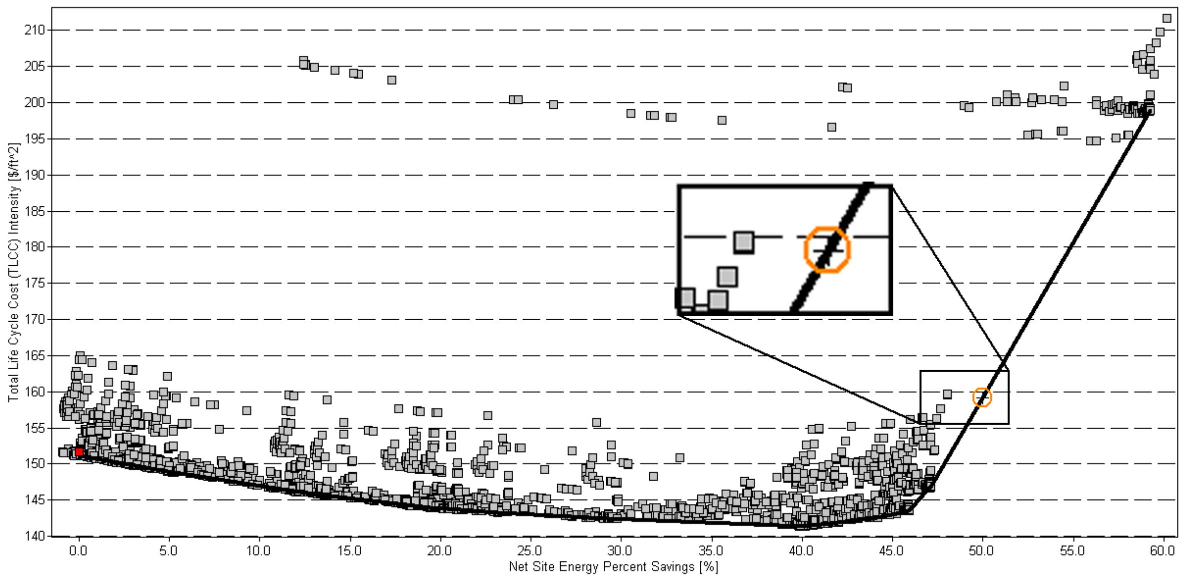

Figure 2-3 Example Opt-E-Plus output with PV post-processing: Climate zone 1A (Miami, Florida)

2.5.2 Finding Families of Solutions

For most climate zones, this TSD presents a single low-energy model for each plug load scenario. However, we appreciate that one size does not fit all. Design teams are subject to constraints imposed by the owner and other stakeholders, and may be interested in alternative designs that also reach 50% energy savings.

Although the standard Opt-E-Plus output appears to produce a number of models near the 50% target, those models are closely related to the Pareto front models and are thus not able to fully answer questions such as, “Is daylighting required to reach my target?”

To address this issue, we created a new post-processing routine for Opt-E-Plus that creates new searches based on turning sets of EDMs off and on. For instance, to determine whether daylighting is required to reach the target, we remove daylighting controls and skylights from the selected point and from the search options. The resulting search will then either reach the energy target or not, and the best building design (determined in the same way as described in Section 2.5.1) from that search is identified.

Starting with the selected low-energy model, one new search is created for each strategy (each group of EDMs the user clusters together) used in that model. Then, if at least one of the new searches can reach the target, more searches can be created to see if the goal can be reached without combinations of two strategies. This process may be repeated as often as the user wishes, as long as new searches that reach the goal remain unexplored.

This analysis is computationally intensive, so it was not completed for all climate zones, and we conducted only the first iteration of searches. Section 0 describes the results of this analysis for a subset of climate zones that we feel represents the categories of climates in the full set: 1A, hot and humid; 3B, hot and arid; 4C, marine; 5A, cold and humid; and 8, very cold.

2.6 External Review Process and Results

Our assumptions were reviewed by several members of the REA (DOE 2008a) and by several engineering firms. All retailers in the REA were invited to submit comments on a document that summarized our prototype model assumptions and our list of EDMs. NREL has contractual relationships with several engineering firms that were asked to review an earlier draft of this document that contained our assumptions (Section 3.0) and preliminary results (parts of Section 4.0).

Everyone in the REA was invited to comment. Our request form was quite brief, but the e-mail request for review (see Appendix F), produced only a few responses. We were also able to obtain helpful information from NREL's National Account partners. Both sources provided information about occupancy and HVAC schedules, LPDs, HVAC equipment, and refrigeration systems.

An early draft of this report was reviewed by CxGBS, Speller Energy Consulting, and Moser Mayer Phoenix Associates. The comments we received led us to:

- Update the baseline exterior wall construction prices using recent data from the ASHRAE 90.1 Envelope Subcommittee.
- Correct the EDM window costs to reflect the inflation of the original data to 2008 dollars.
- Investigate adding a tankless water heater EDM. In the end, we did not add one because its implementation would require a significant programming effort and hot water accounts for only about 0.5% of baseline energy use.
- Modify the inputs for and the implementation of the ERV EDM.

3.0 Model Development and Assumptions

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

3.1 Analysis Assumptions

Most of Section 3.0 concerns the assembly of valid and useful building energy and cost models, component by component. Here we touch on two types of assumptions that color our entire analysis: the often implicit assumptions required to conduct building energy simulation studies, and our economic model.

3.1.1 Integrity of Simulation Models

We made the following assumptions in this study:

1. The models developed in this work represent typical grocery stores well enough to provide climate-specific guidance as to the kinds of design changes that should be considered first when plans for a high-performance grocery store are developed.
2. These virtual buildings are well maintained and operated.

In reality, the anticipated energy savings are often not achieved or erode over time because buildings are not properly commissioned, operated, or maintained. For example, economizer dampers are notorious for failing, and rooftop HVAC equipment must be shielded from adverse weather conditions such as hail to maintain performance. Periodic recommissioning finds and resolves some of these problems.

3.1.2 Economics

One outcome of this project is a list of cost-effective design recommendations. The objective function of interest is 5-TLCC, which is described in Section 3.1.2.6.

3.1.2.1 Building Economic Parameters

Our statement of work mandates that the design recommendations be analyzed for cost effectiveness based on a five-year analysis period, which is assumed acceptable to a majority of developers and owners. The other basic economic parameters required for the 5-TLCC calculation were taken from RSMeans and the Office of Management and Budget (OMB) (Balboni 2008b; OMB 2008).

This analysis uses the real discount rate, which accounts for the projected rate of general inflation found in the Report of the President's Economic Advisors, Analytical Perspectives, and is equal to 2.3% for a five-year analysis period (OMB 2008). By using this rate, we do not have to explicitly account for energy and product inflation rates.

Regional capital cost modifiers are used to convert national averages to regional values. These are available from the RSMeans data sets and are applied before any of the additional fees listed in Table 3-1, three of which are also provided by RSMeans (Balboni 2008b).

Table 3-1 Economic Parameter Values

Economic Parameter	Value	Data Source
Analysis Period	5 Years	DOE
Discount Rate	2.3%	OMB
O&M Cost Inflation	0%	OMB
Gas Cost Inflation	0%	OMB
Electricity Cost Inflation	0%	OMB
Bond Fee	10%	RSMeans
Contractor Fee	10%	RSMeans
Contingency Fee	12%	RSMeans
Commissioning Fee	0.5%	Assumption

3.1.2.2 Energy Design Measure Cost Parameters

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

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

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

3.1.2.3 Costing Methodology

Unless otherwise stated, all costs are in 2008 dollars. Costs originally from another year are adjusted according to the Consumer Price Index inflation calculator (Labor 2009).

The cost data used for the EDMs and the baseline walls, roofs, windows, lighting systems, and HVAC equipment are adapted from multiple sources and adjusted to 2008 dollars. The envelope costs were acquired from personal communications with the ASHRAE 90.1 Envelope Subcommittee (ASHRAE 2007a; ASHRAE 2008). The ABO Group developed a cost database for energy-efficient overhang designs (Priebe 2006). The HVAC cost data were generated by the RMH Group (RMH Group 2006), a mechanical design contractor who received price quotes on a range of HVAC system types and sizes. All other cost data, including maintenance costs, come from the RSMeans data set (Balboni 2008a; Balboni 2008b; Greene 2008; Mossman 2005; Plotner 2009; Waier 2008; Waier 2005), the PNNL AEDG TSDs (Liu et al. 2006; Liu et al. 2007), and other sources (Emmerich et al. 2005; Roth et al. 2005; Westphalen et al. 1996). The cost data sources and values are listed explicitly throughout Section 3.3 and Section 3.4.

3.1.2.4 Baseline Capital Costs

Cost estimates at early planning stages are not very accurate. This report also includes data on technologies that are not fully mature, so the reported costs may be even less accurate than usual.

Nevertheless, we wanted to start with reasonable baseline costs, and so we adjusted our baseline cost per unit area to match that found for supermarkets in the *2008 RSMeans Square Foot Costs* book (Balboni 2008b). The adjustment is made before regional adjustments, contractor fees, and architecture fees are applied, excludes all refrigeration equipment, and results in an approximate baseline cost of $\$66.48/ft^2$ ($\$715.58/m^2$) in 2008 dollars. This cost assumes stucco on concrete block, bearing exterior walls; a floor area of 45,000 ft^2 (4,181 m^2); a perimeter of 866 ft (264 m); and a height of 20 ft (6.1 m). The cost is implemented in Opt-E-Plus, under a category that is not affected by any EDMs. The baseline capital cost is therefore fixed, thus enabling realistic estimates of the percent change in 5-TLCC when the low-energy models are compared to the baselines.

3.1.2.5 Utility Tariffs

One set of utility tariffs is used for all locations to make the results from each climate zone easier to compare. We chose Florida Power and Light's 2008 General Service Demand (GSD-1) electricity tariff because of data availability, the closeness of Florida's average commercial electricity rates to the national average, and the electricity demand of our models (generally within the required range of 20–500 kW) (EIA, 2009 #90; Florida Power & Light 2008 #95). The tariff is summarized in Table 3-2. The tax rate is a population-weighted average of state plus average county and city sales taxes from Sales Tax Clearinghouse (2009 #93) and U.S. Census Bureau (2009 #94).

Table 3-2 Electricity Tariff

Tariff Name	General Service Demand
Monthly Charge	$33.10
Base Demand Charge	$5.10/kW
Demand Capacity Charge	$1.63/kW
Non-fuel Energy Charge	$0.01392/kWh
Fuel Energy Charge	$0.05564/kWh
Conservation Energy Charge	$0.00133/kWh
Environmental Energy Charge	$0.00038/kWh
Taxes	7.1%

A national average gas tariff was calculated by averaging the Energy Information Administration compilation of national average monthly prices for April 2006 through March 2009 (EIA 2007; EIA 2009). Multiple years were averaged together, rather than simply taking the last year's worth of data, because recent prices are highly volatile. The resulting tariff and source data are reproduced in Table 3-3. While using a national-average tariff might lead to some design solutions that are suboptimal because of regional tariff variability, it allows us to isolate climate variability as a driving factor in designing buildings to save energy. For specific case studies, it is recommended that both regional tariff structures and incentives be considered in the economic side of the analysis.

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

Month	Year				Tariff
	2006	2007	2008	2009	
January	–	11.15	11.01	11.04	11.07
February	–	11.21	11.32	10.68	11.07
March	–	11.79	11.81	10.1	11.23
April	11.57	11.49	12.44	–	11.83
May	11.61	11.48	13.24	–	12.11
June	11.09	11.86	14.39	–	12.45
July	10.98	11.61	15.45	–	12.68
August	11.2	11.16	14.04	–	12.13
September	11.16	10.9	13.02	–	11.69
October	10.05	10.9	11.83	–	10.93
November	11.05	11.19	11.45	–	11.23
December	11.61	11.02	11.32	–	11.32

3.1.2.6 Total Life Cycle Cost

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

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

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

Where:

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

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

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

Where:

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

3.2 Prototype Model

We surveyed a number of reports and datasets to develop typical grocery store characteristics and obtain energy performance estimates. These include:

- *2003 Commercial Buildings Energy Consumption Survey* (CBECS) (EIA 2005)
- *DOE Commercial Building Research Benchmarks for Commercial Buildings* (Deru et al. 2008)
- *Energy Savings Potential for Commercial Refrigeration Equipment* (Westphalen et al. 1996)
- *Methodology for Modeling Building Energy Performance Across the Commercial Sector* (Griffith et al. 2008).

Each data source is described briefly; then the reasoning behind the prototype model assumptions is described in several functional groupings. The grocery store prototype models are summarized in Section 3.2.5.

3.2.1 Program

This section addresses programmatic considerations that are not affected by Standard 90.1-2004: building size, space types, and internal loads.

3.2.1.1 Building Size

The size distribution of grocery stores built since 1970, according to the *2003 CBECS*, is shown in Figure 3-1. The labels correspond to bin maxima. Only 30 CBECS grocery stores have been built since 1970. Nonetheless, those are most representative of the new construction we are trying to influence, and thus form the sole basis of the CBECS statistics we present.

Our prototype store is 45,000 ft^2 (4,181 m^2), a size that lies between the area-weighted mean and median of the *2003 CBECS* post-1970 grocery stores, and matches that of the benchmark supermarket (Deru et al. 2008).

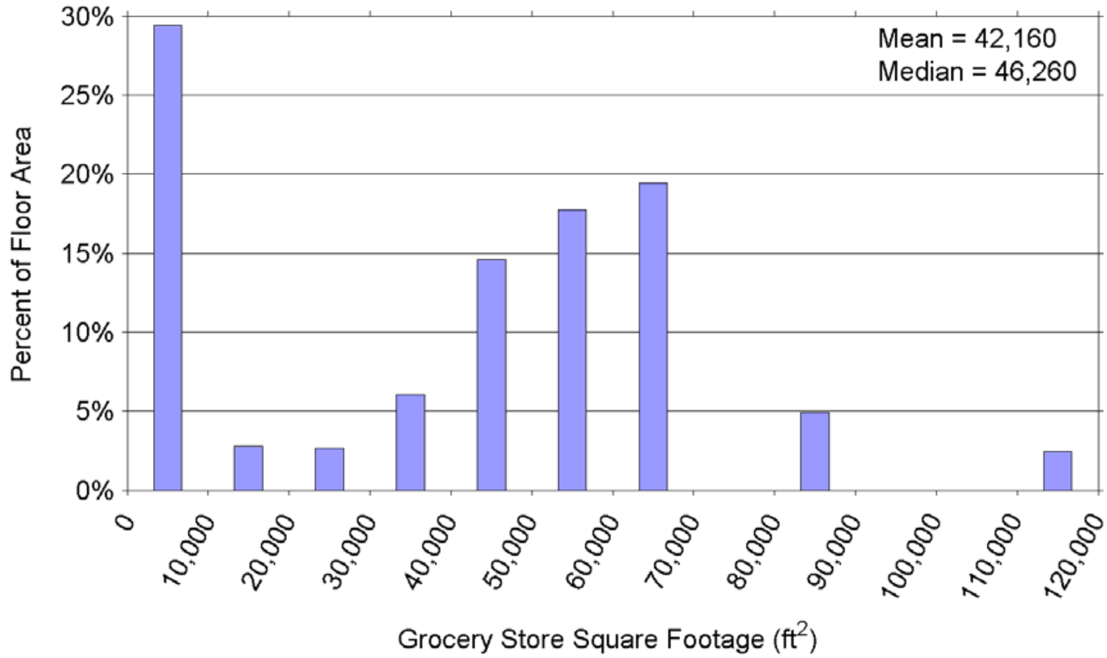

Figure 3-1 Area-weighted histogram of post-1970 grocery store size

3.2.1.2 Space Types

This project adopts many aspects of the benchmark project supermarket model (Deru et al. 2008). That work states that the geometry and thermal zones were originally set by Lawrence Berkeley National Laboratory; NREL updated the model to reflect the larger supermarket sizes common in new construction. The benchmark layout contains six space types, whose names and sizes are shown in Table 3-4. Our prototype contains a more detailed space breakdown than the benchmark model. It contains 14 space types, whose names and floor areas are shown in Table 3-5.

A more detailed layout provides a number of benefits. First, it results in a more accurate representation of an actual grocery store. In our model, each space type has a well-defined function, with correspondingly well-defined loads. Lumping different space types together into more general categories requires load averaging, which obscures the inputs to the model. Second, more specific characterization of space types results in greater flexibility in terms of how equipment is distributed and controlled. By subdividing the sales area, for instance, we are able to capture the effects of installing a vestibule and of combining the use of both windows and skylights to facilitate daylighting. As greater complexity is added to future iterations (such as the routing of exhaust air to facilitate ERV, for instance), details such as accurate space type characterization and organization become increasingly important.

Table 3-4 Benchmark Project Supermarket Space Types

Space Type	Floor Area (ft^2)	Floor Area (m^2)	Percent of Total
Sales	25,029	2,325	56
Produce	7,658	711	17
Deli	2,419	225	5
Bakery	2,251	209	5
Dry Storage	6,694	622	15
Office	956	89	2
Total	45,000	4,181	100

Table 3-5 TSD Grocery Space Types

Space Type	Floor Area (ft^2)	Floor Area (m^2)	Percent of Total
Main Sales	22,415	2,082	49.8
Perimeter Sales	2,312	215	5.1
Produce	7,657	711	17.0
Deli	2,419	225	5.4
Bakery	2,250	209	5.0
Enclosed Office	300	28	0.7
Meeting Room	500	47	1.1
Dining Room	500	47	1.1
Restroom	675	63	1.5
Mechanical Room	600	56	1.3
Corridor	532	49	1.2
Vestibule	300	28	0.7
Active Storage	4,544	422	10.1
Total	45,002	4,181	100.0

3.2.1.3 Internal Load Densities

Internal loads include the heat generated by occupants, lights, and appliances (plug and process loads). This section addresses the aspects of these loads not addressed in Standard 90.1, including peak occupant and plug load densities.

3.2.1.3.1 Occupancy Density

Occupancy density values by space type are defined according to ASHRAE Standard 62.1-2004 (ASHRAE 2004b). The mapping between each space type and the standard and the resulting occupancy density value are presented in Table 3-6. Values for space types without direct mapping to the standard were estimated. Restrooms were assumed to be a continuation of the sales areas, and thus assigned the corresponding occupancy density value. Mechanical rooms were assumed empty most of the time, and thus were assigned an occupancy density value of zero. The occupancy density value for the active storage zone was taken from the benchmark report (Deru et al. 2008).

Table 3-6 Occupancy Density Mapping and Peak Values

Space Type	Mapping to ASHRAE 62.1-2004	Occupancy Density	
		(#/1000 ft^2)	(#/100 m^2)
Main Sales	Retail::Supermarket	8	8.61
Perimeter Sales	Retail::Supermarket	8	8.61
Produce	Retail::Supermarket	8	8.61
Deli	Retail::Supermarket	8	8.61
Bakery	Retail::Supermarket	8	8.61
Enclosed Office	Offices::Office space	5	5.38
Meeting Room	Offices::Conference/meeting	50	53.82
Dining Room	Food & Beverage::Restaurant dining rooms	70	75.35
Restroom	Retail::Supermarket	8	8.61
Mechanical Room	CUSTOM VALUE	0	0.00
Corridor	Retail::Supermarket	8	8.61
Vestibule	Retail::Supermarket	8	8.61
Active Storage	CUSTOM VALUE	3.33	3.59

3.2.1.3.2 Plug and Process Loads

Plug and process loads are notoriously difficult to estimate. Griffith et al. (2008) tried to reconcile the *2003 CBECS* and Commercial End Use Survey (CEUS) data on such loads, settling on an area-weighted average peak electric plug load of 0.480 W/ft^2 (5.13 W/m^2) in the *2003 CBECS* grocery store models (with little variation—the loads ranged from 0.474 to 0.482 W/ft^2 [5.10 to 5.19 W/m^2]). The gas process loads for those buildings correspond to the EUI reported by the Commercial End Use Survey and were 0.35 W/ft^2 (3.74 W/m^2) operating on a constant, always on schedule.

The benchmark study has higher average electric and gas plug loads: 0.884 W/ft^2 (9.52 W/m^2) and 0.384 W/ft^2 (4.14 W/m^2), respectively. We use the benchmark study plug and process loads, because that study carefully modeled commercial kitchens (Deru et al. 2008). The peak plug and process loads are listed by space type in Table 3-7.

Table 3-7 Peak Plug and Process Loads

Space Type	Peak Electric Plug Load (W/ft^2)	Peak Electric Plug Load (W/m^2)	Peak Gas Process Load (W/ft^2)	Peak Gas Process Load (W/m^2)
Main Sales	0.50	5.4	0.00	0.00
Perimeter Sales	0.50	5.4	0.00	0.00
Produce	0.50	5.4	0.00	0.00
Deli	5.00	53.8	2.50	26.9
Bakery	2.50	26.9	5.00	53.8
Enclosed Office	0.75	8.1	0.00	0.00
Meeting Room	0.75	8.1	0.00	0.00
Dining Room	2.60	28.0	0.00	0.00
Restroom	0.10	1.1	0.00	0.00
Mechanical Room	0.00	0.0	0.00	0.00
Corridor	0.00	0.0	0.00	0.00
Vestibule	0.00	0.0	0.00	0.00
Active Storage	0.75	8.1	0.00	0.00
Average	0.88	9.5	0.38	4.1

3.2.1.4 Schedules

3.2.1.4.1 Operating Hours

The operating hours are defined according to ASHRAE 90.1-1989 (ASHRAE 1989) as 6:00 a.m. to 10:00 p.m., seven days per week.

3.2.1.4.2 Occupancy Schedule

The occupancy schedule (see Table 3-8) is defined according to ASHRAE 90.1-1989 (ASHRAE 1989), which was also used to establish the occupancy schedule for the benchmark grocery store (Deru et al. 2008).

Table 3-8 Occupancy Schedule, in Fraction of Peak Occupancy

Hour	Weekdays	Saturdays	Sundays, Holidays, Other
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0.10	0.10	0.10
8	0.10	0.10	0.10
9	0.20	0.20	0.10
10	0.50	0.50	0.10
11	0.50	0.60	0.20
12	0.70	0.80	0.20
13	0.70	0.80	0.40
14	0.70	0.80	0.40
15	0.70	0.80	0.40
16	0.80	0.80	0.40
17	0.70	0.80	0.40
18	0.50	0.60	0.20
19	0.50	0.20	0.10
20	0.30	0.20	0.10
21	0.30	0.20	0.10
22	0.30	0.10	0.10
23	0	0	0
24	0	0	0

3.2.1.4.3 Lighting Schedule

The *2003 CBECS* data indicate that almost no post-1970 grocery stores have independent lighting controls or sensors. However, all the surveyed grocery stores stated that an energy management control system controls the lighting, and 92% of the represented floor area is lighted with electronic ballast fixtures. Figure 3-2 and Figure 3-3 show the distribution of lighting percentage when the store is open and closed, respectively. These figures and the abundance of energy management control systems support a lighting schedule with significant reductions during unoccupied hours. The lighting schedule for this TSD is defined according to ASHRAE 90.1-1989 (ASHRAE 1989) and is listed in Table 3-9.

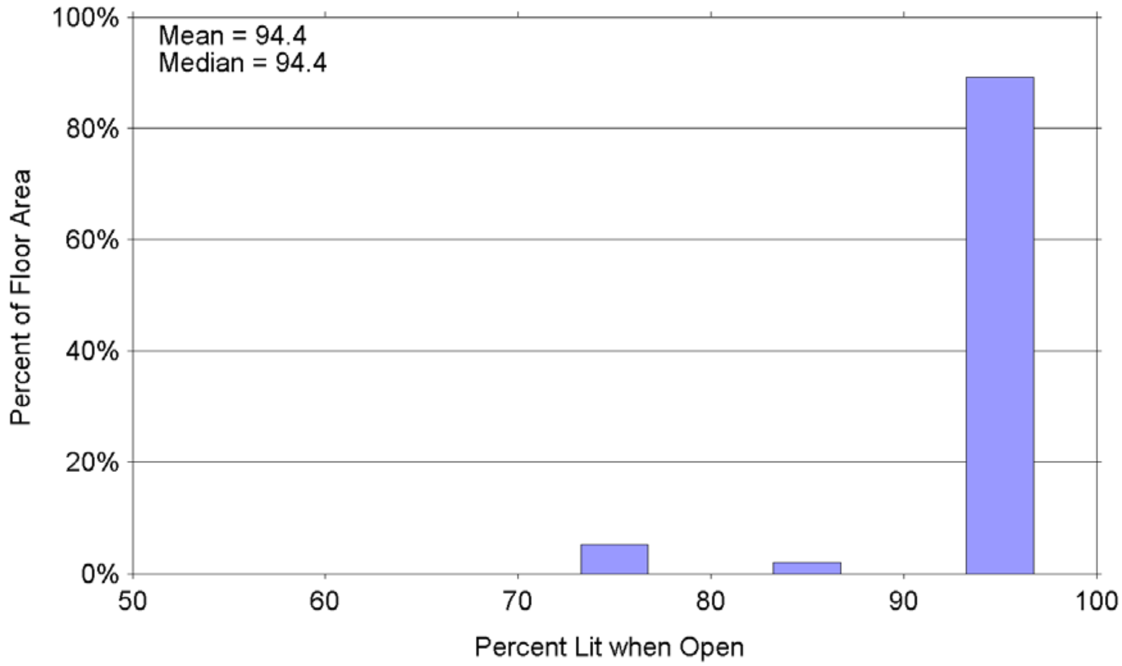

Figure 3-2 Area-weighted histogram of post-1970 grocery store open hours lighting percentage

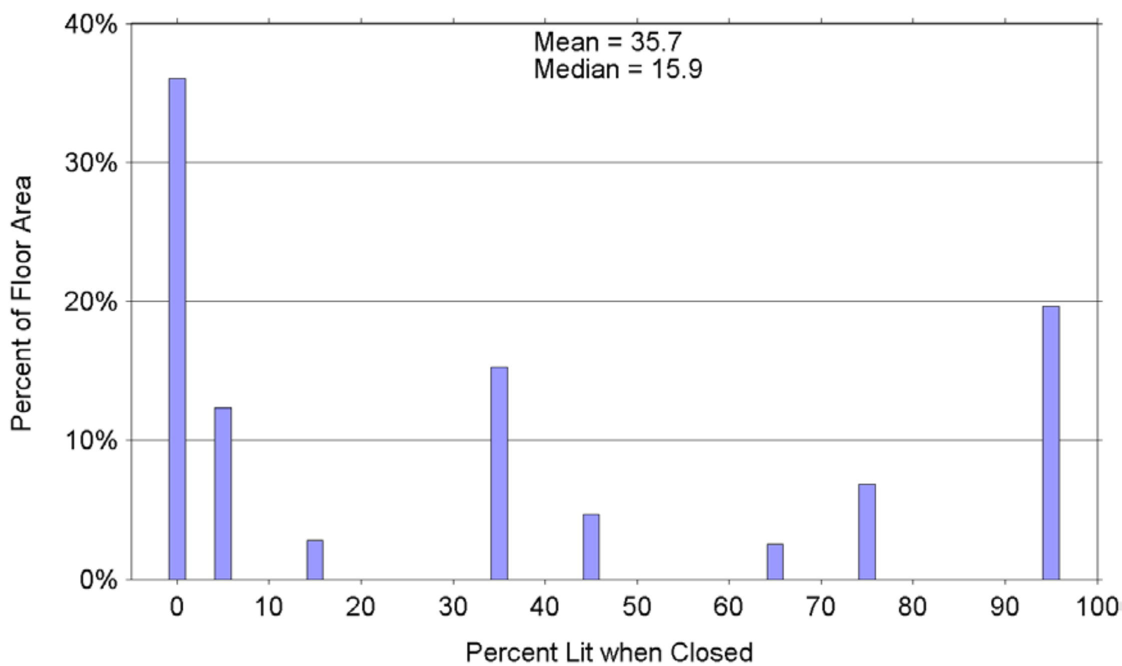

Figure 3-3 Area-weighted histogram of post-1970 grocery store closed hours lighting percentage

Table 3-9 Lighting Schedule, in Fraction of Peak Lighting Density

Hour	Weekdays	Saturdays	Sundays, Holidays, Other
1	0.05	0.05	0.05
2	0.05	0.05	0.05
3	0.05	0.05	0.05
4	0.05	0.05	0.05
5	0.05	0.05	0.05
6	0.05	0.05	0.05
7	0.20	0.10	0.10
8	0.20	0.10	0.10
9	0.50	0.30	0.10
10	0.90	0.60	0.10
11	0.90	0.90	0.40
12	0.90	0.90	0.40
13	0.90	0.90	0.60
14	0.90	0.90	0.60
15	0.90	0.90	0.60
16	0.90	0.90	0.60
17	0.90	0.90	0.60
18	0.90	0.90	0.40
19	0.60	0.50	0.20
20	0.60	0.30	0.20
21	0.50	0.30	0.20
22	0.20	0.10	0.20
23	0.05	0.05	0.05
24	0.05	0.05	0.05
Total Hours/Day	11.30	9.90	5.80

3.2.1.4.4 Plug and Process Load Schedule

Our plug and process load schedule was taken from the benchmark study (Deru et al. 2008) (see Table 3-10).

Table 3-10 Plug and Process Load Schedule, in Fraction of Peak Load

Hour	Weekdays	Saturdays	Sundays, Holidays, Other
1	0.20	0.15	0.15
2	0.20	0.15	0.15
3	0.20	0.15	0.15
4	0.20	0.15	0.15
5	0.20	0.15	0.15
6	0.20	0.15	0.15
7	0.40	0.30	0.30
8	0.40	0.30	0.30
9	0.70	0.50	0.30
10	0.90	0.80	0.30
11	0.90	0.90	0.60
12	0.90	0.90	0.60
13	0.90	0.90	0.80
14	0.90	0.90	0.80
15	0.90	0.90	0.80
16	0.90	0.90	0.80
17	0.90	0.90	0.80
18	0.90	0.90	0.60
19	0.80	0.70	0.40
20	0.80	0.50	0.40
21	0.70	0.50	0.40
22	0.40	0.30	0.40
23	0.20	0.15	0.15
24	0.20	0.15	0.15
Total Hours/Day	13.90	12.30	9.80

3.2.2 Form

This section completes the characterization of the prototype model's shape and size by specifying aspect ratio, floor-to-floor and ceiling height, and fenestration amount and placement.

3.2.2.1 Building Shape

Based on *2003 CBECS* statistics (see Figure 3-4), the 45,000 ft^2 (4,181 m^2) prototype grocery store is a one-story rectangular building. The aspect ratio, footprint, and floor-to-floor height match those of the benchmark supermarket model: 1.5, 259.8 ft × 173.2 ft (79.2 m × 52.8 m), and 20 ft (6.1 m), respectively. The ceiling height is also 20 ft (6.1 m) – there is no drop ceiling or plenum.

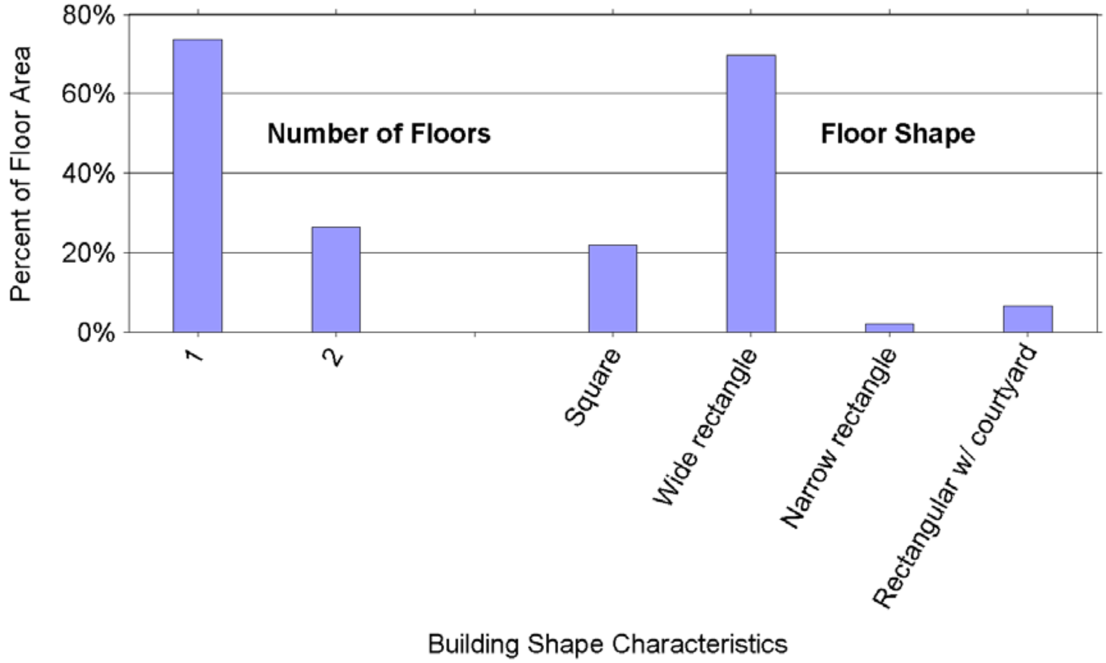

Figure 3-4 Area-weighted histograms of post-1970 grocery store shape characteristics

3.2.2.2   Fenestration

The *2003 CBECS* reports on several aspects of fenestration form. Figure 3-5 shows statistics on the number and distribution of windows. Figure 3-6 gives statistics on window shading (with awnings or overhangs), skylights, and percentage daylit floor area. These data indicate that our prototype store should have 10% or less of its wall area glazed, and that the glazing should be unevenly distributed. For our prototype, we adopt the typical glazing distribution for grocery stores, which is to install all of the glazing in the main entrance wall, the south façade in this case. Awnings and overhangs are common, but not dominant, so they are not included in the prototype. The baseline store does not include skylights or daylighting controls.

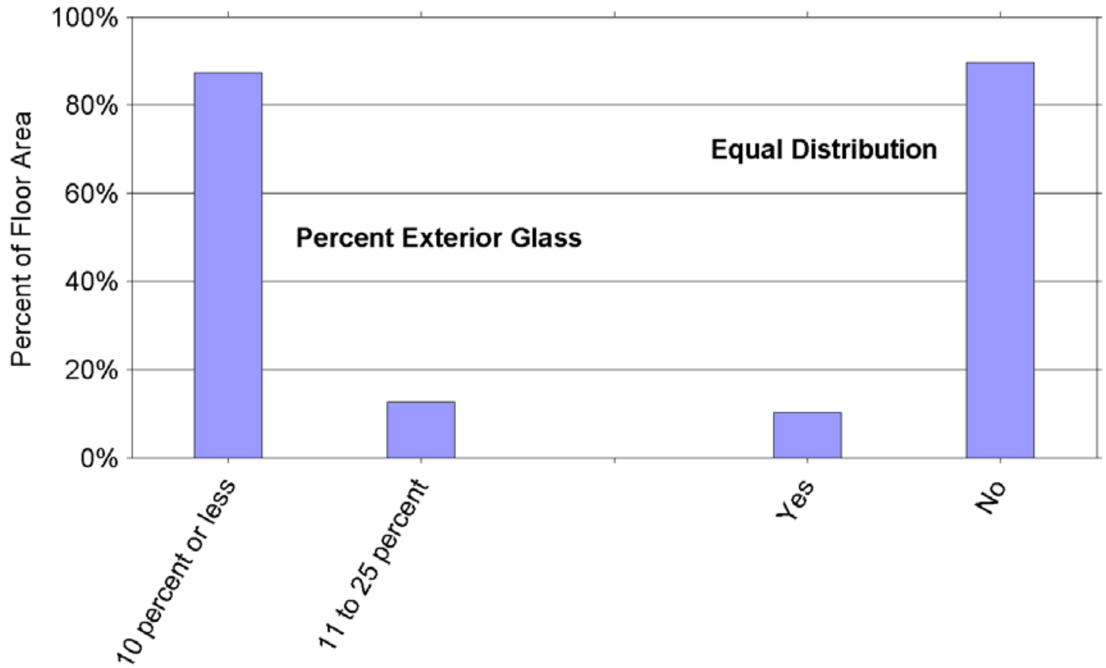

Figure 3-5 Area-weighted histograms of post-1970 grocery store fenestration amounts

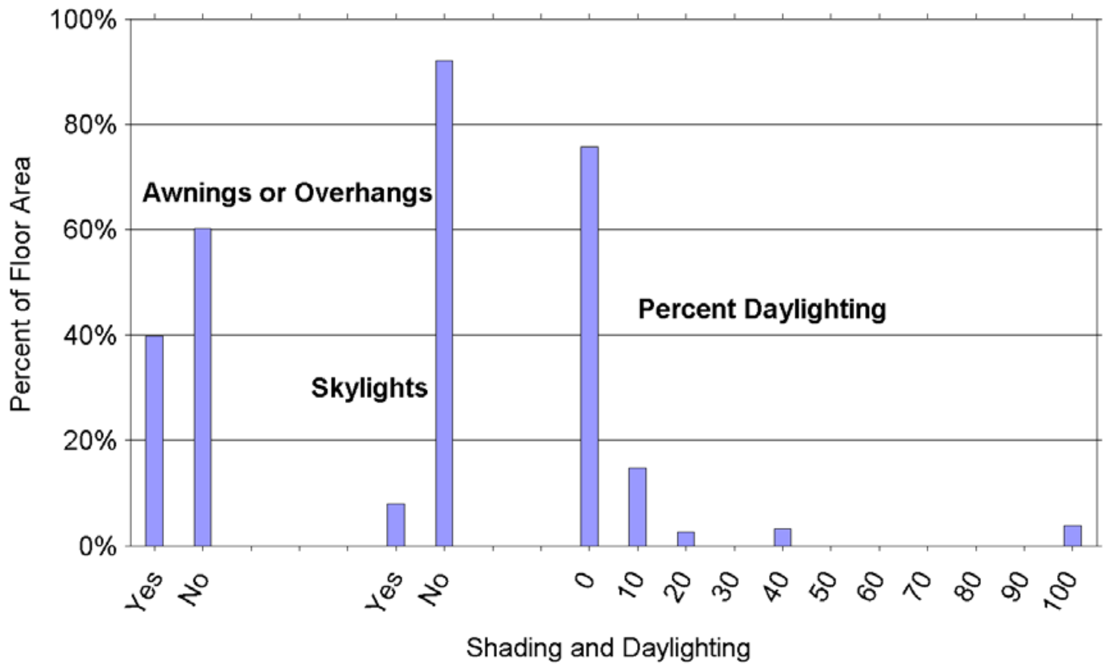

Figure 3-6 Area-weighted histograms of post-1970 grocery store sunlight management

The supermarket model in Deru et al. (2008) has 1,880 ft^2 (174 m^2) of glazing on the front façade, for a total window-to-wall ratio (WWR) of 11%. This is slightly larger than what is supportable by *CBECS*, so this work uses an 8.1% WWR, which amounts to 1,400 ft^2 (130 m^2) of glazing.

3.2.3 Fabric

This section specifies the types of envelope and interior constructions used in the prototype and baseline models. Specific fenestration constructions and insulation levels are listed in Section

3.3.3, as Standard 90.1-2004 (ASHRAE 2004a) specifies the minimum performance of these components.

3.2.3.1 Construction Types

The *2003 CBECS* data for wall and roof construction types are shown in Figure 3-7. The prototype building has masonry wall construction (which includes the brick, stucco, and concrete construction categories) and a roof with all insulation above deck (which includes the built-up and plastic/rubber/synthetic sheeting construction categories).

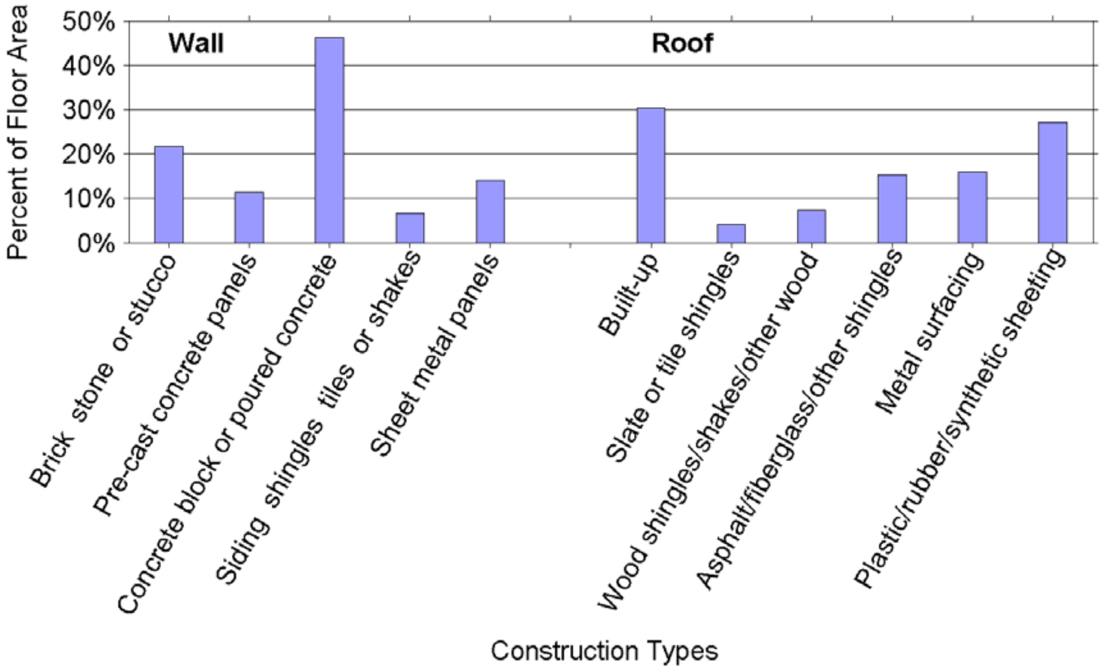

Figure 3-7 Area-weighted histograms of post-1970 grocery store construction types

3.2.3.2 Interior Partitions and Mass

We assume that the interior partitions that separate zones are composed of 4-in. (0.1-m) thick steel-frame walls covered with gypsum board. Internal mass is modeled as 90,000 ft^2 (8,361 m^2) of 6-in. (0.15-m) thick wood.

3.2.4 Equipment

This section specifies the types of HVAC, refrigeration and service water heating equipment used in the prototype and baseline models. Performance and cost data are discussed in Sections 3.3.4.2 to 3.3.4.4.

3.2.4.1 Heating, Ventilating, and Air-Conditioning

According to the *2003 CBECS*, all stores have some heating (and the vast majority are 100% heated) and all but 2.8% of sector floor area has some cooling. We therefore assume that the prototype is fully heated and cooled.

Figure 3-8 summarizes the *2003 CBECS* statistics on the types of heating and cooling equipment used in grocery stores. All cooling is electric; the types of fuel used for heating are shown in Figure 3-9. Most stores (about 73% of the floor area) do not have secondary heating sources.

Based on these findings, the prototype HVAC equipment consists of packaged rooftop units (RTUs) with natural gas furnaces for heating, and electric direct expansion (DX) coils with air-cooled condensers for cooling. Based on industry feedback, grocery stores commonly control humidity to a dew point of 55°F (13°C), which, according to our thermostat set points (see Appendix B.5), corresponds to a relative humidity of approximately 55%. The standard dehumidification strategy is subcooling and superheat, where a reheat coil uses DX condenser waste heat (superheat) to reheat the subcooled, dehumidified air stream at zero additional energy cost (notwithstanding the pressure drop that occurs across the reheat coil). Accordingly, each RTU is equipped with a superheat coil and each thermal zone is equipped with a humidistat to monitor humidity. The units do not have variable air volume (VAV) systems, because the *2003 CBECS* reports that only 24% of grocery store floor area uses them. Economizers are applied per Standard 90.1-2004.

Most stores (more than 60% of the floor area) do not attenuate their heating or cooling set points over the course of a day, see Figure 3-10. However, setup and setback are good operational practice, and Standard 90.1-2004 requires most HVAC system controls to be able to implement basic thermostat schedules. Our thermostat schedules are listed in Table B-6 and Table B-7.

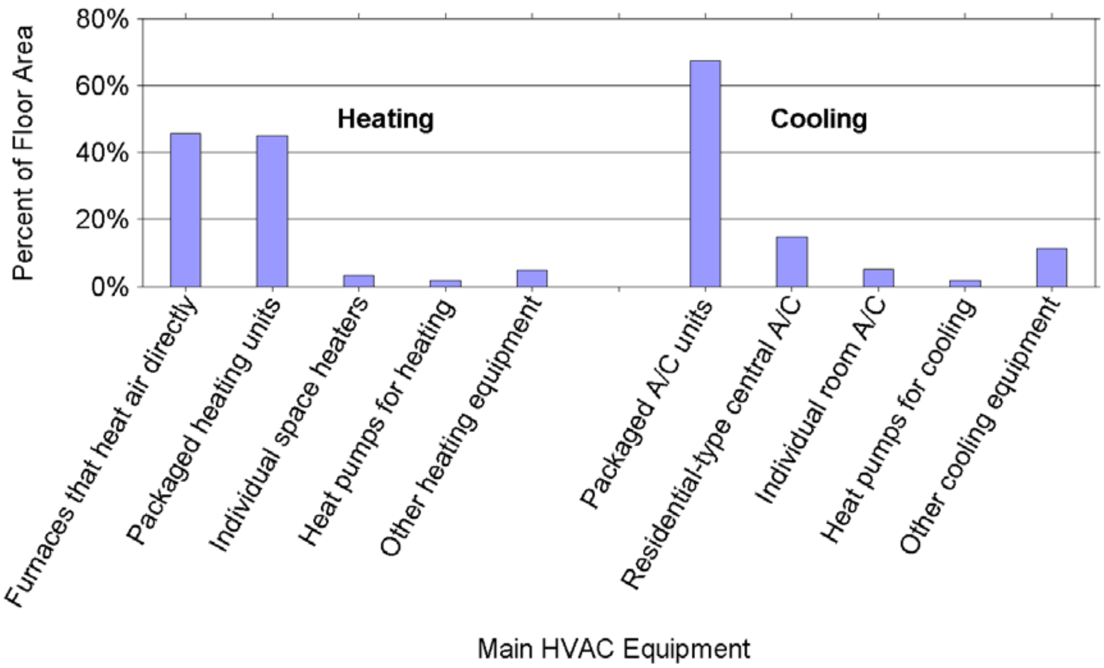

Figure 3-8 Area-weighted histograms of post-1970 grocery store heating and cooling equipment

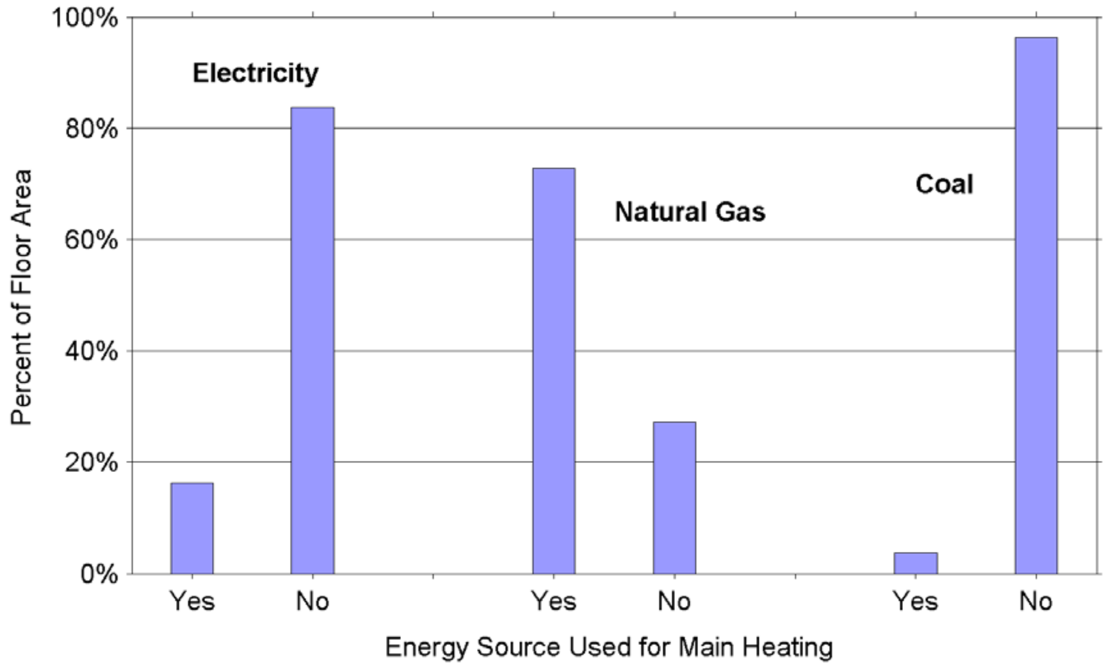

Figure 3-9 Area-weighted histograms of post-1970 grocery stores' main heating source

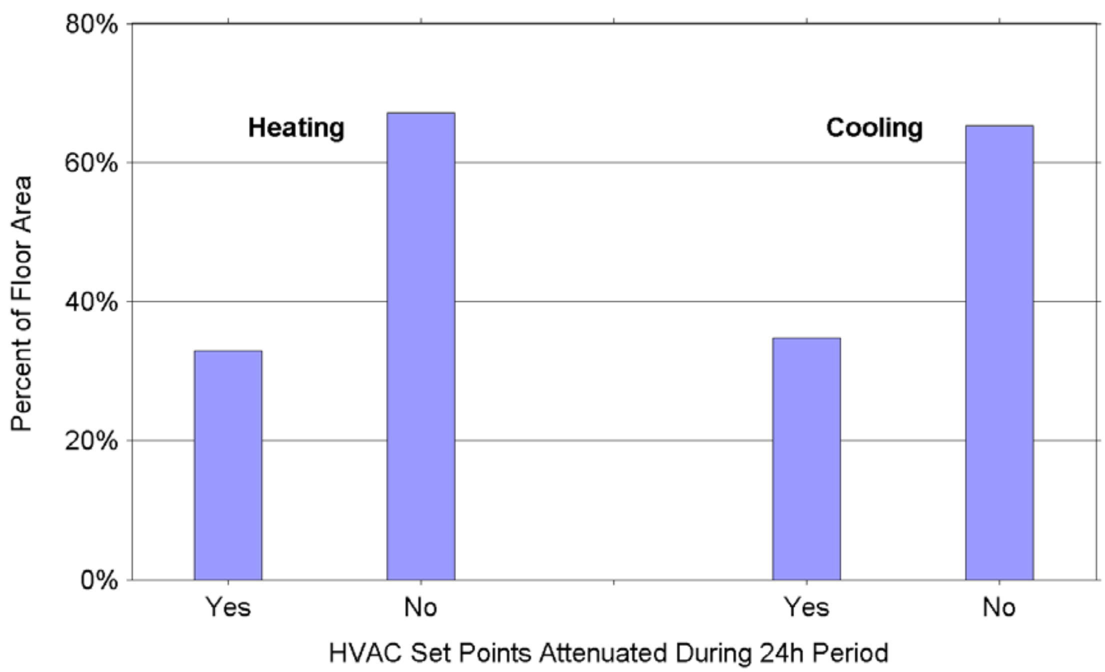

Figure 3-10 Area-weighted histograms of post-1970 grocery store setback and setup practices

3.2.4.2 Refrigeration

The prototype refrigeration system is adapted from the benchmark supermarket model system (Deru et al. 2008), which is largely based on an example in Westphalen et al. (1996). There are four compressor racks: two low-temperature racks (serving frozen food cases, ice cream cases, and walk-in freezers), and two medium-temperature racks (serving meat cases, dairy/deli cases, and walk-in coolers). The heat from the compressor racks is rejected by air-cooled condensers. The types, sizes, and number of cases and walk-in units are listed in Table 3-11. Technical details and cost estimates are provided in Section 3.3.4.3.

Table 3-11 Refrigerated Cases and Walk-In Units by Zone

Zone Name	Case/Walk-in Type	Case Length	Number of Units	Total Length or Area
Sales	Island Single Deck Meat	12 ft (3.66 m)	13.9	167 ft (50.9 m)
Sales	Multi-Deck Dairy/Deli	12 ft (3.66 m)	14.3	172 ft (52.4 m)
Sales	Vertical Frozen Food with Doors	15 ft (4.57 m)	15.6	234 ft (71.3 m)
Sales	Island Single Deck Ice Cream	12 ft (3.66 m)	12	36 ft (11.0 m)
Sales	Walk-In Cooler (Medium Temperature)	N/A	2	2,545 ft^2 (236.4 m^2)
Sales	Walk-In Freezer (Low Temperature)	N/A	1	691 ft^2 (64.2 m^2)
Produce	Multi-Deck Dairy/Deli	12 ft (3.66 m)	8.8	106 ft (32.3 m)
Deli	Multi-Deck Dairy/Deli	12 ft (3.66 m)	1.1	13.2 ft (4.0 m)
Deli	Walk-In Cooler (Medium Temperature)	N/A	1	115 ft^2 (10.7 m^2)
Bakery	Walk-In Cooler (Medium Temperature)	N/A	1	57 ft^2 (5.3 m^2)

3.2.4.3 Service Water Heating

Figure 3-11 summarizes much of the *2003 CBECS* information on service water heating (SWH) in post-1970 grocery stores. No stores reported using instant hot water. Thus, our prototype model has a centralized natural gas water heater. The system size is determined based on (ASHRAE 2003) (see Section 3.3.4.4).

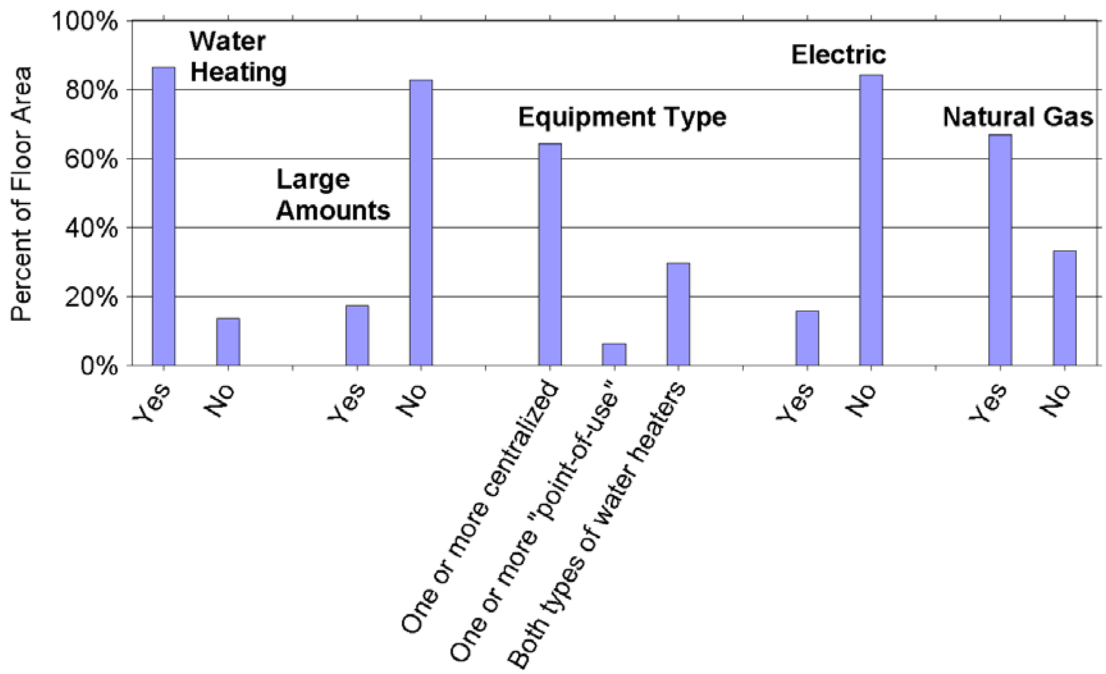

Figure 3-11 Area-weighted histograms of post-1970 grocery store service water heating characteristics

3.2.5 Prototype Model Summary

This section summarizes the building characteristics that define the grocery store prototype model, which must specify characteristics that are not found in ASHRAE 90.1-2004 or ASHRAE 62.1-1999 (ASHRAE 1999; ASHRAE 2004a), but are needed to develop baseline and low-energy models. Many characteristics are summarized in Table 3-12, the space type sizes are in Table 3-13, and the floor plan is shown in Figure 3-12.

Table 3-12 Grocery Store Prototype Model Characteristics and Data Sources

Grocery Store Characteristic	Grocery TSD Prototype	Source
Program		
Size	45,000 ft^2 (4,181 m^2)	2003 CBECS; DOE Benchmark Supermarket
Space Types	See Table 3-13.	DOE Benchmark Supermarket; Assumption
Operating Hours	Monday through Sunday, 6:00 a.m. to 10:00 p.m.	ASHRAE 90.1-1989
Occupancy	See Table 3-6 for density; see Table 3-8 for schedule	ASHRAE 62.1-2004; ASHRAE 90.1-1989
Lighting	See Table 3-9 for schedule	ASHRAE 90.1-1989
Plug and Process	See Table 3-7 for density; see Table 3-10 for schedule	DOE Benchmark Supermarket
Form		
Number of Floors	1	2003 CBECS
Aspect Ratio	1.5	2003 CBECS; DOE Benchmark Supermarket
Floor-to-Floor Height	20 ft (6.10 m)	DOE Benchmark Supermarket
Window Area	1400 ft^2 (130 m^2, 0.081 WWR)	*2003 CBECS*; Assumption
Floor Plan	See Figure 3-12	DOE Benchmark Supermarket; Assumption
Fabric		
Wall Type	Mass (brick, stone, stucco or concrete)	2003 CBECS
Roof Type	All insulation above deck	2003 CBECS
Interior Partitions	2 x 4 steel frame with gypsum boards	Assumption
Internal Mass	90,000 ft^2 (8,360 m^2) of 6” wood	Assumption
Equipment		
HVAC System Type	Unitary rooftop units with DX coils, natural gas heating, and constant volume fans; Economizer as per 90.1	2003 CBECS
HVAC Unit Size	10 tons (35 kW) cooling	Assumption
HVAC Controls	No thermostat setback	2003 CBECS
Refrigeration	2 medium-temperature and 2 low-temperature compressor racks; air-cooled condensers; cases and walk-in units listed in Table 3-11	DOE Benchmark Supermarket; Arthur D. Little Report
Service Water Heating	Natural gas heating with storage tank	2003 CBECS

Table 3-13 Space Types and Sizes in the Grocery Store Prototype Model

Space Type Name	Floor Area (ft^2)	Floor Area (m^2)	Percent of Total
Main Sales	22,415	2,082	49.8
Perimeter Sales	2,312	215	5.1
Produce	7,657	711	17.0
Deli	2,419	225	5.4
Bakery	2,250	209	5.0
Enclosed Office	300	28	0.7
Meeting Room	500	47	1.1
Dining Room	500	47	1.1
Restroom	675	63	1.5
Mechanical Room	600	56	1.3
Corridor	532	49	1.2
Vestibule	300	28	0.7
Active Storage	4,544	422	10.1
Total	45,002	4,181	100.0

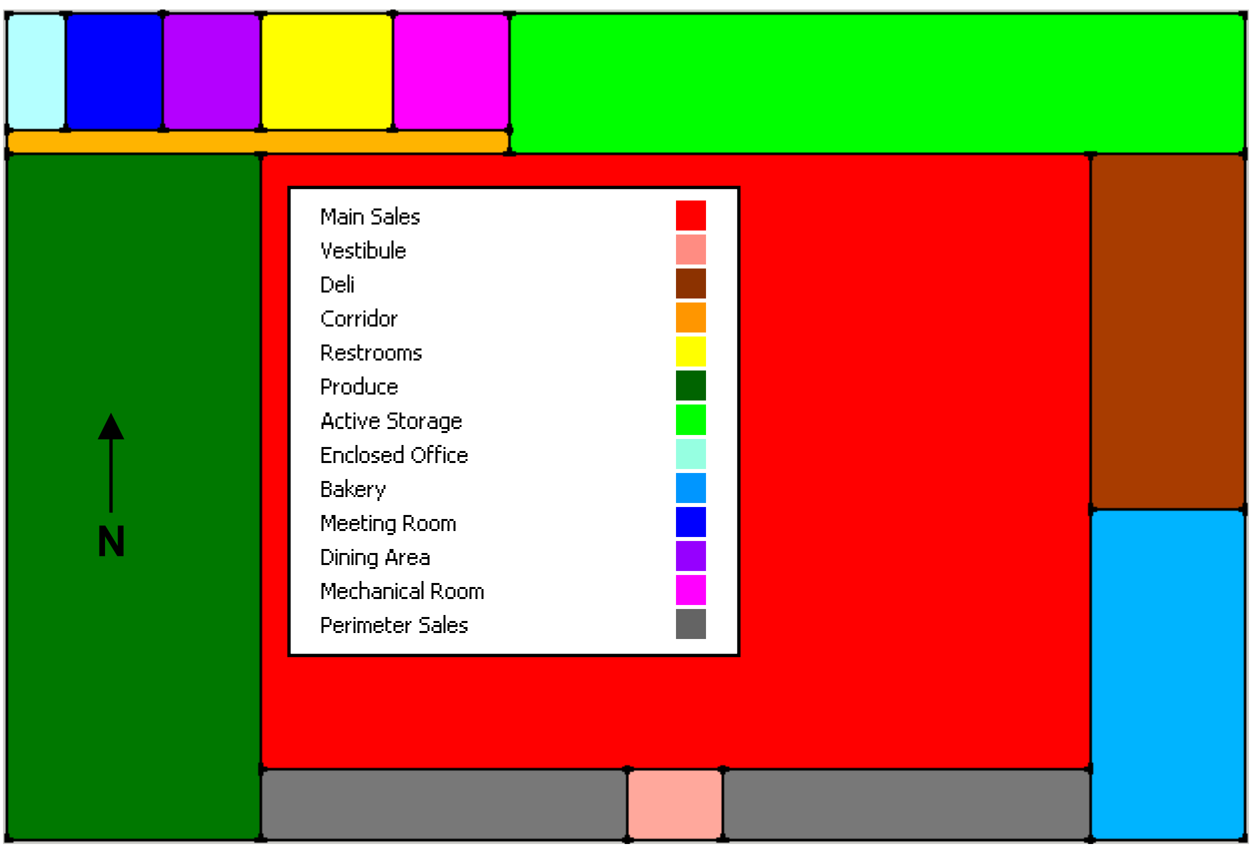

Figure 3-12 Grocery store prototype model floor plan

3.3 Baseline Model

This section contains a topic-by-topic description of the baseline building models' EnergyPlus inputs, including the building form and floor plate; envelope characteristics; internal loads; HVAC equipment efficiency, operation, control, and sizing; service water heating; and schedules. We also list the costs that were used by Opt-E-Plus to compute 5-TLCC. The baseline models were developed by applying the criteria in ASHRAE Standard 90.1-2004 and ASHRAE Standard 62.1-1999 (ASHRAE 1999; ASHRAE 2004a) to the prototype characteristics. (ASHRAE Standard 90.1-2004 explicitly references, and thereby includes, Standard 62.1-1999.)

3.3.1 Program

3.3.1.1 Occupancy

The internal load derived from occupants is calculated assuming 120 W (409 Btu/h) of heat per person, which falls between the values listed for "seated, very light work" and "standing, light work; walking" in Chapter 30 of the *ASHRAE 2005 Fundamentals Handbook* (ASHRAE 2005). Occupant comfort is calculated assuming clothing levels of 1.0 clo October through April, and 0.5 clo May through September; and an in-building air velocity of 0.66 ft/s (0.2 m/s).

3.3.2 Form

The prototype characteristics, together with a few modeling assumptions, are used to generate the baseline models' form and floor plate. Per Appendix G of ASHRAE 90.1-2004, overhangs are not included in the baseline models.

Form and floor plate parameters are listed in Table 3-14. A rendering of the grocery store baseline model is shown in Figure 3-13, which shows an isometric view from the southwest. All parameters except glazing sill height are specified in the prototype model.

Table 3-14 Selected Baseline Modeling Assumptions

Model Parameters	Value
Floor area	45,000 ft^2 (4,181 m^2)
Aspect ratio	1.5
Ceiling height	20 ft (6.096 m)
Fraction of fenestration to gross wall area	8.1%
Glazing sill height	3.609 ft (1.1 m)

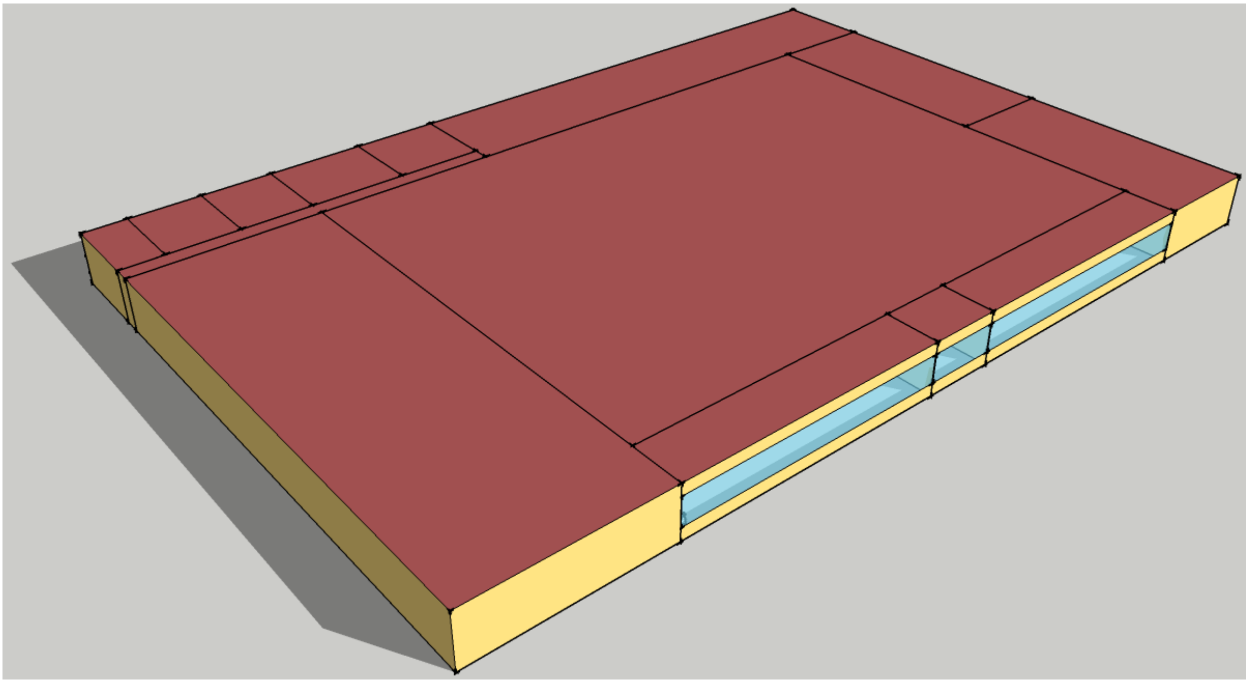

Figure 3-13 Grocery store baseline model rendering: View from southwest

3.3.3 Fabric

Based on the *2003 CBECS* and engineering experience, we assume that grocery stores are typically constructed with mass exterior walls, built-up roofs, and slab-on-grade floors. These choices are further developed to meet the prescriptive design option requirements of ASHRAE 90.1-2004 Section 5.5. Layer-by-layer descriptions of the exterior surface constructions were used to model the building thermal envelope in EnergyPlus.

3.3.3.1 Exterior Walls

The baselines are modeled with mass wall constructions. The layers consist of stucco, concrete block, rigid isocyanurate insulation, and gypsum board. The assembly U-factors vary based on the climate zone and are adjusted to account for standard film coefficients. R-values for most of the layers are derived from Appendix A of ASHRAE 90.1-2004. Continuous insulation (c.i.) R-values are selected to meet the minimum R-values required in Section 5 of ASHRAE 90.1-2004. The baseline exterior walls' performance metrics, including costs, are listed in Table 3-15 (see Table C-1 for metric units). The mass wall includes the following layers:

- Exterior air film (calculated by EnergyPlus)
- 1-in (2.5 cm) exterior stucco, 116 lb/ft^3 (1858 kg/m^3)
- 8-in. (20.3 cm) heavy weight concrete block with solid grouted cores, 140 lb/ft^3 (2243 kg/m^3)
- Rigid insulation (R-value varies by climate) with 1-in. (2.5 cm) metal clips
- 0.5-in. (1.3 cm) thick gypsum board, 49 lb/ft^3 (785 kg/m^3)
- Interior air film (calculated by EnergyPlus).

The capital costs are based on personal communication with the ASHRAE 90.1 Envelope Subcommittee (ASHRAE 2008). The thermal performance of the interior and exterior air films are calculated with the EnergyPlus "detailed" algorithm for surface heat transfer film coefficients, which is based on linearized radiation coefficients separate from the convection coefficients determined by surface roughness, wind speed, and terrain.

Table 3-15 Baseline Exterior Wall Constructions

Properties	Climate Zone					
	1 and 2	3 and 4	5	6	7	8
Key	Baseline Wall Construction, No c.i.	Baseline Wall Construction, R-5.7 c.i.	Baseline Wall Construction, R-7.6 c.i.	Baseline Wall Construction, R-9.5 c.i.	Baseline Wall Construction, R-11.4 c.i.	Baseline Wall Construction, R-13.3 c.i.
U-Factor (Btu/h·ft^2·°F)	0.754	0.173	0.137	0.114	0.0975	0.0859
Capital Cost ($/ft^2)	$20.37	$21.06	$21.42	$21.68	$21.80	$21.86

3.3.3.2 Roofs

The baseline model roofs are built up, with rigid insulation above a structural metal deck. The layers consist of roof membrane, insulation, and metal decking. The assembly U-factors vary by climate zone and are adjusted to account for the standard film coefficients. R-values for most of the layers are derived from Appendix A of ASHRAE 90.1-2004. Insulation R-values for continuous insulations are selected to meet the minimum R-values required in Section 5 of ASHRAE 90.1-2004, which vary by climate zone. The thermal performance metrics and construction costs are listed by climate zone in Table 3-16 (see Table C-2 for metric units). The costs are estimated based on (Balboni 2008a) and assume:

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

Table 3-16 Baseline Roof Constructions

Properties	Climate Zone	
	1 through 7	8
Key	Baseline Roof Construction, R-15 c.i.	Baseline Roof Construction, R-20 c.i.
U-Factor (Btu/h·ft^2·°F)	0.0675	0.0506
Capital Cost ($/ft^2)	$8.69	$9.11

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

3.3.3.3 Slab-on-Grade Floors

The baseline buildings are modeled with slab-on-grade floors, made up of carpet pad over 8 in. (0.2 m) thick heavyweight concrete. A separate program, *slab.exe*, was used to model the ground coupling (DOE 2008b). It determines the temperature of the ground under the slab based on the area of the slab, the location of the building, and the type of insulation under or around the slab; and reports the perimeter ground monthly temperatures, the core ground monthly temperatures, and average monthly temperatures. For this analysis, the core average monthly temperatures are passed to EnergyPlus to specify the ground temperatures under the slab.

3.3.3.4 Fenestration

The baseline grocery stores' fenestration systems are modeled as three windows on the façade totaling 1,400 ft^2 (130 m^2) of glazing area. Windows are collected into a single object per zone and frames are not explicitly modeled to reduce model complexity and make the EnergyPlus simulations run faster. However, the U-factors and solar heat gain coefficients (SHGCs) are whole-assembly values that include frames. Those performance criteria were set to match the requirements of Appendix B of ASHRAE 90.1-2004. If a particular climate zone has no ASHRAE 90.1-2004 SHGC recommendation, its SHGC value is set to that of the previous (next warmest) climate zone.

The multipliers from the visible light transmittance (VLT) table, Table C3.5 in ASHRAE 90.1-2004 Appendix C (ASHRAE 2004a), are used to calculate VLT values for the baseline windows. An iterative process is used to refine the material properties in the layer-by-layer descriptions to just match the required assembly performance level. The baseline window constructions and costs are summarized in Table 3-17 (see Table C-3 for metric units). The costs are based on personal communication with the ASHRAE 90.1 Envelope Subcommittee (ASHRAE 2007a).

Table 3-17 Baseline Window Constructions

Properties	Climate Zone				
	1 and 2	3 and 4	5 and 6	7	8
Key	Baseline Window Construction	Baseline Window Construction	Baseline Window Construction	Baseline Window Construction	Baseline Window Construction
SHGC	0.250	0.390	0.490	0.490	0.490
VLT	0.250	0.495	0.622	0.490	0.490
U-Factor (Btu/h·ft^2·°F)	1.21	0.570	0.570	0.570	0.460
Capital Cost ($/$ft^2$)	$44.00	$47.23	$46.65	$47.23	$49.97
Fixed O&M Cost ($/$ft^2$)	$0.22	$0.22	$0.22	$0.22	$0.22

Some of the recommended designs for 50% energy savings include skylight-facilitated daylighting. Four of the skylight construction choices match the fenestration performance criteria outlined in Appendix B of ASHRAE 90.1-2004. These baseline skylight constructions are summarized in Table 3-18 (see Table C-4 for metric units). Costs based on personal communication with the ASHRAE 90.1 Envelope Subcommittee are also listed (ASHRAE 2007a).

Table 3-18 Baseline Skylight Constructions

Property	Climate Zone			
	1 through 3	4 through 6	7	8
Key	Baseline Skylight Construction	Baseline Skylight Construction	Baseline Skylight Construction	Baseline Skylight Construction
SHGC	0.36	0.490	0.490	0.490
VLT	0.457	0.622	0.490	0.490
U-Factor (Btu/h·ft^2·°F)	1.22	0.690	0.690	0.580
Capital Cost ($/ft^2)	$46.28	$47.23	$47.22	$51.04
Fixed O&M Cost ($/ft^2)	$0.22	$0.22	$0.22	$0.22

3.3.3.5 Infiltration

Building air infiltration is addressed indirectly in ASHRAE 90.1-2004 through requirements for building envelope sealing, fenestration, door air leakage, etc. The air infiltration rate is not specified. This analysis assumes that the peak infiltration rate is 0.268 air changes per hour (ACH) during operating hours, when the HVAC system is on and customers are entering and leaving the store. At night, when the HVAC system is off and the doors are closed, we assume that the infiltration rate reduces to 0.086 ACH (see Appendix B.4 for the hourly infiltration schedule). Infiltration through a surface is dependent on the pressure gradient acting on the surface. We calculated pressure gradients for each of the four walls according to the following assumptions:

- A constant 8 mph (3.6 m/s) wind blows directly into the front of the store.
- The wind creates a constant, uniform, positive pressure (0.023 in. w.c. [5.8 Pa]) on the front wall and a constant, uniform, negative pressure of equal magnitude (0.023 in. w.c. [5.8 Pa]) on the back wall
- The wind exerts no external pressure on the side walls.
- When the HVAC system is on, the building is pressurized to 0.016 in. w.c. (4 Pa) above the ambient air pressure.
- When the HVAC system is off, the building is not pressurized with respect to the outside air.

The resulting pressures (magnitudes and directions) acting on each exterior wall during operating and non-operating hours are listed in Table 3-19 and Table 3-20, respectively (see Table C-5 and Table C-6 for metric units), and presented graphically in Figure 3-14.

Table 3-19 Pressures Acting on Exterior Walls During Operating Hours

Exterior Wall	Resultant Pressure Gradient	
	Magnitude (in. w.c.)	Direction
Front	0.007	Infiltration
Back	0.039	Exfiltration
Side	0.016	Exfiltration

Table 3-20 Pressures Acting on Exterior Walls During Non-Operating Hours

Exterior Wall	Resultant Pressure Gradient	
	Magnitude (in. w.c.)	Direction
Front	0.023	Infiltration
Back	0.023	Exfiltration
Side	0	NA

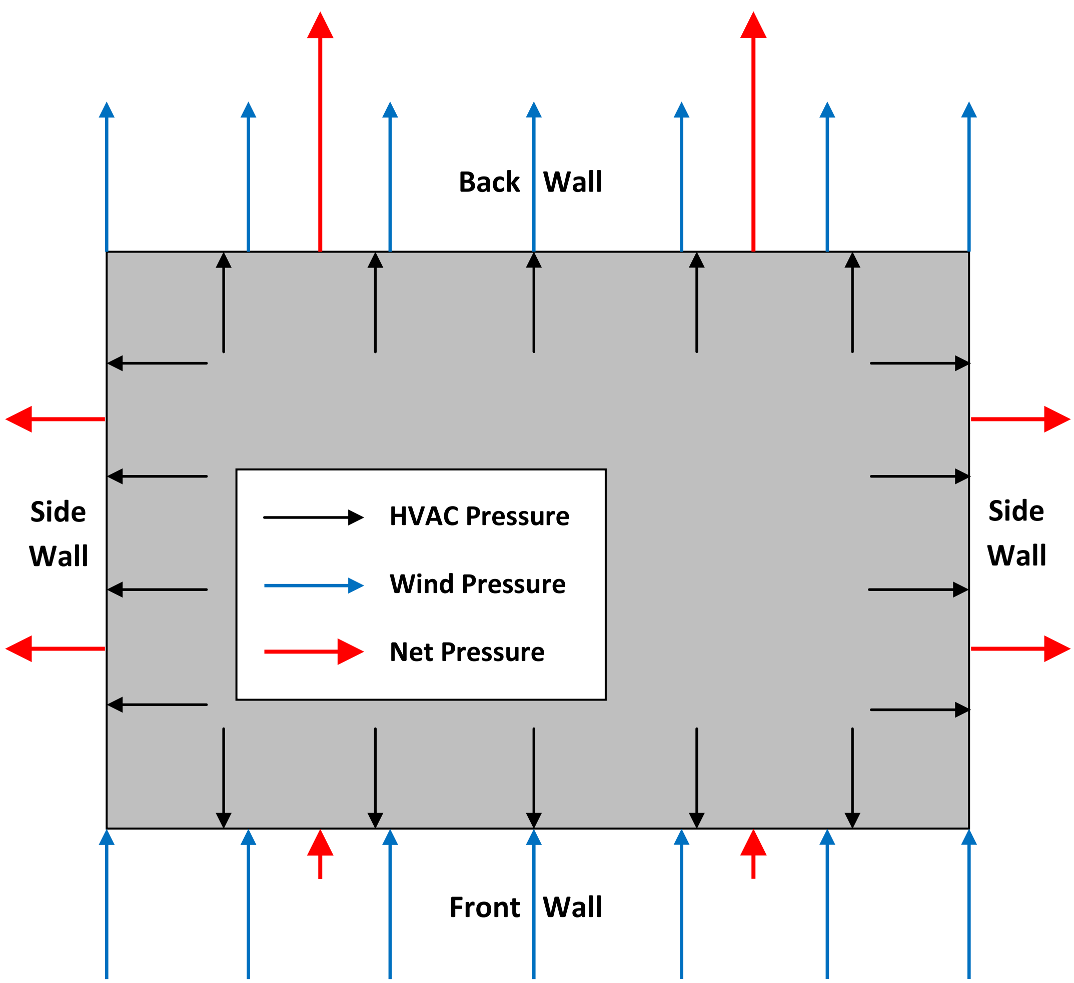

Figure 3-14 Building flow balance diagram

Pressure gradients driving infiltration are used to calculate infiltration rates for the building. The envelope infiltration rate is derived from CIBSE-T23 building tightness specifications for good construction practice (CIBSE 2000). The infiltration through the sliding doors is modeled using the door opening event modeling of Yuill et al. (2000). Pressure gradients driving exfiltration are used to calculate exfiltration rates, which have implications in regards to the flow of air available for ERV. See Section 3.4.3.4.2 for more detail.

3.3.4 Equipment

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

3.3.4.1 Lighting

3.3.4.1.1 Interior

The baseline interior LPD for each space type is derived using the space-by-space method described in ASHRAE 90.1-2004 (ASHRAE 2004a). The mapping between each space type and the standard, and the resulting baseline LPDs are presented in Table 3-21. For the location of each space type, see Figure 3-12.

Table 3-21 Baseline Lighting and Occupancy Loads by Space Type

Space Type	Mapping to ASHRAE 90.1-2004	LPD (W/ft^2)	LPD (W/m^2)
Main Sales	Sales area	1.7	18.3
Perimeter Sales	Sales area	1.7	18.3
Produce	Sales area	1.7	18.3
Deli	Food preparation	1.2	12.9
Bakery	Food preparation	1.2	12.9
Enclosed Office	Office-enclosed	1.1	11.8
Meeting Room	Conference/meeting/multi-purpose	1.3	14.0
Dining Room	Dining area	0.9	9.7
Restrooms	Restrooms	0.9	9.7
Mechanical Room	Electrical/mechanical	1.5	16.1
Corridor	Corridor/transition	0.5	5.4
Vestibule	Corridor/transition	0.5	5.4
Active Storage	Active Storage	0.8	8.6
Whole Building		1.5	16.2

The baseline cost of the lighting system is modeled as $10.51/ft^2 ($34.48/m^2, $6,996/kW) for capital costs, and $0.12/ft^2·yr ($0.38/m^2·yr, $77.24/kW·yr) for maintenance, where kW refers to the total installed lighting power. The material and installation costs are estimated based on (Balboni 2008b); the maintenance costs are estimated using (Plotner 2009). Thus the baseline capital costs are approximately $473,000, and the baseline maintenance costs are about $5,220/yr.

3.3.4.1.2 Exterior

The baseline grocery stores have 1 W/ft (3.28 W/m) of exterior façade lighting, per ASHRAE 90.1-2004, Table 9.4.5 (ASHRAE 2004a). The model does not include a parking lot or parking lot lighting.

3.3.4.2 HVAC Systems and Components

3.3.4.2.1 System Type and Sizing

This *TSD* assumes packaged single-zone (PSZ) unitary heating and cooling equipment, based on the *2003 CBECS*. These systems are modeled by placing an autosized PSZ system with a constant volume fan, DX cooling, and gas-fired furnace in each thermal zone (the disjoint rectangles in Figure 3-12). To apply ASHRAE 90.1-2004, we develop performance data consistent with 10-ton, 4,000 cfm (1.88 m^3/s) RTUs, under the assumption that the larger zones would be served by multiple units.

We use the design-day method to autosize the cooling capacity of the DX cooling coil and the heating capacity of the furnace in the packaged RTUs. The design-day data for all 16 climate locations are developed from (ASHRAE 2005). In those data sets, we base the heating design condition on 99.6% annual percentiles, and the cooling design condition on 0.4% annual percentiles. The internal loads (occupancy, lights, and plug loads) were scheduled as zero on the heating design day, and at their peak on the cooling design day. A 1.2 sizing factor was applied to all autosized heating and cooling capacities and air flow rates. Because EnergyPlus autosizes HVAC equipment according to sensible load, additional sizing factors needed to be applied in humid climates to zones with large outdoor air requirements to handle the large latent loads.

3.3.4.2.2 Outside Air

Ventilation rates by zone are defined according to ASHRAE Standard 62-1999 (ASHRAE 1999). The mapping between each space type and the standard and the resulting ventilation rate are presented in Table 3-22. Rates for spaces without direct mapping to the standard were estimated. ASHRAE 62-1999 requires 50 cfm (24 L/s) of OA per toilet for restrooms, and we assume an area of roughly 48 ft^2 (4.5 m) per toilet. Mechanical rooms were assigned a ventilation rate of zero, based on the assumption that they are unoccupied most of the time.

OA intake follows the same schedule as the HVAC system, which turns on an hour before the store is occupied in the morning and turns off when the store closes in the evening. The HVAC system also runs intermittently during off hours to adhere to the off hours temperature requirements.

Table 3-22 Baseline Minimum Ventilation Rates

Space Type	Mapping to ASHRAE 62-1999	Ventilation per Person		Ventilation per Area	
		cfm/person	L/s·person	cfm/ft^2	$L/ s·m^2$
Main Sales	Retail::Basement and street	–	–	0.30	1.50
Perimeter Sales	Retail::Basement and street	–	–	0.30	1.50
Produce	Retail::Basement and street	–	–	0.30	1.50
Deli	Food & Beverage::Kitchens	15.0	7.5	–	–
Bakery	Food & Beverage::Kitchens	15.0	7.5	–	–
Enclosed Office	Offices::Office space	20.0	10.0	–	–
Meeting Room	Offices::Conference rooms	20.0	10.0	–	–
Dining Room	Food & Beverage::Dining rooms	20.0	10.0	–	–
Restrooms	CUSTOM VALUE	–	–	1.04	5.20
Mechanical Room	CUSTOM VALUE	–	–	0.00	0.00
Corridor	Public Spaces::Corridors & utilities	–	–	0.05	0.25
Vestibule	Public Spaces::Corridors & utilities	–	–	0.05	0.25
Active Storage	Retail::Shipping and receiving	–	–	0.15	0.75

3.3.4.2.3 Economizers

In accordance with ASHRAE 90.1-2004, Section 6.5.1, an economizer is required in climate zones 3B, 3C, 4B, 4C, 5B, 5C, and 6B for systems between 65,000 Btu/h (19 kW) and 135,000 Btu/h (40 kW) cooling capacity. Therefore, the 10-ton (120,000 Btu/h, 35.16 kW) baseline RTUs include economizers in these climate zones only.

3.3.4.2.4 Minimum Efficiency

The code-minimum efficiency for cooling equipment is determined based on cooling system type and size. To apply ASHRAE 90.1-2004, we assume baseline RTUs with 10 tons cooling and 4,000 cfm (1.88 m^3/s) air flow. ASHRAE 90.1-2004 requires single packaged unitary air conditioners of this size (between 65,000 Btu/h [19 kW] and 135,000 Btu/h [40 kW]) and with nonelectric heating units to have a minimum EER of 10.1. The gas-fired furnace efficiency levels were set to 80% to match the efficiency requirements for gas heating.

The ASHRAE 90.1-2004 minimum EER values include fan, compressor, and condenser power. EnergyPlus, however, models compressor and condenser power separately from fan power. We assume EER and compressor/condenser coefficient of performance (COP) values, and then use them to calculate fan efficiency. As stated above, the EER is 10.1. We assume a compressor/condenser COP of 3.69, based on publically available industrial spec sheets for EER 10.1 units.

3.3.4.2.5 Fan Power Assumptions

We assume that the package RTU contains only a supply fan, and no return or central exhaust fans. The constant volume supply fan energy use is determined from three primary input parameters: system-wide EER, compressor/condenser COP, and total static pressure drop. ASHRAE 90.1-2004 specifies maximum fan motor power, which, together with static pressure drop, can be used to determine fan efficiency and compressor/condenser COP for a given EER.

We choose to deviate from this practice to obtain a more realistic split between fan and compressor/condenser power; we recognize, however, that our fan efficiencies are better than code minimum.

The total supply fan static pressure drops are based on the 10-ton units modeled in Liu et al. (2007) plus 50% more supply and return ductwork. Table 3-23 (see Table C-7 for metric units) summarizes the breakdown of the fan total static pressure for the baseline RTU. The 10-ton unit without an economizer has a total fan static pressure of 1.53 in. w.c. (381 Pa); those with economizers have a total static pressure of 1.62 in. w.c. (404 Pa).

Table 3-23 Baseline Fan System Total Pressure Drops

Component	Package Rooftop, Constant Volume, 10-ton, 4000 cfm, no Economizer (in. w.c.)	Package Rooftop, Constant Volume, 10-ton, 4000 cfm, with Economizer (in. w.c.)
Internal Static Pressure Drop	0.67	0.76
External Static Pressure Drop	0.86	0.86
Total Static Pressure Drop	1.53	1.62

*Used friction rate of 0.1 in. w.c./100 ft (25 Pa/30 m) for the baseline duct pressure drop.

We back out the baseline total fan efficiency from the 10.1 EER requirement, the static pressures just listed, and a combined compressor and condenser COP of 3.69. This calculation proceeds in three steps:

1. Determine the portion of the EER dedicated to the supply fan by subtracting out the compressor/condenser contribution:

   After converting EER and COP to units of tons of cooling per kilowatt of electricity, we find that the supply fan uses 0.235 kW (0.8 kBtu/hr) of electricity for every ton of cooling.

$$\frac{kW\ fan\ power}{ton\ cooling} = \frac{12}{EER} - \frac{3.516}{COP}$$

2. Determine the nameplate motor power per supply air volume:

   Assuming 400 cfm per ton of cooling (0.054 $(m^3/s)/kW$), the fan power per volumetric unit of air is 0.788 hp/1000 cfm (1245 $W/(m^3/s)$). This is well within the Standard 90.1-2004 requirement that units with less than 20,000 cfm (9.44 m^3/s) have fans with nameplate motor power less than 1.2 hp/1000 cfm (1896 $W/(m^3/s)$).

$$\frac{motor\ hp}{1000\ cfm} = \frac{kW\ fan\ power}{ton\ cooling} \cdot \frac{1\,ton\ cooling}{400\,cfm} \cdot 1341$$

3. Calculate fan efficiency:

   The fan efficiency is equal to the total static pressure (using the external static pressure value specified by the ARI standard) divided by the nameplate motor power per supply air volume, in compatible units. Thus, the RTUs without economizers have a fan efficiency of 30.6%; those with economizers require an efficiency of 32.4%.

3.3.4.2.6 Summary and Costs

This report uses HVAC system cost data prepared for NREL by the RMH Group (2006). The 10-ton RTUs described in that report have EER values of 9.0, 10.4, and 11.0. The baseline unit costs are assumed to be the same as the lowest efficiency unit's even though the EER of our baseline unit is higher (10.1 instead of 9.0). This cost is \$8,478 plus \$1.89/cfm (\$4,005/(m^3/s)) for ductwork materials and installation. Assuming 400 cfm per ton of cooling (0.054 (m^3/s)/kW), the cost of ductwork for a 10-ton unit is \$7,560, and the total system capital cost is \$1603.75/ton of cooling (\$456.13/kW). The cost of an economizer, including controls and an additional relief hood, is given as \$1002 for a 10-ton unit, that is, an extra \$100.20/ton of cooling (\$28.48/kW). Maintenance costs for the 10-ton unit are \$160/yr for fixed O&M plus \$1,240/yr for repair and replacement costs: \$140/ton·yr (\$39.87/kW·yr) total. Table 3-24 (see Table C-8 for metric units) summarizes the primary HVAC performance characteristics and cost data for the baseline grocery stores.

Table 3-24 Baseline HVAC Models Summary

HVAC Input	ASHRAE 90.1-2004 Baseline PSZ DX, Furnace, No Economizer	ASHRAE 90.1-2004 Baseline PSZ DX, Furnace, With Economizer
System EER	10.1	10.1
COP of Compressor/Condenser	3.69	3.69
Heating Efficiency	80%	80%
Fan Power	0.788 hp/1000 cfm	0.788 hp/1000 cfm
Fan Static Pressure	1.53 in. w.c.	1.62 in. w.c.
Fan Efficiency	30.6%	32.4%
Economizers	None	Included
Capital Cost (\$/ton cooling)	\$1,604	\$1,704
O&M Cost (\$/ton cooling·yr)	\$140	\$140

3.3.4.3 Refrigeration

This section augments the Section 3.2.4.2 refrigeration system description with performance and cost data.

3.3.4.3.1 Refrigerated Cases

Four types of refrigerated cases are modeled: Island Single-Deck Meat, Multi-Deck Dairy/Deli, Vertical Frozen Food with Doors, and Island Single-Deck Ice Cream. The energy models for these cases are developed from publically available manufacturers' data; the costs are estimated from industry quotes and RSMeans (Waier 2005). The baseline lighting levels for each case are somewhat arbitrary, in line with a personal communication indicating that installed lighting varies tremendously from customer to customer. The rated performance conditions for all cases are 75°F (24°C) and 55% relative humidity, per ARI Standard 1200-2002 (ARI 2002).

Table 3-25 (see Table C-9 for metric units) summarizes the performance and cost data of the baseline refrigerated cases. The rated capacity is the cooling load of the case at rated conditions, which includes fan, lighting, anti-sweat heater power, and heat transfer from the store. The heat transfer can be decomposed into an infiltration load caused by the mixing of store and case air, transfer from the surrounding air through the case walls, and radiant heat transfer. The infiltration load includes sensible and latent components. The infiltration ratio is the proportion of the rated capacity caused by infiltration; the latent heat ratio is the proportion of the rated capacity caused by the latent component. EnergyPlus uses the latent heat ratio directly to calculate latent load; we use the infiltration ratio to reduce the baseline EnergyPlus case credit schedules during the summer design day. In Section 3.4.3.5.1 the infiltration ratio is used to estimate the effects of adding night covers or case doors.

The operating temperature is the temperature inside the case. The restocking load and schedule attempt to model the periodic additional cooling loads that result from placing new product in the cases. These loads are estimated by assuming the average specific heat and density of the product, the temperature difference of the product before and after loading, the proportion of case volume filled with product, and volumetric proportion of product restocked per day. These inputs are summarized in Table 3-26 (see Table C-10 for metric units).

Time-off defrost always uses all allotted defrost time. Electric defrost with temperature termination may end early, depending on the relative humidity of the store. Whenever we use temperature termination, this feature is modeled in EnergyPlus with the case temperature method and the coefficients provided in Howell and Adams (1991) for horizontal and vertical cases, see the EnergyPlus documentation for Case:Refrigerated (DOE 2008b).

Table 3-25 Baseline Refrigerated Case Characteristics

Characteristic	Island Single-Deck Meat	Multi-Deck Dairy/Deli	Vertical Frozen Food with Doors	Island Single-Deck Ice Cream
Rated Capacity (Btu/h·ft)	770	1500	538	740
Operating Temperature (°F)	28.5	41.0	–1.5	–13.0
Latent Heat Ratio	0.361	0.241	0.061	0.147
Infiltration Ratio	0.686	0.579	0.152	0.412
Fan Power (Btu/h·ft)	38.7	42.6	40.9	29.0
Lighting Power (Btu/h·ft)	0	215	92.8	255
Anti-Sweat Heater Power (Btu/h·ft)	37.0	0	259	135
Defrost Type	Time-off	Time-off	Electric with temperature termination	Electric with temperature termination
Defrost Power (Btu/h·ft)	0	0	1311	1032
Maximum Defrost Time (min)	45	42	46	60
Drip-Down Time (min)	8	8	15	15
Defrost Start Time(s)	6:00 a.m. 2:00 p.m. 10:00 p.m.	1:00 a.m. 7:00 a.m. 1:00 p.m. 7:00 p.m.	10:00 p.m.	10:00 p.m.
Restocking Load (Btu/h·ft) and Schedule	65 from 1:00 p.m. to 4:00 p.m.	325 from 9:00 a.m. to 12:00 p.m.	16.0 from 6:00 p.m. to 9:00 p.m.	27.4 from 7:00 a.m. to 10:00 a.m.
Materials Cost ($/ft)	$753.28	$583.02	$647.71	$773.94

Table 3-26 Refrigerated Case Restocking Assumptions

Case Type	Case Volume/ft (ft^3/ft)	Volume Filled by Product (%)	Volume of Product Restocked (%)	Specific Heat of Product (Btu/lb·°F)	Density of Product (lb/ft^3)	Temp. Difference (°F)	Daily Restocking Load (Btu/ft·day)
Island Single-Deck Meat	1.67	30	20	0.75	60	43	194
Multi-Deck Dairy/Deli	13.1	50	40	0.75	62	8	975
Vertical Frozen Food with Doors	13.5	50	5	0.50	57	5	48.1
Island Single-Deck Ice Cream	6.35	70	10	0.65	57	5	82.3

3.3.4.3.2 Walk-In Coolers and Freezers

Under the assumption that walk-in coolers and freezers are already designed for energy efficiency, we directly adopt the benchmark project models for these units, and do not develop

EDMs for these units. For completeness, their performance characteristics are summarized in Table 3-27. See Section 3.3.4.3.1 for a discussion of the listed characteristics.

Table 3-27 Walk-In Cooler and Freezer Characteristics

Characteristic	Walk-In Cooler (IP Units)	Walk-In Freezer (IP Units)	Walk-In Cooler (SI Units)	Walk-In Freezer (SI Units)
Rated Capacity (Btu/h·ft or W/m)	480.0	640.0	461.5	615.4
Operating Temperature (°F or °C)	36	-10	2.2	-23.3
Latent Heat Ratio	0.1	0.1	0.1	0.1
Fan Power (Btu/h·ft or W/m)	101	109	97.1	105
Lighting Power (Btu/h·ft or W/m)	27.30	27.30	26.25	26.25
Anti-Sweat Heater Power (Btu/h·ft or W/m)	0	0	0	0
Defrost Type	Electric	Electric	Electric	Electric
Defrost Power (Btu/h·ft or W/m)	532.26	791.58	511.8	761.15
Max. Defrost Time (min)	20	20	20	20
Drip-Down Time (min)	10	10	10	10
Defrost Start Time(s)	11:00 a.m. 11:00 p.m.	11:00 a.m. 11:00 p.m.	11:00 a.m. 11:00 p.m.	11:00 a.m. 11:00 p.m.
Restocking Load (Btu/ft or kJ/m)	1,489 on Tuesdays and Fridays; 690.4 all other days	1,489 on Tuesdays and Fridays; 690.4 all other days	5,155 on Tuesdays and Fridays; 2,390 all other days	5,155 on Tuesdays and Fridays; 2,390 all other days

3.3.4.3.3 Compressor racks

EnergyPlus assumes that compressor racks can always satisfy the case load connected to them. It also models compressor racks and their associated condensers as one unit. Air-cooled condensers are assumed for the baseline models.

The COPs at rated conditions (104°F [40°C] condensing temperature) are assumed to be 2.5 and 1.3 for the medium- and low-temperature racks, respectively, based on Westphalen et al. (1996). The fan power for each rack is estimated using the sum of the rated case loads connected to that rack, the rated rack COPs, and the statistic that 55% and 7% of the refrigeration electricity in a typical grocery store is used to power the compressors and the condenser fans, respectively (Westphalen et al. 1996). This results in a total of 19,000 W (64,831 Btu/hr) of condenser fan power, with 11,860 W (40,468 Btu/hr) for the medium-temperature racks, and 7,140 W (24,363 Btu/hr) for the low-temperature racks.

The variation of COP and condenser fan power with temperature is modeled using the normalized curves in the EnergyPlus Supermarket example files. Overall, the low-temperature rack COPs are modeled as

$$COP = 1.5\left(1.7603 - 0.0377\,T + 0.0004\,T^2\right),$$

and the medium-temperature rack COPs are

$$COP = 2.8\left(1.7603 - 0.0377\,T + 0.0004\,T^2\right),$$

where T is the condensing (outdoor) temperature in °C. The fan power for the low-temperature racks is

$$P_{fan} = 0.0286\,T \cdot P_{fan,rated},$$

and the medium-temperature racks use

$$P_{fan} = \left(0.3 + 0.02\,T\right)P_{fan,rated}.$$

The cost of the racks and condensers is based on the cost of an entire refrigeration system ($1 million to $1.1 million) and the percentage of that cost that is dedicated to compressor racks, condensers, and installation, as described in Westphalen et al. (1996). The compressor and condenser equipment is 16% of the total cost, which, after applying a 38% increase for inflation (to 2008 dollars), is $220,200. The total installation cost comes out to $288,000. After subtracting $33,000 for case and walk-in installation, $255,300 is attributed to compressor rack and condenser installation. Thus, the total capital cost of the racks and condensers is $475,500.

Finally, Westphalen et al. (1996) estimated $83/100 ft^2·yr ($8.93/m^2·yr) to maintain the refrigeration system. After converting to 2008 dollars and multiplying by the size of the store, we estimate $46,450/yr for O&M costs for the whole system.

3.3.4.4 Service Water Heating

The baseline service water heating system for the grocery stores is a gas-fired storage water heater that meets the ASHRAE 90.1-2004 requirements. We assume a thermal efficiency of 80% to meet the requirements for units with rated input power greater than 75,000 Btu/h (22 kW) and expending less than 4000 Btu/h·gal (309.7 kW/m^3).

The baseline grocery stores' peak hot water consumption rate is modeled as 116 gph (0.44 m^3/h), based on the statement in (ASHRAE 2003) that grocery stores typically use 300–1000 gal (1.136–3.785 m^3) hot water per day. The storage tank has a volume of 250 gal (0.95 m^3). The consumption schedule as a fraction of peak load is shown in Table B-8. It dictates the use of 768 gpd (2,907 L/d) on weekdays, 800 L/d (3,028 lpd) on Saturdays, and 532 gpd (2,014 L/d) on Sundays. The hot water outlet temperature is assumed to be 110ºF (43.3ºC). The water heater set point is 140ºF (60ºC).

3.4 Energy Design Measures

The optimization algorithm described in Section 2.4 determines which EDMs are applied to the baseline models to create low-energy models that meet the 50% energy savings target. This section contains a topic-by-topic description of the EDMs under consideration. They fall into the following categories:

- Reduced LPD and occupancy controls
- PV electricity generation
- Varying levels of façade glazing and skylights
- Overhangs to shade the façade glazing

- Daylighting controls
- Enhanced opaque envelope insulation
- Window and skylight glazing constructions
- Reduced infiltration via the installation of an air barrier and/or vestibule
- Higher efficiency HVAC equipment
- Higher efficiency fans
- Demand controlled ventilation (DCV)
- ERVs
- Economizers
- Higher efficiency refrigerated cases
- Evaporatively cooled refrigeration condensers.

The low-energy building models are built by perturbing the baseline models with the efficiency measures described below. Any aspect of the building previously discussed but not mentioned is constant across all models.

We were not able to include all efficiency measures of interest in this analysis. For a discussion of items that could be included in a subsequent study, see Section 5.0.

3.4.1 Form

3.4.1.1 Fenestration

These EDMs change the amount of horizontal and vertical glazing on the building. None has an inherent cost; instead, each determines the amount of glazing. Window and skylight costs are calculated by multiplying the glazing areas (as determined by the baseline glazing amount and these EDMs) by the cost per unit area of the selected glazing types (see Section 3.4.2.3).

3.4.1.1.1 Front Façade Windows

One EDM reduces the amount of façade fenestration by 50%. This results in a reduction in the south façade WWR from 26.9% to 13.5%. The sill height for this EDM is consistent with that of the baseline building.

3.4.1.1.2 Skylights

Another set of EDMs adds skylights to the baseline building. Skylights can be added to all zones except the perimeter sales zones and the vestibule zone (see Figure 3-15). The skylight EDMs result in 2%, 3%, or 4% coverage of the roof area in the applicable zones.

3.4.1.2 Overhangs

Roof-framed overhangs were added assuming a 0.82 ft (0.25 m) offset from the top of each window, and a projection factor of 0.5 to 1.1, in steps of 0.2. This yields four EDMs, which were all priced at \$10.09/ft^2 (\$108.63/m^2) of overhang in 2008 dollars (ABO Group 2006). The size of each overhang was determined using the height of the window, the offset, and the projection factor. For instance, a 3-ft (0.91-m) wide, 2-ft (0.61-m) tall window, a 0.25-ft (0.076-m) offset, and a projection factor of 1.1 yields a 2.475-ft (0.75-m) deep by 3-ft (0.91-m) wide overhang.

3.4.2 Fabric

3.4.2.1 Exterior Walls

The mass wall EDMs are shown in Table 3-28 (see Table C-11 for metric units), along with capital costs that are based on personal communication with the ASHRAE 90.1 Envelope Subcommittee (ASHRAE 2008). Construction method, insulation material and insulation thickness are listed independently for each exterior wall construction to provide sufficient means for comparison.

The interior insulation construction is the baseline construction (see Section 3.3.3.1). Its layers are:

- Exterior air film (calculated by EnergyPlus)
- 1-in (2.5 cm) exterior stucco, 116 lb/ft^3 (1858 kg/m^3)
- 8-in. (20.3 cm) heavyweight concrete block with solid grouted cores, 140 lb/ft^3 (2243 kg/m^3)
- Rigid insulation (varying R-value) with 1-in. (2.5 cm) metal clips
- 0.5-in. (1.3 cm) thick gypsum board, 49 lb/ft^3 (785 kg/m^3)
- Interior air film (calculated by EnergyPlus)

The exterior insulation construction has a different insulation location and slightly different layer materials and thicknesses from those reported above. The latter differences stem from the fact that the exterior insulation construction is representative of the most recent ASHRAE 90.1 Envelope Subcommittee data, whereas the interior insulation construction was developed from an earlier data set. The layers of the exterior insulation construction are:

- Exterior air film (calculated by EnergyPlus)
- 0.75-in (1.9 cm) exterior stucco, 120 lb/ft^3 (1920 kg/m^3)
- Rigid insulation (varying R-value)
- 7.625-in. (20.1 cm) light weight concrete block with partially grouted cores, 38 lb/ft^3 (609 kg/m^3)
- 1-in. (2.5 cm) metal clips with air
- 0.5-in. (1.3 cm) thick gypsum board, 49 lb/ft^3 (785 kg/m^3)
- Interior air film (calculated by EnergyPlus)

The brick cavity construction consists of two "skin" layers, in this case an exterior brick layer and an interior concrete block layer, separated by a hollow space (cavity) that can be filled with insulation. Cavity walls are more expensive to build, but provide better sound and heat insulation and have a higher resistance to rain penetration. The layers of the brick cavity construction are identical to those of the exterior insulation construction, except that the stucco layer is replaced with brick:

- Exterior air film (calculated by EnergyPlus)
- 3.625-in (9.2 cm) medium-weight brick, 110 lb/ft^3 (1760 kg/m^3)
- Rigid insulation (varying R-value)
- 7.625-in. (20.1 cm) light weight concrete block with partially grouted cores, 38 lb/ft^3 (609 kg/m^3)
- 1-in. (2.5 cm) metal clips with air
- 0.5-in. (1.3 cm) thick gypsum board, 49 lb/ft^3 (785 kg/m^3)
- Interior air film (calculated by EnergyPlus)

Table 3-28 Exterior Wall EDMs

Insulation R-value, Nominal	Assembly U-Factor (Btu/h·ft^2·°F)	Construction Method	Insulation Material	Insulation Thickness (in)	Capital Cost ($/ft^2)
R-5.7 c.i.	0.1754	Interior Insulation	Isocyanurate	1.3	$21.06
R-9.5 c.i.	0.1053	Interior Insulation	Isocyanurate	2.2	$21.68
R-13.3 c.i.	0.0752	Interior Insulation	Isocyanurate	3.1	$21.86
R-15.0 c.i.	0.0532	Exterior Insulation	Polystyrene Extruded	3	$22.42
R-19.5 c.i.	0.0430	Exterior Insulation	Polyisocyanurate	3	$22.75
R-22.5 c.i.	0.0372	Brick Cavity	Polyurethane Foam	3.75	$28.35
R-28.5 c.i.	0.0303	Brick Cavity	Polyurethane Foam	4.75	$28.83

3.4.2.2 Roofs

The insulation above deck roof EDMs are shown in Table 3-29 (see Table C-12 for metric units), along with capital costs that are estimated based on (Balboni 2008a). The construction of the EDM roofs in the EnergyPlus models is identical to that of the baseline roofs, except for the amount of c.i. and the possible addition of high albedo (cool) roof membranes. Thus, the roofs are described by the R-value of the c.i. and the presence or absence of a cool roof.

The high albedo/cool roofs have a Solar Reflective Index of 78 and an outer layer with a thermal absorption of 0.9, a solar reflectivity of 0.7, and a visible absorption of 0.3.

Table 3-29 Roof EDMs

EDM Key	U-Factor (Btu/h·ft^2·°F)	Capital Cost ($/ft^2)
R-20 c.i.	0.0507	$5.43
R-20 c.i. with cool roof	0.0507	$5.43
R-25 c.i.	0.0405	$5.82
R-25 c.i. with cool roof	0.0405	$5.82
R-30 c.i.	0.0332	$6.25
R-30 c.i. with cool roof	0.0332	$6.25
R-35 c.i.	0.0289	$6.64
R-35 c.i. with cool roof	0.0289	$6.64
R-40 c.i.	0.0229	$7.20
R-50 c.i.	0.0201	$7.60
R-60 c.i.	0.0161	$8.43
R-75 c.i.	0.0134	$9.29
R-95 c.i.	0.0109	$10.13

3.4.2.3 Fenestration

3.4.2.3.1 Front Façade Windows

Table 3-30 (see Table C-13 for metric units) lists the seven window EDMs, including a short description, performance data, and cost data. The set is selected from a list of glazing systems compiled by the ABO Group to provide a good mix of available performances (Priebe 2006).

Table 3-30 South Fenestration Construction EDMs

EDM Key	SHGC	VLT	U-Factor (Btu/h·ft^2·°F)	Capital Cost ($/ft^2)	Fixed O&M Cost ($/ft^2·yr)
Single pane with clear glass	0.810	0.881	1.08	$37.40	$0.21
Single pane with pyrolytic low-e	0.710	0.811	0.745	$40.70	$0.21
Double pane with low-e and argon	0.564	0.745	0.264	$44.00	$0.21
Double pane with low-e2 and argon	0.416	0.750	0.235	$50.60	$0.21
Double pane with low-e2 and tinted glass	0.282	0.550	0.288	$50.60	$0.21
Triple layer with low-e polyester film	0.355	0.535	0.215	$59.75	$0.21
Quadruple layer with low-e polyester films and krypton	0.461	0.624	0.136	$62.59	$0.21

3.4.2.3.2 Skylights

Several skylight EDMs are similarly chosen from a list of constructions provided by the ASHRAE 90.1 Envelope Subcommittee (ASHRAE 2007a) in an attempt to select high/low U-factors and high/low SHGCs, see Table 3-31 (Table C-14 for metric units).

Table 3-31 Skylight Fenestration Construction EDMs

EDM Key	SHGC	VLT	U-Factor (Btu/h·ft^2·°F)	Capital Cost ($/ft^2)	Fixed O&M Cost ($/ft^2·yr)
Single pane with high solar gain	0.610	0.672	1.22	$47.22	$0.24
Single pane with medium solar gain	0.250	0.245	1.22	$51.22	$0.24
Single pane with low solar gain	0.190	0.174	1.22	$51.22	$0.24
Double pane with high solar gain	0.490	0.622	0.580	$45.68	$0.24
Double pane with low-e and high solar gain	0.460	0.584	0.451	$45.78	$0.24
Double pane with medium solar gain	0.390	0.495	0.580	$57.70	$0.24
Double pane with low-e and medium solar gain	0.320	0.406	0.451	$63.17	$0.24
Double pane with low solar gain	0.190	0.241	0.580	$58.83	$0.24
Double pane with low-e and low solar gain	0.190	0.240	0.451	$63.54	$0.24

3.4.2.4 Infiltration

The infiltration EDMs reduce the baseline infiltration rate by applying an envelope air barrier or a front entrance vestibule. The air barrier is assumed to reduce the envelope infiltration from 0.040 to 0.016 ACH, based on CIBSE-T23 building tightness specifications for good or best construction practice, respectively (CIBSE 2000). The cost of the air barrier is estimated at $1.40/ft^2 ($15.07/m^2) of exterior wall area (Emmerich et al. 2005). A vestibule is assumed to reduce the front door infiltration from 0.228 to 0.142 ACH, based on the door opening event modeling of Yuill et al. (2000). The cost of this EDM is assumed to be that of replacing two 8-ft (2.44-m) tall sliding doors having a total surface area of 120 ft^2 (11.15 m^2) with four, 7-ft (2.13-m) tall sliding doors (adding the vestibule requires a second set of doors) having a total surface area of 210 ft^2 (19.51 m^2) and adding 30 linear feet (9.14 m) of interior walls (based on a 15-ft. [4.6-m] deep vestibule), corresponding to an additional interior wall area of 600 ft^2 (55.74 m^2). According to that assumption, the cost associated with adding a vestibule is $5,853 (Waier 2008).

3.4.3 Equipment

3.4.3.1 Daylighting Controls

The daylighting EDM adds light sensors and dimming controls to zones with windows or skylights. Skylights or windows (depending on the source of daylighting for the zone) are not added by this EDM, rather, the EDM impact and cost are dependent on how many skylights or windows are installed.

Each zone has access to, at most, one daylighting source. As depicted in Figure 3-15, most of the store only receives daylight from skylights, which may or may not be included in a given model. The front zones containing windows are limited to a depth of 15 ft. to ensure good sidelighting of those zones.

There is one light sensor per zone, placed in the center at a height of 2.95 ft (0.90 m) from the floor. For zones daylit by skylights, the sensor is placed between two skylights (if the skylight is directly above the center). The dimming controls are continuous; they start dimming when the lighting set point is exceeded, linearly decreasing until the lighting set point is met or the input power decreases to 30% of its maximum (where the light output is 20% of its maximum), whichever comes first.

Based on feedback from retailers, we chose a daylighting set point of 46.5 fc (500 lux). The cost of this set point system is \$0.38/ft^2 (\$4.10/m^2) of daylit area (Liu et al. 2007).

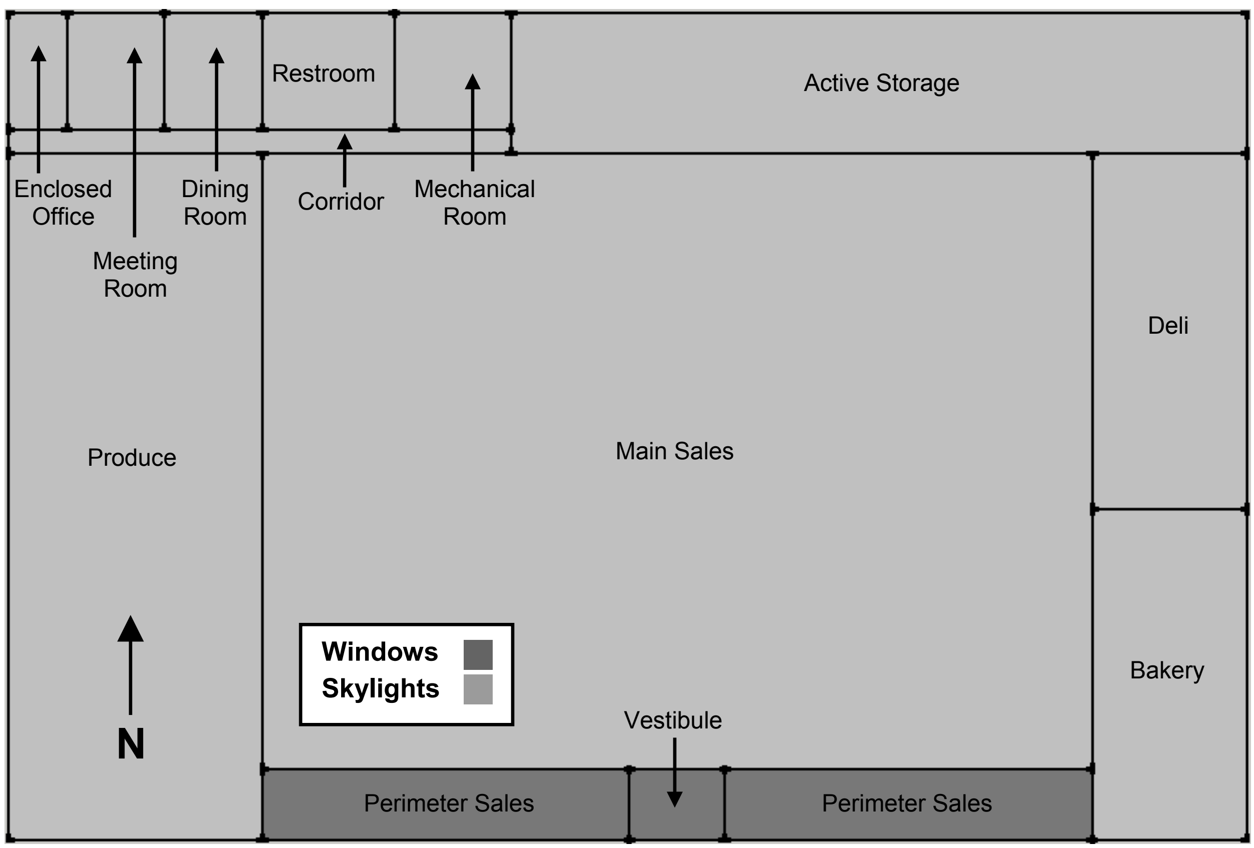

Figure 3-15 Potential daylight sources for each zone

3.4.3.2 Interior Lighting

Two whole-building LPD reductions are considered: 30% and 47%. For the sales areas, this corresponds to LPDs of 1.20 W/ft^2 (12.9 W/m^2) and 0.90 W/ft^2 (9.7 W/m^2), respectively.

The baseline system is modeled as T12 lamps with electronic ballasts in a basic luminaire with 40.3 ft^2 (3.74 m^2) per fixture. The ballast factor is 0.85, and the luminaire efficiency is 0.90.

The first EDM (30% reduction) corresponds to Super T8s, ballast factors of 0.88, and a luminaire efficiency of 0.93. This system covers 44.6 ft^2 (4.15 m^2) with a single fixture, and has an incremental capital cost of \$82/kW of lighting power reduction. The total incremental cost is thus \$1,663, because the EDM reduces the lighting power installed in the store from 67.6 kW to 47.3 kW.

The second EDM system can be realized with some combination of luminaires that do not direct any light upwards, and modest reductions in lighting levels. For instance, with Super T8s and ballast factors of 0.88, a basic luminaire (with 17% of the light directed upward) results in an LPD of 1.19 W/ft^2 (12.8 W/m^2) at 49 fc (527 lux), and 0.72 W/ft^2 (7.8 W/m^2) at 30 fc (323 lux). On the other hand, a more directed luminaire requires just 1.06 W/ft^2 (11.4 W/m^2) to achieve 49 fc (527 lux), and 0.64 W/ft^2 (6.9 W/m^2) for 29 fc (312 lux). We model the 47% reduction (0.90 W/ ft^2) as costing an additional \$225/kW of lighting power reduction over the first EDM. Thus, the total incremental cost of EDM 2 over baseline is \$4,249.

The first EDM maintenance costs are the same as the baseline case: \$5,222/yr. The second EDM includes an increase in the cost of changing out a lamp, but a decrease in the number of lamps and in the frequency of lamp change-outs (from 5 years in the baseline and first EDM scenarios to 5.5 years) resulting in maintenance costs of \$3,156/yr.

Each LPD EDM includes a 1% LPD reduction based on the inclusion of occupancy sensors in all of the back-of-store zones (storage, restrooms, office, etc.). The whole-building LPD reduction of 1% is calculated by assuming that the sensors achieve 10% savings in the areas where they are installed. Because those areas comprise just 17% (7,651 ft^2 [711 m^2]) of the building and have lower LPDs than the sales floor, one arrives at a conservative whole-building LPD reduction of approximately 1%.

The cost of one occupancy sensor is \$150, including materials and labor (Greene 2008). The cost of a power pack, which powers the occupancy sensors and activates the lighting control relay, is \$63.50. Two sensors and one power pack are required for every 1000 ft^2 (93 m^2) (Roth et al. 2005), such that the approximate cost of this EDM is \$0.36/ft^2 (\$3.88/m^2).

In Opt-E-Plus, the lighting costs are expressed in dollars per installed kilowatt. Each EDM results in fewer installed kilowatts, so the baseline and marginal costs are summed on a whole building basis, then divided by the actual installed kilowatts to arrive at the EDM cost. The resulting EDM LPDs and costs are shown in Table 3-32 (see Table C-15 for metric units).

Table 3-32 Lighting Power Density EDMs

EDM Key	LPD (W/ft^2)	Capital Cost (\$/kW)	Capital Cost (\$/ft^2)	Fixed O&M Cost (\$/kW·yr)	Fixed O&M Cost (\$/ft^2·yr)
Baseline	1.50	\$6,996	\$10.51	\$77.24	\$0.12
30% LPD reduction	1.05	\$10,234	\$10.76	\$110.34	\$0.12
47% LPD reduction	0.80	\$13,653	\$10.87	\$88.07	\$0.07

3.4.3.3 HVAC Systems and Components

3.4.3.3.1 Direct Expansion Coil Efficiency

Possible DX coil efficiency improvements are developed from publically available industry spec sheets for 10-ton unitary DX units with constant volume supply fans over an EER range of 10.1 to 12.3. These data suggest that the COP of the 10-ton RTUs, which includes compressor and condenser, but not supply fan, power, can be improved as much as 20% over the baseline of 3.69. Thus, we have two EDMs that improve DX coil efficiency: a 10% increase in COP that increases capital cost by \$61.43/ton cooling (\$17.47/kW); and a 20% increase in COP that increases capital cost by $123.94/ton cooling ($35.25/kW). The incremental cost for these improvements is taken as the cost to upgrade from the baseline model to each of the two higher efficiency units mentioned in Section 3.3.4.2.6: from 9.0 to 10.4 EER and from 9.0 to 11.0 EER, respectively (RMH Group 2006).

3.4.3.3.2 Higher Efficiency Fans

The baseline HVAC unit has an EER of 10.1, a COP of 3.69, and a total static pressure drop of 1.53 in. w.c. (381 Pa) (without an economizer). We use those specifications to calculate a baseline fan efficiency of 30.6%. We set our EDM fan efficiency to 63%, which, according to industry data, is near the upper bound for RTU fan efficiency. The cost of the EDM for increased fan efficiency is assumed to be 10% of the baseline HVAC system capital cost, that is, an additional $160.38/ton cooling ($45.61/kW). This cost premium is roughly based on the incremental cost of upgrading from a constant volume supply fan to a VAV supply fan (Mossman 2005).

3.4.3.3.3 Economizers

In this analysis, economizers can be combined with any available HVAC system. They are controlled with a mix of dry bulb temperature (OA of 36º–66ºF [2º–19ºC]), and enthalpy limits (OA less than 14 Btu/lb [32,000 J/kg]). An economizer increases system cost by $100.20/ton cooling ($28.48/kW), adds 0.09 in. w.c. (22.4 Pa) of static pressure, and replaces gravity dampers with motorized dampers.

The DX coil efficiency, fan efficiency, and economizer EDMs are implemented together as HVAC system EDMs. A summary of the available systems is presented in Table 3-33 (see Table C-16 for metric units).

3.4.3.4 Outside Air

This report considers two options beyond code-minimum for reducing OA loads: carbon dioxide (CO_2) DCV, and energy recovery from exhaust air.

3.4.3.4.1 Demand Controlled Ventilation

The CO_2 DCV EDM is modeled by matching the outdoor air schedules (by person and by area) to the occupancy schedules using the Ventilation:Mechanical object in EnergyPlus. A motorized OA damper is applied with DCV to prevent unwanted OA from entering. The cost of installing DCV is equal to the cost of installing one CO_2 sensor per RTU, since the RTUs should be able to implement DCV without major modification. The cost of one sensor is $185.50, such that DCV has a capital cost of $18.55/ton cooling ($5.28/kW) (Greene 2008).

3.4.3.4.2 Energy Recovery Ventilators

ERVs with sensible effectiveness of 60% or 80% and latent effectiveness 10 percentage points lower are available as EDMs. For each ERV unit, Table 3-34 (see Table C-17 for metric units) lists the associated pressure drop and implementation cost, which vary with effectiveness.

Table 3-33 HVAC System EDMs

EDM Key	Cooling COP (Ratio)	Heating Efficiency (%)	Economizer	Motorized Damper	Fan Efficiency (%)	Fan Static Pressure (in. w.c.)	Capital Cost ($/ton)	Fixed O&M Cost ($/ton·yr)
Baseline without economizer	3.69	80.0	No	No	30.6	1.53	$1,603.75	$140.18
10% increased COP	4.06	80.0	No	No	30.6	1.53	$1,665.18	$140.18
Baseline with economizer	3.69	80.0	Yes	Yes	32.4	1.62	$1,703.89	$140.18
20% increased COP	4.43	80.0	No	No	30.6	1.53	$1,727.69	$140.18
Baseline COP with efficient fan	3.69	80.0	No	No	63.0	1.53	$1,747.31	$140.18
10% increased COP with economizer	4.06	80.0	Yes	Yes	32.4	1.62	$1,765.31	$140.18
10% increased COP with efficient fan	4.06	80.0	No	No	63.0	1.53	$1,808.74	$140.18
20% increased COP with economizer	4.43	80.0	Yes	Yes	32.4	1.62	$1,827.83	$140.18
Baseline COP with economizer and efficient fan	3.69	80.0	Yes	Yes	64.8	1.62	$1,847.48	$140.18
20% increased COP with efficient fan	4.43	80.0	No	No	63.0	1.53	$1,871.25	$140.18
10% increased COP with economizer and efficient fan	4.06	80.0	Yes	Yes	64.8	1.62	$1,908.91	$140.18
20% increased COP with economizer and efficient fan	4.43	80.0	Yes	Yes	64.8	1.62	$1,973.46	$140.18

Table 3-34 Energy Recovery EDMs

EDM Key	Sensible Effectiveness (%)	Latent Effectiveness (%)	Pressure Drop (in. w.c.)	Capital Cost ($/unit)	Capital Cost ($)
Low effectiveness	60.0	50.0	0.42	$7,927	$15,854
High effectiveness	80.0	70.0	0.60	$11,465	$22,930

In general, more effective ERVs have higher pressure drops. The pressure drops listed in Table 3-34 (see Table C-17 for metric units) are based on internal data, which predict the pressure drop through one side of the high effectiveness energy recovery wheel at 1 in. w.c (249 Pa). Based on the fact that air passes through the wheel twice (once when it enters the store as unconditioned OA and once when it leaves the store as conditioned return air), and on the assumption of roughly 30% OA, an overall pressure drop of 0.6 in. w.c. (150 Pa) is applied to the implementation of high effectiveness ERV. The pressure drop for the low effectiveness ERV unit (0.42 in. w.c. [105 Pa]) is scaled according to our internal ERV data.

The modeling of ERV in EnergyPlus assumes that the exhaust air stream, which powers the ERVs, is equal in magnitude to the OA intake. For this assumption to be valid, the building must be airtight and all the exhaust air must be usable. Neither is generally the case for a grocery store, so we performed an air flow balance calculation to determine the fraction of OA that would be available for energy recovery. The air flow balance can be defined as follows.

$$F_{ERV} = \frac{OA - DEA - EA}{OA} \tag{3-3}$$

where,

F_{ERV} = the fraction of OA available for energy recovery

DEA = the amount of dedicated exhaust air from which energy cannot be recovered

EA = the amount of air that leaves the building through exfiltration, which is driven by HVAC and wind pressurization.

Infiltrated air is intentionally omitted from this equation because unconditioned air cannot be used for energy recovery. All air quantities are measured in units of flow (cfm or m^3/s).

For a grocery store, DEA comprises restroom and kitchen exhaust. Per Table 3-22, restroom DEA was given a value of 1.04 cfm/ft^2 (0.005 (m^3/s)/m^2), which amounts to a total flow rate of approximately 700 cfm (0.33 m^3/s). Kitchen DEA was estimated using the *ASHRAE 2003 HVAC Applications Handbook* (ASHRAE 2003)and validated by industry feedback. A detailed breakdown of DEA by space type is presented in Table 3-35 (see Table C-18 for metric units).

Table 3-35 Dedicated Exhaust by Space Type

Space Type	Equipment	ASHRAE Classification	Quantity	ASHRAE Prescription	DEA (cfm)
Restroom	Toilet	Toilet	675 ft^2	1.04 cfm/ft^2	700
Bakery	Rack Oven	Oven: Light Duty	7.0 ft.	200 cfm/ft	1400
Deli	Revolving Oven	Oven: Light Duty	2.7 ft	200 cfm/ft	540
Deli	Fryer	Fryer: Medium Duty	4.5 ft.	300 cfm/ft	1350
Total					3990

EA is calculated according to the pressurization analysis described in Section 3.3.3.5. From the exfiltration pressure gradients in Table 3-19, we estimated a peak exfiltration rate of 0.212 ACH (3,174 cfm [1.5 m^3/s]) during operating hours, when the HVAC system is on (ERV units operate only when the HVAC system is on). ASHRAE 62-1999 requires 12,930 cfm (6.1 m^3/s) of OA intake, such that F_{ERV} for the baseline grocery store is 0.45. With the application of infiltration reduction EDMs (addition of envelope air barrier and vestibule), F_{ERV} increases to 0.50. The appropriate value for F_{ERV} is achieved by adding (in EnergyPlus) idealized, energy free exhaust fans to each zone to exhaust the fraction of OA not available for ERV ($1-F_{ERV}$).

The cost of implementing the least effective ERV unit is adapted from the cost of 4,000 cfm (1.9 m^3/s) ERVs given by (Greene 2008). Our assumption is that two units could serve the entire building (up to 6,465 cfm [3.1 m^3/s]) of air is available for energy recovery).

3.4.3.5 Refrigeration Equipment

This TSD includes EDMs for the refrigerated cases and the refrigeration condensers. We emphasize the refrigerated cases, because the primary criterion for their selection is typically not energy efficiency. There is one EDM for the compressor rack/condenser systems: evaporatively cooled condensers.

3.4.3.5.1 Refrigerated Cases

Several EDMs are available for each refrigerated case type. Most are not single changes, but are combinations of one or more of the following recommendations:

- High-efficiency fans
- Reduced lighting power
- Anti-sweat heater controls
- High-efficiency anti-sweat heaters
- Alternative defrost systems. The medium-temperature cases use time-off defrost or electric defrost with temperature termination. The low-temperature cases use electric defrost with temperature termination or hot gas defrost with temperature termination.
- Adding night covers or doors, or switching to a vertical case with doors.

The performance and cost data for each baseline and EDM case are presented in Table 3-36 through Table 3-39 (see Table C-19 through Table C-22 for metric units). The relative costs of the EDM cases compared to the baseline cases are determined using data from Waier (2005), Westphalen et al. (1996), and industry quotes. Most of the table entries are described in Section 3.3.4.3.1. We now describe the new entries and EDM-specific details.

In the brief descriptions of the EDMs found in the table headings, high-efficiency fans are listed as Eff. Fans, anti-sweat heater controls are listed as A-S Controls, and groups of measures are identified and referred to using the notations #1, #2, and #3. The rated capacities reflect the impact of reduced fan, lighting, and anti-sweat heater power, but do not reflect schedule or control changes. Values that differ from the baseline are highlighted in green.

Anti-sweat heater controls are modeled using the EnergyPlus "dewpoint method", which assumes that the actual anti-sweat heater power is equal to the power at rated conditions multiplied by the ratio

$$\frac{T_{dp,store} - T_{case}}{T_{dp,rated} - T_{case}},$$

where $T_{dp,store}$ is the dew point of the store, $T_{dp,rated}$ is the dew point at rated conditions, and T_{case} is the operating temperature of the refrigerated case. The cost is modeled assuming one sensor for every 30-36 ft (9-11 m) of cases.

In EnergyPlus, case credits refer to the sensible and latent heat that is transferred from the thermal zone to the refrigerated case. The credits are adjusted for temperature and humidity using polynomial curve fits. Case credit schedules allow further modulation via the specification of what proportion of the standard credits should be applied at a given time. The schedules are typically used to model doors and other types of devices that reduce a refrigerated case's infiltration load. Because the rated capacities of the models with doors already include the effects of door openings, the baseline cases and most of the EDM cases have a case credit schedule that is always equal to 1.0. However, the single-deck meat case EDMs with night covers and doors are modeled with case credit schedules.

The nighttime loads of the single-deck meat cases with night covers and doors are set to the minimum possible value, which is obtained by subtracting the fraction of the sensible and latent loads caused by infiltration from 1.0. The infiltration load is equal to the infiltration ratio times the rated capacity; the total sensible and latent loads are equal to the rated capacity minus all the electrical equipment loads. The night cover EDM models the placement of insulated panels over the refrigerated case openings. Thus, the daytime case credits are set to 1.0 and the schedule is set to the average of the daytime and nighttime values during the employee-only transition hours. The sliding door EDM has a daytime case credit schedule based on the assumption that the doors are open for 10 seconds 6 times per hour.

For cases with light-emitting diodes (LEDs), the maximum lighting power is listed in the tables, but the implemented power is equal to half this value to model the effects of occupancy sensors.

It is difficult to find accurate data on the energy delivered to refrigerated cases by hot gas defrost. Based on the EnergyPlus documentation, we assume that the total energy delivered during the hot gas defrost cycle is equal to that delivered by an electric defrost cycle. Because hot gas defrost cycles are typically shorter than the corresponding electric defrost cycles, the listed defrost powers are higher in the former case. Hot gas defrost is achieved by rerouting hot gases coming off of the compressors, so there is no extra energy penalty, as there is with electric defrost, for generating the heat used to defrost the coils.

The total length of each case category stays constant when the EDMs are applied, except when the single-deck ice cream cases are replaced with efficient vertical door models. In this situation, based on the useful volumes of the two types of cases, we assume that only 0.659 ft (0.2 m) of efficient vertical cases are required for every 1 ft (0.35 m) of baseline single-deck cases.

Table 3-36 Island Single-Deck Meat Case EDMs

Characteristic	Baseline	Electric Defrost	#1: Eff. Fans and A-S Controls	#1 with Electric Defrost	#2: #1 and Covered at Night	#2 with Electric Defrost	#3: #1 and Sliding Doors	#3 with Electric Defrost
Rated Capacity (Btu/h·ft)	770	770	756	756	756	756	756	756
Operating Temperature (°F)	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5
Latent Heat Ratio	0.361	0.361	0.367	0.367	0.367	0.367	0.367	0.367
Infiltration Ratio	0.686	0.686	0.698	0.698	0.698	0.698	0.698	0.698
Fan Power (Btu/h·ft)	38.7	38.7	25.0	25.0	25.0	25.0	25.0	25.0
Lighting Power (Btu/h·ft)	0	0	0	0	0	0	0	0
Anti-Sweat Heater Power (Btu/h·ft)	37.0	37.0	37.0	37.0	37.0	37.0	79.7	79.7
Anti-Sweat Heater Control Method	None	None	Dewpoint Method	Dewpoint Method	Dewpoint Method	Dewpoint Method	Dewpoint Method	Dewpoint Method
Defrost Type	Time-off	Electric w/ Temp. Term.	Time-off	Electric w/ Temp. Term.	Time-off	Electric w/ Temp. Term.	Time-off	Electric w/ Temp. Term.
Defrost Power (Btu/h·ft)	0	427	0	427	0	427	0	427
Maximum Defrost Time (min)	45	40	45	40	45	40	45	40
Drip-Down Time (min)	8	8	8	8	8	8	8	8
Defrost Start Time(s)	6:00 a.m. 2:00 p.m. 10:00 p.m.	6:00 a.m. 2:00 p.m. 10:00 p.m.	6:00 a.m. 2:00 p.m. 10:00 p.m.	6:00 a.m. 2:00 p.m. 10:00 p.m.	6:00 a.m. 2:00 p.m. 10:00 p.m.	6:00 a.m. 2:00 p.m. 10:00 p.m.	6:00 a.m. 2:00 p.m. 10:00 p.m.	6:00 a.m. 2:00 p.m. 10:00 p.m.
Restocking Load (Btu/h·ft) and Schedule	65 from 1:00 p.m. to 4:00 p.m.	65 from 1:00 p.m. to 4:00 p.m.	65 from 1:00 p.m. to 4:00 p.m.	65 from 1:00 p.m. to 4:00 p.m.	65 from 1:00 p.m. to 4:00 p.m.	65 from 1:00 p.m. to 4:00 p.m.	65 from 1:00 p.m. to 4:00 p.m.	65 from 1:00 p.m. to 4:00 p.m.
Case Credit Schedule	All Days, 1.0	All Days, 1.0	All Days, 1.0	All Days, 1.0	Night, 0.24; Open Hrs, 1.0	Night, 0.24; Open Hrs, 1.0	Night, 0.19; Open Hrs, 0.20	Night, 0.19; Open Hrs, 0.20
Capital Cost ($/ft)	$753.28	$758.14	$794.64	$800.85	$813.25	$818.10	$910.36	$915.21
Maintenance Cost ($/ft·yr)	$0.00	$0.00	$0.00	$0.00	$18.50	$18.50	$0.00	$0.00

Table 3-37 Multi-Deck Dairy/Deli Case EDMs

Characteristic	Baseline	Baseline with Electric Defrost	#1: Eff. Fans and Standard Lighting	#1 with Electric Defrost	Replace w/ Eff. Vertical Door Model
Rated Capacity (Btu/h·ft)	1500	1500	1285	1285	272
Operating Temperature (°F)	41.0	41.0	41.0	41.0	2.8
Latent Heat Ratio	0.241	0.241	0.281	0.281	0.100
Infiltration Ratio	0.579	0.579	0.676	0.676	0.250
Fan Power (Btu/h·ft)	42.6	42.6	19.9	19.9	12.6
Lighting Power (Btu/h·ft)	215	215	23.9	23.9	62.1
Anti-Sweat Heater Power (Btu/h·ft)	0	0	0	0	79.7
Anti-Sweat Heater Control Method	None	None	None	None	Dewpoint Method
Defrost Type	Time-off	Electric w/ Temp. Term.	Time-off	Electric w/ Temp. Term.	Electric w/ Temp. Term.
Defrost Power (Btu/h·ft)	0	341	0	341	445
Maximum Defrost Time (min)	42	32	42	32	30
Drip-Down Time (min)	8	8	8	8	20
Defrost Start Time(s)	1:00 a.m., 7:00 a.m., 1:00 p.m., 7:00 p.m.	1:00 a.m., 7:00 a.m., 1:00 p.m., 7:00 p.m.	1:00 a.m., 7:00 a.m., 1:00 p.m., 7:00 p.m.	1:00 a.m., 7:00 a.m., 1:00 p.m., 7:00 p.m.	1:00 a.m.
Restocking Load (Btu/h·ft) and Schedule	325 from 9:00 a.m. to 12:00 p.m.	325 from 9:00 a.m. to 12:00 p.m.	325 from 9:00 a.m. to 12:00 p.m.	325 from 9:00 a.m. to 12:00 p.m.	312.5 from 9:00 a.m. to 12:00 p.m.
Capital Cost ($/ft)	$583.02	$595.27	$498.43	$510.69	$749.55

Table 3-38 Vertical Frozen Food with Doors Case EDMs

Characteristic	Baseline	Baseline with Hot Gas Defrost	#1: Eff. Fans and A-S Controls	#1 with Hot Gas Defrost	#2: #1, Eff. A-S Heaters and LEDs	#2 with Hot Gas Defrost
Rated Capacity (Btu/h·ft)	538	538	510	510	317	317
Operating Temperature (°F)	–1.5	–1.5	–1.5	–1.5	–1.5	–1.5
Latent Heat Ratio	0.061	0.061	0.064	0.064	0.103	0.103
Infiltration Ratio	0.152	0.152	0.160	0.160	0.257	0.257
Fan Power (Btu/h·ft)	40.9	40.9	12.6	12.6	12.6	12.6
Lighting Power (Btu/h·ft)	92.8	92.8	92.8	92.8	62.1	62.1
Anti-Sweat Heater Power (Btu/h·ft)	259	259	259	259	97	97
Anti-Sweat Heater Control Method	None	None	Dewpoint Method	Dewpoint Method	Dewpoint Method	Dewpoint Method
Defrost Type	Electric w/ Temp. Term.	Hot Gas w/ Temp. Term.	Electric w/ Temp. Term.	Hot Gas w/ Temp. Term.	Electric w/ Temp. Term.	Hot Gas w/ Temp. Term.
Defrost Power (Btu/h·ft)	1311	2491	1311	2491	1311	2491
Maximum Defrost Time (min)	46	24	46	24	46	24
Drip-Down Time (min)	15	15	15	15	15	15
Defrost Start Time(s)	10:00 p.m.	10:00 p.m.	10:00 p.m.	10:00 p.m.	10:00 p.m.	10:00 p.m.
Restocking Load (Btu/h·ft) and Schedule	16.0 from 6:00 p.m. to 9:00 p.m.	15.4 from 6:00 p.m. to 9:00 p.m.	16.0 from 6:00 p.m. to 9:00 p.m.	15.4 from 6:00 p.m. to 9:00 p.m.	16.0 from 6:00 p.m. to 9:00 p.m.	15.4 from 6:00 p.m. to 9:00 p.m.
Capital Cost ($/ft)	$647.71	$656.61	$682.85	$691.76	$803.22	$812.48

Table 3-39 Island Single-Deck Ice Cream Case EDMs

Characteristic	Baseline	Baseline with Hot Gas Defrost	#1: Eff. Fans, A-S Control and No Lighting	#1 with Hot Gas Defrost	Replace with Eff. Vert. Model, Elec. Def.	Replace with Eff. Vert. Model, Hot Gas
Rated Capacity (Btu/h·ft)	740	740	474	474	341	341
Operating Temperature (°F)	–13.0	–13.0	–13.0	–13.0	–6.5	–6.5
Total Length (ft)	120	120	120	120	79	79
Latent Heat Ratio	0.147	0.147	0.230	0.230	0.111	0.111
Infiltration Ratio	0.412	0.412	0.643	0.643	0.280	0.280
Fan Power (Btu/h·ft)	29.0	29.0	18.7	18.7	12.6	12.6
Lighting Power (Btu/h·ft)	255	255	0	0	62.1	62.1
Anti-Sweat Heater Power (Btu/h·ft)	135	135	135	135	97.1	97.1
Anti-Sweat Heater Control Method	None	None	Dewpoint Method	Dewpoint Method	Dewpoint Method	Dewpoint Method
Defrost Type	Electric w/ Temp. Term.	Hot Gas w/ Temp. Term.	Electric w/ Temp. Term.	Hot Gas w/ Temp. Term.	Electric w/ Temp. Term.	Hot Gas w/ Temp. Term.
Defrost Power (Btu/h·ft)	1032	3079	1032	3079	1310	2491
Maximum Defrost Time (min)	60	20	60	20	46	24
Drip-Down Time (min)	15	15	15	15	15	15
Defrost Start Time(s)	10:00 p.m.	10:00 p.m.	10:00 p.m.	10:00 p.m.	10:00 p.m.	10:00 p.m.
Restocking Load (Btu/h·ft) and Schedule	27.4 from 7:00 a.m. to 10:00 a.m.	27.4 from 7:00 a.m. to 10:00 a.m.	27.4 from 7:00 a.m. to 10:00 a.m.	27.4 from 7:00 a.m. to 10:00 a.m.	27.4 from 7:00 a.m. to 10:00 a.m.	27.4 from 7:00 a.m. to 10:00 a.m.
Capital Cost ($/ft)	$773.94	$776.42	$681.33	$683.46	$803.22	$812.48

3.4.3.5.2 Compressor Racks and Condensers

Commercial refrigeration compressor racks and condensers are designed for energy efficiency. We therefore limit our efforts in this area to replacing air-cooled condensers with evaporatively cooled condensers. Other possible measures are discussed in Section 5.0.

Evaporative condensers apply water to the air-cooled heat exchanger coils to lower the outside coil temperature, and thus improve efficiency. We assume that the outside coil temperature is equal to the wet bulb temperature of the air, and that evaporative cooling is available at all times in all climates.

Installing evaporative instead of basic air-cooled condensers costs $9,741 less on a whole-store basis, but requires $4,941/yr more in maintenance costs (Westphalen et al. 1996). Split evenly across the four racks, we obtain a per-rack capital cost of $116,445 and a maintenance cost of

$12,849/yr. For reference, the baseline per-rack capital cost is $118,881, and the baseline maintenance cost is $11,613/yr.

3.4.3.6 Photovoltaic Panels

Ignoring any electricity tariff changes associated with varying amounts of PV, 5-TLCC and the amount of electricity generated by the PV panels vary linearly with panel area. We thus include a single PV EDM, and then use a post-processing step to determine the PV panel area needed to reach 50% energy savings.

We assume the following for all cases:

- The panels are 10% efficient.
- The DC to AC inverters are 90% efficient.
- The panels are installed flat on the roof.
- The PV efficiency does not degrade with increasing temperature.
- The panels do not shade the roof.
- The cost is $6.65 for materials and $1.16 for installation per installed Watt based on the price of a 10-kW, grid-connected system (Greene 2008) minus the 30% Federal Tax Credit that is available through 2016 (DSIRE 2009).
- The EDM used by Opt-E-Plus covers 60% of the net roof area (total area minus skylight area) with PV panels and is sized assuming 1000 W/m^2 incident solar radiation.

4.0 Results

This section describes simulation results for a number of building models. Section **4.1** describes the baseline models, both the ASHRAE 90.1-2004 (ASHRAE 2004a) baselines that serve as the standard for our percent energy savings calculations, and ASHRAE 90.1-2007 (ASHRAE 2007b) baselines that are provided for reference purposes (for individuals wishing to compare the two and to see what 50% energy savings versus 90.1-2004 means when it is replaced by 90.1-2007). Section **4.2** describes the selected low-energy models for each climate zone, and compares their energy and economic performance to the baseline. The low-energy models are described by enumerating which EDM perturbations were applied to the baseline model to arrive at the low-energy model. Finally, Section **4.3** briefly describes some alternative low-energy models for selected climate zones. These models are not described in full, but we report whether we were able to achieve the 50% energy savings goal without certain strategies.

In this section, we use the following metrics to report performance:

- **Net site EUI.** This is reported in $MJ/m^2 \cdot yr$ or $kBtu/ft^2 \cdot yr$. It is the whole-building net site yearly energy use (Section 2.2.1) divided by the building floor area.
- **5-TLCC intensity.** This is reported in $\$/m^2$ or $\$/ft^2$. It is the 5-TLCC divided by the building floor area. It represents the total cost of the building for a five-year analysis period (see Section 3.1.2.6).
- **Electricity intensity.** This is reported in $kWh/m^2 \cdot yr$ or $kWh/ft^2 \cdot yr$ and is the yearly electricity consumption divided by the building floor area.
- **Natural gas intensity.** This is reported in $kWh/m^2 \cdot yr$ or $Therms/ft^2 \cdot yr$ and is the yearly natural gas consumption divided by the building floor area.
- **PV power intensity.** This is reported in $kWh/m^2 \cdot yr$ or $kWh/ft^2 \cdot yr$ and is the yearly electricity production of the PV panels divided by the building floor area.
- **Capital cost.** This is reported in $\$/m^2$ or $\$/ft^2$ and is the total cost for materials, installation, fees, and commissioning divided by the building floor area.
- **Min/max monthly electricity demand.** This is reported in kW and is the net electricity demand, taking credit for electricity produced by PV, computed for each month of the annual simulation.
- **Min/max monthly load factor.** This is the average net monthly electricity demand (net kWh divided by the number of hours in the month) divided by the overall net monthly electricity demand.

4.1 Baseline Models

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

4.1.1 ASHRAE 90.1-2004 Baseline Models: Performance

The energy and cost intensities of the ASHRAE 90.1-2004 baseline models are shown in Table 4-1 to Table 4-3. The EUIs vary substantially across the climate zones, such that the difficulty in achieving 50% energy savings and the amount of energy saved in doing so vary by climate zone. Costs vary in response to climate-specific constructions, equipment, and thermal loads.

Table 4-1 ASHRAE 90.1-2004 Baseline Model Performance: Humid Climates

Units	Metric	Humid					
		1A	2A	3A	4A	5A	6A
SI	EUI (MJ/m²·yr)	2,780	2,930	2,620	2,800	2,920	3,100
	5-TLCC Intensity ($/m²)	1,630	1,660	1,570	1,580	1,580	1,590
	Electricity Intensity (kWh/m²yr)	695	685	532	514	499	496
	Natural Gas Intensity (kWh/m²yr)	79.0	130	195	264	312	364
	Capital Cost ($/m²)	1,260	1,280	1,240	1,250	1,250	1,250
IP	EUI (kBtu/ft²yr)	245	258	231	246	257	273
	5-TLCC Intensity ($/ft²)	152	154	146	146	147	148
	Electricity Intensity (kWh/ft²yr)	64.5	63.6	49.5	47.8	46.4	46.1
	Natural Gas Intensity (Therms/ft²yr)	0.250	0.413	0.619	0.835	0.989	1.15
	Capital Cost ($/ft²)	117	119	116	116	116	116
N/A	Max. Elec. Demand (kW)	562	622	467	479	477	467
	Min. Load Factor	0.589	0.506	0.608	0.560	0.565	0.520

Table 4-2 ASHRAE 90.1-2004 Baseline Model Performance: Arid Climates

Units	Metric	Arid					
		2B	3B-CA	3B-NV	4B	5B	6B
SI	EUI (MJ/m²·yr)	2,350	2,360	2,370	2,530	2,690	2,920
	5-TLCC Intensity ($/m²)	1,540	1,530	1,540	1,550	1,560	1,570
	Electricity Intensity (kWh/m²yr)	538	494	506	486	480	474
	Natural Gas Intensity (kWh/m²yr)	116	163	154	216	267	337
	Capital Cost ($/m²)	1,230	1,230	1,240	1,240	1,240	1,240
IP	EUI (kBtu/ft²yr)	207	208	209	223	237	257
	5-TLCC Intensity ($/ft²)	143	142	143	144	145	146
	Electricity Intensity (kWh/ft²yr)	50.0	45.9	47.0	45.2	44.6	44.0
	Natural Gas Intensity (Therms/ft²yr)	0.368	0.517	0.488	0.684	0.845	1.07
	Capital Cost ($/ft²)	114	114	115	115	115	116
N/A	Max. Elec. Demand (kW)	437	398	420	389	393	385
	Min. Load Factor	0.643	0.618	0.641	0.632	0.616	0.619

Table 4-3 ASHRAE 90.1-2004 Baseline Model Performance: Marine and Cold Climates

Units	Metric	Marine		Cold	
		3C	4C	7	8
SI	EUI ($MJ/m^2 \cdot yr$)	2,500	2,680	3,280	3,820
	5-TLCC Intensity ($\$/m^2$)	1,530	1,550	1,600	1,680
	Electricity Intensity (kWh/m^2yr)	464	462	474	467
	Natural Gas Intensity (kWh/m^2yr)	230	284	437	595
	Capital Cost ($\$/m^2$)	1,230	1,240	1,260	1,300
IP	EUI ($kBtu/ft^2yr$)	220	236	289	337
	5-TLCC Intensity ($\$/ft^2$)	142	144	149	156
	Electricity Intensity (kWh/ft^2yr)	43.1	42.9	44.0	43.4
	Natural Gas Intensity ($Therms/ft^2yr$)	0.729	0.900	1.38	1.89
	Capital Cost ($\$/ft^2$)	114	115	117	121
N/A	Max. Elec. Demand (kW)	362	375	450	353
	Min. Load Factor	0.642	0.611	0.555	0.675

4.1.2 ASHRAE 90.1-2007 Baseline Models: Performance

For comparison, we also constructed baseline models that satisfy ASHRAE 90.1-2007 and ASHRAE 62.1-2004 (ASHRAE Standard 90.1-2007 explicitly references, and thereby includes, Standard 62.1-2004). The differences between the ASHRAE 90.1-2004 and ASHRAE 90.1-2007 baselines are the window, wall, and roof performance requirements, and the OA requirements. The OA requirements differ in structure and amount: starting in 2004, ASHRAE 62.1 started specifying OA requirements per area and per person in many space types. ASHRAE 62-1999 (the ventilation standard corresponding to ASHRAE 90.1-2004), on the other hand, specifies OA requirements as either per area or per person. For instance, in applying ASHRAE 62.1-2004 instead of ASHRAE 62-1999 for a grocery sales zone, the ventilation prescription changes from a flat per area requirement of 0.30 cfm/ft^2 (0.0015 $(m^3/s)/m^2$) to a combined per area and per person requirement of 0.12 cfm/ft^2 (0.0006 $(m^3/s)/m^2$) and 7.5 cfm/person (0.0038 (m^3/s)/person), where the number of people is taken as the peak occupancy of that zone.

For completeness, the 90.1-2007 baseline windows, walls, and roofs are summarized in Table 4-4 to Table 4-7. The OA requirements are summarized in Table 4-8. To compare to the 90.1-2004 values, please see Table 3-15 to Table 3-18, and Table 3-22.

Table 4-4 ASHRAE 90.1-2007 Baseline Exterior Wall Constructions

Properties	Climate Zone						
	1	2	3	4	5	6	7 and 8
Key	Baseline Wall Construction, No c.i.	Baseline Wall Construction, R-5.7 c.i.	Baseline Wall Construction, R-7.6 c.i.	Baseline Wall Construction, R-9.5 c.i.	Baseline Wall Construction, R-11.4 c.i.	Baseline Wall Construction, R-13.3 c.i.	Baseline Wall Construction, R-15.2 c.i.
U-Factor (Btu/h·ft^2·°F)	0.754	0.173	0.137	0.114	0.0975	0.0859	0.0756
Capital Cost ($/ft^2)	$20.37	$21.06	$21.42	$21.68	$21.80	$21.86	$21.97

Table 4-5 ASHRAE 90.1-2007 Baseline Roof Constructions

Properties	Climate Zone	
	1	2 through 8
Key	Baseline Roof Construction, R-15 c.i.	Baseline Roof Construction, R-20 c.i.
U-Factor (Btu/h·ft^2·°F)	0.0675	0.0506
Capital Cost ($/ft^2)	$8.69	$9.11

Table 4-6 ASHRAE 90.1-2007 Baseline Window Constructions

Properties	Climate Zone		
	1 through 3	4 through 6	7 and 8
Key	Baseline Window Construction	Baseline Window Construction	Baseline Window Construction
SHGC	0.390	0.400	0.450
VLT	0.495	0.508	0.450
U-Factor (Btu/h·ft^2·°F)	0.570	0.550	0.450
Capital Cost ($/ft^2)	$47.23	$47.57	$47.23
Fixed O&M Cost ($/ft^2)	$0.22	$0.22	$0.22

Table 4-7 ASHRAE 90.1-2007 Baseline Skylight Constructions

Property	Climate Zone				
	1 and 2	3	4 through 6	7	8
Key	Baseline Skylight Construction	Baseline Skylight Construction	Baseline Skylight Construction	Baseline Skylight Construction	Baseline Skylight Construction
SHGC	0.360	0.390	0.490	0.680	0.710
VLT	0.457	0.490	0.622	0.680	0.710
U-Factor (Btu/h·ft^2·°F)	1.22	0.690	0.690	0.690	0.580
Capital Cost ($/ft^2)	$46.28	$48.91	$47.24	$45.90	$50.46
Fixed O&M Cost ($/ft^2)	$0.22	$0.22	$0.22	$0.22	$0.22

Table 4-8 ASHRAE 90.1-2007 Baseline Minimum Ventilation Rates

Space Type	Mapping to ASHRAE 62.1-2004	Ventilation per Person		Ventilation per Area	
		cfm/person	L/s·person	cfm/ft^2	L/ s·m^2
Main Sales	Retail::Sales	7.5	3.8	0.12	0.60
Perimeter Sales	Retail::Sales	7.5	3.8	0.12	0.60
Produce	Retail::Sales	7.5	3.8	0.12	0.60
Deli	CUSTOM VALUE*	–	–	0.34	1.70
Bakery	CUSTOM VALUE*	–	–	0.34	1.70
Enclosed Office	Office Buildings::Office space	5.0	2.5	0.06	0.30
Meeting Room	Offices::Conference/meeting	5.0	2.5	0.06	0.30
Dining Room	Food & Beverage::Restaurant dining rooms	7.5	3.8	0.18	0.90
Restrooms	CUSTOM VALUE	7.5	3.8	0.06	0.30
Mechanical Room	CUSTOM VALUE	–	–	0.00	0.00
Corridor	General::Corridors	–	–	0.06	0.30
Vestibule	General::Corridors	–	–	0.06	0.30
Active Storage	General::Storage rooms	–	–	0.12	0.60

*The ventilation rate for the kitchen zones (deli, bakery) is set to fill half of the exhaust requirement specified by ASHRAE 62.1-2004. It is assumed that the rest of the exhaust is pulled from other zones.

The performance of the ASHRAE 90.1-2007 baseline models is summarized in Table 4-9 to Table 4-11.

Table 4-9 ASHRAE 90.1-2007 Baseline Model Performance: Humid Climates

Units	Metric	Humid					
		1A	2A	3A	4A	5A	6A
SI	EUI (MJ/m^2·yr)	2,650	2,740	2,460	2,580	2,650	2,780
	5-TLCC Intensity (\$/m^2)	1,700	1,730	1,650	1,650	1,660	1,660
	Electricity Intensity (kWh/m^{2}yr)	666	652	520	504	490	488
	Natural Gas Intensity (kWh/m^{2}yr)	70.9	110	164	212	245	284
	Capital Cost (\$/m^2)	1,340	1,370	1,330	1,340	1,340	1,340
IP	EUI (kBtu/ft^{2}yr)	234	241	217	227	233	245
	5-TLCC Intensity (\$/ft^2)	158	161	153	153	154	155
	Electricity Intensity (kWh/ft^{2}yr)	61.9	60.6	48.3	46.8	45.5	45.3
	Natural Gas Intensity (Therms/ft^{2}yr)	0.225	0.348	0.520	0.672	0.778	0.900
	Capital Cost (\$/ft^2)	125	127	124	124	125	125
N/A	Max. Elec. Demand (kW)	541	594	450	468	456	451
	Min. Load Factor	0.598	0.525	0.627	0.585	0.569	0.537

Table 4-10 ASHRAE 90.1-2007 Baseline Model Performance: Arid Climates

Units	Metric	Arid					
		2B	3B-CA	3B-NV	4B	5B	6B
SI	EUI (MJ/m^2·yr)	2,260	2,290	2,280	2,380	2,490	2,650
	5-TLCC Intensity (\$/m^2)	1,620	1,620	1,620	1,630	1,640	1,640
	Electricity Intensity (kWh/m^{2}yr)	522	489	500	483	476	469
	Natural Gas Intensity (kWh/m^{2}yr)	105	147	134	178	216	266
	Capital Cost (\$/m^2)	1,320	1,320	1,330	1,330	1,330	1,340
IP	EUI (kBtu/ft^{2}yr)	199	201	201	209	219	233
	5-TLCC Intensity (\$/ft^2)	151	150	151	151	152	153
	Electricity Intensity (kWh/ft^{2}yr)	48.5	45.4	46.4	44.8	44.2	43.5
	Natural Gas Intensity (Therms/ft^{2}yr)	0.332	0.465	0.424	0.565	0.684	0.844
	Capital Cost (\$/ft^2)	123	123	123	124	124	124
N/A	Max. Elec. Demand (kW)	420	388	407	371	370	369
	Min. Load Factor	0.653	0.643	0.653	0.634	0.639	0.639

Table 4-11 ASHRAE 90.1-2007 Baseline Model Performance: Marine and Cold Climates

Units	Metric	Marine		Cold	
		3C	4C	7	8
SI	EUI ($MJ/m^2 \cdot yr$)	2,360	2,480	2,890	3,360
	5-TLCC Intensity ($\$/m^2$)	1,610	1,630	1,670	1,680
	Electricity Intensity ($kWh/m^2 yr$)	460	459	467	465
	Natural Gas Intensity ($kWh/m^2 yr$)	195	230	337	469
	Capital Cost ($\$/m^2$)	1,320	1,330	1,340	1,340
IP	EUI ($kBtu/ft^2 yr$)	208	218	255	296
	5-TLCC Intensity ($\$/ft^2$)	150	151	155	156
	Electricity Intensity ($kWh/ft^2 yr$)	42.7	42.6	43.4	43.2
	Natural Gas Intensity ($Therms/ft^2 yr$)	0.619	0.730	1.07	1.49
	Capital Cost ($\$/ft^2$)	123	123	125	124
N/A	Max. Elec. Demand (kW)	352	362	429	351
	Min. Load Factor	0.653	0.629	0.583	0.673

4.1.3 Comparison to CBECS

To compare the EUIs of the ASHRAE 90.1-2004 and ASHRAE 90.1-2007 baseline models to the *2003 CBECS* data, we use climate zone weighting factors from (Deru et al. 2008) to calculate average baseline EUIs, electricity intensities, and natural gas intensities for each numerical climate zone. The weightings are shown in Table 4-12; the resulting EUIs, electricity intensities, and natural gas intensities are depicted graphically in Figure 4-1 to Figure 4-3, where they are compared against the corresponding values from the *2003 CBECS* survey. Only supermarkets built since 1980, or built since 1970 and renovated since 1980, which were occupied for the full survey year are used: 28 CBECS buildings match that description. The climate zone for each is determined by following the procedure described in Griffith (Griffith et al.). No CBECS buildings are located in climate zones 1, 6, or 8. Climate zones 3 and 5 are best represented, with 9 and 12 CBECS buildings, respectively.

Table 4-12 Retail Building Climate Zone Weighting Factors

ASHRAE Climate Zone	Weighting Factor
1A	80.57
2A	570.62
2B	125.71
3A	648.97
3B-CA	607.32
3B-NV	97.03
3C	27.85
4A	1,137.03
4B	35.98
4C	129.68
5A	1,144.83
5B	288.69
6A	321.90
6B	4.94
7	45.22
8	2.93

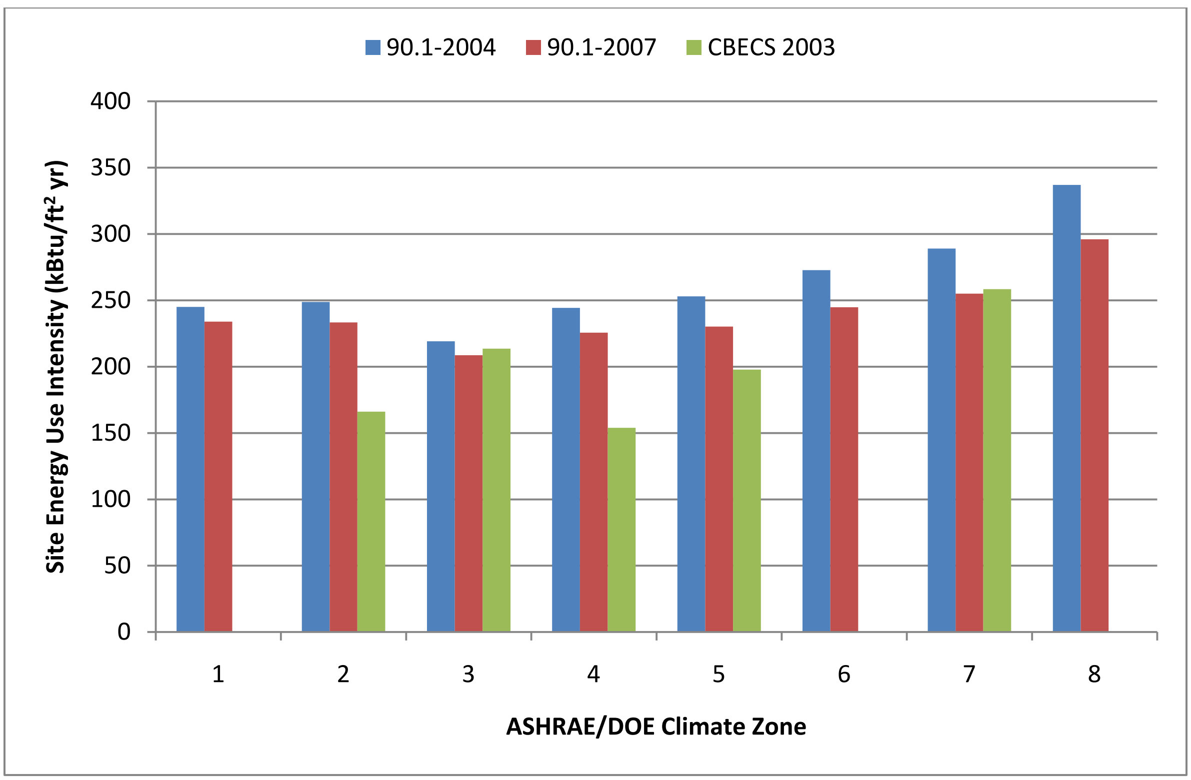

Figure 4-1 EUI comparison for baseline and CBECS survey buildings

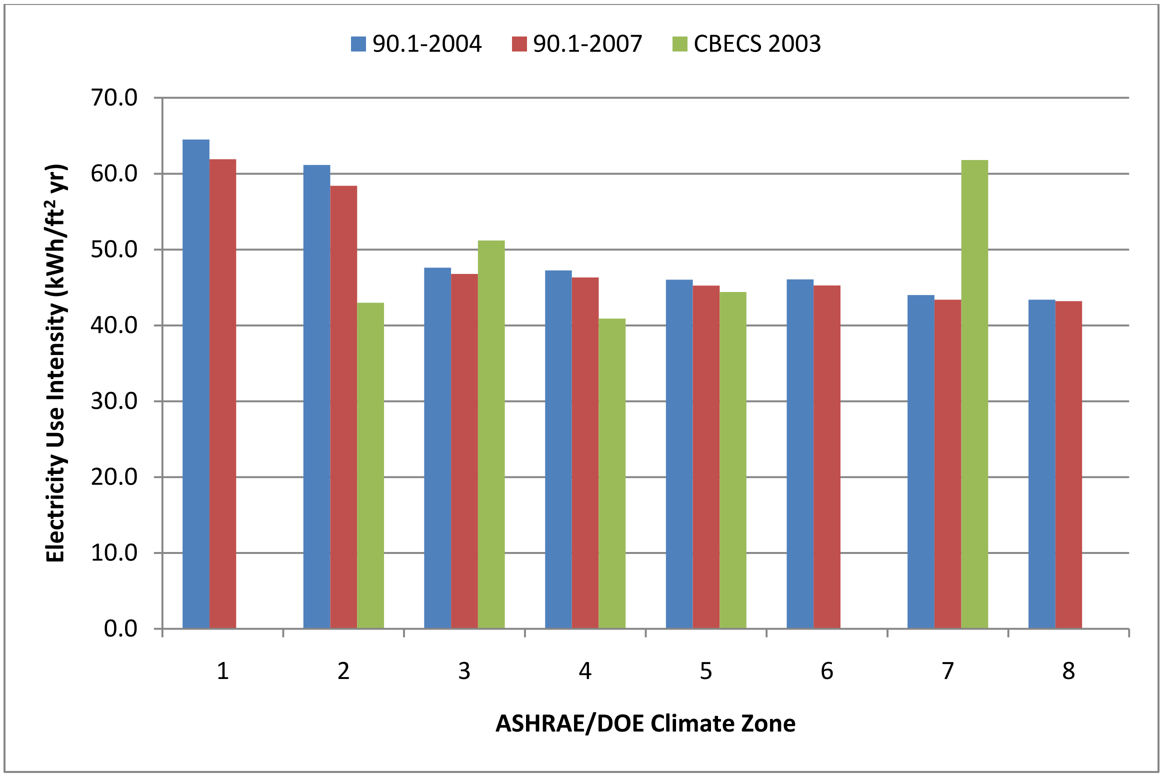

Figure 4-2 Electricity use intensity comparison for baseline and CBECS survey buildings

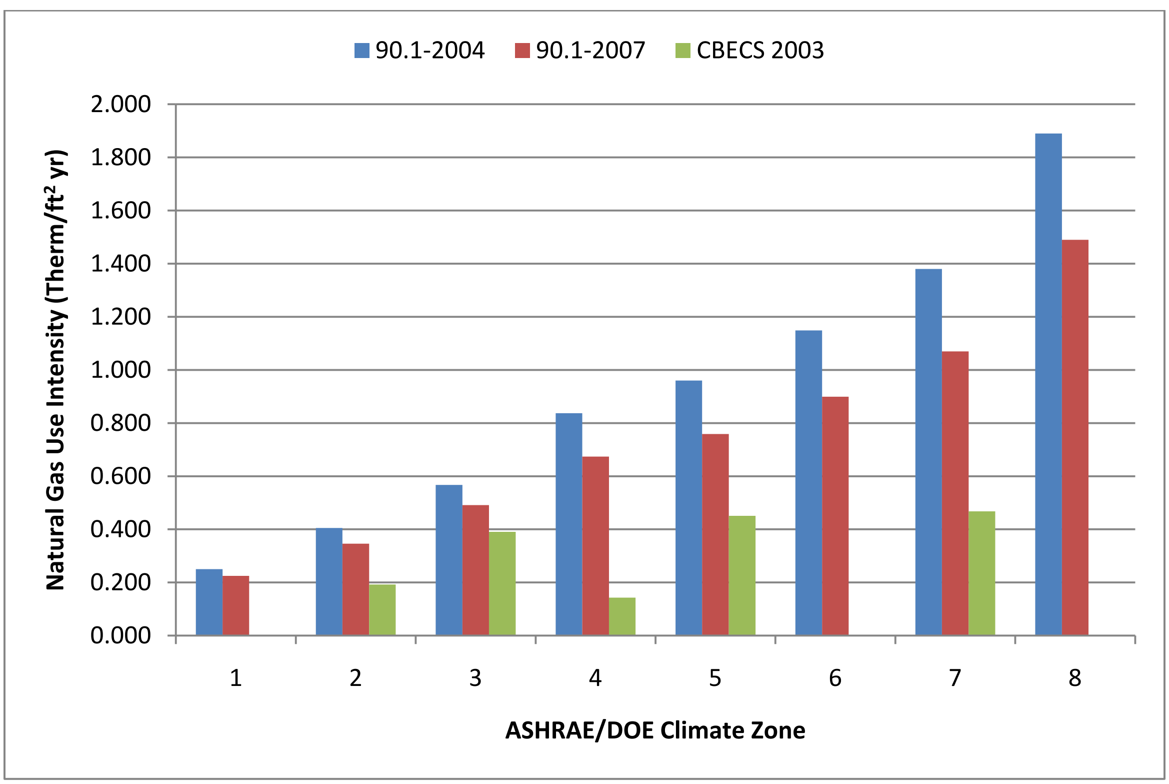

Figure 4-3 Natural gas intensity comparison for baseline and CBECS survey buildings

4.1.4 Discussion

There is reasonable agreement between our data and the *2003 CBECS* for annual EUI, but much less so for natural gas use intensity. Our baseline models use consistently more natural gas than was reported for the 28 CBECS buildings. Only 18 of the CBECS buildings report using natural gas as their primary heating source, so that alone may account for the natural gas discrepancy. Some other discrepancies also stand out (electricity use in climate zone 7, our buildings having a higher overall EUI than the CBECS buildings), but we chose not to pursue this line of investigation in depth, in part because of the nature of the CBECS data (small sample sizes of unverifiable survey data).

The ASHRAE 90.1-2007 baseline models use less energy than the ASHRAE 90.1-2004 baseline models, with much of the savings coming from reduced natural gas consumption. This result is to be expected since the improvements of ASHRAE 90.1-2007 over ASHRAE 90.1-2004 are in areas (envelope insulation and ventilation) that are more critical for heating mode than for cooling mode.

The improved energy performance of the ASHRAE 90.1-2007 baselines comes at the expense of an increase in capital cost. This is due to the fact that ASHRAE 90.1-2007 requires better insulated, and thus costlier, opaque envelope and fenestration constructions than those required by ASHRAE 90.1-2004. Although ASHRAE 90.1-2007 requires a lower ventilation rate in sales areas than does ASHRAE 90.1-2004, the resulting reduction in overall HVAC system size in the 90.1-2007 baseline models did not lower capital costs enough to offset the increase in costs of the opaque envelope and fenestration constructions.

The energy savings provided by the updates required to satisfy ASHRAE 90.1-2007 were not enough to offset the associated increase in capital cost, resulting in larger 5-TLCC values for the ASHRAE 90.1-2007 baseline models than for the ASHRAE 90.1-2004 baseline models (except in climate 8).

As ASHRAE 90.1 evolves to require more and more energy efficiency, it will become increasingly difficult to achieve the same percent energy savings targets. This point is discussed further in Section 5.1.1, which contains a general discussion of alternative metrics that might be of interest for future AEDG work.

4.2 Selected Low-Energy Models

The models described in this section meet the goal of 50% energy savings over ASHRAE 90.1-2004. The models are assembled by applying a number of the EDMs to the baseline models described in Section 3.3. The models are chosen according to the procedures outlined in Sections 2.4 and 2.5.1.

4.2.1 Description

The selected low-energy models are described in terms of the EDMs chosen to achieve 50% energy savings. These choices are summarized for each climate zone in Table 4-13 to Table 4-15. The data reveal that several options were chosen in all climate zones, namely:

- South façade WWR is reduced by 50%, likely because opaque constructions are less expensive than fenestration constructions and have better insulation properties.

- Vestibules are added to the front entrance. In the baseline models, 85% of infiltrated air enters the store through the front entrance. Adding a vestibule is a relatively inexpensive way to significantly reduce infiltration through the front entrance.
- HVAC RTUs are equipped with efficient fans.
- LPD is reduced by 47%, and occupancy sensors are installed in the active storage, mechanical room, restroom, and office zones.
- Daylighting sensors (with 46.5 fc [500 lux] set points) are installed. Note that skylights are not included in every climate zone. In the absence of skylights, daylighting controls are installed only in the zones adjacent to the south façade fenestration (within 15 ft [4.6 m] of the view glass).
- Baseline frozen food and ice cream refrigerated cases are replaced with efficient, vertical models with doors and hot gas defrost.
- Baseline dairy/deli refrigerated cases are replaced with efficient, vertical models with doors.
- Baseline meat display cases are replaced with models with efficient fans, anti-sweat heater controls, electric defrost, and sliding doors.

Two EDMs were not chosen for any location:

- Shaded overhangs above the windows on the south façade.
- Replacing the refrigeration system air-cooled condensers with evaporative ones.

Some general trends noted are:

- Skylights are chosen in warm climates only (zones 1 through 4), likely because colder climates receive too little sun for the energy saved by daylighting to compensate for the increase in capital costs and reduction in insulation associated with skylights. In all cases where skylights are installed, high solar gain constructions are selected. This is likely because high solar gain skylights also have the highest VLT values, which maximize daylighting performance.
- Fenestration constructions with poor insulation properties are selected in the hottest climates, possibly to counteract the effects of the refrigerated cases. All selected skylights have double-pane constructions (most also have low-e and argon), except that selected in climate zone 1A, which has single-pane construction. All selected windows are double pane with low-e and argon, except those selected in climates 1A (baseline construction) and 2B (single pane, clear).
- In general, baseline opaque constructions (exterior walls and roofs) are selected. Exceptions mostly occur at climate extremes, as expected: exterior wall constructions with better insulation properties are selected in the hottest climates (1A, 2A, and 2B); a roof construction with better insulation properties is selected in the coldest climate (8). An unexpected exception occurs in climate zone 4C. However, examining the Pareto front for the 4C optimization reveals that higher cost, lower yield EDMs (such as opaque construction EDMs) needed to be implemented to reach 50% savings without PV.
- Infiltration reduction EDMs are almost universally selected. Vestibules are chosen for all climates. Envelope air barriers (which reduce infiltration by eliminating cracks) are

selected in all humid, cold, and marine climates, and in all but the warmest arid climates (2B and 3B-CA).

- Twenty percent increased COP is selected for RTUs in all except the coldest climate (8), likely because too little cooling is needed in such a cold climate to justify the cost associated with upgrading RTU COPs.
- Economizers are not selected in any humid or cold climates, as expected. They are selected in all marine climates and in all hot and warm arid climates except 3B-NV.
- Because of a modeling artifact (see Section 5.1.3), DCV and ERV could be selected individually, but not in combination. ERV is selected in all colder climates (5 through 8) and in all humid climates except 1A. DCV is selected in all climates in which ERV was not selected, including in all hot and warm arid climates except 3B-NV, and in all marine climates. The current trends show that ERV should be most effective in humid and cold climates, but we expect that DCV and ERV would work well in combination in many cases, such that DCV and ERV would have been selected in more climates were it not for the modeling artifact.

Table 4-13 Selected Low-Energy Models: Humid Climates

Category	Subcategory	EDM Type	Humid					
			1A	2A	3A	4A	5A	6A
Form	Fenestration	Skylight Fraction	2% roof area in non-sidelit zones	3% roof area in non-sidelit zones	3% roof area in non-sidelit zones	None	None	None
		South Window Fraction	50% of baseline glazing	50% of baseline glazing	50% of baseline glazing	50% of baseline glazing	50% of baseline glazing	50% of baseline glazing
	Shading	Shading Depth	None	None	None	None	None	None
Fabric	Fenestration	Skylights	Single pane with high solar gain	Double pane with low-e and high solar gain	Double pane with low-e and high solar gain	Baseline Skylight Construction	Baseline Skylight Construction	Baseline Skylight Construction
		South Windows	Baseline Window Construction	Double pane with low-e and argon	Double pane with low-e and argon	Double pane with low-e and argon	Double pane with low-e and argon	Double pane with low-e and argon
	Infiltration	Infiltration	Tighter envelope and front door vestibule.	Tighter envelope and front door vestibule.	Tighter envelope and front door vestibule.	Tighter envelope and front door vestibule.	Tighter envelope and front door vestibule.	Tighter envelope and front door vestibule.
	Opaque Constructions	Walls	Mass_ASHRAE 90.1 2008_pg c.i. mtl frame ext ins R-22.6	Mass_ASHRAE 90.1 2008_pg c.i. mtl frame ext ins R-22.6	Baseline Wall Construction, R-5.7 c.i.	Baseline Wall Construction, R-5.7 c.i.	Baseline Wall Construction, R-7.6 c.i.	Baseline Wall Construction, R-9.5 c.i.
		Roof	Baseline Roof Construction, R-15 c.i.	Baseline Roof Construction, R-15 c.i.	Baseline Roof Construction, R-15 c.i.	Baseline Roof Construction, R-15 c.i.	Baseline Roof Construction, R-15 c.i.	Baseline Roof Construction, R-15 c.i.

Category	Subcategory	EDM Type	Humid					
			1A	2A	3A	4A	5A	6A
Equipment	Energy Generation	PV	14% of net roof area	None	None	None	None	None
	HVAC System	System	20% increased COP with efficient fan	20% increased COP with efficient fan	20% increased COP with efficient fan	20% increased COP with efficient fan	20% increased COP with efficient fan	20% increased COP with efficient fan
	Lighting	Daylighting Controls	500 lux set point	500 lux set point	500 lux set point	500 lux set point	500 lux set point	500 lux set point
		LPD	47% LPD reduction and occupancy sensors	47% LPD reduction and occupancy sensors	47% LPD reduction and occupancy sensors	47% LPD reduction and occupancy sensors	47% LPD reduction and occupancy sensors	47% LPD reduction and occupancy sensors
	Outdoor Air	DCV	Installed	None	None	None	None	None
		ERV	None	70% effective	50% effective	50% effective	50% effective	50% effective
Refrigeration	Low Temp	Ice Cream	Replace with efficient vertical door model, hot gas defrost	Replace with efficient vertical door model, hot gas defrost	Replace with efficient vertical door model, hot gas defrost	Replace with efficient vertical door model, hot gas defrost	Replace with efficient vertical door model, hot gas defrost	Replace with efficient vertical door model, hot gas defrost
		Frozen Food	#2 with hot gas defrost	#2 with hot gas defrost	#2 with hot gas defrost	#2 with hot gas defrost	#2 with hot gas defrost	#2 with hot gas defrost
		Low Temp. Rack	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
	Med Temp	Dairy/Deli	Replace with efficient vertical door model	Replace with efficient vertical door model	Replace with efficient vertical door model	Replace with efficient vertical door model	Replace with efficient vertical door model	Replace with efficient vertical door model
		Meat Display	#3: #1 plus sliding doors	#3: #1 plus sliding doors	#3: #1 plus sliding doors	#3: #1 plus sliding doors	#3: #1 plus sliding doors	#3: #1 plus sliding doors
		Med. Temp. Rack	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline

Table 4-14 Selected Low-Energy Models: Arid Climates

Category	Subcategory	EDM Type	Arid					
			2B	3B-CA	3B-NV	4B	5B	6B
Form	Fenestration	Skylight Fraction	2% roof area in non-sidelit zones	2% roof area in non-sidelit zones	3% roof area in non-sidelit zones	2% roof area in non-sidelit zones	None	None
		South Window Fraction	50% of baseline glazing	50% of baseline glazing	50% of baseline glazing	50% of baseline glazing	50% of baseline glazing	50% of baseline glazing
	Shading	Shading Depth	None	None	None	None	None	None
Fabric	Fenestration	Skylights	Double pane with high solar gain	Double pane with high solar gain	Double pane with low-e and high solar gain	Double pane with low-e and high solar gain	Baseline Skylight Construction	Baseline Skylight Construction
		South Windows	Single pane with clear glass	Double pane with low-e and argon	Double pane with low-e and argon	Double pane with low-e and argon	Double pane with low-e and argon	Double pane with low-e and argon
	Infiltration	Infiltration	Front door vestibule	Front door vestibule	Tighter envelope and front door vestibule.	Tighter envelope and front door vestibule.	Tighter envelope and front door vestibule.	Tighter envelope and front door vestibule.
	Opaque Constructions	Walls	Mass_ASHRAE 90.1 2008_pg c.i. mtl frame ext ins R-18.1	Baseline Wall Construction, R-5.7 c.i.	Baseline Wall Construction, R-5.7 c.i.	Baseline Wall Construction, R-5.7 c.i.	Baseline Wall Construction, R-7.6 c.i.	Baseline Wall Construction, R-9.5 c.i.
		Roof	Baseline Roof Construction, R-15 c.i.	Baseline Roof Construction, R-15 c.i.	Baseline Roof Construction, R-15 c.i.	Baseline Roof Construction, R-15 c.i.	Baseline Roof Construction, R-15 c.i.	Baseline Roof Construction, R-15 c.i.

Category	Subcategory	EDM Type	Arid					
			2B	3B-CA	3B-NV	4B	5B	6B
Equipment	Energy Generation	PV	None	None	None	None	None	None
	HVAC System	System	20% increased COP with economizer and efficient fan	20% increased COP with economizer and efficient fan	20% increased COP with efficient fan	20% increased COP with economizer and efficient fan	20% increased COP with efficient fan	20% increased COP with efficient fan
	Lighting	Daylighting Controls	500 lux set point	500 lux set point	500 lux set point	500 lux set point	500 lux set point	500 lux set point
		LPD	47% LPD reduction and occupancy sensors	47% LPD reduction and occupancy sensors	47% LPD reduction and occupancy sensors	47% LPD reduction and occupancy sensors	47% LPD reduction and occupancy sensors	47% LPD reduction and occupancy sensors
	Outdoor Air	DCV	Installed	Installed	None	Installed	None	None
		ERV	None	None	50% effective	None	50% effective	50% effective
Refrigeration	Low Temp	Ice Cream	Replace with efficient vertical door model, hot gas defrost	Replace with efficient vertical door model, hot gas defrost	Replace with efficient vertical door model, hot gas defrost	Replace with efficient vertical door model, hot gas defrost	Replace with efficient vertical door model, hot gas defrost	Replace with efficient vertical door model, hot gas defrost
		Frozen Food	#2 with hot gas defrost	#2 with hot gas defrost	#2 with hot gas defrost	#2 with hot gas defrost	#2 with hot gas defrost	#2 with hot gas defrost
		Low Temp. Rack	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
	Med Temp	Dairy/Deli	Replace with efficient vertical door model	Replace with efficient vertical door model	Replace with efficient vertical door model	Replace with efficient vertical door model	Replace with efficient vertical door model	Replace with efficient vertical door model
		Meat Display	#3: #1 plus sliding doors	#3: #1 plus sliding doors	#3: #1 plus sliding doors	#3: #1 plus sliding doors	#3: #1 plus sliding doors	#3: #1 plus sliding doors
		Med. Temp. Rack	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline

Table 4-15 Selected Low-Energy Models: Marine and Cold Climates

Category	Subcategory	EDM Type	Marine		Cold	
			3C	4C	7	8
Form	Fenestration	Skylight Fraction	3% roof area in non-sidelit zones	4% roof area in non-sidelit zones	None	None
		South Window Fraction	50% of baseline glazing	50% of baseline glazing	50% of baseline glazing	50% of baseline glazing
	Shading	Shading Depth	None	None	None	None
Fabric	Fenestration	Skylights	Double pane with low-e and high solar gain	Double pane with low-e and high solar gain	Baseline Skylight Construction	Baseline Skylight Construction
		South Windows	Double pane with low-e and argon	Double pane with low-e and argon	Double pane with low-e and argon	Double pane with low-e and argon
	Infiltration	Infiltration	Tighter envelope and front door vestibule.	Tighter envelope and front door vestibule.	Tighter envelope and front door vestibule.	Tighter envelope and front door vestibule.
	Opaque Constructions	Walls	Baseline Wall Construction, R-5.7 c.i.	Mass_ASHRAE 90.1 2008_pg c.i. mtl frame ext ins R-22.6	Baseline Wall Construction, R-11.4 c.i.	Baseline Wall Construction, R-13.3 c.i.
		Roof	Baseline Roof Construction, R-15 c.i.	R-40 c.i.	Baseline Roof Construction, R-15 c.i.	R-25 c.i.
Equipment	Energy Generation	PV	None	None	None	None
	HVAC System	System	20% increased COP with economizer and efficient fan	20% increased COP with economizer and efficient fan	20% increased COP with efficient fan	Baseline COP with efficient fan
	Lighting	Daylighting Controls	500 lux set point	500 lux set point	500 lux set point	500 lux set point
		LPD	47% LPD reduction and occupancy sensors	47% LPD reduction and occupancy sensors	47% LPD reduction and occupancy sensors	47% LPD reduction and occupancy sensors
	Outdoor Air	DCV	Installed	Installed	None	None
		ERV	None	None	50% effective	50% effective

Category	Subcategory	EDM Type	Marine		Cold	
			3C	4C	7	8
Refrigeration	Low Temp	Ice Cream	Replace with efficient vertical door model, hot gas defrost	Replace with efficient vertical door model, hot gas defrost	Replace with efficient vertical door model, hot gas defrost	Replace with efficient vertical door model, hot gas defrost
		Frozen Food	#2 with hot gas defrost	#2 with hot gas defrost	#2 with hot gas defrost	#2 with hot gas defrost
		Low Temp. Rack	Baseline	Baseline	Baseline	Baseline
	Med Temp	Dairy/Deli	Replace with efficient vertical door model	Replace with efficient vertical door model	Replace with efficient vertical door model	Replace with efficient vertical door model
		Meat Display	#3: #1 plus sliding doors	#3: #1 plus sliding doors	#3: #1 plus sliding doors	#3: #1 plus sliding doors
		Med. Temp. Rack	Baseline	Baseline	Baseline	Baseline

4.2.2 Performance

The energy performance of the selected low-energy models is summarized in Table 4-16 to Table 4-18, and depicted graphically in Figure 4-4. The tables report several whole-building metrics; the figure depicts site energy use broken out into end uses. The data shown in the figure are also listed in table form in Appendix D.

Table 4-16 Selected Low-Energy Model Energy Performance: Humid Climates

Building Name	Metric	Humid					
		1A	2A	3A	4A	5A	6A
Low-Energy	Percent Energy Savings	50.0%	50.9%	51.6%	51.0%	51.3%	51.4%
Baseline (SI units)	EUI ($MJ/m^2 \cdot yr$)	2,780	2,930	2,620	2,800	2,920	3,100
Low-Energy (SI units)	EUI ($MJ/m^2 \cdot yr$)	1,390	1,440	1,270	1,370	1,420	1,510
Baseline (SI units)	Electricity Intensity (kWh/m^2yr)	695	685	532	514	499	496
Low-Energy (SI units)	Electricity Intensity (kWh/m^2yr)	370	344	266	262	248	243
Baseline (SI units)	Natural Gas Intensity (kWh/m^2yr)	79.0	130	195	264	312	364
Low-Energy (SI units)	Natural Gas Intensity (kWh/m^2yr)	38.8	56.4	85.8	120	147	175
Low-Energy (SI units)	PV Power Intensity (kWh/m^2yr)	22.4	0.000	0.000	0.000	0.000	0.000
Baseline (IP units)	EUI ($kBtu/ft^2yr$)	245	258	231	246	257	273
Low-Energy (IP units)	EUI ($kBtu/ft^2yr$)	123	127	112	121	125	133
Baseline (IP units)	Electricity Intensity (kWh/ft^2yr)	64.5	63.6	49.5	47.8	46.4	46.1
Low-Energy (IP units)	Electricity Intensity (kWh/ft^2yr)	34.4	32.0	24.7	24.3	23.0	22.6
Baseline (IP units)	Natural Gas Intensity ($Therms/ft^2yr$)	0.250	0.413	0.619	0.835	0.989	1.15
Low-Energy (IP units)	Natural Gas Intensity ($Therms/ft^2yr$)	0.123	0.179	0.272	0.379	0.465	0.556
Low-Energy (IP units)	PV Power Intensity (kWh/ft^2yr)	2.08	0.000	0.000	0.000	0.000	0.000

Table 4-17 Selected Low-Energy Model Energy Performance: Arid Climates

Building Name	Metric	Arid					
		2B	3B-CA	3B-NV	4B	5B	6B
Low-Energy	Percent Energy Savings	50.7%	50.1%	53.9%	50.3%	53.2%	52.9%
Baseline (SI units)	EUI ($MJ/m^2 \cdot yr$)	2,350	2,360	2,370	2,530	2,690	2,920
Low-Energy (SI units)	EUI ($MJ/m^2 \cdot yr$)	1,160	1,180	1,100	1,260	1,260	1,370
Baseline (SI units)	Electricity Intensity ($kWh/m^2 yr$)	538	494	506	486	480	474
Low-Energy (SI units)	Electricity Intensity ($kWh/m^2 yr$)	259	251	238	224	228	222
Baseline (SI units)	Natural Gas Intensity ($kWh/m^2 yr$)	116	163	154	216	267	337
Low-Energy (SI units)	Natural Gas Intensity ($kWh/m^2 yr$)	63.1	76.2	66.5	125	121	160
Low-Energy (SI units)	PV Power Intensity ($kWh/m^2 yr$)	0.000	0.000	0.000	0.000	0.000	0.000
Baseline (IP units)	EUI ($kBtu/ft^2 yr$)	207	208	209	223	237	257
Low-Energy (IP units)	EUI ($kBtu/ft^2 yr$)	102	104	96.4	111	111	121
Baseline (IP units)	Electricity Intensity ($kWh/ft^2 yr$)	50.0	45.9	47.0	45.2	44.6	44.0
Low-Energy (IP units)	Electricity Intensity ($kWh/ft^2 yr$)	24.1	23.3	22.1	20.8	21.2	20.6
Baseline (IP units)	Natural Gas Intensity ($Therms/ft^2 yr$)	0.368	0.517	0.488	0.684	0.845	1.07
Low-Energy (IP units)	Natural Gas Intensity ($Therms/ft^2 yr$)	0.200	0.241	0.211	0.395	0.384	0.506
Low-Energy (IP units)	PV Power Intensity ($kWh/ft^2 yr$)	0.000	0.000	0.000	0.000	0.000	0.000

Table 4-18 Selected Low-Energy Model Energy Performance: Marine and Cold Climates

Building Name	Metric	Marine		Cold	
		3C	4C	7	8
Low-Energy	Percent Energy Savings	51.2%	50.9%	52.1%	52.4%
Baseline (SI units)	EUI ($MJ/m^2 \cdot yr$)	2,500	2,680	3,280	3,820
Low-Energy (SI units)	EUI ($MJ/m^2 \cdot yr$)	1,220	1,320	1,570	1,820
Baseline (SI units)	Electricity Intensity (kWh/m^2yr)	464	462	474	467
Low-Energy (SI units)	Electricity Intensity (kWh/m^2yr)	220	213	223	212
Baseline (SI units)	Natural Gas Intensity (kWh/m^2yr)	230	284	437	595
Low-Energy (SI units)	Natural Gas Intensity (kWh/m^2yr)	119	153	213	294
Low-Energy (SI units)	PV Power Intensity (kWh/m^2yr)	0.000	0.000	0.000	0.000
Baseline (IP units)	EUI ($kBtu/ft^2yr$)	220	236	289	337
Low-Energy (IP units)	EUI ($kBtu/ft^2yr$)	107	116	138	160
Baseline (IP units)	Electricity Intensity (kWh/ft^2yr)	43.1	42.9	44.0	43.4
Low-Energy (IP units)	Electricity Intensity (kWh/ft^2yr)	20.4	19.8	20.8	19.7
Baseline (IP units)	Natural Gas Intensity ($Therms/ft^2yr$)	0.729	0.900	1.38	1.89
Low-Energy (IP units)	Natural Gas Intensity ($Therms/ft^2yr$)	0.376	0.486	0.674	0.933
Low-Energy (IP units)	PV Power Intensity (kWh/ft^2yr)	0.000	0.000	0.000	0.000

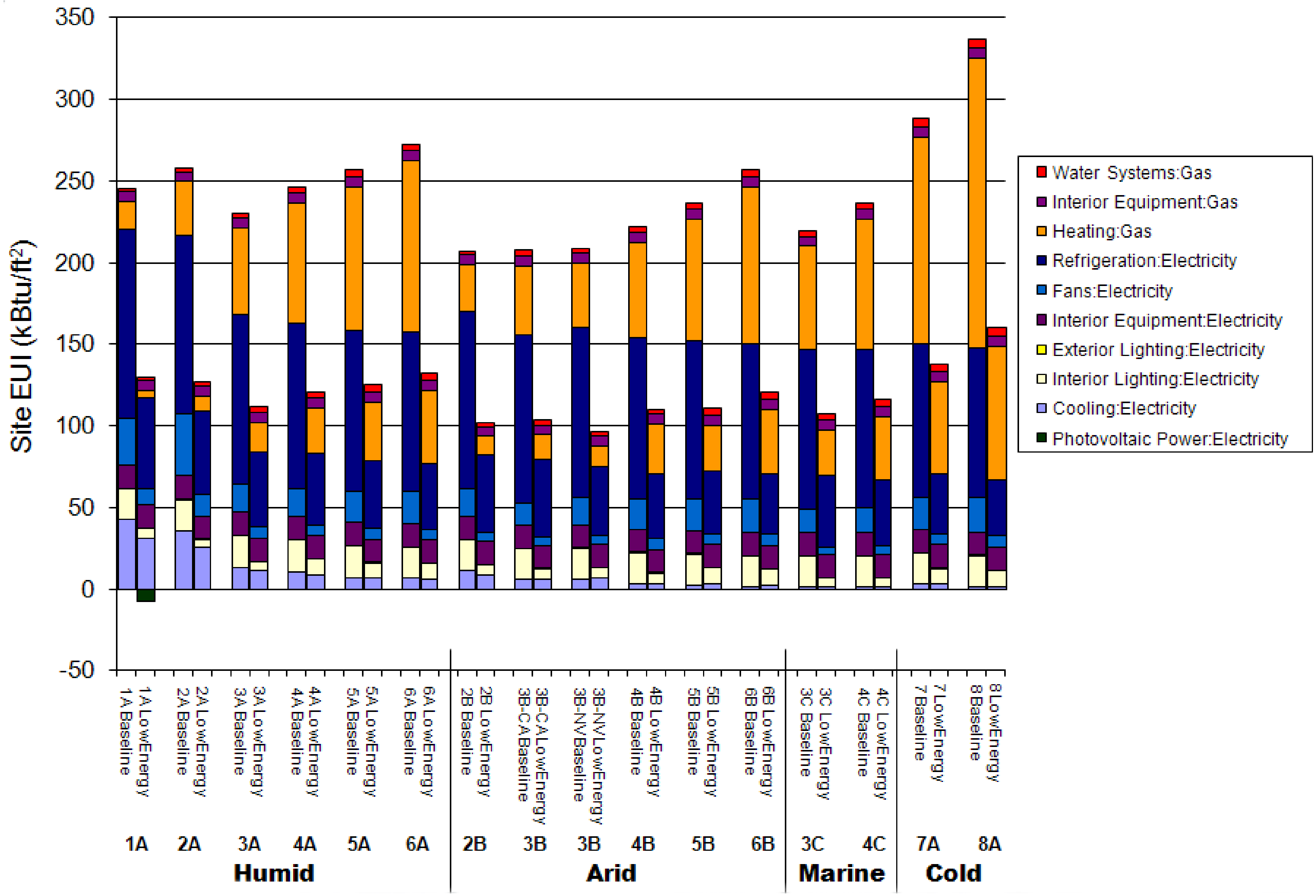

Figure 4-4 Energy intensity by end use for baseline and selected low-energy models

The economic performance of the selected low-energy models is summarized in Table 4-19 to Table 4-21.

Table 4-19 Selected Low-Energy Model Costs: Humid Climates

Building Name	Metric	Humid					
		1A	2A	3A	4A	5A	6A
Baseline (SI units)	5-TLCC Intensity ($/m^2)	1,630	1,660	1,570	1,580	1,580	1,590
Low-Energy (SI units)	5-TLCC Intensity ($/m^2)	1,710	1,690	1,560	1,540	1,550	1,550
Baseline (SI units)	Capital Cost ($/m^2)	1,260	1,280	1,240	1,250	1,250	1,250
Low-Energy (SI units)	Capital Cost ($/m^2)	1,500	1,470	1,370	1,350	1,350	1,350
Baseline (IP units)	5-TLCC Intensity ($/ft^2)	152	154	146	146	147	148
Low-Energy (IP units)	5-TLCC Intensity ($/ft^2)	159	157	145	143	144	144
Baseline (IP units)	Capital Cost ($/ft^2)	117	119	116	116	116	116
Low-Energy (IP units)	Capital Cost ($/ft^2)	139	137	127	125	126	126

Table 4-20 Selected Low-Energy Model Costs: Arid Climates

Building Name	Metric	Arid					
		2B	3B-CA	3B-NV	4B	5B	6B
Baseline (SI units)	5-TLCC Intensity ($/m^2)	1,540	1,530	1,540	1,550	1,560	1,570
Low-Energy (SI units)	5-TLCC Intensity ($/m^2)	1,500	1,460	1,540	1,470	1,520	1,530
Baseline (SI units)	Capital Cost ($/m^2)	1,230	1,230	1,240	1,240	1,240	1,240
Low-Energy (SI units)	Capital Cost ($/m^2)	1,320	1,280	1,370	1,290	1,340	1,350
Baseline (IP units)	5-TLCC Intensity ($/ft^2)	143	142	143	144	145	146
Low-Energy (IP units)	5-TLCC Intensity ($/ft^2)	139	135	143	137	141	142
Baseline (IP units)	Capital Cost ($/ft^2)	114	114	115	115	115	116
Low-Energy (IP units)	Capital Cost ($/ft^2)	122	119	127	120	125	125

Table 4-21 Selected Low-Energy Model Costs: Marine and Cold Climates

Building Name	Metric	Marine		Cold	
		3C	4C	7	8
Baseline (SI units)	5-TLCC Intensity ($/m^2)	1,530	1,550	1,600	1,680
Low-Energy (SI units)	5-TLCC Intensity ($/m^2)	1,460	1,590	1,550	1,610
Baseline (SI units)	Capital Cost ($/m^2)	1,230	1,240	1,260	1,300
Low-Energy (SI units)	Capital Cost ($/m^2)	1,290	1,410	1,360	1,410
Baseline (IP units)	5-TLCC Intensity ($/ft^2)	142	144	149	156
Low-Energy (IP units)	5-TLCC Intensity ($/ft^2)	136	148	144	150
Baseline (IP units)	Capital Cost ($/ft^2)	114	115	117	121
Low-Energy (IP units)	Capital Cost ($/ft^2)	120	131	126	131

The electricity demand performance of the selected low-energy models is summarized in Table 4-22 to Table 4-24.

Table 4-22 Selected Low-Energy Model Electricity Demand: Humid Climates

Building Name	Metric	Humid					
		1A	2A	3A	4A	5A	6A
Baseline	Monthly Max Electric Demand [min-max] (kW)	485–562	458–622	327–467	307–479	296–477	291–467
Low-Energy	Monthly Max Electric Demand [min-max] (kW)	252–284	243–331	172–256	157–284	151–282	147–275
Baseline	Monthly Electrical Load Factor [min-max]	0.589–0.683	0.506–0.648	0.608–0.677	0.560–0.701	0.565–0.731	0.520–0.741
Low-Energy	Monthly Electrical Load Factor [min-max]	0.546–0.688	0.435–0.646	0.502–0.655	0.446–0.615	0.440–0.629	0.457–0.635

Table 4-23 Selected Low-Energy Model Electricity Demand: Arid Climates

Building Name	Metric	Arid					
		2B	3B-CA	3B-NV	4B	5B	6B
Baseline	Monthly Max Electric Demand [min-max] (kW)	333–437	327–398	314–420	298–389	299–393	289–385
Low-Energy	Monthly Max Electric Demand [min-max] (kW)	155–233	156–208	146–235	135–220	151–225	148–220
Baseline	Monthly Electrical Load Factor [min-max]	0.643–0.695	0.618–0.689	0.641–0.680	0.632–0.715	0.616–0.719	0.619–0.748
Low-Energy	Monthly Electrical Load Factor [min-max]	0.587–0.698	0.569–0.680	0.585–0.660	0.583–0.677	0.547–0.629	0.537–0.640

Table 4-24 Selected Low-Energy Model Electricity Demand: Marine and Cold Climates

Building Name	Metric	Marine		Cold	
		3C	4C	7	8
Baseline	Monthly Max Electric Demand [min-max] (kW)	292–362	286–375	289–450	291–353
Low-Energy	Monthly Max Electric Demand [min-max] (kW)	144–196	140–202	144–260	143–216
Baseline	Monthly Electrical Load Factor [min-max]	0.642–0.729	0.611–0.738	0.555–0.743	0.675–0.746
Low-Energy	Monthly Electrical Load Factor [min-max]	0.575–0.676	0.548–0.675	0.500–0.638	0.571–0.641

4.2.3 Discussion

The economic performance data indicate that achieving the 50% energy savings goal in grocery stores is largely cost effective. Because of the upgraded and additional constructions and equipment associated with the implementation of the EDM selections, the low-energy buildings have higher capital costs than their corresponding baseline buildings. In most cases, though, those costs are paid back through energy savings. The low-energy buildings cost less than or the same as (based on 5-TLCC and our other economic parameters) the baseline buildings in all climate zones except for 1A (where PV was needed to reach the energy goal, likely because of a modeling artifact [as discussed in the bulleted list, below]), 2A, and 4C. However, the low-energy models require putting doors on a number of refrigerated cases. Stores not willing to put more products behind glass may be unable to reach high levels of energy efficiency. In many cases, ERV played an important role in reaching 50% energy savings.

Several modeling errors were uncovered near the end of the month-long super-computer simulation runs. These errors affect both the baseline and low-energy model results and to varying degrees, but were discovered too late in the process to be remedied. Whereas we feel that these errors have not fundamentally changed the results of the overall analysis, we include them here for completeness:

- A costing bug in Opt-E-Plus resulted in an underestimation of HVAC capital costs. The size of the HVAC system in the largest zone (main sales) was taken as the total cost of the HVAC system for the whole building.
- Costs for infiltration reduction measures, which were calculated per zone based on the total number of zones, were not updated when the number of zones was reduced from 18 to 14.
- A costing bug in Opt-E-Plus resulted in an overestimation of the cost of ERV by an order of magnitude. Each of the 14 zones was assigned an ERV cost equivalent to what the cost of ERV for the entire building should have been. It appears that ERV was not selected in climate zone 1A due to this bug. In climate zone 1A, the ratio of energy savings provided to incremental cost was slightly higher for PV than for ERV, such that PV was selected before (and instead of) ERV. This likely would not have happened were it not for the ERV costing bug. Therefore, we strongly recommend that ERV still be considered in zone 1A. Further, in all cases in which ERV was selected, the low-energy

model building costs are significantly overestimated. The fact that ERV was still deemed a sufficiently cost-effective EDM to be selected in those cases is a testament to the significant energy savings that ERV can provide in certain climate zones.

- The cost of shaded overhangs was not updated for the inflation that occurred between 2006 and 2008. Shaded overhangs were not selected in any climate zone, however, so this error had no effect on the overall analysis.
- The cost of meat display refrigeration case maintenance was not updated for the inflation that occurred between 2005 and 2008.
- High effectiveness ERV was assigned the same pressure drop (0.42 in. w.c. [105 Pa]) as low effectiveness ERV. High effectiveness ERV should have been assigned a pressure drop of 0.7 in. w.c. (150 Pa), according to the assumption that higher effectiveness ERV would result in a larger pressure drop.
- The cost of the R-15 roof construction was not updated according to the new roof construction calculations.
- An EnergyPlus requirement associated with the allowable ratio between OA intake and exhaust fan flow rate for ERV operation prevented DCV and ERV from being selected in combination as EDMs. With DCV installed, OA intake in one or more zones reduces to the point that the ratio of OA intake to exhaust fan flow rate reaches a threshold value for ERV control in EnergyPlus that results in a fatal error.
- Exhaust Fan ACH values were incorrectly entered at 80% of their calculated values. This increased the air available for energy recovery by 10%.
- Finally, the original configuration of the HVAC RTUs with the desuperheat option for reheat did not properly control nighttime relative humidity. At night, the RTUs were only cycled to meet the dry bulb temperature set point; the humidistat set point (55%) was ignored.

4.3 Alternative Low-Energy Models

The methodology described in Section 2.5.2 is used to find alternative designs that also reach 50% energy savings for a subset of the climate zones. Each design is found with a new search designed to determine whether a specific high-performance strategy is required to meet the energy savings goal.

For this algorithm, a *strategy* is an EDM category or set of categories that can be turned off or on. To turn a strategy off means to set each EDM category to its baseline value. To turn a strategy on means to fix each EDM category to the value taken in a selected low-energy model. The strategy definitions used in this work are summarized in Table 4-25. Each strategy is a set of one or more EDM types.

In what follows, the PV strategy was treated differently from the others. In particular, the PV EDM defines an upper limit on the amount of PV. Then for any selected points that achieve the 50% energy savings target with PV, we calculated the actual amount of PV required to reach the target and reran the selected model after making just that change. Models that included PV and still did not reach the target were marked as unsuccessful.

The algorithm used to find alternative models that meet the target is computationally intensive, requiring 63% to 281% of the effort of the original search. For this reason, we only ran it in five climate zones: 1A (Miami, Florida), 3B-NV (Las Vegas, Nevada), 4C (Seattle, Washington), 5A

(Chicago, Illinois), and 8 (Fairbanks, Alaska). We also ran only one iteration of the algorithm, which means that each new search was generated directly from the selected low energy models described in Section 4.2 by removing a single strategy.

Table 4-25 High Performance Building Strategies as used in the Algorithm for Identifying Alternative Low-Energy Models

Strategy Name	EDM Type	See Section
Infiltration	Infiltration	0
Elec. Lighting	LPD	3.4.3.2
Daylighting	Daylighting controls	3.4.3.1
	Skylight Fraction	3.4.1.1.2
Window Area	South Window Fraction	3.4.1.1.1
Window Shading	Shading Depth	3.4.1.2
Wall Insulation	Walls	3.4.2.1
Roof Insulation	Roof	3.4.2.2
Fenestration Types	South Windows	3.4.2.3.1
	Skylights	0
HVAC	System	3.4.3.3
DCV	DCV	3.4.3.4.1
ERV	ERV	3.4.3.4.2
Frozen Food Cases	Frozen Food	3.4.3.5.1
Ice Cream Cases	Ice Cream	3.4.3.5.1
Meat Cases	Meat Display	3.4.3.5.1
Dairy/Deli Cases	Dairy/Deli	3.4.3.5.1
Refrig. Racks	Low Temp. Rack	0
	Med. Temp. Rack	0
PV	PV	3.4.3.6

4.3.1 Results

The bulk of the results are listed in Appendix E. Here we walk through the results for one climate zone, and summarize the overall results in a few tables.

4.3.1.1 Example Results for One Building

By starting with the selected low-energy model, removing a strategy from both the model and the search, and then restarting the search, one ends up with two new models of interest: the new start point, and the new selected point. The results reported in Appendix E summarize both for every strategy used in the original selected models.

After a brief summary of the computational effort required for the searches, the next two items in each subsection of Appendix E, a figure and an accompanying table, provide information on the new selected points. For convenience, here we reproduce those items for climate zone 5A, see Figure 4-5 and Table 4-26.

The figure represents each low-energy model as a node. Circular nodes meet the 50% energy savings goal; octagonal nodes do not. Nodes outlined in gold contain PV; black nodes do not. The root node (the top circle labeled 00) represents the selected low-energy model described in Section 4.2. Each child node represents a model chosen in the same way as the root node, but from a new search that excluded the indicated strategy from the search options, and that started from the model defined by removing that strategy from the root node.

The accompanying table further summarizes the low-energy models represented in the figure. The two are linked by the node labels 00, 01, 02, etc. The first row repeats a subset of the performance data listed above for the original selected low-energy model, and adds to that an explicit listing of which strategies were used in that model. For example, the original low-energy model chosen for Chicago, Illinois applies at least one infiltration EDM, an electric lighting EDM, and some aspect of daylighting (controls, skylights, or both).

The subsequent rows summarize the new low-energy models. Each one excludes one of the strategies used by the original selected model. In some cases, the new low-energy models use strategies that were not used in the original model. This is to be expected since different actions must be taken to reach the 50% goal in the absence of the excluded strategy. Sometimes those actions are more extreme measures taken within the confines of one of the strategies used in the original model, but at other times entirely new strategies are introduced.

The performance data allow interested parties to screen all of the models that reach the 50% goal against several criteria, including some that are not used directly in the search. Recall that the search simultaneously minimizes net site energy and lifetime cost. To these, the table adds PV energy, capital cost, and peak demand.

The results in Appendix E also summarize the new start points as they relate to the original low-energy model. Those two points only differ by one strategy (any PV effects are removed) such that the difference in their performance data can be interpreted as sensitivity data and answers the question, “How much impact does the given strategy have on the EUI of the selected low-energy model?” The table that summarizes this data for climate zone 5A is reproduced in Table 4-27. Except for Equivalent PV, each reported quantity is the result of taking the value of the listed performance metric for the original low-energy model and subtracting that for the new start point (original model minus the indicated strategy). Thus, in most cases we expect EUI Savings to be a positive number.

Equivalent PV is provided as an alternative valuation for the given strategy. For each location, we use EnergyPlus to calculate the annual amount of energy produced per unit area of PV assuming horizontal orientation, 10% cell efficiency, 90% inverter efficiency, and the insolation data provided in the appropriate TMY2 weather file. It is then possible to convert the EUI savings provided by a strategy to an equivalent area of PV panels. Although equivalent to EUI savings, equivalent PV gives readers a more tangible way to think about a given level of energy savings and provides an alternative cost metric (a maximum allowable capital cost) once a realistic PV cost is chosen. With incentives and more PV production capacity coming online, we have heard of costs as low as \$2.50-\$5 per Watt of PV capacity; installed capacity is about 100 W/m^2.

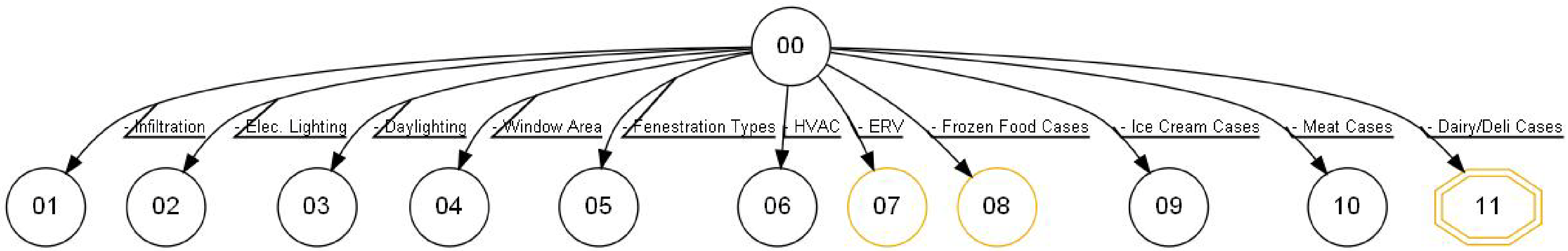

Figure 4-5 Visualization of original and alternative low-energy models for the Chicago, Illinois grocery store

Node 00 represents the original low-energy model. The other nodes represent the result of searches formed by taking Node 00 and removing the indicated strategy. Models that include PV are in gold. Any models that do not reach the 50% energy savings goal are indicated by octagons.

Table 4-26 Summary of the Chicago, Illinois Low Energy Models

Node	Infiltration	Elec. Lighting	Daylighting	Window Area	Wall Insulation	Roof Insulation	Fenestration Types	HVAC	DCV	ERV	Frozen Food Cases	Ice Cream Cases	Meat Cases	Dairy/Deli Cases	Net Site Energy		PV Energy		Lifetime Cost		Capital Cost		Peak Demand (kW)	Energy Savings (%)
															$MJ/m^2 \cdot yr$	$kBtu/ft^2 \cdot yr$	$MJ/m^2 \cdot yr$	$kBtu/ft^2 \cdot yr$	$\$/m^2$	$\$/ft^2$	$\$/m^2$	$\$/ft^2$		
0	X	X	X	X			X	X		X	X	X	X	X	1,421	125.0	0	0.0	1,546	143.59	1,352	125.59	282	51.3
1		X	X	X			X	X		X	X	X	X	X	1,419	124.9	0	0.0	1,576	146.37	1,381	128.30	289	51.4
2	X		X	X			X	X		X	X	X	X	X	1,436	126.3	0	0.0	1,567	145.60	1,367	127.03	278	50.8
3	X	X		X			X	X		X	X	X	X	X	1,424	125.3	0	0.0	1,546	143.60	1,352	125.56	283	51.2
4	X	X	X				X	X		X	X	X	X	X	1,420	125.0	0	0.0	1,551	144.10	1,357	126.07	281	51.4
5	X	X	X	X				X		X	X	X	X	X	1,426	125.5	0	0.0	1,546	143.66	1,352	125.63	281	51.2
6	X	X	X	X			X			X	X	X	X	X	1,407	123.8	0	0.0	1,579	146.73	1,379	128.12	314	51.8
7	X	X	X	X	X	X	X	X	X		X	X	X	X	1,460	128.4	26	2.3	1,676	155.72	1,484	137.91	237	50.0
8	X	X	X	X	X	X	X	X		X		X	X	X	1,460	128.5	26	2.2	1,772	164.65	1,568	145.70	268	50.0
9	X	X	X	X			X	X		X	X		X	X	1,407	123.8	0	0.0	1,582	146.99	1,386	128.78	289	51.8
10	X	X	X	X			X	X		X	X	X		X	1,435	126.3	0	0.0	1,591	147.84	1,398	129.88	265	50.8
11	X	X	X	X	X	X	X	X		X	X	X	X		1,582	139.2	265	23.3	2,292	212.96	2,090	194.21	301	45.8

Node numbers correspond to Figure 4-5. An ‘X’ under a strategy name indicates that the strategy is used in the model.

Table 4-27 Sensitivity Analysis for the Strategies used in the Selected Low-Energy Model for Chicago, Illinois

Strategy	Search No.	EUI Savings		Lifetime Cost Savings		Capital Cost Savings		Equivalent PV	
		MJ/m²·yr	kBtu/ft²·yr	$/m²	$/ft²	$/m²	$/ft²	m²	ft²
Infiltration	00	71.5	6.29	2.70	0.25	–2.26	–0.21	626.0	6,738
Elec. Lighting	01	60.4	5.32	11.19	1.04	–2.19	–0.20	528.9	5,693
Daylighting	02	2.6	0.23	0.13	0.01	–0.31	–0.03	23.1	249
Window Area	03	–1.0	–0.09	5.50	0.51	5.18	0.48	–8.5	–91
Fenestration Types	04	5.0	0.44	0.78	0.07	0.47	0.04	43.6	469
HVAC	05	55.2	4.86	6.32	0.59	–4.11	–0.38	483.5	5,204
ERV	06	219.7	19.34	–58.38	–5.42	–70.34	–6.53	1,923.1	20,700
Frozen Food Cases	07	244.6	21.52	14.99	1.39	–12.25	–1.14	2,140.5	23,040
Ice Cream Cases	08	58.3	5.13	9.13	0.85	2.94	0.27	510.1	5,491
Meat Cases	09	120.2	10.58	0.69	0.06	–7.99	–0.74	1,051.8	11,321
Dairy/Deli Cases	10	622.1	54.74	41.31	3.84	–9.51	–0.88	5,443.9	58,598

4.3.1.2 Summary Tables

Table 4-28 lists the number of low-energy models found for each climate zones to which the analysis was applied. Since some models did not reach 50% savings, the number of models that did is also listed. The rest of the data indicates the range of performances seen in those models that did reach the energy savings goal. These data are provided to give the reader an idea of the amount of diversity present in the sets of alternative designs.

Table 4-29 attempts to summarize the value of the high performance design strategies across climate zones. Each cell is shaded to indicate whether the given metric always improves (green), sometimes improves (gray), or always degrades (orange) in response to the addition of the indicated strategy.

Table 4-28 Summary of Each Climate Zone's Low-Energy Models

Climate Zone	No. of 50% Models/Total No. of Models	PV Energy Intensity Range (50% Models)		5-TLCC Intensity Range (50% Models)		Capital Cost Intensity Range (50% Models)		Maximum Electricity Demand Range (50% Models)
		MJ/m²·yr	kBtu/ft²·yr	$/m²	$/ft²	$/m²	$/ft²	kW
1A	12/13	73–317	6.4–27.9	1,707–2,121	158.56–197.00	1,490–1,901	138.42–176.62	284–328
3B-NV	11/12	0–143	0.0–12.6	1,473–1,789	136.81–166.20	1,296–1,604	120.43–149.06	229–252
4C	13/14	0–214	0.0–18.8	1,556–2,128	144.52–197.68	1,375–1,945	127.72–180.66	185–221
5A	11/12	0–26	0.0–2.3	1,546–1,772	143.59–164.65	1,352–1,568	125.56–145.70	237–314
8	12/13	0–127	0.0–11.2	1,611–2,130	149.64–197.92	1,404–1,930	130.47–179.26	170–243

Table 4-29 Sensitivity Analysis Summary by Strategy

Green (orange) indicates that the strategy always improves (degrades) the performance metric.

Strategy	No. of Data Points	EUI Savings Range		5-TLCC Savings Range		Capital Cost Savings Range		Equivalent PV Range	
		MJ/m²·yr	kBtu/ft²·yr	$/m²	$/ft²	$/m²	$/ft²	m²	ft²
Infiltration	5	23.5 to 154.5	2.07 to 13.60	–4.59 to 8.11	–0.43 to 0.75	–6.31 to 0.54	–0.59 to 0.05	141.5 to 2,161	1,523 to 23,262
Elec. Lighting	5	26.3 to 132.9	2.31 to 11.69	2.74 to 36.59	0.25 to 3.40	–8.10 to 16.59	–0.75 to 1.54	269.8 to 945.9	2,904 to 10,181
Daylighting	5	1.8 to 60.7	0.16 to 5.35	–23.40 to 0.13	–2.17 to 0.01	–28.83 to –0.31	–2.68 to –0.03	23.1 to 432.4	249 to 4,654
Window Area	5	–1.0 to 4.1	–0.09 to 0.36	3.78 to 5.85	0.35 to 0.54	3.57 to 5.18	0.33 to 0.48	–9.1 to 29.5	–98 to 317
Wall Insulation	2	23.1 to 33.4	2.03 to 2.94	–37.72 to –35.99	–3.50 to –3.34	–40.43 to –39.28	–3.76 to –3.65	236.9 to 237.6	2,550 to 2,558
Roof Insulation	2	41.0 to 42.4	3.60 to 3.73	–70.21 to –2.41	–6.52 to –0.22	–72.90 to –4.86	–6.77 to –0.45	420.4 to 592.7	4,525 to 6,379
Fenestration Types	5	5.0 to 16.3	0.44 to 1.43	–0.66 to 2.56	–0.06 to 0.24	–1.19 to 1.58	–0.11 to 0.15	41.5 to 131.2	446 to 1,412
HVAC	5	16.7 to 207.2	1.47 to 18.23	3.98 to 20.78	0.37 to 1.93	–5.49 to –1.74	–0.51 to –0.16	233 to 1,474	2,510 to 15,872
DCV	2	28.3 to 33.7	2.49 to 2.97	–5.10 to –1.49	–0.47 to –0.14	–5.34 to –1.95	–0.50 to –0.18	240.1 to 290.9	2,585 to 3,131
ERV	3	78.5 to 471.7	6.91 to 41.51	–65.56 to –45.14	–6.09 to –4.19	–70.34	–6.53	472.9 to 6,597	5,090 to 71,010
Frozen Food Cases	5	236 to 263	20.81 to 23.14	14.24 to 17.16	1.32 to 1.59	–12.60 to –12.14	–1.14 to –1.13	1,583 to 3,636	17,041 to 39,145
Ice Cream Cases	5	57.9 to 62.5	5.10 to 5.50	9.08 to 9.59	0.84 to 0.89	2.85 to 3.27	0.26 to 0.30	358.4 to 873.6	3,858 to 9,404
Meat Cases	5	62.9 to 174.9	5.53 to 15.39	–0.49 to 4.02	–0.05 to 0.37	–8.11 to –6.09	–0.75 to –0.57	447.6 to 2445.6	4,817 to 26,325
Dairy/Deli Cases	5	466 to 740	41.0 to 65.2	34.33 to 45.96	3.19 to 4.27	–11.73 to –6.20	–1.09 to –0.58	3,142 to 10,361	33,820 to 111,531

4.3.2 Discussion

The algorithm described here and in Section 2.5.2 allowed us to identify 11 to 13 low-energy models for each of the five climate zones analyzed in this manner. Each model meets the 50% energy savings goal in a significantly different way, concretely demonstrating that there are multiple ways to meet most energy efficiency goals. Furthermore, because different EDMs provide different performance in terms of 5-TLCC, capital cost, and electricity demand changes per unit of energy savings, the performance of the models are significantly different when compared using those criteria (and likely any others of interest that are not reported here).

Perhaps the most significant finding of this exercise is that dairy/deli cases are a game-changing energy drain on grocery stores—under our analysis assumptions, it was not possible to reach the 50% goal in any climate without mitigating this source of energy consumption. From another perspective, replacing open (no door) dairy/deli cases with closed door models was equivalent to adding 33,820 ft^2 to 111,531 ft^2 (3,142 m^2 to 10,361 m^2 or approximately 314 kW to 1,036 kW nameplate capacity) of PV panels. No other strategy was found to be required in any climate.

The necessity of using PV to reach the 50% goal varied across climates. It was used in every low-energy model for Miami, and in nine of the twelve goal-fulfilling models found for Seattle, but in just 1-2 of the other climates' designs. Whether or not PV is needed is in some ways a surrogate for how easy it is to reach the 50% goal in a given climate. For instance, there must be other, cheaper ways to reduce energy use in Las Vegas, since one would generally expect PV to be quite effective there.

As in the original search, the two modeling errors related to ERV had a significant effect on our findings. In particular, ERV and DCV could not be implemented simultaneously, so each climate zone's models mostly use one or the other. In addition, the artificially high cost of ERV may have artificially kept it from being added to the Miami and Seattle stores even when DCV was removed.

For the sake of brevity, we are not providing detailed descriptions of each low-energy model found in this study or poring through our data to answer admittedly interesting questions such as "What is the relationship between the high performance strategies and maximum electricity demand?" The main contribution of this work is to demonstrate a new methodology that enables users to generate a number of significantly different designs that meet a common energy efficiency goal.

4.4 Addressing Known Issues

Due to the large number of simulation runs required for this analysis, time constraints did not allow us to rerun full optimizations after discovering the modeling errors listed in Section 4.2.3. Those errors have since been addressed however, and we feel that it is worth presenting a set of modified results to illustrate their effects on the analysis. Most of the modeling errors affected costs and EDM selection order rather than the final list of chosen EDMs. The exceptions to this rule are related to the ERV EDMs: the ERV costing bug, which overpriced ERV by an order of magnitude; and the ERV-DCV interaction bug, which prevented ERV and DCV from being selected simultaneously. In some cases, it appeared that PV was erroneously selected instead of ERV. In others, it seemed as though the selection of either ERV or DCV was prevented by the presence of the other. In an attempt to predict what the results of the optimizations would have been in the absence of these modeling errors, we took the following steps:

1. Removed any ERV, DCV, or PV EDMs from the selected low-energy model.
2. Fixed the remaining EDM selections.
3. Performed an abbreviated optimization over the ERV, DCV, and PV EDMs to determine corrected low-energy models.

In climate zone 1A, DCV and PV were removed from the selected building (from the original optimization) in favor of 50% ERV. Similarly, in climate zones 2B, 3B-CA, 3C, and 4B, DCV was removed in favor of 50% ERV. In climate zones 3A and 3B-NV, 50% ERV was replaced with DCV. In climate zone 4C, more EDMs were allowed to vary based on the peculiar results from the original optimization: in the corrected model, the skylights were removed and windows and roofs were downgraded to constructions with less insulation.

Addressing the modeling errors resulted in baseline models with higher EUIs (due to the energy cost of controlling humidity at night), capital costs, and TLCCs (due to the previous underestimation of HVAC and roofing costs). It also resulted in low-energy models with even better economic performance relative to their corresponding baselines than was seen in the original analysis. Detailed energy and economic performance data for the models selected from the abbreviated optimizations are presented in Appendix F.

5.0 Suggestions for Future Work

In this section we outline several types of improvements recommended for future *AEDG* work.

5.1.1 Problem Formulation

The current problem formulation could be adapted to make the 50% AEDG/TSD guide more useful in the future. Energy savings is currently defined against a baseline (ASHRAE Standard 90.1) that is changing steadily over time (see Section 4.1.4). Unless the 90.1-2004/62-1999 baseline is used in perpetuity, it may be advantageous to use a different energy metric. One possible approach would be to use targets based on EUI levels rather than percent savings. Eventually, a net EUI of zero will be the goal. Some work would be required to determine how or if the EUI goals should vary across climate zones on the way to net zero energy use. A consideration of the Pareto front as a whole would give a sense of the effort required to achieve different EUIs on the way to net zero. Several key features for guiding the choice of absolute EUI goals are illustrated in Figure 5-1, which shows results for Miami (Climate Zone 1A). Notice that the graph uses EUI on the *x*-axis rather than percent energy savings. "BL" designates the baseline point as defined in this study. The other points labeled on the Pareto Front are:

1) The minimum 5-TLCC design
2) The "knee" of the Pareto front, before the cost escalates dramatically due to inclusion of PV in the design
3) A design equal in 5-TLCC cost to the baseline building
4) The 50% energy savings building identified as the low-energy model in this study
5) A design meeting an arbitrary net 100 kBtu/ft^2 target (could be any target down to, or even past net zero EUI)

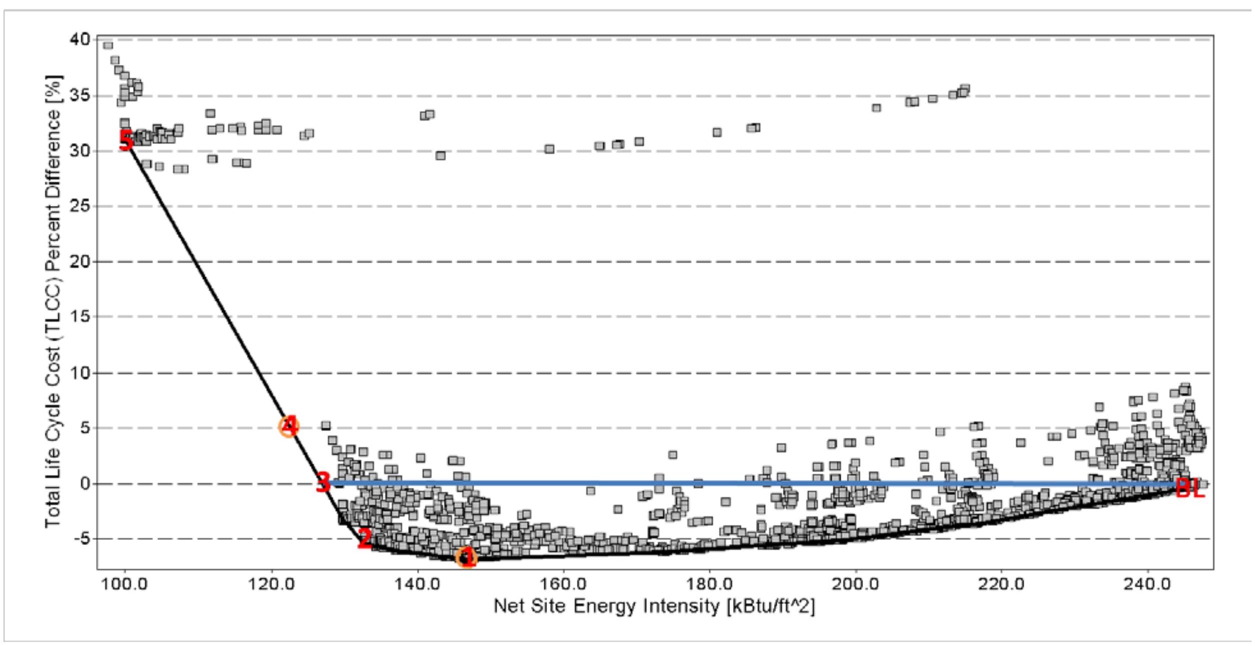

Figure 5-1 Key Pareto curve features to provide absolute EUI targets

An additional consideration is that there are often a number of building design options that are clustered around 50% energy savings; choosing a single "solution" is somewhat arbitrary, given uncertainties in modeling assumptions and inputs. The "family enumeration" analysis used in this study is an effort to start down the road of identifying multiple solution sets for providing more general design guidance.

5.1.2 Economic Data

It is important to weigh capital and maintenance costs versus future energy costs, both for the whole building and for individual EDMs. However, doing so is difficult. Today's costs for basic building materials, new technologies, and energy are constantly moving targets; energy costs cannot be predicted with reasonable accuracy; economic parameters such as discount rates and acceptable payback periods vary by building owner; and one goal of the Energy Alliances is to provide enough buying power to drive the underlying economics, thereby rendering the current costs moot.

Several approaches that address one or more of these problems are:

1. Ignore economics in all general analyses. Instead, work with a specified set of EDMs that are deemed reasonably mature and cost effective. Recommend only EDMs that have an appreciable impact on energy use.
2. Integrate algorithms and methodologies that can deal with data uncertainties into Opt-E-Plus, and exercise them by providing ranges or probability distributions, rather than single values, for highly uncertain economic and performance parameters.
3. Develop automatic or industry-assisted methods for obtaining up-to-date cost data on well-established items such as basic construction materials, common HVAC technologies, and utility tariffs. For more uncertain costs, that is, new technology and future energy costs, develop methods for handling uncertainty information, exercising different scenarios, and calculating what the cost would have to be for the item to be cost effective.

5.1.3 Energy Modeling

A number of EDMs were not included in this report due to limitations in EnergyPlus or Opt-E-Plus, lack of reliable input data, or the added simulation time that would have been required. Measures we feel deserve increased attention are:

- **Alternative HVAC systems.** For simplicity, we assumed that all HVAC needs were supplied with 10-ton DX RTUs. DX RTUs are by far the most common HVAC systems used in grocery stores, but they are not necessarily the best choice. Future studies could consider the use of centralized systems, radiant heating and cooling, thermal storage systems, ground source heat pumps, and other technologies. Also, to obtain true comparisons with a baseline building that uses RTUs, the dynamics of each system should be modeled more accurately, especially at part load conditions. This would require developing much more accurate input data for models of HVAC systems and their controls. Adding such capability would require a large effort, both from the Opt-E-Plus team, and in acquiring accurate measured data.

- **Integrated HVAC and refrigeration.** The heating loads in grocery stores, which are exacerbated by refrigerated cases, could be partially offset by using waste heat from the compressors for space heating. Several HVAC types could be used to do this. Such integration may be necessary to achieve 70% and 100% net site energy savings.
- **Air flow models.** Right now, our EnergyPlus models assume that air masses in different thermal zones are isolated from one another. Modeling air transfers between zones would increase the accuracy of our models and allow us to better study design features such as vestibules. For instance, infiltration through the front entrance is currently divided on an area-weighted basis between the vestibule and the main sales area, based on the assumption that the air would pass through the vestibule and into the main sales area. According to that division, most of the air infiltrating through the front entrance is applied directly to the main sales area. In reality, vestibules are equipped with dedicated HVAC units that precondition the air before it passes through to the rest of the store. A more accurate model (EnergyPlus's AirFlowNetwork) would allow us to capture the significance of using the vestibule to precondition infiltrated air.
- **Reduced static pressure drops via better RTU and ductwork design.** We did not undertake a detailed study of the range of possible internal and external static pressures, so we did not attempt to define an EDM along these lines. Industry feedback suggested that we may be able to reduce our total static pressure by 50%, but we have yet to verify that suggestion by matching it to available equipment. Reliable information about standard and best practice static pressures would be a welcome addition to the next study.
- **Direct and indirect evaporative cooling.** We attempted to model indirect evaporative cooling in the RTUs, but were unsatisfied with the modeling results. We could not dynamically model the effects of bypassing the indirect evaporative cooler when it was not needed, so we are uncertain of our previous finding (Hale et al. 2008a) that evaporative cooling should not be used in any climate zone. The EnergyPlus modeling methods and the input data need to be refined.
- **Alternative service hot water systems.** We did not model solar or instantaneous hot water systems. Including these technologies would require modifications to the Opt-E-Plus platform to handle sizing and design issues, and would only affect about 0.5% of baseline energy use.
- **Plug and process load EDMs.** Although a plug and process load EDM was included in the previous version of this report, it was removed from this year's analysis because there were too few credible inputs about performance and implementation cost. A detailed study of plug and process loads and their reduction measures in grocery stores should be undertaken to answer questions about realistic performance metrics and costs for possible EDMs.
- **Secondary loop refrigeration.** An emerging trend in commercial refrigeration is the use of a secondary refrigerant loop on the case side of the system. The primary driver for this change is the subsequent reduction in refrigerant charge. Whether these systems can be more energy efficient than traditional systems is unclear, but some studies show that they can be as efficient, and substantially reduce climate change and ozone-depleting effects.
- **Multiple compressor types.** The efficiency of compressors varies significantly with condensing temperature, and the shapes of compressor efficiency curves differ depending on the compressor type. The next grocery store study should develop the input data needed to model several types of compressors, determine which type should be used in which climate zone, and compare that determination to current practice.

- **Under-case HVAC return air.** Pulling HVAC return air under refrigerated cases is a common practice for reducing the amount of cold air that enters the refrigerated case isles. Reliable input data are needed to model this HVAC system feature and quantify its benefits.
- **Desiccant-based humidity control.** Unlike earlier work (Hale et al. 2008a), this TSD enforces a humidity set point using humidistats and reheat coils fed by DX condenser waste heat (superheat). The next step is to explore advanced dehumidification strategies such as desiccant-based humidity control.
- **Walk-in coolers and freezers.** A redesign of walk-in coolers and freezers would probably not save significant energy, but their quantity, distribution, and input data should be revisited.
- **Alternative business models.** If more groceries were delivered after being ordered online or over the phone, some sales space could be replaced with storage space, and some refrigerated cases could be replaced with walk-in cooler capacity. Alternatively, building grocery stores with smaller footprints provides faster shopping trips and less energy use at the expense of reducing customer choice. Such design measures are well beyond the scope of this study, but could have a large impact on grocery store design and sector energy efficiency.

We also recommend that the following model inputs be re-evaluated or validated:

- **Whole-building pressurization analysis.** The model inputs for infiltration and ERV are based on a whole-building pressurization analysis (see Section 3.3.3.5), which depends heavily on a number of simple assumptions. The EnergyPlus AirFlowNetwork should be used to determine the validity of those assumptions.
- **Infiltration.** The whole-building pressurization analysis (through which infiltration inputs were developed) was based on driving pressures associated with HVAC pressurization and wind speed. To strengthen the analysis, stack effect should be factored in. Stack effect was omitted from the current analysis because of its strong dependence on ambient temperature, which varies by seasonal and location. Updates will likely need to be made to EnergyPlus to accommodate stack effect analysis.

5.1.4 Search Algorithms

Opt-E-Plus currently uses a sequential search routine to approximate the Pareto front associated with two design objectives. This search algorithm has advantages of efficiency and dual-criteria optimization, but also has several drawbacks in the context of this study:

- The search routine is heuristic, and therefore not guaranteed to find the true Pareto curve.
- We were not interested in the Pareto curve per se, but in designs that achieve 50% energy savings cost effectively. Our computation time would have been better used fleshing out multiple designs that meet this criterion, rather than tracing out the entire Pareto front.
- The EDMs are all discrete choices. Continuous methods could be used to expedite the determination of design features by initially using continuous variables such as R-values, and only later determining the actual construction or product.

- There is no way to express or use uncertainty information such as cost or performance variable ranges.

The next generation of Opt-E-Plus should be equipped with better search routines that address varying numbers of objective functions (0, 1, 2, etc.), use continuous variables in early iterations, and propagate uncertainty information.

5.1.5 Advanced Energy Design Guide Format

The current AEDGs are meant to provide easily accessible design recommendations that can be incorporated into real-world projects. However, these guides do not respond to the needs and desires of specific projects, and are thus unable to provide truly integrated designs. If the development of low-energy design recommendations were automated with technologies such as Opt-E-Plus, it would be possible to offer direct Web- or software-based assistance to building projects. One possible path would be to use the TSD process to develop a list of acceptable EDMs for a given building type. An AEDG would then be a portal through which designers could select EDMs that are acceptable to their specific projects, enter basic geometric information, and obtain a customized set of recommendations.

6.0 Conclusions

This report finds that achieving 50% energy savings is possible for grocery stores in each U.S. climate zone. Reaching 50% is cost-effective in all climate zones, both in terms of capital costs and 5-TLCC. However, these findings depend on a willingness to put doors on a number of refrigerated cases—stores not willing to do this may be unable to reach high levels of energy efficiency cost effectively. Our findings confirm that ASHRAE 90.1-2007 provides energy savings over ASHRAE 90.1-2004, but subject to increased capital and lifetime costs. (Only in climate zone 8 did reduced energy use balance out the additional capital costs within the five-year analysis period.)

A methodology for identifying a diverse set of low-energy designs is introduced and applied in five climate zones. Eleven to thirteen models, each differing by the presence or absence of at least one type of EDM (for instance, increased wall insulation) were automatically identified for each climate zone. The algorithm also yields perturbation information on the cost and energy savings provided by EDM categories used in the original low-energy design. An equivalent PV metric is calculated based on these results; our intention is for this to be used as an alternative valuation of energy efficient design changes.

A number of modeling errors skewed the results of our original optimizations over the complete set of EDMs. The original results indicated that the low-energy models would require a larger initial capital investment than the corresponding baseline models and that the climate zone 1A and 2A stores would not be able to save enough energy to offset those higher capital costs within the five-year analysis period. By correcting the modeling errors and performing abbreviated optimization runs to determine which of ERV, DCV, and PV should actually be included in each low-energy model, we were able to show that 50% energy savings can be achieved cost effectively in terms of both lifetime and capital cost.

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

For both sector-wide studies and individual projects, the approach used in this study has several advantages: it allows for the exploration of thousands of different building design options in an efficient manner, and economic considerations are explicitly considered so that the most cost-efficient solutions can be identified. The design features explored by the analysis can be tailored to match the energy savings target and climate zone, and a new methodology for identifying multiple designs that meet a common target provides additional flexibility.

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Appendix A. Space Types and ASHRAE Standards

The mapping between our space types and ASHRAE Standards 62.1-1999 and 62.1-2004 is listed in Table A-1. The mapping between our spaces types and ASHRAE Standards 90.1-2004 and 90.1-2007 is listed in Table A-2.

Table A-1 Mapping Between Analysis Space Types and ASHRAE Standard 62.1

Space Type	Mapping to ASHRAE 62.1-1999	Mapping to ASHRAE 62.1-2004
Main Sales	Retail::Basement and street	Retail::Sales
Perimeter Sales	Retail::Basement and street	Retail::Sales
Produce	Retail::Basement and street	Retail::Sales
Deli	Food & Beverage::Kitchens	CUSTOM VALUE*
Bakery	Food & Beverage::Kitchens	CUSTOM VALUE*
Enclosed Office	Offices::Office space	Office Buildings::Office space
Meeting Room	Offices::Conference rooms	Offices::Conference/meeting
Dining Room	Food & Beverage::Dining rooms	Food & Beverage::Restaurant dining rooms
Restrooms	CUSTOM VALUE	CUSTOM VALUE
Mechanical Room	CUSTOM VALUE	CUSTOM VALUE
Corridor	Public Spaces::Corridors & utilities	General::Corridors
Vestibule	Public Spaces::Corridors & utilities	General::Corridors
Active Storage	Retail::Shipping and receiving	General::Storage rooms

Table A-2 Mapping Between Analysis Space Types and ASHRAE Standard 90.1

Space Type	Mapping to ASHRAE 90.1-2004	Mapping to ASHRAE 90.1-2007
Main Sales	Sales area	Sales area
Perimeter Sales	Sales area	Sales area
Produce	Sales area	Sales area
Deli	Food preparation	Food preparation
Bakery	Food preparation	Food preparation
Enclosed Office	Office-enclosed	Office-enclosed
Meeting Room	Conference/meeting/multi-purpose	Conference/meeting/multi-purpose
Dining Room	Dining area	Dining area
Restrooms	Restrooms	Restrooms
Mechanical Room	Electrical/mechanical	Electrical/mechanical
Corridor	Corridor/transition	Corridor/transition
Vestibule	Corridor/transition	Corridor/transition
Active Storage	Active Storage	Active Storage

Appendix B. Baseline Schedules

The following schedules are a combination of prototype characteristics, assumptions, and the retail building schedule sets available in ASHRAE 90.1-1989 (ASHRAE 1989). Schedules are presented as fractions of peak, unless otherwise noted. The entries for total hours/day, etc. are the equivalent number of peak hours during the given time period. For instance, the total lighting load for the year can be calculated by multiplying the peak load density by the value given for total hours/year.

B.1   Occupancy

The occupancy schedule for all zones, as described in Section 3.2.1.4.2, is shown in Table B-1.

Table B-1 Occupancy Schedule

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	0	0	1	0	0
2	0	0	1	0	0
3	0	0	1	0	0
4	0	0	1	0	0
5	0	0	1	0	0
6	0	0	1	0	0
7	0.10	0.10	1	0	0.10
8	0.10	0.10	1	0	0.10
9	0.20	0.20	1	0	0.10
10	0.50	0.50	1	0	0.10
11	0.50	0.60	1	0	0.20
12	0.70	0.80	1	0	0.20
13	0.70	0.80	1	0	0.40
14	0.70	0.80	1	0	0.40
15	0.70	0.80	1	0	0.40
16	0.80	0.80	1	0	0.40
17	0.70	0.80	1	0	0.40
18	0.50	0.60	1	0	0.20
19	0.50	0.20	1	0	0.10
20	0.30	0.20	1	0	0.10
21	0.30	0.20	1	0	0.10
22	0.30	0.10	1	0	0.10
23	0	0	1	0	0
24	0	0	1	0	0
Total Hours/Day	7.60	7.60	24.00	0.00	3.40
Total Hours/Week	49.00				

B.2 Lighting

Each zone in the baseline models uses the lighting schedule developed in Section 3.2.1.4.3 and shown in Table B-2.

Table B-2 Lighting Schedule

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	0.05	0.05	1	0	0.05
2	0.05	0.05	1	0	0.05
3	0.05	0.05	1	0	0.05
4	0.05	0.05	1	0	0.05
5	0.05	0.05	1	0	0.05
6	0.05	0.05	1	0	0.05
7	0.20	0.10	1	0	0.10
8	0.20	0.10	1	0	0.10
9	0.50	0.30	1	0	0.10
10	0.90	0.60	1	0	0.10
11	0.90	0.90	1	0	0.40
12	0.90	0.90	1	0	0.40
13	0.90	0.90	1	0	0.60
14	0.90	0.90	1	0	0.60
15	0.90	0.90	1	0	0.60
16	0.90	0.90	1	0	0.60
17	0.90	0.90	1	0	0.60
18	0.90	0.90	1	0	0.40
19	0.60	0.50	1	0	0.20
20	0.60	0.30	1	0	0.20
21	0.50	0.30	1	0	0.20
22	0.20	0.10	1	0	0.20
23	0.05	0.05	1	0	0.05
24	0.05	0.05	1	0	0.05
Total Hours/Day	11.30	9.90	24.00	0.00	5.80
Total Hours/Week	72.20				

B.3 Plug and Process Loads

Each zone in the baseline models uses the equipment schedules shown in Table B-3, which were developed in Section 3.2.1.4.4.

Table B-3 Plug and Process Load Schedule

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	0.20	0.15	1	0	0.15
2	0.20	0.15	1	0	0.15
3	0.20	0.15	1	0	0.15
4	0.20	0.15	1	0	0.15
5	0.20	0.15	1	0	0.15
6	0.20	0.15	1	0	0.15
7	0.40	0.30	1	0	0.30
8	0.40	0.30	1	0	0.30
9	0.70	0.50	1	0	0.30
10	0.90	0.80	1	0	0.30
11	0.90	0.90	1	0	0.60
12	0.90	0.90	1	0	0.60
13	0.90	0.90	1	0	0.80
14	0.90	0.90	1	0	0.80
15	0.90	0.90	1	0	0.80
16	0.90	0.90	1	0	0.80
17	0.90	0.90	1	0	0.80
18	0.90	0.90	1	0	0.60
19	0.80	0.70	1	0	0.40
20	0.80	0.50	1	0	0.40
21	0.70	0.50	1	0	0.40
22	0.40	0.30	1	0	0.40
23	0.20	0.15	1	0	0.15
24	0.20	0.15	1	0	0.15
Total Hours/Day	13.90	12.30	24.00	0.00	9.80
Total Hours/Week	91.60				

B.4 Infiltration and HVAC

The infiltration schedule is tied to the HVAC schedule in that it is on at peak value when the HVAC system is running. When the HVAC system is off, infiltration reduces to a fraction of peak value, based on changes in building pressurization and front entrance door opening frequency. The HVAC schedule is set to turn on one hour before occupancy each day to allow the system to bring the space conditions within operating limits during occupancy. The baseline model HVAC and infiltration schedules are listed in Table B-4 and Table B-5, respectively.

Table B-4 HVAC Schedule

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	1	1	1	1	1
7	1	1	1	1	1
8	1	1	1	1	1
9	1	1	1	1	1
10	1	1	1	1	1
11	1	1	1	1	1
12	1	1	1	1	1
13	1	1	1	1	1
14	1	1	1	1	1
15	1	1	1	1	1
16	1	1	1	1	1
17	1	1	1	1	1
18	1	1	1	1	1
19	1	1	1	1	1
20	1	1	1	1	1
21	1	1	1	1	1
22	1	1	1	1	1
23	0	0	0	0	0
24	0	0	0	0	0
Total Hours/Day	17.00	17.00	17.00	17.00	17.00
Total Hours/Week	119.00				

Table B-5 Infiltration Schedule

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	0.32	0.32	0.32	1	0.32
2	0.32	0.32	0.32	1	0.32
3	0.32	0.32	0.32	1	0.32
4	0.32	0.32	0.32	1	0.32
5	0.32	0.32	0.32	1	0.32
6	1.00	1.00	1.00	1	1.00
7	1.00	1.00	1.00	1	1.00
8	1.00	1.00	1.00	1	1.00
9	1.00	1.00	1.00	1	1.00
10	1.00	1.00	1.00	1	1.00
11	1.00	1.00	1.00	1	1.00
12	1.00	1.00	1.00	1	1.00
13	1.00	1.00	1.00	1	1.00
14	1.00	1.00	1.00	1	1.00
15	1.00	1.00	1.00	1	1.00
16	1.00	1.00	1.00	1	1.00
17	1.00	1.00	1.00	1	1.00
18	1.00	1.00	1.00	1	1.00
19	1.00	1.00	1.00	1	1.00
20	1.00	1.00	1.00	1	1.00
21	1.00	1.00	1.00	1	1.00
22	1.00	1.00	1.00	1	1.00
23	0.32	0.32	0.32	1	0.32
24	0.32	0.32	0.32	1	0.32
Total Hours/Day	19.24	19.24	19.24	24.00	19.24
Total Hours/Week	134.68				

B.5 Thermostat Set Points

Each zone in the baseline models uses the heating and cooling schedules shown in Table B-6 and Table B-7, respectively, which list temperatures in ºC. The HVAC systems have dual thermostatic control based on dry bulb temperature in the zones. The thermostat set points are 70ºF (21ºC) for heating and 75ºF (24ºC) for cooling. Thermostat setup to 86ºF (30ºC) and setback to 60.1ºF (15.6ºC) is included in the models.

Table B-6 Heating Set Point Schedule (ºC)

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	15.6	15.6	15.6	15.6	15.6
2	15.6	15.6	15.6	15.6	15.6
3	15.6	15.6	15.6	15.6	15.6
4	15.6	15.6	15.6	15.6	15.6
5	15.6	15.6	15.6	15.6	15.6
6	15.6	15.6	15.6	15.6	15.6
7	21.0	21.0	15.6	21.0	21.0
8	21.0	21.0	15.6	21.0	21.0
9	21.0	21.0	15.6	21.0	21.0
10	21.0	21.0	15.6	21.0	21.0
11	21.0	21.0	15.6	21.0	21.0
12	21.0	21.0	15.6	21.0	21.0
13	21.0	21.0	15.6	21.0	21.0
14	21.0	21.0	15.6	21.0	21.0
15	21.0	21.0	15.6	21.0	21.0
16	21.0	21.0	15.6	21.0	21.0
17	21.0	21.0	15.6	21.0	21.0
18	21.0	21.0	15.6	21.0	21.0
19	21.0	21.0	15.6	21.0	21.0
20	21.0	21.0	15.6	21.0	21.0
21	21.0	21.0	15.6	21.0	21.0
22	21.0	21.0	15.6	21.0	21.0
23	15.6	15.6	15.6	15.6	15.6
24	15.6	15.6	15.6	15.6	15.6

Table B-7 Cooling Set Point Schedule (ºC)

Hour	Weekdays	Saturdays	Summer Design	Winter Design	Sundays, Holidays, Other
1	30.0	30.0	30.0	30.0	30.0
2	30.0	30.0	30.0	30.0	30.0
3	30.0	30.0	30.0	30.0	30.0
4	30.0	30.0	30.0	30.0	30.0
5	30.0	30.0	30.0	30.0	30.0
6	30.0	30.0	30.0	30.0	30.0
7	24.0	24.0	24.0	30.0	24.0
8	24.0	24.0	24.0	30.0	24.0
9	24.0	24.0	24.0	30.0	24.0
10	24.0	24.0	24.0	30.0	24.0
11	24.0	24.0	24.0	30.0	24.0
12	24.0	24.0	24.0	30.0	24.0
13	24.0	24.0	24.0	30.0	24.0
14	24.0	24.0	24.0	30.0	24.0
15	24.0	24.0	24.0	30.0	24.0
16	24.0	24.0	24.0	30.0	24.0
17	24.0	24.0	24.0	30.0	24.0
18	24.0	24.0	24.0	30.0	24.0
19	24.0	24.0	24.0	30.0	24.0
20	24.0	24.0	24.0	30.0	24.0
21	24.0	24.0	24.0	30.0	24.0
22	24.0	24.0	24.0	30.0	24.0
23	30.0	30.0	30.0	30.0	30.0
24	30.0	30.0	30.0	30.0	30.0

B.6 Service Water Heating

The service water heating schedules are adopted from ASHRAE 90.1-1989, and are shown in Table B-8.

Table B-8 Service Water Heating Schedule

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

Appendix C. Metric Unit Tables

Table C-1 Baseline Exterior Wall Constructions (SI Units)

Properties	Climate Zone					
	1 and 2	3 and 4	5	6	7	8
Key	Baseline Wall Construction, No c.i.	Baseline Wall Construction, R-5.7 c.i.	Baseline Wall Construction, R-7.6 c.i.	Baseline Wall Construction, R-9.5 c.i.	Baseline Wall Construction, R-11.4 c.i.	Baseline Wall Construction, R-13.3 c.i.
U-Factor ($W/m^2 \cdot K$)	4.28	0.98	0.78	0.65	0.55	0.49
Capital Cost ($\$/m^2$)	$219.26	$226.69	$230.56	$233.36	$234.65	$235.30

Table C-2 Baseline Roof Constructions (SI Units)

Properties	Climate Zone	
	1 through 7	8
Key	Baseline Roof Construction, R-15 c.i.	Baseline Roof Construction, R-20 c.i.
U-Factor ($W/m^2 \cdot K$)	0.38	0.29
Capital Cost ($\$/m^2$)	$93.54	$98.06

Table C-3 Baseline Window Constructions (SI Units)

Properties	Climate Zone				
	1 and 2	3 and 4	5 and 6	7	8
Key	Baseline Window Construction	Baseline Window Construction	Baseline Window Construction	Baseline Window Construction	Baseline Window Construction
SHGC	0.250	0.390	0.490	0.490	0.490
VLT	0.250	0.495	0.622	0.490	0.490
U-Factor ($W/m^2 \cdot K$)	6.87	3.24	3.24	3.24	2.61
Capital Cost ($\$/m^2$)	$473.61	$508.38	$502.14	$508.38	$537.87
Fixed O&M Cost ($\$/m^2$)	$2.37	$2.37	$2.37	$2.37	$2.37

Table C-4 Baseline Skylight Constructions (SI Units)

Property	Climate Zone			
	1 through 3	4 through 6	7	8
Key	Baseline Skylight Construction	Baseline Skylight Construction	Baseline Skylight Construction	Baseline Skylight Construction
SHGC	0.36	0.490	0.490	0.490
VLT	0.457	0.622	0.490	0.490
U-Factor (Btu/h·ft^2·°F)	6.93	3.92	3.92	3.29
Capital Cost ($/ft^2)	$498.15	$508.38	$508.27	$549.39
Fixed O&M Cost ($/ft^2)	$2.37	$2.37	$2.37	$2.37

Table C-5 Pressures Acting on Exterior Walls During Operating Hours (SI Units)

Exterior Wall	Resultant Pressure Gradient	
	Magnitude (Pa)	Direction
Front	1.8	Infiltration
Back	9.8	Exfiltration
Side	4.0	Exfiltration

Table C-6 Pressures Acting on Exterior Walls During Non-Operating Hours (SI Units)

Exterior Wall	Resultant Pressure Gradient	
	Magnitude (Pa)	Direction
Front	5.8	Infiltration
Back	5.8	Exfiltration
Side	0	NA

Table C-7 Baseline Fan System Total Pressure Drops (SI Units)

Component	Package Rooftop, Constant Volume, 10-ton, 4000 cfm, no Economizer (Pa)	Package Rooftop, Constant Volume, 10-ton, 4000 cfm, with Economizer (Pa)
Internal Static Pressure Drop	167	189
External Static Pressure Drop	214	214
Total Static Pressure Drop	381	404

*Used friction rate of 25 Pa/30 m for the baseline duct pressure drop.

Table C-8 Baseline HVAC Models Summary (SI Units)

HVAC Input	ASHRAE 90.1-2004 Baseline PSZ DX, Furnace, No Economizer	ASHRAE 90.1-2004 Baseline PSZ DX, Furnace, With Economizer
System EER	10.1	10.1
COP of Compressor/Condenser	3.69	3.69
Heating Efficiency	80%	80%
Fan Power	1,245 W/(m^3/s)	1,245 W/(m^3/s)
Fan Static Pressure	381.1 Pa	403.5 Pa
Fan Efficiency	30.6%	32.4%
Economizers	None	Included
Capital Cost ($/kW cooling)	$456.20	$484.64
O&M Cost ($/kW cooling·yr)	$39.82	$39.82

Table C-9 Baseline Refrigerated Case Characteristics (SI Units)

Characteristic	Island Single-Deck Meat	Multi-Deck Dairy/Deli	Vertical Frozen Food with Doors	Island Single-Deck Ice Cream
Rated Capacity (W/m)	740	1442	517	712
Operating Temperature (°C)	-1.9	5.0	-18.6	-25.0
Latent Heat Ratio	0.361	0.241	0.061	0.147
Infiltration Ratio	0.686	0.579	0.152	0.412
Fan Power (W/m)	37.2	41.0	39.3	27.9
Lighting Power (W/m)	0	207	89	245
Anti-Sweat Heater Power (W/m)	36	0	249	130
Defrost Type	Time-off	Time-off	Electric with temperature termination	Electric with temperature termination
Defrost Power (W/m)	0	0	1261	992
Maximum Defrost Time (min)	45	42	46	60
Drip-Down Time (min)	8	8	15	15
Defrost Start Time(s)	6:00 a.m. 2:00 p.m. 10:00 p.m.	1:00 a.m. 7:00 a.m. 1:00 p.m. 7:00 p.m.	10:00 p.m.	10:00 p.m.
Restocking Load (W/m) and Schedule	62.5 from 1:00 p.m. to 4:00 p.m.	313 from 9:00 a.m. to 12:00 p.m.	15.4 from 6:00 p.m. to 9:00 p.m.	26.3 from 7:00 a.m. to 10:00 a.m.
Materials Cost ($/m)	$2,471	$1,913	$2,125	$2,539

Table C-10 Refrigerated Case Restocking Assumptions (SI Units)

Case Type	Case Volume/ft (m^3/m)	Volume Filled by Product (%)	Volume of Product Restocked (%)	Specific Heat of Product (kJ/kg·K)	Density of Product (kg/m^3)	Temp. Difference (°C)	Daily Restocking Load (W/m)
Island Single-Deck Meat	0.16	30	20	3.1	960	23.9	28.0
Multi-Deck Dairy/Deli	1.22	50	40	3.1	992	4.4	140.6
Vertical Frozen Food with Doors	1.25	50	5	2.1	912	2.8	6.9
Island Single-Deck Ice Cream	0.59	70	10	2.7	912	2.8	11.9

Table C-11 Exterior Wall EDMs (SI Units)

Insulation R-value, Nominal	Assembly U-Factor (W/m·K)	Construction Method	Insulation Material	Insulation Thickness (cm)	Capital Cost ($/$m^2$)
R-5.7 c.i.	0.996	Interior Insulation	Isocyanurate	3.3	$226.69
R-9.5 c.i.	0.598	Interior Insulation	Isocyanurate	5.6	$233.36
R-13.3 c.i.	0.427	Interior Insulation	Isocyanurate	7.9	$235.30
R-15.0 c.i.	0.302	Exterior Insulation	Polystyrene Extruded	7.6	$241.33
R-19.5 c.i.	0.244	Exterior Insulation	Polyisocyanurate	7.6	$244.88
R-22.5 c.i.	0.211	Brick Cavity	Polyurethane Foam	9.5	$305.16
R-28.5 c.i.	0.172	Brick Cavity	Polyurethane Foam	12.1	$310.32

Table C-12 Roof EDMs (SI Units)

EDM Key	U-Factor (W/m·K)	Capital Cost ($/m^2)
R-20 c.i.	0.288	$58.45
R-20 c.i. with cool roof	0.288	$58.45
R-25 c.i.	0.230	$62.65
R-25 c.i. with cool roof	0.230	$62.65
R-30 c.i.	0.189	$67.27
R-30 c.i. with cool roof	0.189	$67.27
R-35 c.i.	0.164	$71.47
R-35 c.i. with cool roof	0.164	$71.47
R-40 c.i.	0.130	$77.50
R-50 c.i.	0.114	$81.81
R-60 c.i.	0.091	$90.74
R-75 c.i.	0.076	$100.00
R-95 c.i.	0.062	$109.04

Table C-13 South Fenestration Construction EDMs (SI Units)

EDM Key	SHGC	VLT	U-Factor (W/m·K)	Capital Cost ($/m^2)	Fixed O&M Cost ($/m^2·yr)
Single pane with clear glass	0.810	0.881	6.13	$402.57	$2.26
Single pane with pyrolytic low-e	0.710	0.811	4.23	$438.09	$2.26
Double pane with low-e and argon	0.564	0.745	1.50	$473.61	$2.26
Double pane with low-e2 and argon	0.416	0.750	1.33	$544.65	$2.26
Double pane with low-e2 and tinted glass	0.282	0.550	1.64	$544.65	$2.26
Triple layer with low-e polyester film	0.355	0.535	1.22	$643.14	$2.26
Quadruple layer with low-e polyester films and krypton	0.461	0.624	0.77	$673.71	$2.26

Table C-14 Skylight Fenestration Construction EDMs (SI Units)

EDM Key	SHGC	VLT	U-Factor (W/m·K)	Capital Cost ($/m^2)	Fixed O&M Cost ($/m^2·yr)
Single pane with high solar gain	0.610	0.672	6.93	$508.27	$2.58
Single pane with medium solar gain	0.250	0.245	6.93	$551.33	$2.58
Single pane with low solar gain	0.190	0.174	6.93	$551.33	$2.58
Double pane with high solar gain	0.490	0.622	3.29	$491.70	$2.58
Double pane with low-e and high solar gain	0.460	0.584	2.56	$492.77	$2.58
Double pane with medium solar gain	0.390	0.495	3.29	$621.08	$2.58
Double pane with low-e and medium solar gain	0.320	0.406	2.56	$679.96	$2.58
Double pane with low solar gain	0.190	0.241	3.29	$633.24	$2.58
Double pane with low-e and low solar gain	0.190	0.240	2.56	$683.94	$2.58

Table C-15 Lighting Power Density EDMs (SI Units)

EDM Key	LPD (W/m^2)	Capital Cost ($/kW)	Capital Cost ($/m^2)	Fixed O&M Cost ($/kW·yr)	Fixed O&M Cost ($/m^2·yr)
Baseline	16.2	$6,996	$113.13	$831.40	$1.31
30% LPD reduction	11.3	$10,234	$115.82	$1,187.69	$1.31
47% LPD reduction	8.6	$13,653	$117.00	$947.98	$0.80

Table C-16 HVAC System EDMs (SI Units)

EDM Key	Cooling COP (Ratio)	Heating Efficiency (%)	Economizer	Motorized Damper	Fan Efficiency (%)	Fan Static Pressure (Pa)	Capital Cost ($/kW)	Fixed O&M Cost ($/kW·yr)
Baseline without economizer	3.69	80.0	No	No	30.6	381.1	$456.13	$39.87
10% increased COP	4.06	80.0	No	No	30.6	381.1	$473.60	$39.87
Baseline with economizer	3.69	80.0	Yes	Yes	32.4	403.5	$484.61	$39.87
20% increased COP	4.43	80.0	No	No	30.6	381.1	$491.38	$39.87
Baseline COP with efficient fan	3.69	80.0	No	No	63.0	381.1	$496.96	$39.87
10% increased COP with economizer	4.06	80.0	Yes	Yes	32.4	403.5	$502.08	$39.87
10% increased COP with efficient fan	4.06	80.0	No	No	63.0	381.1	$514.43	$39.87
20% increased COP with economizer	4.43	80.0	Yes	Yes	32.4	403.5	$519.86	$39.87
Baseline COP with economizer and efficient fan	3.69	80.0	Yes	Yes	64.8	403.5	$525.45	$39.87
20% increased COP with efficient fan	4.43	80.0	No	No	63.0	381.1	$532.21	$39.87
10% increased COP with economizer and efficient fan	4.06	80.0	Yes	Yes	64.8	403.5	$542.92	$39.87
20% increased COP with economizer and efficient fan	4.43	80.0	Yes	Yes	64.8	403.5	$561.28	$39.87

Table C-17 Energy Recovery EDMs (SI Units)

EDM Key	Sensible Effectiveness (%)	Latent Effectiveness (%)	Pressure Drop (Pa)	Capital Cost ($/unit)	Capital Cost ($)
Low effectiveness	60.0	50.0	105	$7,927	$15,854
High effectiveness	80.0	70.0	150	$11,465	$22,930

Table C-18 Dedicated Exhaust by Space Type (SI Units)

Space Type	Equipment	ASHRAE Classification	Quantity	ASHRAE Prescription	DEA (m^3/s)
Restroom	Toilet	Toilet	62.7 m^2	0.0053 (m^3/s)/m^2	0.33
Bakery	Rack Oven	Oven: Light Duty	2.1 m	0.31 (m^3/s)/m	0.66
Deli	Revolving Oven	Oven: Light Duty	0.8 m	0.31 (m^3/s)/m	0.25
Deli	Fryer	Fryer: Medium Duty	1.4 m	0.46 (m^3/s)/m	0.64
Total					1.88

Table C-19 Island Single-Deck Meat Case EDMs (SI Units)

Characteristic	Baseline	Electric Defrost	#1: Eff. Fans and A-S Controls	#1 with Electric Defrost	#2: #1 and Covered at Night	#2 with Electric Defrost	#3: #1 and Sliding Doors	#3 with Electric Defrost
Rated Capacity (W/m)	740	740	727	727	727	727	727	727
Operating Temperature (°C)	–1.9	–1.9	–1.9	–1.9	–1.9	–1.9	–1.9	–1.9
Latent Heat Ratio	0.361	0.361	0.367	0.367	0.367	0.367	0.367	0.367
Infiltration Ratio	0.686	0.686	0.698	0.698	0.698	0.698	0.698	0.698
Fan Power (W/m)	37.2	37.2	24.0	24.0	24.0	24.0	24.0	24.0
Lighting Power (W/m)	0	0	0	0	0	0	0	0
Anti-Sweat Heater Power (W/m)	35.5	35.5	35.5	35.5	35.5	35.5	76.6	76.6
Anti-Sweat Heater Control Method	None	None	Dewpoint Method	Dewpoint Method	Dewpoint Method	Dewpoint Method	Dewpoint Method	Dewpoint Method
Defrost Type	Time-off	Electric w/ Temp. Term.	Time-off	Electric w/ Temp. Term.	Time-off	Electric w/ Temp. Term.	Time-off	Electric w/ Temp. Term.
Defrost Power (W/m)	0	411	0	411	0	411	0	411
Maximum Defrost Time (min)	45	40	45	40	45	40	45	40
Drip-Down Time (min)	8	8	8	8	8	8	8	8
Defrost Start Time(s)	6:00 a.m. 2:00 p.m. 10:00 p.m.	6:00 a.m. 2:00 p.m. 10:00 p.m.	6:00 a.m. 2:00 p.m. 10:00 p.m.	6:00 a.m. 2:00 p.m. 10:00 p.m.	6:00 a.m. 2:00 p.m. 10:00 p.m.	6:00 a.m. 2:00 p.m. 10:00 p.m.	6:00 a.m. 2:00 p.m. 10:00 p.m.	6:00 a.m. 2:00 p.m. 10:00 p.m.
Restocking Load (W/m) and Schedule	62 from 1:00 p.m. to 4:00 p.m.	62 from 1:00 p.m. to 4:00 p.m.	62 from 1:00 p.m. to 4:00 p.m.	62 from 1:00 p.m. to 4:00 p.m.	62 from 1:00 p.m. to 4:00 p.m.	62 from 1:00 p.m. to 4:00 p.m.	62 from 1:00 p.m. to 4:00 p.m.	62 from 1:00 p.m. to 4:00 p.m.
Case Credit Schedule	All Times, 1.0	All Times, 1.0	All Times, 1.0	All Times, 1.0	Night, 0.24; Open Hrs, 1.0	Night, 0.24; Open Hrs, 1.0	Night, 0.19; Open Hrs, 0.20	Night, 0.19; Open Hrs, 0.20
Capital Cost ($/m)	$2,471.42	$2,487.32	$2,607.11	$2,624.13	$2,668.16	$2,684.07	$2,986.73	$3,002.64
Maintenance Cost ($/m·yr)	$0.00	$0.00	$0.00	$0.00	$60.69	$60.69	$0.00	$0.00

Table C-20 Multi-Deck Dairy/Deli Case EDMs (SI Units)

Characteristic	Baseline	Baseline with Electric Defrost	#1: Eff. Fans and Standard Lighting	#1 with Electric Defrost	Replace w/ Eff. Vertical Door Model
Rated Capacity (W/m)	1442	1442	1236	1236	262
Operating Temperature (°C)	5.0	5.0	5.0	5.0	2.8
Latent Heat Ratio	0.241	0.241	0.281	0.281	0.100
Infiltration Ratio	0.579	0.579	0.676	0.676	0.250
Fan Power (W/m)	41.0	41.0	19.1	19.1	12.1
Lighting Power (W/m)	207	207	23	23	59.7
Anti-Sweat Heater Power (W/m)	0	0	0	0	76.6
Anti-Sweat Heater Control Method	None	None	None	None	Dewpoint Method
Defrost Type	Time-off	Electric w/ Temp. Term.	Time-off	Electric w/ Temp. Term.	Electric w/ Temp. Term.
Defrost Power (W/m)	0	328	0	328	428
Maximum Defrost Time (min)	42	32	42	32	30
Drip-Down Time (min)	8	8	8	8	20
Defrost Start Time(s)	1:00 a.m., 7:00 a.m., 1:00 p.m., 7:00 p.m.	1:00 a.m., 7:00 a.m., 1:00 p.m., 7:00 p.m.	1:00 a.m., 7:00 a.m., 1:00 p.m., 7:00 p.m.	1:00 a.m., 7:00 a.m., 1:00 p.m., 7:00 p.m.	1:00 a.m.
Restocking Load (W/m) and Schedule	312.5 from 9:00 a.m. to 12:00 p.m.	312.5 from 9:00 a.m. to 12:00 p.m.	312.5 from 9:00 a.m. to 12:00 p.m.	312.5 from 9:00 a.m. to 12:00 p.m.	312.5 from 9:00 a.m. to 12:00 p.m.
Capital Cost ($/m)	$1,912.75	$1,953.01	$1,635.25	$1,675.51	$2,459.16

Table C-21 Vertical Frozen Food with Doors Case EDMs (SI Units)

Characteristic	Baseline	Baseline with Hot Gas Defrost	#1: Eff. Fans and A-S Controls	#1 with Hot Gas Defrost	#2: #1, Eff. A-S Heaters and LEDs	#2 with Hot Gas Defrost
Rated Capacity (W/m)	517	517	490	490	305	305
Operating Temperature (°C)	–18.6	–18.6	–18.6	–18.6	–18.6	–18.6
Latent Heat Ratio	0.061	0.061	0.064	0.064	0.103	0.103
Infiltration Ratio	0.152	0.152	0.160	0.160	0.257	0.257
Fan Power (W/m)	39.4	39.4	12.1	12.1	12.1	12.1
Lighting Power (W/m)	89.2	89.2	89.2	89.2	59.7	59.7
Anti-Sweat Heater Power (W/m)	249	249	249	249	93.4	93.4
Anti-Sweat Heater Control Method	None	None	Dewpoint Method	Dewpoint Method	Dewpoint Method	Dewpoint Method
Defrost Type	Electric w/ Temp. Term.	Hot Gas w/ Temp. Term.	Electric w/ Temp. Term.	Hot Gas w/ Temp. Term.	Electric w/ Temp. Term.	Hot Gas w/ Temp. Term.
Defrost Power (W/m)	1260	2395	1260	2395	1260	2395
Maximum Defrost Time (min)	46	24	46	24	46	24
Drip-Down Time (min)	15	15	15	15	15	15
Defrost Start Time(s)	10:00 p.m.	10:00 p.m.	10:00 p.m.	10:00 p.m.	10:00 p.m.	10:00 p.m.
Restocking Load (W/m) and Schedule	15.4 from 6:00 p.m. to 9:00 p.m.	15.4 from 6:00 p.m. to 9:00 p.m.	15.4 from 6:00 p.m. to 9:00 p.m.	15.4 from 6:00 p.m. to 9:00 p.m.	15.4 from 6:00 p.m. to 9:00 p.m.	15.4 from 6:00 p.m. to 9:00 p.m.
Capital Cost ($/m)	$2,125.02	$2,154.24	$2,240.35	$2,269.57	$2,635.25	$2,665.59

Table C-22 Island Single-Deck Ice Cream Case EDMs (SI Units)

Characteristic	Baseline	Baseline with Hot Gas Defrost	#1: Eff. Fans, A-S Control and No Lighting	#1 with Hot Gas Defrost	Replace with Eff. Vert. Model, Elec. Def.	Replace with Eff. Vert. Model, Hot Gas
Rated Capacity (W/m)	712	712	456	456	328	328
Operating Temperature (°C)	–25.0	–25.0	–25.0	–25.0	–21.4	–21.4
Total Length (m)	36.6	36.6	36.6	36.6	24.1	24.1
Latent Heat Ratio	0.147	0.147	0.230	0.230	0.111	0.111
Infiltration Ratio	0.412	0.412	0.643	0.643	0.280	0.280
Fan Power (W/m)	27.9	27.9	18.0	18.0	12.1	12.1
Lighting Power (W/m)	246	246	0	0	59.7	59.7
Anti-Sweat Heater Power (W/m)	130	130	130	130	93.4	93.4
Anti-Sweat Heater Control Method	None	None	Dewpoint Method	Dewpoint Method	Dewpoint Method	Dewpoint Method
Defrost Type	Electric w/ Temp. Term.	Hot Gas w/ Temp. Term.	Electric w/ Temp. Term.	Hot Gas w/ Temp. Term.	Electric w/ Temp. Term.	Hot Gas w/ Temp. Term.
Defrost Power (W/m)	992	2961	992	2961	1260	2395
Maximum Defrost Time (min)	60	20	60	20	46	24
Drip-Down Time (min)	15	15	15	15	15	15
Defrost Start Time(s)	10:00 p.m.	10:00 p.m.	10:00 p.m.	10:00 p.m.	10:00 p.m.	10:00 p.m.
Restocking Load (W/m) and Schedule	26.4 from 7:00 a.m. to 10:00 a.m.	26.4 from 7:00 a.m. to 10:00 a.m.	26.4 from 7:00 a.m. to 10:00 a.m.	26.4 from 7:00 a.m. to 10:00 a.m.	26.4 from 7:00 a.m. to 10:00 a.m.	26.4 from 7:00 a.m. to 10:00 a.m.
Capital Cost ($/m)	$2,539.17	$2,547.31	$2,235.31	$2,242.33	$2,635.25	$2,665.59

Appendix D. Energy Use Data by End Use

Table D-1 Energy Use Intensity Decomposed by End Use

Baseline and selected low-energy models only. All numbers are in kBtu/ft^2.

	Electricity							Natural Gas		
	PV Power	Cooling	Interior Lighting	Exterior Lighting	Plug Loads	Fans	Refrig.	Heating	Process Loads	Water Heating
1A Baseline	0.0	42.4	19.0	0.3	14.1	28.8	116.0	16.7	6.2	2.1
1A Low-Energy	-7.1	31.6	5.5	0.3	14.1	10.5	55.5	3.9	6.2	2.1
2A Baseline	0.0	35.9	19.0	0.3	14.1	37.9	110.0	32.4	6.2	2.7
2A Low-Energy	0.0	25.5	5.1	0.3	14.1	13.3	50.8	9.0	6.2	2.7
3A Baseline	0.0	13.6	19.0	0.3	14.1	17.6	104.0	52.5	6.2	3.2
3A Low-Energy	0.0	11.6	5.2	0.3	14.1	6.8	46.4	17.8	6.2	3.2
4A Baseline	0.0	10.9	19.0	0.3	14.1	17.8	101.0	73.7	6.2	3.7
4A Low-Energy	0.0	9.1	9.6	0.3	14.1	6.6	43.4	28.0	6.2	3.7
5A Baseline	0.0	7.3	19.0	0.3	14.1	18.9	98.6	88.6	6.2	4.0
5A Low-Energy	0.0	6.6	9.6	0.3	14.1	6.7	41.3	36.3	6.2	4.0
6A Baseline	0.0	6.7	19.0	0.3	14.1	19.5	97.6	105.0	6.2	4.3
6A Low-Energy	0.0	6.0	9.6	0.3	14.1	6.8	40.3	45.0	6.2	4.3
2B Baseline	0.0	11.4	19.0	0.3	14.1	16.6	109.0	28.2	6.2	2.4
2B Low-Energy	0.0	9.1	5.9	0.3	14.1	5.6	47.1	11.4	6.2	2.4
3B-CA Baseline	0.0	6.0	19.0	0.3	14.1	13.6	103.0	42.4	6.2	3.1
3B-CA Low-Energy	0.0	6.5	6.1	0.3	14.1	5.1	47.6	14.8	6.2	3.1
3B-NV Baseline	0.0	6.3	19.0	0.3	14.1	16.3	104.0	39.8	6.2	2.8
3B-NV Low-Energy	0.0	7.2	5.6	0.3	14.1	6.2	42.0	12.1	6.2	2.8
4B Baseline	0.0	3.4	19.0	0.3	14.1	18.2	99.2	58.6	6.2	3.6
4B Low-Energy	0.0	3.6	6.3	0.3	14.1	6.8	40.0	29.7	6.2	3.6
5B Baseline	0.0	2.5	19.0	0.3	14.1	19.7	96.6	74.3	6.2	4.0
5B Low-Energy	0.0	3.4	9.6	0.3	14.1	6.9	38.1	28.1	6.2	4.0
6B Baseline	0.0	1.5	19.0	0.3	14.1	20.6	94.6	96.1	6.2	4.4
6B Low-Energy	0.0	2.6	9.6	0.3	14.1	7.1	36.8	40.0	6.2	4.4
3C Baseline	0.0	1.5	19.0	0.3	14.1	14.0	98.2	63.1	6.2	3.6
3C Low-Energy	0.0	1.4	5.5	0.3	14.1	4.8	43.6	27.8	6.2	3.6
4C Baseline	0.0	1.3	19.0	0.3	14.1	15.2	96.5	79.9	6.2	3.9
4C Low-Energy	0.0	1.3	5.5	0.3	14.1	5.2	41.1	38.5	6.2	3.9
7A Baseline	0.0	3.3	19.0	0.3	14.1	19.5	94.0	127.0	6.2	4.9
7A Low-Energy	0.0	3.2	9.6	0.3	14.1	6.6	37.1	56.3	6.2	4.9
8A Baseline	0.0	1.7	19.0	0.3	14.1	21.1	92.0	177.0	6.2	5.5
8A Low-Energy	0.0	1.9	9.6	0.3	14.1	6.8	34.4	81.6	6.2	5.5

Table D-2 Percent of Energy Use Intensity Devoted to Each End Use

Baseline and selected low-energy models only. All numbers are a percent of Site EUI (sum of the corresponding row in Table D-1, excluding PV Power).

	Electricity							Natural Gas		
	PV Power	Cooling	Interior Lighting	Exterior Lighting	Plug Loads	Fans	Refrig.	Heating	Process Loads	Water Heating
1A Baseline	0.0	17.3	7.7	0.1	5.7	11.7	47.2	6.8	2.5	0.9
1A Low-Energy	-5.5	24.3	4.2	0.2	10.9	8.1	42.8	3.0	4.8	1.6
2A Baseline	0.0	13.9	7.4	0.1	5.5	14.7	42.6	12.5	2.4	1.0
2A Low-Energy	0.0	20.1	4.0	0.2	11.1	10.5	40.0	7.1	4.9	2.1
3A Baseline	0.0	5.9	8.2	0.1	6.1	7.6	45.1	22.8	2.7	1.4
3A Low-Energy	0.0	10.4	4.7	0.3	12.6	6.1	41.6	16.0	5.6	2.9
4A Baseline	0.0	4.4	7.7	0.1	5.7	7.2	40.9	29.9	2.5	1.5
4A Low-Energy	0.0	7.5	7.9	0.2	11.7	5.4	35.9	23.2	5.1	3.0
5A Baseline	0.0	2.8	7.4	0.1	5.5	7.4	38.4	34.5	2.4	1.6
5A Low-Energy	0.0	5.3	7.7	0.2	11.3	5.4	33.0	29.0	5.0	3.2
6A Baseline	0.0	2.5	7.0	0.1	5.2	7.1	35.8	38.5	2.3	1.6
6A Low-Energy	0.0	4.5	7.2	0.2	10.6	5.2	30.4	33.9	4.7	3.3
2B Baseline	0.0	5.5	9.2	0.1	6.8	8.0	52.6	13.6	3.0	1.1
2B Low-Energy	0.0	8.9	5.8	0.3	13.8	5.5	46.1	11.2	6.1	2.3
3B-CA Baseline	0.0	2.9	9.1	0.1	6.8	6.5	49.6	20.4	3.0	1.5
3B-CA Low-Energy	0.0	6.2	5.8	0.3	13.6	4.9	45.9	14.3	6.0	3.0
3B-NV Baseline	0.0	3.0	9.1	0.1	6.8	7.8	49.8	19.1	3.0	1.3
3B-NV Low-Energy	0.0	7.5	5.8	0.3	14.6	6.4	43.6	12.5	6.4	2.9
4B Baseline	0.0	1.5	8.5	0.1	6.3	8.2	44.6	26.3	2.8	1.6
4B Low-Energy	0.0	3.2	5.7	0.3	12.8	6.1	36.2	26.9	5.6	3.2
5B Baseline	0.0	1.1	8.0	0.1	6.0	8.3	40.8	31.4	2.6	1.7
5B Low-Energy	0.0	3.1	8.6	0.3	12.7	6.2	34.4	25.4	5.6	3.6
6B Baseline	0.0	0.6	7.4	0.1	5.5	8.0	36.8	37.4	2.4	1.7
6B Low-Energy	0.0	2.1	7.9	0.2	11.6	5.9	30.4	33.0	5.1	3.6
3C Baseline	0.0	0.7	8.6	0.1	6.4	6.4	44.6	28.7	2.8	1.6
3C Low-Energy	0.0	1.3	5.1	0.3	13.2	4.4	40.7	25.9	5.8	3.3
4C Baseline	0.0	0.6	8.0	0.1	6.0	6.4	40.8	33.8	2.6	1.6
4C Low-Energy	0.0	1.1	4.7	0.2	12.2	4.5	35.4	33.2	5.4	3.3
7A Baseline	0.0	1.2	6.6	0.1	4.9	6.8	32.6	44.1	2.2	1.7
7A Low-Energy	0.0	2.3	6.9	0.2	10.2	4.8	26.8	40.7	4.5	3.5
8A Baseline	0.0	0.5	5.6	0.1	4.2	6.3	27.3	52.5	1.8	1.6
8A Low-Energy	0.0	1.2	6.0	0.2	8.8	4.2	21.4	50.9	3.9	3.4

Appendix E. Alternative Low-Energy Model and Sensitivity Analysis Results

Please see Section 4.3.1.1 for an explanation of the figures and tables that follow.

E.1 Climate Zone 1A (Miami, Florida)

Computational Effort. Original search: 2,681 EnergyPlus simulations, 39 days of CPU time. Enumeration of additional models: 12 new searches; 4,511 new simulations; 397 total and 376 new simulations per search on average.

Alternative Low-Energy Models

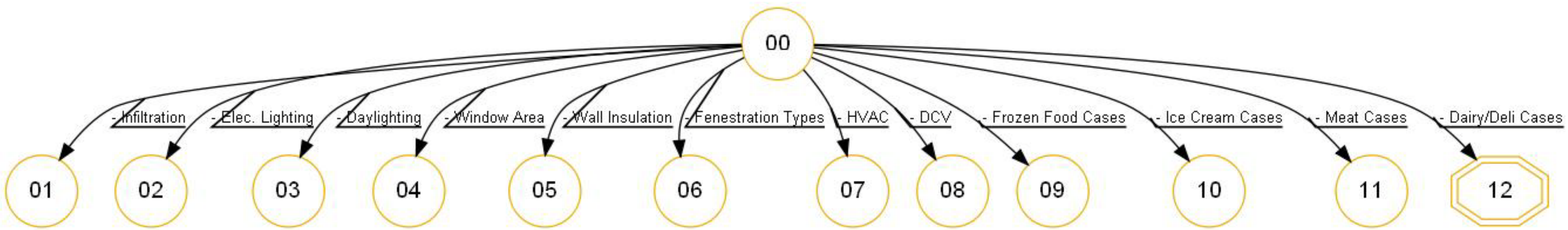

Figure E-1 Visualization of original and alternative low-energy models for the Miami, Florida, grocery store

Node 00 represents the original low-energy model. The other nodes represent the result of searches formed by taking Node 00 and removing the indicated strategy. Models that include PV are in gold. Any models that do not reach the 50% energy savings goal are indicated by octagons.

Table E-1 Summary of the Miami, Florida, Low-Energy Models

Node numbers correspond to Figure E-1. An 'X' under a strategy name indicates that the strategy is used in the model.

Node	Infiltration	Elec. Lighting	Daylighting	Window Area	Wall Insulation	Roof Insulation	Fenestration Types	HVAC	DCV	ERV	Frozen Food Cases	Ice Cream Cases	Meat Cases	Dairy/Deli Cases	Net Site Energy		PV Energy		Lifetime Cost		Capital Cost		Peak Demand (kW)	Energy Savings (%)
															MJ/^{2}·yr	kBtu/ft^{2}·yr	MJ/m^{2}·yr	kBtu/ft^{2}·yr	\$/m^{2}	\$/ft^{2}	\$/m^{2}	\$/ft^{2}		
00	X	X	X	X	X		X	X	X		X	X	X	X	1,392	122.5	81	7.1	1,713	159.18	1,497	139.04	284	50.0
01		X	X	X	X		X	X	X		X	X	X	X	1,392	122.5	126	11.1	1,788	166.12	1,571	145.96	290	50.0
02	X		X	X	X		X	X	X		X	X	X	X	1,392	122.5	200	17.6	1,953	181.45	1,729	160.6	327	50.0
03	X	X		X	X		X	X	X		X	X	X	X	1,392	122.5	142	12.5	1,811	168.26	1,594	148.07	295	50.0
04	X	X	X		X		X	X	X		X	X	X	X	1,392	122.5	82	7.2	1,720	159.83	1,503	139.67	289	50.0
05	X	X	X	X			X	X	X		X	X	X	X	1,392	122.5	114	10	1,733	160.99	1,515	140.74	294	50.0
06	X	X	X	X	X			X	X		X	X	X	X	1,392	122.5	73	6.4	1,707	158.56	1,490	138.42	284	50.0
07	X	X	X	X	X		X		X		X	X	X	X	1,392	122.5	288	25.3	2,078	193.03	1,856	172.44	328	50.0
08	X	X	X	X	X		X	X			X	X	X	X	1,392	122.5	115	10.1	1,765	163.95	1,551	144.05	294	50.0
09	X	X	X	X	X		X	X	X			X	X	X	1,392	122.5	317	27.9	2,121	197	1,901	176.62	309	50.0
10	X	X	X	X	X		X	X	X		X		X	X	1,392	122.5	139	12.3	1,819	169.01	1,602	148.81	294	50.0
11	X	X	X	X	X		X	X	X		X	X		X	1,392	122.5	132	11.7	1,792	166.5	1,576	146.45	290	50.0
12	X	X	X	X	X		X	X	X		X	X	X		1,578	138.9	332	29.2	2,158	200.53	1,925	178.86	344	43.3

Sensitivity Analysis by Strategy

Table E-2 Sensitivity Analysis for the Strategies Used in the Selected Low-Energy Model for Miami, Florida

Savings numbers are calculated between the selected low-energy model (with PV removed as necessary), and the model created by removing the indicated strategy. Equivalent PV areas are calculated assuming a 0.1 cell efficiency and a 0.9 inverter efficiency, and the EnergyPlus algorithm for determining the annual amount of electricity produced given building geometry and local weather conditions.

Strategy	Search No.	EUI Savings		Lifetime Cost Savings		Capital Cost Savings		Equivalent PV	
		MJ/m²·yr	kBtu/ft²·yr	$/m²	$/ft²	$/m²	$/ft²	m²	ft²
Infiltration	01	67.6	5.95	8.11	0.75	0.54	0.05	481.0	5,177
Elec. Lighting	02	132.9	11.69	36.59	3.40	16.59	1.54	945.9	10,181
Daylighting	03	60.7	5.35	–7.25	–0.67	–15.31	–1.42	432.4	4,654
Window Area	04	4.1	0.36	4.22	0.39	3.65	0.34	29.5	317
Wall Insulation	05	33.4	2.94	–35.99	–3.34	–40.43	–3.76	237.6	2,558
Fenestration Types	06	5.8	0.51	–0.66	–0.06	–1.19	–0.11	41.5	446
HVAC	07	207.2	18.23	20.78	1.93	–5.49	–0.51	1,474.6	15,872
DCV	08	33.7	2.97	–5.10	–0.47	–5.34	–0.50	240.1	2,585
Frozen Food Cases	09	236.5	20.81	14.33	1.33	–12.14	–1.13	1,683.7	18,123
Ice Cream Cases	10	57.9	5.10	9.59	0.89	3.27	0.30	412.3	4,438
Meat Cases	11	62.9	5.53	–0.49	–0.05	–6.09	–0.57	447.6	4,817
Dairy/Deli Cases	12	466.0	41.01	34.33	3.19	–8.22	–0.76	3,316.9	35,702

E.2 Climate Zone 3B-NV (Las Vegas, Nevada)

Computational Effort. Original search: 2,852 EnergyPlus simulations, 30 days of CPU time. Enumeration of additional models: 11 new searches; 3,716 new simulations; 350 total and 338 new simulations per search on average.

Alternative Low-Energy Models

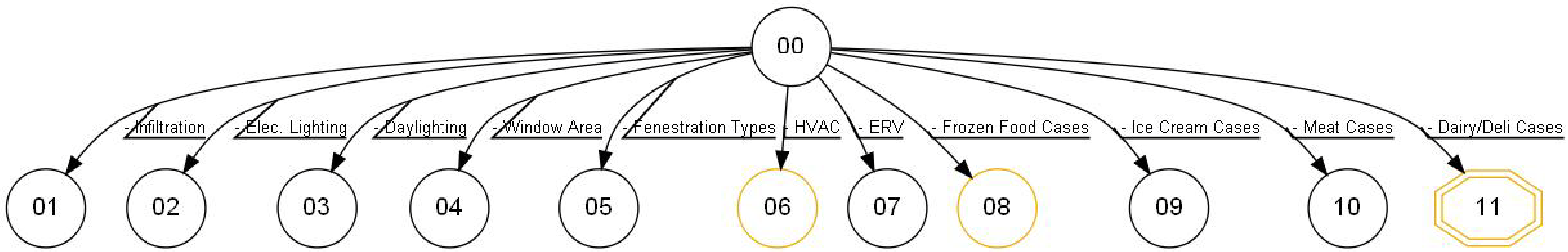

Figure E-2 Visualization of original and alternative low-energy models for the Las Vegas, Nevada, grocery store

Node 00 represents the original low-energy model. The other nodes represent the result of searches formed by taking Node 00 and removing the indicated strategy. Models that include PV are in gold. Any models that do not reach the 50% energy savings goal are indicated by octagons.

Table E-3 Summary of the Las Vegas, Nevada, Low-Energy Models

Node numbers correspond to Figure E-2. An 'X' under a strategy name indicates that the strategy is used in the model.

Node	Infiltration	Elec. Lighting	Daylighting	Window Area	Wall Insulation	Roof Insulation	Fenestration Types	HVAC	DCV	ERV	Frozen Food Cases	Ice Cream Cases	Meat Cases	Dairy/Deli Cases	Net Site Energy		PV Energy		Lifetime Cost		Capital Cost		Peak Demand (kW)	Energy Savings (%)
															$MJ/m^2 \cdot yr$	$kBtu/ft^2 \cdot yr$	$MJ/m^2 \cdot yr$	$kBtu/ft^2 \cdot yr$	$\$/m^2$	$\$/ft^2$	$\$/m^2$	$\$/ft^2$		
00	X	X	X	X			X	X		X	X	X	X	X	1,095	96.4	0	0	1,538	142.90	1,367	126.97	235	53.9
01		X	X	X			X	X		X	X	X	X	X	1,119	98.4	0	0	1,534	142.47	1,360	126.38	243	52.9
02	X		X	X			X	X		X	X	X	X	X	1,148	101.0	0	0	1,541	143.16	1,359	126.21	249	51.6
03	X	X		X			X	X		X	X	X	X	X	1,138	100.2	0	0	1,515	140.73	1,338	124.29	252	52.1
04	X	X	X				X	X		X	X	X	X	X	1,099	96.7	0	0	1,544	143.44	1,372	127.45	237	53.7
05	X	X	X	X				X		X	X	X	X	X	1,111	97.8	0	0	1,541	143.14	1,368	127.11	244	53.2
06	X	X	X	X			X			X	X	X	X	X	1,187	104.4	42	3.7	1,612	149.75	1,432	133.02	249	50.0
07	X	X	X	X			X	X			X	X	X	X	1,174	103.3	0	0	1,473	136.81	1,296	120.43	241	50.6
08	X	X	X	X			X	X		X		X	X	X	1,187	104.4	143	12.6	1,789	166.20	1,604	149.06	247	50.0
09	X	X	X	X			X	X		X	X		X	X	1,155	101.6	0	0	1,547	143.76	1,370	127.23	243	51.4
10	X	X	X	X			X	X		X	X	X		X	1,169	102.9	0	0	1,568	145.67	1,390	129.16	229	50.7
11	X	X	X	X			X	X		X	X	X	X		1,199	105.6	385	33.9	2,146	199.34	1,970	182.99	254	49.5

Sensitivity Analysis by Strategy

Table E-4 Sensitivity Analysis for the Strategies used in the Selected Low-Energy Model for Las Vegas, Nevada

Savings numbers are calculated between the selected low-energy model (with PV removed as necessary), and the model created by removing the indicated strategy. Equivalent PV areas are calculated assuming 0.1 cell efficiency and a 0.9 inverter efficiency, and the EnergyPlus algorithm for determining the annual amount of electricity produced given building geometry and local weather conditions.

Strategy	Search No.	EUI Savings		Lifetime Cost Savings		Capital Cost Savings		Equivalent PV	
		$MJ/m^2 \cdot yr$	$kBtu/ft^2 \cdot yr$	$\$/m^2$	$\$/ft^2$	$\$/m^2$	$\$/ft^2$	m^2	ft^2
Infiltration	01	23.5	2.07	-4.59	-0.43	-6.31	-0.59	141.5	1,523
Elec. Lighting	02	52.7	4.64	2.74	0.25	-8.10	-0.75	317.3	3,415
Daylighting	03	43.0	3.78	-23.40	-2.17	-28.83	-2.68	258.7	2,784
Window Area	04	3.7	0.32	5.85	0.54	5.15	0.48	22.2	239
Fenestration Types	05	16.3	1.43	2.56	0.24	1.58	0.15	98.0	1,055
HVAC	06	136.0	11.96	11.27	1.05	-1.98	-0.18	818.5	8,810
ERV	07	78.5	6.91	-65.56	-6.09	-70.34	-6.53	472.9	5,090
Frozen Food Cases	08	263.0	23.14	17.16	1.59	-12.26	-1.14	1,583.2	17,041
Ice Cream Cases	09	59.5	5.24	9.31	0.86	2.85	0.26	358.4	3,858
Meat Cases	10	100.4	8.84	0.12	0.01	-7.83	-0.73	604.7	6,508
Dairy/Deli Cases	11	521.9	45.93	37.95	3.53	-7.77	-0.72	3,142.0	33,820

E.3 Climate Zone 4C (Seattle, Washington)

Computational Effort. Original search: 2,852 EnergyPlus simulations, 30 days of CPU time. Enumeration of additional models: 13 new searches; 1,808 new simulations; 154 total and 139 new simulations per search on average.

Alternative Low-Energy Models

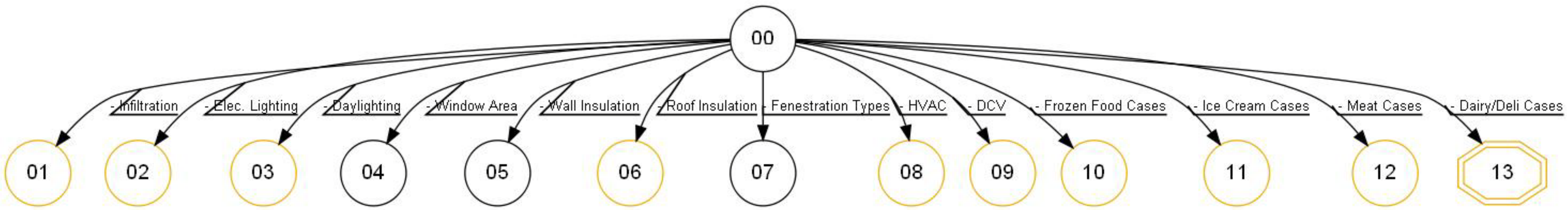

Figure E-3 Visualization of original and alternative low-energy models for the Seattle, Washington, grocery store

Node 00 represents the original low-energy model. The other nodes represent the result of searches formed by taking Node 00 and removing the indicated strategy. Models that include PV are in gold. Any models that do not reach the 50% energy savings goal are indicated by octagons.

Table E-5 Summary of the Seattle, Washington, Low-Energy Models

Node numbers correspond to Figure E-3. An 'X' under a strategy name indicates that the strategy is used in the model.

Node	Infiltration	Elec. Lighting	Daylighting	Window Area	Wall Insulation	Roof Insulation	Fenestration Types	HVAC	DCV	ERV	Frozen Food Cases	Ice Cream Cases	Meat Cases	Dairy/Deli Cases	Net Site Energy		PV Energy		Lifetime Cost		Capital Cost		Peak Demand (kW)	Energy Savings (%)
															$MJ/m^2 \cdot yr$	$kBtu/ft^2 \cdot yr$	$MJ/m^2 \cdot yr$	$kBtu/ft^2 \cdot yr$	$\$/m^2$	$\$/ft^2$	$\$/m^2$	$\$/ft^2$		
00	X	X	X	X	X	X	X	X	X		X	X	X	X	1,318	116.0	0	0.0	1,593	148.02	1,414	131.37	202	50.9
01		X	X	X	X	X	X	X	X		X	X	X	X	1,342	118.1	25	2.2	1,656	153.82	1,476	137.13	189	50.0
02	X		X	X	X	X	X	X	X		X	X	X	X	1,342	118.1	2	0.2	1,605	149.15	1,418	131.72	213	50.0
03	X	X		X	X	X	X	X	X		X	X	X	X	1,342	118.1	11	1.0	1,602	148.80	1,419	131.79	215	50.0
04	X	X	X		X	X	X	X	X		X	X	X	X	1,317	115.9	0	0.0	1,597	148.37	1,418	131.70	206	50.9
05	X	X	X	X		X	X	X	X		X	X	X	X	1,341	118.0	0	0.0	1,556	144.52	1,375	127.72	204	50.0
06	X	X	X	X	X		X	X	X		X	X	X	X	1,342	118.1	17	1.5	1,564	145.32	1,384	128.61	195	50.0
07	X	X	X	X	X	X		X	X		X	X	X	X	1,331	117.1	0	0.0	1,595	148.22	1,416	131.52	199	50.4
08	X	X	X	X	X	X	X		X		X	X	X	X	1,342	118.1	4	0.3	1,606	149.22	1,421	132.06	221	50.0
09	X	X	X	X	X	X	X	X			X	X	X	X	1,342	118.1	4	0.4	1,602	148.86	1,423	132.22	200	50.0
10	X	X	X	X	X	X	X	X	X			X	X	X	1,342	118.1	214	18.8	2,128	197.68	1,945	180.66	206	50.0
11	X	X	X	X	X	X	X	X	X		X		X	X	1,342	118.1	35	3.0	1,686	156.66	1,505	139.82	193	50.0
12	X	X	X	X	X	X	X	X	X		X	X		X	1,342	118.1	108	9.5	1,857	172.50	1,680	156.07	185	50.0
13	X	X	X	X	X	X	X	X	X		X	X	X		1,727	152.0	226	19.9	2,212	205.51	2,005	186.25	211	35.7

Sensitivity Analysis by Strategy

Table E-6 Sensitivity Analysis for the Strategies Used in the Selected Low-Energy Model for Seattle, Washington

Savings numbers are calculated between the selected low-energy model (with PV removed as necessary), and the model created by removing the indicated strategy. Equivalent PV areas are calculated assuming a 0.1 cell efficiency and a 0.9 inverter efficiency, and the EnergyPlus algorithm for determining the annual amount of electricity produced given building geometry and local weather conditions.

Strategy	Search No.	EUI Savings		Lifetime Cost Savings		Capital Cost Savings		Equivalent PV	
		$MJ/m^2·yr$	$kBtu/ft^2·yr$	$\$/m^2$	$\$/ft^2$	$\$/m^2$	$\$/ft^2$	m^2	ft^2
Infiltration	01	48.8	4.29	2.33	0.22	–1.02	–0.09	500.7	5,389
Elec. Lighting	02	26.3	2.31	6.52	0.61	–2.17	–0.20	269.8	2,904
Daylighting	03	35.1	3.09	–19.62	–1.82	–24.98	–2.32	360.3	3,878
Window Area	04	–0.9	–0.08	3.78	0.35	3.57	0.33	–9.1	–98
Wall Insulation	05	23.1	2.03	–37.72	–3.50	–39.28	–3.65	236.9	2,550
Roof Insulation	06	41.0	3.60	–70.21	–6.52	–72.90	–6.77	420.4	4,525
Fenestration Types	07	12.8	1.12	2.10	0.19	1.57	0.15	131.2	1,412
HVAC	08	27.7	2.43	3.98	0.37	–2.03	–0.19	283.9	3,056
DCV	09	28.3	2.49	–1.49	–0.14	–1.95	–0.18	290.9	3,131
Frozen Food Cases	10	237.7	20.91	14.24	1.32	–12.24	–1.14	2,439.4	26,257
Ice Cream Cases	11	58.6	5.16	9.08	0.84	2.90	0.27	601.6	6,475
Meat Cases	12	131.8	11.60	1.03	0.10	–8.05	–0.75	1,352.9	14,562
Dairy/Deli Cases	13	641.8	56.48	45.89	4.26	–6.20	–0.58	6,587.5	70,908

E.4 Climate Zone 5A (Chicago, Illinois)

Computational Effort. Original search: 2,929 EnergyPlus simulations, 31 days of CPU time. Enumeration of additional models: 11 new searches; 6,580 new simulations; 643 total and 598 new simulations per search on average.

Alternative Low-Energy Models

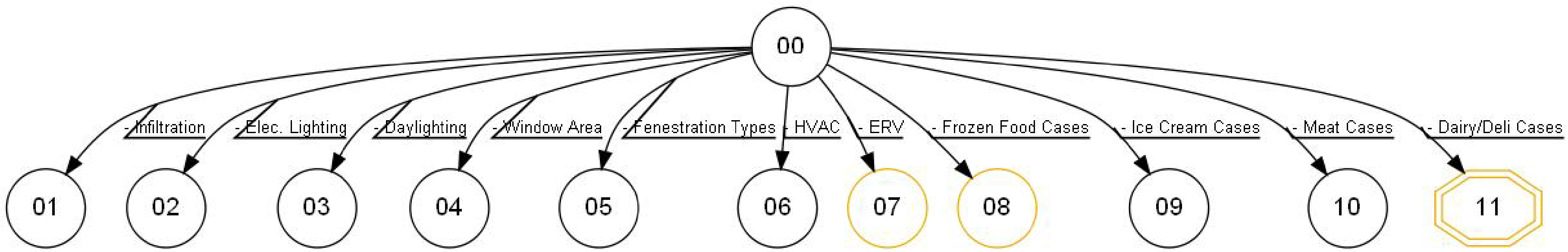

Figure E-4 Visualization of original and alternative low-energy models for the Chicago, Illinois, grocery store

Node 00 represents the original low-energy model. The other nodes represent the result of searches formed by taking Node 00 and removing the indicated strategy. Models that include PV are in gold. Any models that do not reach the 50% energy savings goal are indicated by octagons.

Table E-7 Summary of the Chicago, Illinois Low-Energy Models

Node numbers correspond to Figure E-4. An 'X' under a strategy name indicates that the strategy is used in the model.

Node	Infiltration	Elec. Lighting	Daylighting	Window Area	Wall Insulation	Roof Insulation	Fenestration Types	HVAC	DCV	ERV	Frozen Food Cases	Ice Cream Cases	Meat Cases	Dairy/Deli Cases	Net Site Energy		PV Energy		Lifetime Cost		Capital Cost		Peak Demand (kW)	Energy Savings (%)
															$MJ/m^2 \cdot yr$	$kBtu/ft^2 \cdot yr$	$MJ/m^2 \cdot yr$	$kBtu/ft^2 \cdot yr$	$\$/m^2$	$\$/ft^2$	$\$/m^2$	$\$/ft^2$		
00	X	X	X	X			X	X		X	X	X	X	X	1,421	125.0	0	0.0	1,546	143.59	1,352	125.59	282	51.3
01		X	X	X			X	X		X	X	X	X	X	1,419	124.9	0	0.0	1,576	146.37	1,381	128.30	289	51.4
02	X		X	X			X	X		X	X	X	X	X	1,436	126.3	0	0.0	1,567	145.60	1,367	127.03	278	50.8
03	X	X		X			X	X		X	X	X	X	X	1,424	125.3	0	0.0	1,546	143.60	1,352	125.56	283	51.2
04	X	X	X				X	X		X	X	X	X	X	1,420	125.0	0	0.0	1,551	144.10	1,357	126.07	281	51.4
05	X	X	X	X				X		X	X	X	X	X	1,426	125.5	0	0.0	1,546	143.66	1,352	125.63	281	51.2
06	X	X	X	X			X			X	X	X	X	X	1,407	123.8	0	0.0	1,579	146.73	1,379	128.12	314	51.8
07	X	X	X	X	X	X	X	X	X		X	X	X	X	1,460	128.4	26	2.3	1,676	155.72	1,484	137.91	237	50.0
08	X	X	X	X	X	X	X	X		X		X	X	X	1,460	128.5	26	2.2	1,772	164.65	1,568	145.70	268	50.0
09	X	X	X	X			X	X		X	X		X	X	1,407	123.8	0	0.0	1,582	146.99	1,386	128.78	289	51.8
10	X	X	X	X			X	X		X	X	X		X	1,435	126.3	0	0.0	1,591	147.84	1,398	129.88	265	50.8
11	X	X	X	X	X	X	X	X		X	X	X	X		1,582	139.2	265	23.3	2,292	212.96	2,090	194.21	301	45.8

Sensitivity Analysis by Strategy

Table E-8 Sensitivity Analysis for the Strategies Used in the Selected Low-Energy Model for Chicago, Illinois

Savings numbers are calculated between the selected low-energy model (with PV removed as necessary), and the model created by removing the indicated strategy. Equivalent PV areas are calculated assuming a 0.1 cell efficiency and a 0.9 inverter efficiency, and the EnergyPlus algorithm for determining the annual amount of electricity produced given building geometry and local weather conditions.

Strategy	Search No.	EUI Savings		Lifetime Cost Savings		Capital Cost Savings		Equivalent PV	
		MJ/m²·yr	kBtu/ft²·yr	\$/m²	\$/ft²	\$/m²	\$/ft²	m²	ft²
Infiltration	00	71.5	6.29	2.70	0.25	–2.26	–0.21	626.0	6,738
Elec. Lighting	01	60.4	5.32	11.19	1.04	–2.19	–0.20	528.9	5,693
Daylighting	02	2.6	0.23	0.13	0.01	–0.31	–0.03	23.1	249
Window Area	03	–1.0	–0.09	5.50	0.51	5.18	0.48	–8.5	–91
Fenestration Types	04	5.0	0.44	0.78	0.07	0.47	0.04	43.6	469
HVAC	05	55.2	4.86	6.32	0.59	–4.11	–0.38	483.5	5,204
ERV	06	219.7	19.34	–58.38	–5.42	–70.34	–6.53	1,923.1	20,700
Frozen Food Cases	07	244.6	21.52	14.99	1.39	–12.25	–1.14	2,140.5	23,040
Ice Cream Cases	08	58.3	5.13	9.13	0.85	2.94	0.27	510.1	5,491
Meat Cases	09	120.2	10.58	0.69	0.06	–7.99	–0.74	1,051.8	11,321
Dairy/Deli Cases	10	622.1	54.74	41.31	3.84	–9.51	–0.88	5,443.9	58,598

E.5 Climate Zone 8 (Fairbanks, Alaska)

Computational Effort. Original search: 3,992 EnergyPlus simulations, 29 days of CPU time. Enumeration of additional models: 12 new searches; 11,225 new simulations; 999 total and 935 new simulations per search on average.

Alternative Low-Energy Models

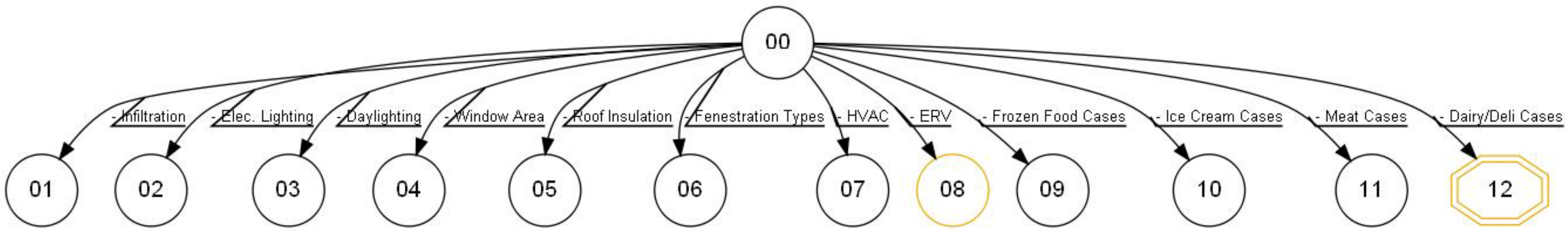

Figure E-5 Visualization of original and alternative low-energy models for the Fairbanks, Alaska, grocery store

Node 00 represents the original low-energy model. The other nodes represent the result of searches formed by taking Node 00 and removing the indicated strategy. Models that include PV are in gold. Any models that do not reach the 50% energy savings goal are indicated by octagons.

Table E-9 Summary of the Fairbanks, Alaska, Low Energy Models

Node numbers correspond to Figure E-5. An 'X' under a strategy name indicates that the strategy is used in the model.

Node	Infiltration	Elec. Lighting	Daylighting	Window Area	Wall Insulation	Roof Insulation	Fenestration Types	HVAC	DCV	ERV	Frozen Food Cases	Ice Cream Cases	Meat Cases	Dairy/Deli Cases	Net Site Energy		PV Energy		Lifetime Cost		Capital Cost		Peak Demand (kW)	Energy Savings (%)
															$MJ/m^2 \cdot yr$	$kBtu/ft^2 \cdot yr$	$MJ/m^2 \cdot yr$	$kBtu/ft^2 \cdot yr$	$\$/m^2$	$\$/ft^2$	$\$/m^2$	$\$/ft^2$		
00	X	X	X	X		X	X	X		X	X	X	X	X	1,821	160.2	0	0.0	1,613	149.87	1,409	130.92	216	52.4
01		X	X	X		X	X	X		X	X	X	X	X	1,787	157.3	0	0.0	1,647	152.99	1,444	134.16	218	53.3
02	X		X	X		X	X	X		X	X	X	X	X	1,853	163.1	0	0.0	1,623	150.76	1,407	130.72	239	51.5
03	X	X		X		X	X	X		X	X	X	X	X	1,823	160.4	0	0.0	1,613	149.88	1,409	130.89	214	52.3
04	X	X	X			X	X	X		X	X	X	X	X	1,823	160.4	0	0.0	1,619	150.40	1,414	131.40	211	52.3
05	X	X	X	X			X	X		X	X	X	X	X	1,863	164.0	0	0.0	1,611	149.64	1,404	130.47	210	51.3
06	X	X	X	X		X		X		X	X	X	X	X	1,829	160.9	0	0.0	1,615	150.00	1,410	131.01	209	52.2
07	X	X	X	X		X	X			X	X	X	X	X	1,838	161.7	0	0.0	1,618	150.32	1,408	130.76	225	51.9
08	X	X	X	X	X	X	X	X	X		X	X	X	X	1,912	168.3	127	11.2	2,130	197.92	1,930	179.26	170	50.0
09	X	X	X	X		X	X	X		X		X	X	X	1,900	167.2	0	0.0	1,657	153.93	1,434	133.21	243	50.3
10	X	X	X	X		X	X	X		X	X		X	X	1,883	165.7	0	0.0	1,622	150.73	1,412	131.19	219	50.8
11	X	X	X	X		X	X	X		X	X	X		X	1,807	159.0	0	0.0	1,644	152.72	1,438	133.59	193	52.7
12	X	X	X	X	X	X	X	X		X	X	X	X		2,046	180.0	179	15.8	2,420	224.84	2,198	204.16	195	46.5

Sensitivity Analysis by Strategy

Table E-10 Sensitivity Analysis for the Strategies Used in the Selected Low-Energy Model for Fairbanks, Alaska

Savings numbers are calculated between the selected low-energy model (with PV removed as necessary), and the model created by removing the indicated strategy. Equivalent PV areas are calculated assuming a 0.1 cell efficiency and a 0.9 inverter efficiency, and the EnergyPlus algorithm for determining the annual amount of electricity produced given building geometry and local weather conditions.

Strategy	Search No.	EUI Savings		Lifetime Cost Savings		Capital Cost Savings		Equivalent PV	
		$MJ/m^2 \cdot yr$	$kBtu/ft^2 \cdot yr$	$\$/m^2$	$\$/ft^2$	$\$/m^2$	$\$/ft^2$	m^2	ft^2
Infiltration	01	154.5	13.60	6.93	0.64	–2.05	–0.19	2,161.2	23,262
Elec. Lighting	02	32.3	2.85	9.58	0.89	–2.23	–0.21	452.2	4,867
Daylighting	03	1.8	0.16	0.12	0.01	–0.31	–0.03	25.0	269
Window Area	04	2.0	0.18	5.78	0.54	5.14	0.48	28.0	301
Roof Insulation	05	42.4	3.73	–2.41	–0.22	–4.86	–0.45	592.7	6,379
Fenestration Types	06	7.9	0.69	1.48	0.14	0.99	0.09	110.1	1,185
HVAC	07	16.7	1.47	4.87	0.45	–1.74	–0.16	233.2	2,510
ERV	08	471.7	41.51	–45.14	–4.19	–70.34	–6.53	6,597.0	71,010
Frozen Food Cases	09	260.0	22.88	16.64	1.55	–12.23	–1.14	3,636.7	39,145
Ice Cream Cases	10	62.5	5.50	9.33	0.87	2.86	0.27	873.6	9,404
Meat Cases	11	174.9	15.39	4.02	0.37	–8.11	–0.75	2,445.6	26,325
Dairy/Deli Cases	12	740.8	65.19	45.96	4.27	–11.73	–1.09	10,361.6	111,531

Appendix F. Corrected Results from Abbreviated Optimization

The corrected energy performance of the selected low-energy models from the abbreviated optimizations described in Section 4.4 is summarized in Table F-1 to Table F-3.

Table F-1 Selected Low-Energy Model Corrected Energy Performance: Humid Climates

Building Name	Metric	Humid					
		1A	2A	3A	4A	5A	6A
Low-Energy	Percent Energy Savings	52.7%	54.6%	50.6%	53.7%	53.5%	53.2%
Baseline (SI units)	EUI ($MJ/m^2 \cdot yr$)	3,150	3,310	2,800	2,990	3,100	3,280
Low-Energy (SI units)	EUI ($MJ/m^2 \cdot yr$)	1,490	1,500	1,390	1,380	1,440	1,540
Baseline (SI units)	Electricity Intensity (kWh/m^2yr)	788	780	572	548	527	524
Low-Energy (SI units)	Electricity Intensity (kWh/m^2yr)	362	333	254	242	228	223
Baseline (SI units)	Natural Gas Intensity (kWh/m^2yr)	86.4	140	207	282	333	389
Low-Energy (SI units)	Natural Gas Intensity (kWh/m^2yr)	51.1	84.3	131	141	172	204
Low-Energy (SI units)	PV Power Intensity (kWh/m^2yr)	0.000	0.000	0.000	0.000	0.000	0.000
Baseline (IP units)	EUI ($kBtu/ft^2yr$)	277	291	247	263	273	289
Low-Energy (IP units)	EUI ($kBtu/ft^2yr$)	131	132	122	122	127	135
Baseline (IP units)	Electricity Intensity (kWh/ft^2yr)	73.2	72.4	53.1	50.9	49.0	48.7
Low-Energy (IP units)	Electricity Intensity (kWh/ft^2yr)	33.7	30.9	23.6	22.5	21.2	20.7
Baseline (IP units)	Natural Gas Intensity ($Therms/ft^2yr$)	0.274	0.442	0.657	0.893	1.06	1.23
Low-Energy (IP units)	Natural Gas Intensity ($Therms/ft^2yr$)	0.162	0.267	0.416	0.449	0.544	0.646
Low-Energy (IP units)	PV Power Intensity (kWh/ft^2yr)	0.000	0.000	0.000	0.000	0.000	0.000

Table F-2 Selected Low-Energy Model Corrected Energy Performance: Arid Climates

Building Name	Metric	Arid					
		2B	3B-CA	3B-NV	4B	5B	6B
Low-Energy	Percent Energy Savings	53.9%	51.8%	53.9%	50.6%	55.9%	54.9%
Baseline (SI units)	EUI ($MJ/m^2 \cdot yr$)	2,460	2,510	2,480	2,660	2,840	3,080
Low-Energy (SI units)	EUI ($MJ/m^2 \cdot yr$)	1,130	1,210	1,140	1,320	1,250	1,390
Baseline (SI units)	Electricity Intensity (kWh/m^2yr)	564	526	528	510	504	496
Low-Energy (SI units)	Electricity Intensity (kWh/m^2yr)	240	242	222	209	207	201
Baseline (SI units)	Natural Gas Intensity (kWh/m^2yr)	118	172	161	230	286	359
Low-Energy (SI units)	Natural Gas Intensity (kWh/m^2yr)	74.4	94.3	95.9	156	142	185
Low-Energy (SI units)	PV Power Intensity (kWh/m^2yr)	0.000	0.000	0.000	0.000	0.000	0.000
Baseline (IP units)	EUI ($kBtu/ft^2yr$)	216	221	218	234	250	271
Low-Energy (IP units)	EUI ($kBtu/ft^2yr$)	99.7	107	101	116	110	122
Baseline (IP units)	Electricity Intensity (kWh/ft^2yr)	52.4	48.8	49.0	47.3	46.8	46.0
Low-Energy (IP units)	Electricity Intensity (kWh/ft^2yr)	22.3	22.5	20.6	19.4	19.2	18.6
Baseline (IP units)	Natural Gas Intensity ($Therms/ft^2yr$)	0.376	0.544	0.511	0.728	0.906	1.14
Low-Energy (IP units)	Natural Gas Intensity ($Therms/ft^2yr$)	0.236	0.299	0.304	0.495	0.449	0.585
Low-Energy (IP units)	PV Power Intensity (kWh/ft^2yr)	0.000	0.000	0.000	0.000	0.000	0.000

Table F-3 Selected Low-Energy Model Corrected Energy Performance: Marine and Cold Climates

Building Name	Metric	Marine		Cold	
		3C	4C	7	8
Low-Energy	Percent Energy Savings	51.6%	50.3%	53.4%	53.1%
Baseline (SI units)	EUI ($MJ/m^2 \cdot yr$)	2,630	2,830	3,470	4,060
Low-Energy (SI units)	EUI ($MJ/m^2 \cdot yr$)	1,270	1,410	1,620	1,900
Baseline (SI units)	Electricity Intensity (kWh/m^2yr)	487	483	495	487
Low-Energy (SI units)	Electricity Intensity (kWh/m^2yr)	210	208	203	192
Baseline (SI units)	Natural Gas Intensity (kWh/m^2yr)	243	302	468	640
Low-Energy (SI units)	Natural Gas Intensity (kWh/m^2yr)	143	182	246	337
Low-Energy (SI units)	PV Power Intensity (kWh/m^2yr)	0.000	0.000	0.000	0.000
Baseline (IP units)	EUI ($kBtu/ft^2yr$)	231	249	305	357
Low-Energy (IP units)	EUI ($kBtu/ft^2yr$)	112	124	142	168
Baseline (IP units)	Electricity Intensity (kWh/ft^2yr)	45.2	44.9	46.0	45.3
Low-Energy (IP units)	Electricity Intensity (kWh/ft^2yr)	19.6	19.3	18.9	17.8
Baseline (IP units)	Natural Gas Intensity ($Therms/ft^2yr$)	0.769	0.956	1.48	2.03
Low-Energy (IP units)	Natural Gas Intensity ($Therms/ft^2yr$)	0.453	0.578	0.780	1.07
Low-Energy (IP units)	PV Power Intensity (kWh/ft^2yr)	0.000	0.000	0.000	0.000

The corrected economic performance of the selected low-energy models from the abbreviated optimizations described in Section 4.4 is summarized in Table F-4 to Table F-6.

Table F-4 Selected Low-Energy Model Corrected Costs: Humid Climates

Building Name	Metric	Humid					
		1A	2A	3A	4A	5A	6A
Baseline (SI units)	5-TLCC Intensity ($/m^2)	1,820	1,860	1,710	1,710	1,720	1,730
Low-Energy (SI units)	5-TLCC Intensity ($/m^2)	1,600	1,620	1,550	1,510	1,520	1,520
Baseline (SI units)	Capital Cost ($/m^2)	1,410	1,440	1,370	1,370	1,370	1,370
Low-Energy (SI units)	Capital Cost ($/m^2)	1,390	1,410	1,350	1,330	1,330	1,330
Baseline (IP units)	5-TLCC Intensity ($/ft^2)	169	173	159	159	160	161
Low-Energy (IP units)	5-TLCC Intensity ($/ft^2)	149	151	144	141	141	141
Baseline (IP units)	Capital Cost ($/ft^2)	131	134	127	127	128	128
Low-Energy (IP units)	Capital Cost ($/ft^2)	129	131	126	123	124	124

Table F-5 Selected Low-Energy Model Corrected Costs: Arid Climates

Building Name	Metric	Arid					
		2B	3B-CA	3B-NV	4B	5B	6B
Baseline (SI units)	5-TLCC Intensity ($\$/m^2$)	1,670	1,660	1,670	1,670	1,690	1,700
Low-Energy (SI units)	5-TLCC Intensity ($\$/m^2$)	1,500	1,490	1,510	1,500	1,490	1,490
Baseline (SI units)	Capital Cost ($\$/m^2$)	1,350	1,340	1,360	1,350	1,360	1,360
Low-Energy (SI units)	Capital Cost ($\$/m^2$)	1,330	1,310	1,340	1,330	1,320	1,320
Baseline (IP units)	5-TLCC Intensity ($\$/ft^2$)	155	154	155	155	157	158
Low-Energy (IP units)	5-TLCC Intensity ($\$/ft^2$)	139	138	140	140	138	139
Baseline (IP units)	Capital Cost ($\$/ft^2$)	125	125	126	126	126	127
Low-Energy (IP units)	Capital Cost ($\$/ft^2$)	123	122	124	124	122	122

Table F-6 Selected Low-Energy Model Corrected Costs: Marine and Cold Climates

Building Name	Metric	Marine		Cold	
		3C	4C	7	8
Baseline (SI units)	5-TLCC Intensity ($\$/m^2$)	1,650	1,670	1,730	1,750
Low-Energy (SI units)	5-TLCC Intensity ($\$/m^2$)	1,490	1,490	1,520	1,530
Baseline (SI units)	Capital Cost ($\$/m^2$)	1,340	1,350	1,370	1,370
Low-Energy (SI units)	Capital Cost ($\$/m^2$)	1,320	1,310	1,330	1,320
Baseline (IP units)	5-TLCC Intensity ($\$/ft^2$)	153	155	161	163
Low-Energy (IP units)	5-TLCC Intensity ($\$/ft^2$)	139	139	141	142
Baseline (IP units)	Capital Cost ($\$/ft^2$)	124	125	128	127
Low-Energy (IP units)	Capital Cost ($\$/ft^2$)	123	122	123	123

Appendix G. General Merchandise and Grocery Store Technical Support Documents: Summary and Information Request

The freely available series of *Advanced Energy Design Guides* (AEDGs) developed by ASHRAE, AIA, IES, USGBC and DOE is supported by technical analysis conducted by NREL or Pacific Northwest National Laboratory. The guides currently target 30% energy savings over ASHRAE 90.1-2004—the next set will target 50% energy savings.

For the past year and a half, NREL has been working to develop 50% energy savings recommendations for retail and grocery stores. Last year's work (medium box retail and grocery stores) established the basic methodology for identifying cost-effective design packages that achieve this goal in each of 15 climate zones. The results are promising, but the analysis input data need a thorough external review to ensure our final recommendations are accurate and useable.

This is where you, as an REA member, come in: We would like you to review our energy modeling inputs. The following pages list our primary assumptions about the layout and operation of prototypical retail and grocery stores (prototype models), plus perturbations of the prototypical designs (EDMs) that we believe (1) some retailers would be comfortable with, and 2) may improve energy efficiency in one or more climate zones. Lists of specific questions and information requests are included, but please feel free to comment on any item of interest or raise other issues.

We hope you will participate so we can provide the REA and the broader community with useful, climate-specific design recommendations for retail and grocery stores. To submit your comments, please either send them to Adam Hirsch (adam.hirsch@nrel.gov) and Matt Leach (matt.leach@nrel.gov), or e-mail Adam and Matt to set up a time to convey your feedback directly over the phone.

Table G-1 TSD Prototype Characteristics and Related Questions*

Store Characteristic	Grocery	General Merchandise	Questions
Program			
Size	45,002 ft^2	40,500 ft^2	
Space Types	See Table G-2.		
Operating Hours	Sun. through Thursday 6 a.m. to 10 p.m., Friday and Saturday 6 a.m. to 12 a.m.	Monday through Saturday 9 a.m. to 9 p.m., Sunday 10 a.m. to 6 p.m.	
Peak Occupancy	8 people/1000 ft^2.	15 people/1000 ft^2.	How does occupancy vary throughout the day/week? How does occupancy affect energy scheduling/usage?
Lighting	15%/50%/95% on during unoccupied/staff-only/operating hours.		Is this a good model of lighting loads?
Plug and Process	See Table G-3.		How do plug and process loads vary throughout the day?
Form			
Number of Floors	1	1	
Aspect Ratio	1.5	1.25	
Floor-to-Floor Height	20 ft	20 ft	
Window Area	1400 ft^2 (0.08 WWR)	1,000 ft^2 (0.056 WWR)	
Floor Plan	See Figure .	See Figure .	
Fabric			
Wall Type	Either concrete block with interior insulation (finished with drywall) or exterior insulation (finished with stucco); or a concrete block cavity wall (finished with brick), depending on climate zone.		What types of wall constructions are acceptable? What considerations affect wall construction selection?
Roof Type	All insulation above deck		
Interior Partitions	2 x 4 steel frame with gypsum boards		
Internal Mass	45,000 ft^3 of wood		Do you have rough estimates of your stores' contents?
Equipment			
HVAC System	Unitary rooftop units with DX coils, natural gas heating, and constant volume fans.		Are other types of HVAC systems considered or used?
HVAC Unit Size	10 tons cooling		Are other size units used? Are units sized differently for different parts of the store or for stores in different locations?
HVAC Controls	No thermostat setback.	Setback during unoccupied hours.	Is thermostat setback used? If so, what is the methodology used to determine the setback?
Refrigeration	4 compressor racks (2 med-temp, 2 low-temp); air-cooled condensers; cases and walk-in units listed in Table G-4.	N/A	Where are compressors and condensers located? Is waste heat recovered from the refrigeration system? Is HVAC return air routed under the refrigerated cases?
Service Hot Water	Natural gas heating with storage tank		

* All comments on any aspect of the prototypes are welcome.

Table G-2 Space Types and Sizes in the Prototype Models

Zone Name	Grocery		General Merchandise	
	Floor Area (ft^2)	Percent of Total	Floor Area (ft^2)	Percent of Total
Main Sales	22,415	49.8	30,375	75.0
Perimeter Sales	2,611	5.8	4,100	10.1
Produce	7,657	17.0	N/A	N/A
Deli	2,419	5.4	N/A	N/A
Bakery	2,250	5.0	N/A	N/A
Enclosed Office	300	0.7	300	0.7
Meeting Room	500	1.1	500	1.2
Dining Room	500	1.1	500	1.2
Restroom	675	1.5	625	1.5
Mechanical Room	600	1.3	200	0.5
Corridor	532	1.2	450	1.1
Vestibule	N/A	N/A	400	1.0
Active Storage	4,544	10.1	3,050	7.5
Total	45,002	100.0	40,500	100.0

Table G-3 Peak Plug (Electric) and Process (Gas) Loads in the Prototype Models

Zone Name	Grocery		General Merchandise: Low Plug Load	General Merchandise: High Plug Load
	Peak Plug Load (W/ft^2)	Peak Process Load (W/ft^2)	Peak Plug Load (W/ft^2)	Peak Plug Load (W/ft^2)
Main Sales	0.50	0.00	0.20	1.20
Perimeter Sales	0.50	0.00	0.40	0.40
Produce	0.50	0.00	N/A	N/A
Deli	5.00	2.50	N/A	N/A
Bakery	2.50	5.00	N/A	N/A
Enclosed Office	0.75	0.00	0.75	0.75
Meeting Room	0.75	0.00	0.75	0.75
Dining Room	2.60	0.00	2.60	2.60
Restroom	0.10	0.00	0.10	0.10
Mechanical Room	0.00	0.00	0.00	0.00
Corridor	0.00	0.00	0.00	0.00
Vestibule	N/A	N/A	0.00	0.00
Active Storage	0.75	0.00	0.75	0.75
Average	0.88	0.38	0.30	1.05

Table G-4 Grocery Prototype: Refrigerated Cases and Walk-In Units by Zone

Zone Name	Case/Walk-in Type	Case Length	Number of Units	Total Length or Area
Main Sales	Island Single Deck Meat	12 ft	9	108 ft
Main Sales	Multi-Deck Dairy/Deli	12 ft	13	156 ft
Main Sales	Vertical Frozen Food with Doors	15 ft	18	270 ft
Main Sales	Island Single Deck Ice Cream	12 ft	10	120 ft
Main Sales	Walk-In Cooler (Med Temp)	N/A	2	2,818 ft^2
Main Sales	Walk-In Freezer (Low Temp)	N/A	1	1,003 ft^2
Produce	Multi-Deck Dairy/Deli	12 ft	8	96 ft
Deli	Multi-Deck Dairy/Deli	12 ft	1	12 ft
Deli	Walk-In Cooler (Med Temp)	N/A	1	127 ft^2
Bakery	Walk-In Cooler (Med Temp)	N/A	1	63 ft^2

Figure G-1 Grocery prototype floor plan

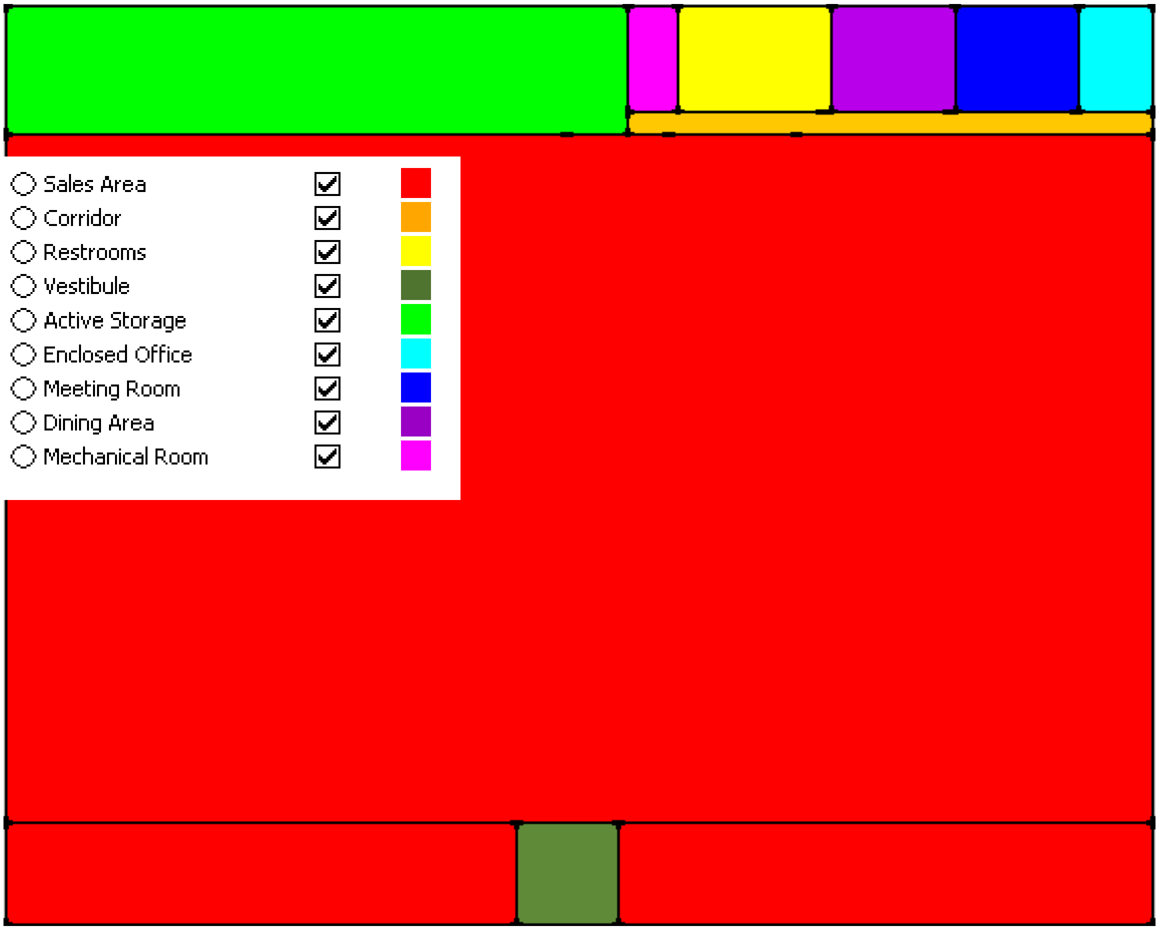

Figure G-2 General merchandise prototype floor plan

Table G-5 Energy Design Measure (EDM) Information Requests

Priority	Store Types*	EDM Category	FY 2008 Assumptions	Information Requests
High	GM, Gro	Plug Loads	10% overall reduction possible; very high costs.	Possible plug load reduction strategies (novel or proven).
	GM, Gro	Energy Recovery Ventilation (ERV)	2000 cfm unit(s) with 60%-80% sensible effectiveness, 50%-70% latent effectiveness.	Experience with or thoughts on designing ERV systems for large one-story buildings.
	GM, Gro	Envelope Infiltration	An envelope air barrier reduces envelope infiltration from 0.24 to 0.05 ACH.	Infiltration levels and sources in typical construction; proven reduction strategies.
	GM, Gro	Daylighting	400 lux (37 fc) and 600 lux (56 fc) set points.	Acceptable daylighting set points in lux or foot-candles (fc).
	GM, Gro	Vertical Fenestration	Amount of fenestration on front façade can be changed ± 20% from 1000 ft^2 (general merchandise) and 1400 ft^2 (grocery) baselines.	Range of acceptable fenestration amounts (WWR) for each façade; acceptability of adding clerestory (high) windows to back of store for daylighting storage areas, etc.
	Gro	Refrigerated Cases	Reduced display lighting; added efficient fan motors, defrost and anti-sweat heater controls; added doors to cases.	Strategies that render doors more acceptable; lighting preferences.
	Gro	Refrigeration System	Evaporative condensers.	Experience with evaporative condensers; decision criteria pertaining to compressor type; interest in particular secondary loop systems.
Medium	GM, Gro	Electric Lighting	Sales floor lighting power densities of 1.36 W/ft^2 (20% below code) and 1.02 W/ft^2 (40% below code).	Typical lighting configurations; best practice/state-of-the-art configurations.
	GM, Gro	Entranceway Infiltration	Adding a main entrance vestibule reduces infiltration through the door from 0.082 to 0.054 ACH.	Whether vestibules are used, and if not, why not; preferred vestibule designs.
	GM, Gro	Static Pressure Drop	Not included.	Typical ductwork designs for rooftop units; minimum length of ductwork runs to and from rooftop units.
	GM, Gro	Envelope	Static construction types with different levels of insulation.	List of acceptable and/or interesting construction assemblies for walls and roofs.
	GM, Gro	HVAC	More efficient rooftop units with DX cooling and natural gas heating.	Alternative HVAC systems that retailers are interested in pursuing or have considered already.
	Gro	HVAC	See above.	HVAC/Refrigeration integration strategies retailers have pursued or would like evaluated.
	GM, Gro	Demand Controlled Ventilation (DCV)	Modeled by having outside air requirements follow the occupancy schedules.	Experience with using DCV in real stores.
	GM, Gro	Overhangs	Framed overhangs offset 0.82 ft from the top of each window; projection factor of 0.1 to 1.5.	Current use and acceptability of overhangs; preferred materials for overhangs.
Low	GM, Gro	Photovoltaics	Possible to cover 30% of the area not used by skylights with PV.	Percent of roof area available for photovoltaic (PV) panels and skylights.
	GM, Gro	Horizontal Fenestration	Skylights are preferred daylighting method.	Preferences concerning skylights and skylight alternatives.

* GM = General Merchandise, Gro = Grocery

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14. ABSTRACT *(Maximum 200 Words)*
This report documents technical analysis for grocery stores aimed at providing design guidance that achieves whole-building energy savings of at least 50% over ASHRAE Standard 90.1-2004. It documents the modeling and integrated analysis methods used to identify cost-effective sets of recommendations for different locations; demonstrates sets of recommendations that meet or exceed the 50% goal; establishes methodology for providing a family of solutions, as opposed to a single solution, that meet the 50% goal as a means of exploring the relative importance of specific design strategies; demonstrates the dependence of the percent energy savings metric on the building standard used to establish the baseline; and explores the effect of floor area on energy use intensity.

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