BUILDING PERFORMANCE SIMULATION: A TOOL FOR POLICYMAKING

Drury Browne Crawley, IV, B. Arch.

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Energy Systems Research Unit
Department of Mechanical Engineering
University of Strathclyde
Glasgow, Scotland, UK

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Abstract

Building energy and environmental performance simulation programs have the capability to evaluate a wide range of responses to external stimulus. Typically, these software tools are used by practitioners evaluating individual building design or retrofits. Other uses for building simulation include overheating prediction, heating and cooling equipment design, evaluation of alternate technologies (energy efficiency and renewable energy), regulatory compliance or, more recently, integrated views of multiple simulation results.

The most powerful use for simulation, however, lies in the ability to look beyond individual buildings to support policy decision making, including mandatory rule makings such as standards and codes, voluntary financial incentive programs such as those used by utilities to incentivize reduced power demand, evaluating and identifying opportunities for voluntary building energy efficiency programs, or to look at potential impacts related to broader policy levels such as heat island and climate change. Simulation, when coupled with building models that represent a range of building types and locations, can represent a portion of or the entire building stock.

This thesis researches how building energy simulation can be used to guide, define, determine, and support decisions by policy makers. Four research studies demonstrate how building performance simulation informs and defines building-related policy for standards, utility incentive programs, energy-efficiency programs, and the determination of climatic influence and sensitivity on building operating performance. These studies show how decision-makers have used building performance simulation to craft voluntary and mandatory programs for building energy efficiency. From these four studies, a generalized framework of building-related policy research is derived with three major categories: research and policy focus, building model, and analysis structure and output data.

Dedication

To my wife, Anne, with thanks for the support, love, belief that it could and would be finally done, and patience for all the long days and nights when I was ‘working on my PhD’.

To Becca and Alex, for sort of understanding that Dad would one day be finished and have more time for them. (And for bringing joy into our lives.)

To my parents for a lifetime of support and belief in me.

To all my colleagues (and friends) at the Energy Systems Research Unit for the encouragement and friendship all these years—stimulating conversations, hill walks, sailing, and outings to the pub. Special thanks to Professor Joe Clarke, advisor extraordinaire and friend; to Jon Hand for unceasing hospitality and a willing ear for half-baked ideas; and to Paul Strachan for insightful review which helped point out clear paths forward. And finally, thanks to Professor Jon Wright of Loughborough University, for careful, perceptive review which significantly improved the final thesis.

Abbreviations

AEDG	Advanced Energy Design Guide
Ag	glazing area
Aw	wall area
AIA	American Institute of Architects
ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
BERR	UK Department for Business Enterprise & Regulatory Reform
BEPS	Building Energy Performance Standards
BIM	building information model
BOMA	Building Owners and Managers Association International
CAD	computer-aided design
CBECS	Commercial Building Energy Consumption Survey
CEC	California Energy Commission
CFC	chlorofluorocarbon
CFM	cubic feet per minute
CGCM2	Canadian General Circulation Model 2
CICES	Commercial and Institutional Consumption of Energy Survey
CO_2	carbon dioxide
COP	coefficient of performance
CSIRO2	Commonwealth Scientific and Industrial Research Organization CSIRO2 GCM
CSV	comma-separated value
CTZ2	California Thermal Zone 2
CV	constant volume
CWEC	Canadian Weather for Energy Calculations
DB	dry bulb
DP	dew point
DTI	UK Department of Trade and Industry
EDEM	ESRU Domestic Energy Model
EFLH	equivalent full-load hours
EIA	Energy Information Administration
ESB	Energy Star Buildings
FWR	fenestration-to-wall ratio
GCM	general circulation model
HadCM3	Hadley Circulation Model 3
HVAC	heating, ventilating, and air-conditioning
IESNA	Illuminating Engineering Society of North America
IPCC	Intergovernmental Panel on Climate Change
IRR	internal rate of return
IWEC	International Weather for Energy Calculations
LBL	Lawrence Berkeley National Laboratory
LCC	life-cycle cost
NBECS	Nonresidential Building Energy Consumption Survey
NCDC	National Climatic Data Center
NECB	National Energy Code for Buildings
NOx	nitrous oxide
NRC	National Research Council of Canada
NRCan	Natural Resources Canada
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Data Base

PCM	National Center for Atmospheric Research GCM
PSZ	packaged single-zone
QA	quality assurance
RH	relative humidity
SAMSON	Solar and Meteorological Surface Observation Network
SBEM	Simplified Building Energy Model
SC	shading coefficient
SO_2	sulfur dioxide
SP41	ASHRAE Special Project 41
SSPC	Standing Standard Project Committee
TMY	Typical Meteorological Year
TMY2	Typical Meteorological Year 2
TRY	Typical Reference Year
UA	U-value times area
Ug	U-value of glazing
US DOE	U. S. Department of Energy
US EPA	U. S. Environmental Protection Agency
USGBC	U. S. Green Building Council
Uw	U-value of wall
VAV	variable air volume
VSD	variable speed drive
WC	water column
WYEC	Weather Year for Energy Calculations
WYEC2	Weather Year for Energy Calculations 2
WWR	window-to-wall ratio
XML	extensible markup language

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Chapter 1
The Power of Building Simulation as a Policy Tool

. . . I feel I have a great lot to learn, or unlearn.
I seem to know far too much, and this knowledge
obscures the really significant facts, but I am getting on.

Charles Rennie Mackintosh

1.1 Importance of Simulation

Simulation is one of the most important tools available in our world. To be able to construct a model and predict an outcome based on what has happened in the past or on current trends is critical to success in many fields, from micro and macro economics, aircraft manufacture, space exploration, and electronic circuit design to traffic planning, fire fighting, warfare, and the planning, design, construction, and operation of buildings.

Although today a simulation is likely to be a computer model of some physical or other predicable process, simulating or modeling systems is an ancient craft. For example, Egyptian pharaohs were buried with model boats several thousand years ago.

Why model or simulate something? First, a model allows evaluation of alternative designs, technologies, or processes without having to create the artifact being modeled. Second, some technologies require models to assess performance relative to competing options. For example, airplane manufacturers use aerodynamic models of their proposed planes to test options and designs virtually. Building airplanes that cost hundreds of millions of dollars without relative certainty—based on simulation—that they will fly is risky at best and prohibitively expensive. Similarly, space exploration depends on models of planetary movement to land a craft on a distant planet on arrival three, five, or more years in the future.

In short, it is cheaper to create a model of the underlying physical processes and test alternative configurations than to build a real prototype and have to change it later based on trial and error.

1.2 What Is Simulation?

Simulation encompasses a number of different but similar terms—modelling or models, simulation, and projection. The *Oxford English Dictionary* (2008) defines modelling as “a simplified mathematical description of a system or process, used to assist calculations and predictions.” WordNet (2006) defines modeling as “the act of representing something (usually on a smaller scale).” The *American Heritage Dictionary* (2008) takes the definition further:

> model
> A schematic description of a system, theory, or phenomenon that accounts for its known or inferred properties and may be used for further study of its characteristics: *a model of generative grammar; a model of an atom; an economic model.*

Similarly, WordNet (2006) defines simulation as “the technique of representing the real world by a computer program; a simulation should imitate the internal processes and not merely the results of the thing being simulated.” Scott (2003) describes the broader aspects of economic models:

> simulation
> A mathematical exercise in which a model of a system is established, then the model’s variables are altered to determine the effects on other variables. For example, a financial analyst might construct a model for predicting a stock’s market price and then manipulate various determinants of the price including earnings, interest rates, and the inflation rate to determine how each of these changes affects the market price.

Howe (2004) goes further and includes types of simulation and modelling, from physical to computer simulation:

> simulation
> Attempting to predict aspects of the behaviour of some system by creating an approximate (mathematical) model of it. This can be done by physical modelling, by writing a special-purpose computer program or using a more general simulation package, probably still aimed at a particular kind of simulation (e.g., structural

engineering, fluid flow). Typical examples are aircraft flight simulators or electronic circuit simulators.

Finally, simulation and modelling also can be used to project future behavior of a system. *Oxford English Dictionary* defines projection as “an estimate or forecast based on present trends” similar to the *American Heritage Dictionary* definition of “a prediction or an estimate of something in the future, based on present data or trends.” In summary, models describe how things work, simulation allows evaluation of physical and operational attributes, and project how that system will perform.

1.3 Modelling Buildings

For thousands of years, architects and engineers have hand drawn scaled, two-dimensional models of their visions for buildings. These drawings—essentially the architect’s and the engineer’s models—are what the builder must interpret to construct the building. The definitions of model and simulation show, however, that building modelling isn’t limited to a paper or electronic geometric description of the building. Architects also create scale physical models to evaluate massing, shading, and daylight and to represent to clients who may not be able to visualize a building from drawings.

During the past several decades, architects and engineers have turned to computerized two-dimensional drafting or computer-aided design (CAD). Recently, CAD has begun to support three-dimensional, object-based representation of buildings, usually called BIM (building information model). Today, designers are likely to use sophisticated rendering and lighting tools to generate realistic-looking images of building designs.

For many years, building design engineers used rules of thumb or simple equations to estimate heating and cooling loads to select equipment sizes. As building systems, such as heating, cooling, water, and lighting, plug and process loads, and onsite power have increased in complexity; designers have turned to computer-based models of the buildings to describe these complex interactions. They also may model the luminous environment of the building to design lighting systems, acoustical attributes, structural systems, or even the water and waste flows in plumbing.

1.4 Energy Use in Buildings

The buildings constructed today might last 100 years or more, a period that will include numerous renovations and changes as well as regular replacement of equipment, systems, and components. Consider the 100-year-old buildings still in use today. During the life of those buildings, gas lighting was replaced by electric incandescent, then fluorescent; tomorrow, lighting will be solid-state. Those buildings' electrical loads have skyrocketed: Manual office equipment changed to electric typewriters, photocopiers, facsimile machines, telephones, mainframe computers, distributed computing, personal computers, and printers. Coal-fired boiler radiant systems were replaced or supplemented by air heating and cooling systems. Single-pane windows became complex multilayered window systems with specialty gases. All these technological changes occurred during 100 years, with many of them happening in the last 60 years.

Today, buildings are one of the largest sectors of energy use (see Figure 1-1). In the United States, buildings account for 40 percent of national energy use; in the United Kingdom nearly 50 percent. In both countries, industrial energy use is now 30 percent or less of total energy use. In developed countries, buildings are also the single largest user of electricity, with buildings accounting for 72 percent of electricity use in the United States and 50 percent globally. Worldwide, total carbon dioxide emissions in 2005 were estimated at 28.051 billion metric tonnes: 40.6 percent from coal use (11.378), 39.1 percent from petroleum use (10.996), and 20.2 percent from natural gas use (5.666). Because buildings are the predominant users of electricity (coal, oil, and natural gas generation) and natural gas, they also are responsible for a large proportion of atmospheric pollution, including carbon dioxide, each year.

Recent studies in the United States have shown that improvements of 50–70 percent lower energy use beyond typical practice are easily attainable today at little or no increase in capital cost (Torcellini et al 2006). In fact, today it is cost-effective to build a net-zero energy building—one that annually produces more energy than it uses (Torcellini and Crawley 2006).

Many approaches are available for reducing the energy use in new and existing buildings. For example, building energy standards such as ASHRAE Standard 90.1-2004 (ASHRAE

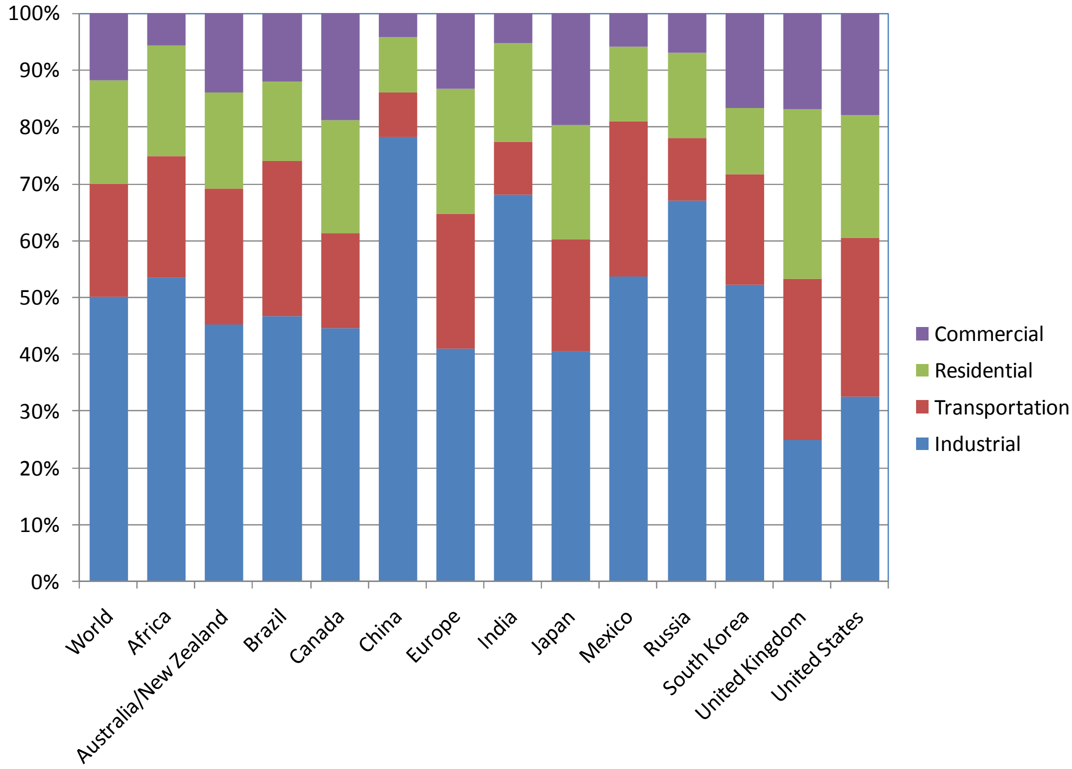

Figure 1-1. Percentage Energy Use by Sector[1] for the World and Selected Countries

2004a) provide guidance on cost-effective performance levels for individual components, systems, or whole buildings. Recently, ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers), the American Institute of Architects (AIA), the Illuminating Engineering Society of North American (IESNA), the U.S. Green Building Council (USGBC), and the U.S. Department of Energy (US DOE) have created a series of Advanced Energy Design Guides (AEDG) (ASHRAE 2004b, 2006, 2008a, 2008b) that provide recommendations for achieving 30 percent energy savings over the minimum code requirements of Standard 90.1. The AEDG provide simple look-up tables of minimum insulation for walls, roofs, and floors, minimum equipment performance, and maximum lighting power by climate zone. Building type experts created these recommendations from a series of alternate packages for reducing energy use. These packages were simulated to determine the best combination that met the 30 percent energy savings target.

1.5 Building Performance Simulation

"Every building is a forecast. Every forecast is wrong." (Brand 1994)

[1] UK data from DTI (2002) and BERR (2008). Other data from EIA (2008).

Every building design is based on assumptions about how the building will be used, but from its opening day, a building will be used differently than its designers assumed or planned. Over time the intended use will change too. The building designed as a warehouse suddenly has a dropped ceiling and an air-conditioning system and is now an office; two years later kitchen equipment turns it into a restaurant.

Buildings entail complex heat and moisture interactions of a physical space and the occupants. Imagine a simple single room with an occupant; the room has four walls, a window in one wall, a floor, and a ceiling. The walls, floor, and ceiling all conduct heat because the temperature on the other side of each is different. If the air is moving, convection moves heat throughout the space. The outside environment—temperature, humidity, wind speed and direction, rain and other precipitation—is changing with weather patterns. The window transfers light and heat into or out of the room. Depending on the colour and reflectance of the surfaces, light is reflected throughout the room. The sun moves across the sky in an annual, seasonal, and diurnal pattern, which varies the direction and intensity of solar radiation. Moving clouds affect the amount of direct and indirect radiation that the window and the walls receive. Active systems for lighting, heating, cooling, ventilation, humidification, dehumidification as well as occupants and their equipment increase the complexity.

For designers to understand how energy is used in a space, they must model these complex interactions of heat, light, and moisture. Thus, tools to support the design of low-energy buildings must adequately represent these complex interactions. No longer are simple rules of thumb and peak load design calculations enough. Designers must have and use building performance simulation software to address the complexity of today’s buildings. Building simulation is key to evaluating critical building performance issues, such as human comfort and productivity, energy efficiency, code compliance, and carbon reduction.

Because no utility bills or other measured data exist to indicate how a new building will perform, simulation is the only means of predicting energy performance before that building is constructed and operated. Simulation also is the most effective way of estimating potential energy savings from retrofits in existing buildings. Energy and environmental performance simulation offers significant opportunities to support practitioners in reducing energy costs and subsequently preventing atmospheric pollution.

It is cheaper to simulate than to build a bad building.

Building performance simulation software has been available for more than 40 years (Clarke 2001), yet substantial recent advances in building simulation capabilities are providing new opportunities for integrating simulation into design practice. These advances range from fundamental improvements in simulation theory and models through software engineering, validation, user support, and systems that integrate multiple domains. During the past decade, building performance simulation programs have evolved from a strictly text-based, language-like input and output to multiple interfaces for different uses and users. Examples of robust building performance simulation programs include DOE-2.1E (Winkelmann et al 1993), EnergyPlus (US DOE 2008), ESP-r (ESRU 2008), and TRNSYS (Klein et al 2004). The robustness of the underlying simulation models and the user-friendliness of these programs have improved dramatically, gaining new users that might not have taken the time to learn the language of the underlying programs. At the same time, new users are demanding more—online help systems, tutorials, and support systems, such as predefined databases of climate, materials, constructions, systems, and exemplars.

Crawley et al (2005) compare the technical capabilities of EnergyPlus, ESP-r, TRNSYS and 17 other building performance simulation programs. This survey includes a brief overview of each program and a series of 14 tables comparing: general modeling features; zone loads; building envelope, daylighting, and solar; infiltration, ventilation, room air, and multizone airflow; renewable energy systems; electrical systems and equipment; HVAC systems; HVAC equipment; environmental emissions; climate data availability; economic evaluation; results reporting; validation; and user interface, links to other programs, and availability.

Building energy and environmental performance simulation programs have the capability to evaluate a wide range of response to external stimulus. Practitioners evaluating individual building design or retrofits often use these software tools. Other uses for building simulation programs include overheating prediction; heating and cooling equipment design, alternate technologies (energy efficiency and renewable energy) evaluation, regulatory compliance, or more recently, integrated performance views.

1.6 Simulation as a Tool for Building Policy

Building performance simulation is regularly used to support decision making in the design or retrofit of individual buildings. Yet, the most powerful use lies beyond the performance of individual buildings in supporting building policy setting and decision making: to develop minimum standard regulations, assess the value of improved building performance for utilities or governments, or support high-level, public decision-making. Examples of policy targets include:

- defining a cost-effective performance level for various aspects of a new building energy efficiency standard,
- evaluating the performance of an existing or proposed building energy standard,
- establishing financial incentives for improved building energy performance, i.e., the value to the utility or political entity,
- evaluating the potential impact of and direction for voluntary programs encouraging energy-efficient new building design or existing building retrofit,
- evaluating the applicability of specific technologies or systems for the new building design or existing building retrofit markets,
- evaluating the potential for introduction of renewable energy technologies at the building, community or regional level,
- evaluating the potential impact of changes in regional, national or international policy,
- evaluating requirements for existing or new energy supply at a regional or national level, and
- evaluating the potential impact on building performance of changes relating to environment.

Coupling simulation with building models, which represent a range of building types and locations, can embody a portion of a building stock (existing or new, domestic, public, commercial, industrial, large, medium, or small) or the entire stock, which allows discrete modeling of building policy direction. Simulation provides policy decision makers a means of assessing what-if scenarios across a spectrum of buildings, ensuring that regulations and policy are set at the most financially and environmentally beneficial levels for individuals and the public.

The research documented here is not about the fundamental theory of building performance simulation or extending the capabilities of building simulation. Instead, a series of building simulation studies demonstrates how building performance simulation informs and defines building energy policy. These studies include evaluating and setting performance levels for building energy standards, determining beyond-code utility incentives, and determining climatic influence and sensitivity on building operating performance. These four studies were selected to cover a range of policy targets where building simulation of large portions of a building sector is commonly used. Throughout the four studies, simulation is the key for evaluating the complex interactions of building thermo-physical characteristics, operation, and climate in support of the particular research goal or question. As a way to introduce building simulation as a policy tool, the examples of building simulation in use will demonstrate how they influenced decision makers crafting voluntary and mandatory programs for building energy efficiency and the policy analysis framework for using building simulation that is derived from these studies.

As Crawley et al (2005) showed, simulation tools can evaluate many aspects of building performance, such as capital and operating costs; energy performance and demand; human comfort, health and productivity; illumination; electrical flows; water and waste; acoustic design; renewable energy; and atmospheric emissions. Because the number of simulations involved was large, the research studies documented here focus on heating and cooling loads, energy use and cost, and capital cost.

THESIS: Building performance simulation is one of the most powerful tools available today for use by policy setters and decision makers looking to influence how buildings perform in terms of energy use and environmental impacts.

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Chapter 2
Building Performance Simulation in Policymaking

We see the world piece by piece,
as the sun, the moon,
the animal, the tree; but the
whole, of which these
are the shining parts, is the soul.

Ralph Waldo Emerson

2.1 Introduction

In the context of building policy, performance simulation has been in wide use for more than 30 years in North America. These include evaluating the performance of new or proposed building energy standards, evaluating the value and design of energy savings programs for a utility or government entity, and evaluating the potential impact on the built environment of actions relating to climate change. Swan and Ugursal (2009) provide a comprehensive review of the various modeling techniques used for modeling residential sector energy consumption and they note:

> "Two distinct approaches are identified: top-down and bottom-up. The top-down approach treats the residential sector as an energy sink and is not concerned with individual end-uses. It utilizes historic aggregate energy values and regresses the energy consumption of the housing stock as a function of top-level variables such as macroeconomic indicators (e.g. gross domestic product, unemployment, and inflation), energy price, and general climate. The bottom-up approach extrapolates the estimated energy consumption of a representative set of individual houses to regional and national levels, and consists of two distinct methodologies: the statistical method and the engineering method. Each technique relies on different levels of input information, different calculation or simulation techniques, and provides results with different applicability."

Swan and Ugursal go further to say that the most appropriate use of these three approaches in modeling residential buildings corresponds to its strongest attribute:

- top-down approaches for supply analysis based on projections of energy demand,

- bottom-up statistical techniques for determining energy end-uses including behaviour based on energy bills and simple surveys, and
- bottom-up engineering techniques for explicitly calculating energy end-uses based on detailed characteristics, enabling impact of new (or alternative) technologies.

This chapter reviews related commercial building research in support of building policy where comparison of alternative technologies, systems, or climatic response is required—a bottom-up engineering approach—building energy standards, building stock models, utility incentives, and climate modeling. These areas are core to the discussion in subsequent chapters.

2.2 Evaluation of Building Energy Standards

Building energy standards are a set of definitions of minimum performance of building components and equipment. They can be as simple as a table of minimum efficiency levels for a packaged air-conditioning unit, minimum insulation levels for walls and roofs, or maximum lighting power density. Building energy standards also can be performance based, requiring that a new or existing building has energy consumption no higher than a prescribed value. Where does building performance simulation fit into building energy standards? The primary aim of performance simulation in standards has been to evaluate the energy savings associated with a proposed standard (as compared to typical building practice or existing standards).

National building energy standards date back to the 1970s. For example, ASHRAE developed Standard 90-75 (ASHRAE 1975) to improve the efficiency of buildings in direct response to the oil embargo of the early 1970s. In the late 1970s, the US DOE proposed Building Energy Performance Standards (BEPS) (US DOE 1979) that set maximum energy performance levels for both residential and commercial buildings. A key feature of both the development and the proposed standards was the innovative use, at that time, of building performance simulation. Characteristics of typical buildings were collected throughout the United States, and baseline simulation models were constructed for more than 20 building types. Simulations were then performed and target levels established. Designers could then use building simulation models to demonstrate that their building performed at an energy level less than the maximum for that building type. Unfortunately, BEPS was too far ahead of the market and was buried under a landslide of adverse public comments.

Subsequent research by Pacific Northwest Laboratory (PNL 1983) used building simulation to propose aggressive updates to the then current Standard 90A-1980 in ASHRAE Special Project 41 (SP41) (Pacific Northwest Laboratory 1983). The SP41 proposals were based on life-cycle cost evaluation of the improved energy performance, evaluating ten buildings in six locations. This research was used as the starting point for the development of the next major update of Standard 90.1 in 1989 (ASHRAE 1989). Many of the public review drafts were tested by Pacific Northwest Laboratory for US DOE from 1985 through 1989, using five building prototypes and five locations (weather data) to evaluate energy savings levels. Interim energy simulation results were reported by Crawley and Briggs (1985a, 1985b), US DOE (1987), and Crawley and Boulin (1989), among others. A regional evaluation of state building energy codes in comparison with Standard 90.1-1989 was reported by Johnson et al (1988). The five building prototypes were developed to be typical of commercial buildings rather than representative of the entire stock of buildings. With only five building prototypes and five weather locations, the results from these studies could not extrapolated to represent the value of potential savings for the new standard across the entire commercial sector.

Carlo et al (2003) reported on an analysis of 12 prototype buildings to establish minimum requirements for a building energy-efficiency code in Brazil. While the code was based on Standard 90.1-1999, simulation allowed the researchers to customize the requirements to the climate and economic situation in Brazil. The goal was to create a multi-variable regression equation from the simulation results for calculating the annual energy consumption of a building in that location. The regression equation was tuned to that location with 10 coefficients. With 12 widely varying prototype buildings (in floor area and number of storeys), this required 1,616 combinations of envelope characteristics to be simulated. Carlo proposed to replicate this analysis for other Brazilian locations—requiring a similar number of simulations for each.

Recently, the European Union (EU) has established a Directive on the Energy Performance of Buildings (CEC 2001), which requires member states to create and deploy calculation methods for rating energy performance for buildings larger than 1,000 m^2. This rating has a scale of A to H, where A is the lowest-energy and H the highest-energy buildings. Throughout Europe, this directive is requiring the use of building performance modeling of many more buildings than in the past. In the United Kingdom, the Netherlands, and a few other countries, the building performance modeling required to rate non-domestic buildings has been implemented in a simple set of equations for predicting energy use, known as

Simplified Building Energy Model (SBEM) (BRE 2008a, 2008b). Rather than a model of energy use of a specific building, the SBEM is a comparative model for rating the relative carbon emissions of the proposed building. The SBEM uses monthly utilization factor calculations and is limited in the technologies that it can evaluate.

2.3 Building Models, Building Stock, and Utility Incentives

In a policy framework relating to building energy performance, the targets are individual buildings, but there is a need to establish how the proposed policy or standard will perform in a broader context—of new or existing buildings within a region or country. This requires an understanding of the building stock:

- the number and size of buildings being built and their operating and thermo-physical characteristics;
- the number and size of existing buildings and their operation schedules, energy consumption, energy costs, and thermo-physical characteristics.

Internationally, detailed data relating new or existing commercial building stocks to actual building energy performance are relatively scarce in comparison to what Swan and Ugursal found for the residential sector. Macmillan and Köhler (2004) found that national residential and commercial sector-level energy use data were generally available throughout the world. But they also found that detailed data on the building stock and its energy use was very limited—citing studies in North America and Europe. Barrett (2009) supports this in a review of recent building stock research—saying that papers “concentrate on domestic buildings in detail with less about the non-domestic buildings.” Barrett goes on to say that the non-domestic sector accounts for a large and growing proportion of energy use (as evidence in Figure 1-1) but the literature he reviewed provides few details of this growth. He asserts that this is due to the more heterogeneous nature of the commercial building stock and that empirical data is sparse.

In the United States, the Energy Information Administration has conducted quadrennial energy consumption surveys since 1979 for commercial, industrial, and residential buildings. These surveys provide a wealth of information about the numbers and consumption of the entire building stock based on a statistical representation of the sector and the representativeness of several thousand buildings for each sector. The Commercial Building Energy Consumption Survey (CBECS) comprises survey data on more than 4,000 U.S. buildings (EIA 2007, 2002). But these data are not complete thermo-physical models of each building. For example, there is little detail on the energy consuming systems or the thermal characteristics of the building envelope. Further, EIA masks certain data such as number of workers, number of floors and floor area in large buildings (more than 20 storeys and/or 45,000 m^2) so that individual buildings cannot be identified. Griffith et al (2008) discusses the limitations of using the survey data in the context of a bottom-up research study—requiring supplementing the data with assumptions, defaults, data from other literature and probabilistic assignments.

Recently, Natural Resources Canada has published a similar commercial building survey for Canada (NRCan 2006), the Commercial and Institutional Consumption of Energy Survey (CICES). CICES includes information on 7,349 buildings, but it focuses on the floor area, building type, and the forms and amounts of energy used in the survey year. Key information such as the number of floors or any information about the building envelope or heating and cooling systems is not collected. This limits the use of the CICES as a source of input for building simulation.

California has created a similar survey with more details on the surveyed buildings (PG&E 1999). This survey was recently updated and extended state-wide as reported by Kinney and Piette (2002). The updated survey included the collection of sufficient building characteristics so that calibrated simulation models of each of the more than 2,800 commercial buildings could be created (Ramirez et al 2005).

The Building Owners and Managers Association (BOMA) publishes an annual report on U.S. office markets (BOMA 2007). BOMA publishes information obtained from more than 3,000 office buildings including income, expenses, energy consumption, rent, and occupancy rate. But similar to the surveys noted above, the minimum geometric and other key information required for simulating the performance of those buildings is not collected by BOMA.

In Scotland, the Energy Systems Research Unit (ESRU) Domestic Energy Model (EDEM) (Clarke et al 2003, Clarke et al 2008, ESRU 2008) supports energy policy formulation for the residential sector. It provides representations of the entire domestic sector for Scotland, which allows policy makers to quickly apply a wide range of improvements analytically and evaluate which will provide the best energy performance or reduction in carbon. Analyses performed include national housing stock fabric upgrade strategies, local community upgrade strategy and carbon roadmap formulation, carbon and energy performance, and energy labelling in compliance with the EU Energy Performance of Buildings Directive. But the EDEM is limited to the domestic sector. An equivalent model for the non-domestic sector is not available.

The International Energy Agency (IEA) also publishes energy use data for buildings in member countries (IEA 2008), but this is a statistically disaggregated estimate, a top-down inference based on energy production and supply data. Little information is available on the average energy performance of buildings by type or climate zone.

While survey data are extremely useful for a building stock snapshot, they usually are limited by the information collected. Only rarely are there enough data to create a building model in energy simulation software. Several projects have worked to use existing survey data to create prototypes that represent large portions or building types and regions. Briggs et al (1987, 1992) created 20 existing office building prototypes, and Crawley and Schliesing (1992) created 10 new office building prototypes for use by the Gas Research Institute in research and market assessment. The existing building models were based on the 1979 Nonresidential Buildings Energy Consumption Survey (NBECS), the first survey in the CBECS. The new building models were based on Standard 90.1. In both cases, substantially more input data were required for the models, and sources are documented in their reports. Huang et al (1991) extended the prototypes to the entire commercial sector for 20 urban markets in the United States. Huang and Franconi (1999) updated the prototypes to evaluate the contributing components of commercial building loads. In all cases, these prototypes were limited by the assumptions that the authors had to make to create complete simulation models. Often these assumptions were not well documented.

Rather than producing prototypes to represent multiple buildings, Griffith et al (2007, 2008) created building simulation models for each of the more than 4,000 buildings in the 2003 CBECS. These building models were developed first as a baseline with energy features and performance consistent with Standard 90.1-2004 (ASHRAE 2004). Then low-energy technologies and renewable energy systems anticipated to be available by 2025 were applied to the models. The result was an assessment of the technical potential for achieving zero-energy buildings throughout the commercial building sector in the United States. The conclusion was that the zero-energy building goal could be, on average, achieved in the commercial building sector. Building types which can reach the zero-energy target easily:

offices, warehouses, schools, and retail. Restaurants, hospitals, and other energy-intensive building types will be the hardest to bring to net zero-energy. While not creating prototypes improved the breadth and representativeness of the analysis, it also created a logistic and quality assurance issue—how to deal with multiple thousands of building models. Griffith used an XML schema associated with a database of inputs to define each model. Since the inputs were derived directly from the CBECS data or related assumptions, the inputs could be automatically verified before a series of simulations were started.

Recently, Deru et al (2008) published a set of 16 benchmarks for new commercial buildings based on the 2003 CBECS and ASHRAE Standard 90.1-2004. The benchmark buildings descriptions include a scorecard comprising detailed documentation of all inputs and assumptions as well as information and data sources. Each benchmark building also has a corresponding EnergyPlus input files (US DOE 2007).

For utilities, the economic benefit of incentives paid for improved energy efficiency is often obscured by their regulated environment and the complex valuation of equitable sharing of net benefits, cost capitalization, and risks with their stakeholders. Rather than evaluating individual incentives, they aggregate the energy efficiency measures into a portfolio, essentially a top-down approach to the utility sector. For example, Cappers et al (2009) present an analysis of energy efficiency incentives in the context of a prototypical investor-owned utility. This analysis adapts a spreadsheet-based financial model (known as the Benefits Calculator) developed in support of the National Action Plan for Energy Efficiency (Jensen 2007).

The literature is full of similar portfolio-centric approaches to energy efficiency with a focus on program costs, costs and benefits to ratepayers, and similar utility rate case calculations. Many consultants offer services to develop and evaluate incentives for utilities but few publish in the peer-reviewed literature, which may indicate that they see their utility incentive calculation methodologies and procedures as a business advantage. Instead, utilities focus on supporting their customers and administering the incentive programs. Ter-Martirosyan (2003) says that this is due to changes which began in the late 1980s, with public utility commissions and other regulators focusing on regulation of the incentives themselves rather than the rate of return the utility could earn. For utilities, this has a two-fold result—decreased quality and cuts in service (as described by Ter-Martirosyan) and less interest in detailed engineering approaches that are overwhelmed by their heavily regulated environment.

2.4 Climate Data in Building Performance Modeling

For many years, the unavailability of data was a limiting factor in what could be done to represent climatic conditions in a specific location or common climate conditions in a zone. More recently, better data sets have allowed aggregation of multiple locations and statistics to create maps and climate zones.

As recently as 15 years ago, limited weather data were available to building simulation users. Even in the early 1990s, the number of weather files available in the United States was fewer than 100 locations for a country of nearly 10 million km^2. Today, the United States has more than 1,000 "typical" weather files available in the TMY3 format (Wilcox and Marion 2008) and another 1,000 weather files are available internationally[1]. Until more typical weather files become available as more meteorological data are collected, tools such as Meteonorm[2] allow knowledgeable users to interpolate and extrapolate weather data for use in simulation tools, but even these tools are limited by the available data and statistics.

Building standards have used a variety of climate zones over the years. In Standard 90.1-1989, 38 climate regions were defined to represent that range of climatic conditions worldwide. A subsequent revision to the climate zones in Standard 90.1-1999 took the number of climate zones to 73. When this number proved unwieldy, research by Briggs et al (2003a, 2003b) evolved eight major climate zones with subcategories of wet and dry. This resulted in 15 climate zones, as shown in Standard 169-2006 (ASHRAE 2006).

Crawley et al (1999) proposed a new, neutral weather data format for building performance simulation programs. In the past nine years, more than 20 simulation tools and providers of weather data have adopted this format or adapted their climate data tools to read or write it. Hensen (1999) reviewed and identified issues with availability, temporal resolution, and data required for building performance simulation. He found that climatic data availability and

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[1] A list of publicly available typical meteorological data for more than 2,100 locations from 20 data sets including source is available: http://energyplus.gov/weatherdata_sources.cfm. This list omits proprietary or older data sets, such as the Test Reference Year (TRY) developed in the EU (CEC 1985), the older TRY in the United States (NCDC 1976), and the Weather Year for Energy Calculations (WYEC) and WYEC2 data sets from ASHRAE (1985, 1997).
[2] http://www.meteotest.ch

resolution was still a significant issue in building performance simulation and that building performance tools increasingly need additional data such as illuminance, sky temperature, and pollutants that have traditionally not been widely available.

2.5 Modeling Climate Change and Urban Heat Islands

During the past 15 years, much scientific work has been published on humans' potential impact on climates. For their Third Assessment Report in 2001 (IPCC 2001), the United Nations Intergovernmental Panel on Climate Change (IPCC) developed a set of economic development scenarios, which were then run with the four major general circulation models (GCM) to estimate the anthropogenesis-forced climate change. These GCMs produce worldwide grids of predicted monthly temperature, cloud, and precipitation deviations from the period of 1961–1990. As this period is the same used for several major typical meteorological year data sets, these typical data sets can be used as a starting point for modifying weather files to represent predicted climate change. The IPCC summarizes the impact on the built environment simply as "increased electric cooling demand and reduced energy supply reliability."

Trigo and Palutikof (1999) reanalyzed the HadCM2 data for Portugal using artificial neural networks to downscale the data to predict future climate conditions in Portugal. They found that the HadCM2 produced unreliable results for local sites in Portugal.

In a proof of concept study, Crawley (2003) found that temperature increases expected from climate change would substantially increase the operating time for cooling equipment in the United States and would shift many locations from heating (typically fossil fuel-based systems with conversion efficiencies of less than 1) to cooling (predominantly electrical systems with COPs greater than 2). By adding the annual average temperature predicted by the IPCC climate change scenarios to existing weather data for a few U. S. locations, he showed that annual average space temperatures would increase toward the cooling temperature set-point (see Figure 2-1).

Hacker et al (2005) looked at the potential summer overheating risks associated with the climate change scenarios in the United Kingdom for offices, schools, and houses. They then proposed measures for mitigating the overheating risks. Levermore took this research further

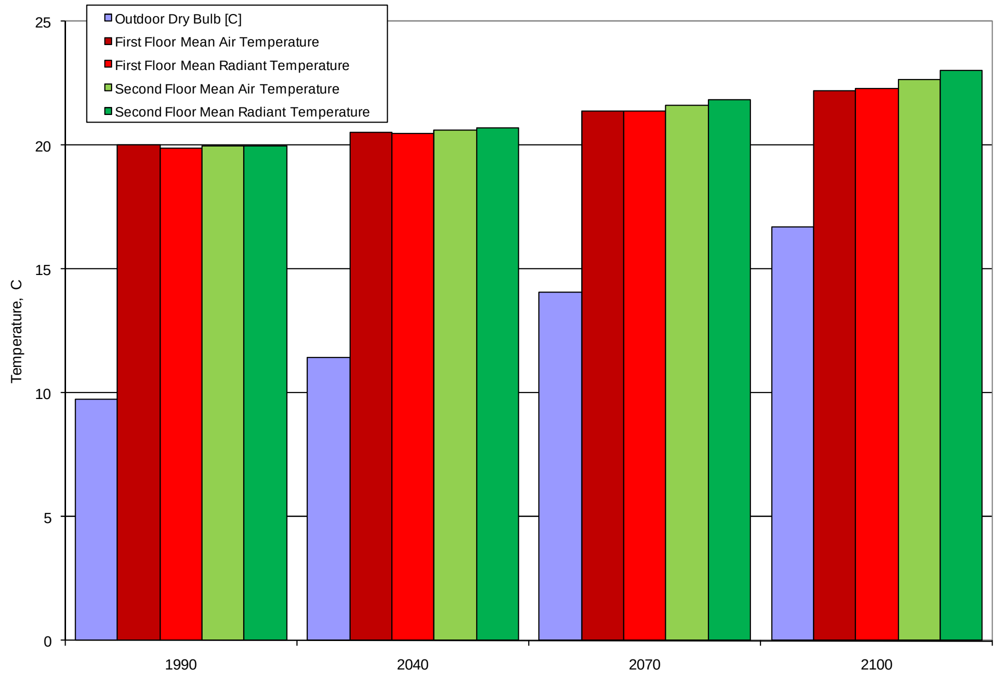

Figure 2-1. Annual Average Outdoor Temperature and Predicted Indoor Mean Air and Radiant Temperature, °C, by Zone in Chicago, Illinois, USA (Crawley 2003)

and created climate change weather data for Edinburgh, Manchester, and London (CIBSE 2004)—tabular design conditions for potential future conditions. This results in a static data set of future climate conditions based on one model.

To support the development of the 2007 update report for the IPCC, Scott et al (2007) evaluated the potential impacts of climate change using a sector-wide, top-down model of the building sector, estimating increases in energy use and the value of building energy-efficiency programs. In their work, they started with an overview of the building sector in terms of energy use and estimated the impacts of changes in climate. Rong et al (2007) and Edmonds et al (2007) document a global macroeconomic model of energy use which includes the building sector by representing the demand for energy services—heating, cooling, and lighting and future scenarios of efficiency, growth in use, and climate change. While this might be useful to estimate the impacts on a sector, it does not provide insights into which building systems are the largest contributors to the changes in energy performance. That information is only available from a bottom-up model of the sector with explicit building models and thermo-physical characteristics.

Studies of urban heat island (UHI) or urbanization conducted during the past 50 years have provided detailed measurements of the diurnal and seasonal patterns and differences between urban and rural climatic conditions. The U.S. Environmental Protection Agency (US EPA) estimates that an annual mean air temperature of the urban center of a city with 1 million people or more can be 1–3°C warmer than its surroundings (US EPA 2008). Wypych and Bokwa (2006) state:

> "In many cities, the air temperature is, on average, 0.5 to 0.8°C higher than the surrounding non-urban areas. In winter, the average temperature difference is even greater, between 1.1 and 1.6°C."

They further state:

> "The number of inhabitants is a major factor controlling the development of the UHI. In cities with populations between 500,000 and 1,000,000 people, air temperatures are usually 1.1 to 1.2°C higher than surrounding non-urban areas. For cities with more than a million people, the difference between urban and non-urban average temperatures increases to between 1.2 and 1.5°C."

They go further to say that "maximum observed differences can be much higher" and cite 10°C for a city with a population of 10 million. While heat islands have been shown to be a function of both population and microclimatic and site conditions, they can be generalized into predictable diurnal and seasonal patterns.

Matsuura (1995) studied the impacts on the performance of two buildings by altering the air temperature in weather data by 1°F and taking into account the shading effects of a nearby building. He found that a significant decrease in energy loads occurred in both cold climates (Duluth, Minnesota) and hot climates (Phoenix, Arizona). Carlo and Lamberts (2001) studied the impact of urbanization on two prototype office buildings using DOE-2.1E. Temperature data from local airports were adjusted to account for microclimatic effects. Solar radiation data were not available and were calculated. Carlo and Lamberts found that microclimatic variation within an urban area can be as great an influence on building performance as building characteristics and configuration. Akbari and Konopacki (2005) evaluated the potential energy savings from mitigating heat island effects. They used a constant change in temperature applied in building simulation models. This constant change in temperature does not take into account the variation in diurnal demonstrated by Oke (1988).

While the scientific literature is full of studies looking at the impact of climate change driven by human activity, there is little research on the impact of climate change or urban heat islands on building operation and performance across the world.

2.6 Data Issues in Multi-Building Studies

The largest challenge of research involving large numbers of simulation models is dealing with the immense amount of data that building performance simulation programs can create. For example, a single EnergyPlus simulation with 10-minute time step output can produce more than 600 megabytes of data. Handling the data from hundreds or thousands of simulations can overwhelm a researcher.

In their studies of Standard 90.1 in the 1980s, Crawley et al (1985a, 1985b, 1989) created five building type DOE-2.1E models for the commercial sector. They were based on the earlier models created for SP 41 and included variants tied to five climate regions throughout the United States. Three variations on the base model were created—Standard 90-75, Standard 90A-1980 (ASHRAE 1980), and the proposed draft standards, which became Standard 90.1-1989. This large number of simulations (5 buildings x 5 climates x 3 standards) required that the structure of the analysis be carefully designed, including a systematic file-name convention that included abbreviations for building type, climate zone, and variant of the standard. The researchers also created batch scripts to automate running the simulations and extracting summary energy results. When the ASHRAE committee developing the standard created three drafts in three years, this structure and automation proved invaluable. When Johnson et al (1988) studied the potential for upgrading building energy standards in the Pacific Northwest, they were able to quickly adapt the 90.1 scripts and input files and complete the analysis in less than two months.

In the study for the Gas Research Institute described above, Briggs et al (1992) chose to create a spreadsheet that included the key characteristics definitions for the building prototypes and all the parts of the simulation input files. Invoking a macro in the spreadsheet automatically generated the input files for the existing office building prototypes. This provided the added advantage of having all the input in tabular form, ready for insertion into the research report. A further advantage was that the prototypes could be modified easily and the data checked carefully.

When Huang and Franconi (1999) created new prototypes, they constructed these as snippets of simulation input files. The user simply invoked a batch script that assembled the correct parts into a complete input file.

Griffith et al (2007, 2008) took a more robust approach in studying the technical potential for achieving zero-energy commercial buildings. Because this study involved creating a building simulation model for each of the more than 5,000 buildings in the 2003 CBECS, it necessitated the development of a method for automatically creating the input files. Griffith created a set of high-level XML definitions for all the key inputs, such as floor area, weather data, floor-to-floor height, lighting power intensity, and HVAC system. He created a specific part of the input file for each of these XML definitions. When the XML scripting tool was passed an XML key, a specific input file could be created. Further scripting tools were created to automatically submit simulations on multi-core computer clusters and extract summary results from the completed simulations.

Creating a structured approach to studies involving multi-building simulations is also vital to quality assurance. Checking the values of individual inputs is not easily accomplished if several hundred or thousand individual input files are involved. Summary tables of the values of key inputs that can be checked easily and then automatically transferred to input files are critical.

Donn (2007) studied the role of Quality Assurance (QA) in environment design decision support tools for architecture, including a variety of building performance simulation tools for daylighting, thermal design, and acoustics. He found that not only was it critical to have QA procedures as a standard part of any building analysis, it was critical to have QA measures that are codified and incorporated into the simulation tools themselves. These QA measures would be reality tests to examine whether outcomes from the design decision tools behave in a believable manner— like a real building. Donn also proposed the establishment of a shared database on QA performance data available to all design decision tool users.

2.7 Summary

This chapter has presented a review of the literature relating to commercial building policy studies in a number of areas:

- development and evaluation of building energy standards
- buildings models and building stock

- utility incentives
- climate data for building performance modeling
- modeling climate change and urban heat islands
- QA and data volume issues in multi-building studies

For the development and evaluation of building energy standards, the literature showed that having a number of prototype buildings which could represent the wider building stock was important. Several of the studies (US DOE 1987, Johnson et al 1988) had few buildings and the results could not be extrapolated to the wider commercial building sector. Similarly, a large number of buildings raised the level of complexity as seen in the work by Carlo et al (2003) which has implications for data management and QA. On the other extreme, a simple model such as the SBEM can inhibit the adoption of new technologies. It is important to be able to adequately cover the range of characteristics expected for the buildings to be simulated.

In setting policy for commercial buildings, the ultimate targets are individual buildings. But how the proposed policy will perform in a broader context of a region or country or a building type or entire building sector is important as well. Policy makers need to be able to relate individual decisions to their impacts. In that context, this requires an understanding of the target building stock including the size and number of buildings as well as their operating and physical characteristics. The literature review of building stock found few sources of detailed data below sector-level energy use. A few building characteristics surveys were available in North America and Europe but they all had limitations in the depth or quality of data available for building modelling. The exception was in California where the commercial building survey was coupled with calibrated building simulation models. Further review found work that filled in the data missing from the surveys with assumptions, rules of thumb, and other data. Often these supplementary data were not described in the reports or other documentation, making it difficult for potential users to fully understand the models. More recent benchmark buildings (Deru et al 2008) are working to overcome these limitations by fully documenting all input assumptions and sources of data in the building models.

Interestingly, there were very few published studies on setting the level and technical attributes for utility incentives in the peer-reviewed literature. Most utility incentives literature focused instead on the delivery and administration of incentive programs for energy efficiency in commercial buildings.

Several studies noted that despite a substantial increase in the number of locations for which climate data are available over the last few years, limited availability and temporal resolution in many areas throughout the world is still an important issue.

In investigating studies relating to modeling climate change and urban heat islands, it was found that most were limited in scope to a small region or were top-down estimates of impacts. In addition, the methods used to create climate data to represent climate change or urban heat islands were usually limited to simply adding the same temperature change to every hour. This does not agree with the findings of the IPCC, Oke, and others that diurnal temperature patterns change along with the average change in temperature. The global circulation models used in the study of climate and the studies where urban heat island is documented show a clear compression of the diurnal temperature range is part of the change in average temperature.

Finally, studies that dealt with large number of building simulations found a number of means of automating the creation of building models. Some used spreadsheets, others scripts, but in all cases, it was critical to having a structured approach for the validation and error checking of individual inputs. This structure forms a critical part of the framework necessary for building research support policy-makers.

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Chapter 3
Defining Models and Processes to Support Policy Analysis

> When you can measure what you are speaking about, and express it in numbers, you know something about it, but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind.
>
> Lord William Thomson Kelvin

3.1 Introduction

A key part of simulating a building is creating a model to represent that building. In the more traditional use of building simulation as described in Chapter 1, a single building may be modeled in detail for response to one or more conditions. But when using building simulation in policy analysis to establish new building standards or looking at impacts of wide changes to the building sector, the interest is not a single building but a segment or entire building stock of a region or country. Thus the analysis must establish not a single representation but a range of attributes, including building size, configuration, internal loading, scheduling, systems, and other key building characteristics. In addition, because these research studies often involve hundreds or thousands of files—input, output, and weather data—the analysis requires a structured approach for constructing inputs, managing the outputs, and deriving summary data.

This chapter first describes the research approach for each of the studies, comparing the simulation programs, building models, climatic data, research questions (of each study) and the parameters that were tested. This chapter then describes the development of building models and processes for the multi-building policy analyses described later in this thesis.

Section 1.6 listed examples of building policy targets including international, national or regional policy, developing and evaluating energy efficiency standards for buildings, establishing the structure and design of a voluntary energy efficiency program, and setting appropriate levels of financial incentives for utilities. Each of these policy-setting projects required a multi-building analytical structure to evaluate multiple building use types; ranges of building thermal characteristics; internal loads; schedules; climate regions; construction methods and costs; and lighting, heating, cooling, and ventilating systems. The following four policy studies cover aspects of all the policy targets identified above. In addition, the structures created to manage the simulation processes are described for each of the studies. The first two studies were conducted from a Canadian view—developing building energy standards or setting utility incentives for Canadian locations. The third study describes analysis performed to support the development of a new voluntary energy efficiency program in the U. S. The fourth is an evaluation of local impacts of climate change and heat island on a small office building, including the influences of energy efficiency and renewable technologies on total energy performance.

Section 3.2 describes a constrained set of models used to create correlations of building loads related to envelope characteristics along with the design of the parametric study. The results and analytical framework required for this study are presented in Chapter 4.

Section 3.3 describes models created to support the development of an electric utility incentive program for new building envelope construction comprising a range of parametric building modeling. This program focuses on financial incentives paid to building owners to improve the energy efficiency of their buildings beyond the provincial building energy standards. The results of the utility incentives modeling and the structure used are also described in Chapter 4.

A series of building energy analyses supporting a voluntary governmental program to promote energy efficiency in commercial buildings also was conducted. These analyses include staged upgrade pathways for improved energy efficiency in existing building envelopes, downsizing chillers when retrofitting for refrigerant replacement, and determining whether the weather data used was important. Section 3.4 describes the models created to support these analyses and the series of simulation suites created to estimate potential savings of the program. The results are also presented in Chapter 4.

Finally, Section 3.5 describes the derivation of building models to represent new, existing, and low-energy buildings to support analysis of the impacts of urban heat islands and predicated climate change. The selection of climatic data and representation of urbanization and climate change also are presented. The results for the analysis of urbanization and climate change and the analytic framework are described in Chapter 5.

These four studies also differed in approach to building models. The first two (parametric study of envelope components and utility incentives for building envelopes) use a simple four-zone model which focuses on the interactions of the building envelope characteristics with solar and internal gains. This four-zone model represents the interactions of a generic envelope surface more than an actual building. In contrast, the other two studies (voluntary energy efficiency program and analysis of climate change impacts) specifically focused on energy performance changes which could be related to new and existing buildings. Thus, both started with available representations of the commercial building sector—in this case a statistical survey of more than 4,000 buildings which included energy consumption and characteristics.

Table 3-1 compares the key research attributes of the four studies. The parameters selected for the analysis were determined from the research questions and the intended use of the building performance data. For example, in the energy standard envelope study, it was important that the data set cover the range of possible combinations of envelope thermal characteristics, internal gains, solar gains, and locations. For the electric utility incentives, the focus was on the energy and cost saving of specific envelope technologies were available in the market place. For the voluntary energy efficiency program research, the parameters were selected based on field studies to support the staged approach. For the climate change impacts study, the focus was to cover a range of climatic conditions (typical, high-, and low-energy years); range of climate change scenarios and heat island cases; and typical, high, and low-energy building energy performance.

The models and data presented in Sections 3.2, 3.3, and 3.4 were originally prepared in Imperial units commonly used in the United States. These data have been converted to Metric units with original Imperial units in parentheses only where it adds clarity (Imperial units were often round numbers, such as 1 W/ft^2 or 48,000 ft^2, translating 10.8 W/m^2 and 4,461 m^2). At the time the work described in Sections 3.2, 3.3, and 3.4 was performed, DOE-2 was the building energy simulation program commonly used for building research and standards development in the United States and Canada. Subsequently, development and support for DOE-2 ended as EnergyPlus was introduced with capabilities that exceed those of DOE-2. For the work described in Section 3.5, EnergyPlus was used for the energy simulation analysis.

Table 3-1. Key Attributes of the Four Studies

Parameter	Research Study			
	Envelope Standard (Section 3.2)	Envelope Utility Incentives (Section 3.3)	Voluntary Energy Efficiency Program (Section 3.4)	Impact of Climate Change on Commercial Building Performance (Section 3.5)
Research focus	Develop envelope thermal response data set	Determine cost-effective envelope upgrades beyond minimum energy code	Determine optimal pathways for energy retrofits in existing office buildings	Evaluate potential impacts of climate change and heat islands on commercial building performance
Simulation Engine	DOE-2.1E	DOE-2.1E	DOE-2.1E	EnergyPlus
Research Parameters	Complete range of envelope characteristics, solar gains and internal loads, generic HVAC	Cost-effective window, wall insulation, and roof insulation upgrades beyond minimum energy standard requirements	Staged pathways for energy efficiency retrofits in commercial buildings including building envelope, internal loads, building operation, and HVAC systems and plant	Adapt existing climate data to represent future climate change and heat islands. Determine response of typical, developing, and low-energy commercial buildings
Climate Data	Typical year data for Canada (25 locations)	Typical year data for Ontario, Canada (5 locations)	Typical and observed year data for United States (18 locations)	Typical and observed year data worldwide in 25 locations (20 climate regions)
Baseline Model	Prototypical thermo-physical four-zone model, parameters varied across range of possible values	Prototypical thermo-physical four-zone model, provincial energy standard	Existing office buildings (low-rise, mid-rise, and high-rise) prototypes derived from existing building stock survey	Typical, developing, and low-energy office building; typical derived from standard and building stock survey
Intended Use for Building Performance Data	Derive building envelope regression model from annual energy performance	Determine cost-effective envelope upgrades	Determine cost-effective staging pathways for upgrades, look-up tables for technology upgrades, promotional material	Building performance response to predicted climate change and heat island cases

3.2 Developing Models to Support Thermal Envelope Analysis in a Building Energy Code

In the early 1990s, the Building Performance Laboratory of the Institute for Research in Construction, National Research Council Canada (NRC) worked with the Standing Committee on Energy Conservation in Buildings, Associate Committee on the National Building Code to develop a new National Energy Code for Buildings (NECB) in Canada. An important part of that work was to review the existing envelope load correlations in *ASHRAE/IES Standard 90.1-1989*, "Energy Efficient Design of New Buildings except Low-Rise Residential Buildings" (ASHRAE 1989a) and to create new correlations if those proved unsuitable for Canadian climatic conditions. This section presents an overview of the building model created for that work as well as the data set created[1].

In this context of this first study, a data set of building simulation results was developed for use in new envelope load equations. These envelope equations correlate envelope characteristics with heating, cooling, and fan loads. This study focuses on establishing the structure of the data set to ensure that it included the range of possible characteristics in commercial buildings.

3.2.1 Background

The Standing Committee on Energy Conservation in Buildings with support from NRC developed the NECB—a new model code for energy efficiency in new buildings. At the time of this work, NRC staff were developing draft text for this code. The draft code contained "empty tables" for prescriptive requirements for thermal characteristics of the building envelope. Canadian provinces and other authorities wishing to implement the model code used a computerized procedure based on life-cycle cost (LCC) analysis (developed by NRC) to determine the thermal envelope values for these tables. Regional economic assumptions and cost data were used in the LCC analyses so that the resulting code would be tailored to regional conditions (similar to the approach used by ARES [US DOE 1989]).

The calculation procedures used to estimate the energy consumption change associated with a change in envelope thermal characteristic form the basis for both the selection of the prescriptive (base) values for the tables and the compliance software. The compliance

[1] Much of this was previously published in Crawley (1992).

software allows users to trade off combinations of envelope characteristics that result in equal or lower consumption.

Standard 90.1-1989 used a procedure in its envelope trade-off performance compliance procedure (implemented in the Standard 90.1 ENVelope STandarD [ENVSTD] software [Crawley et al. 1989]) based on a set of correlations of envelope loads from more than 3,000 DOE-2 simulations in 36 U.S. locations (Berkeley Solar Group 1986; Wilcox 1991). NRC planned to use these correlations in the LCC analyses as an interim solution. They had concerns, however, that the 90.1 correlations were not entirely valid for Canadian weather conditions and that the correlations did not include floors, roofs, and other envelope components.

3.2.2 Review of Standard 90.1 Envelope Load Correlations

Envelope correlations that predict the impact of envelope components in the exterior zones of buildings for energy code purposes were developed initially in 1983 as part of ASHRAE Special Project 41 (SP 41) (Pacific Northwest Laboratory 1983). SP 41 was sponsored by US DOE to develop an update to *ANSI/ASHRAE/IES Standard 90A-1980* (ASHRAE 1980). The issues identified are presented next, and the predicted loads from the correlations are compared with results from DOE-2.1E (LBL 1991).

The Standard 90.1 correlations were derived from statistical regressions of simulated heating and cooling system coil loads for 36 U.S. locations. A prototypical five-zone building was simulated using DOE-2.1B (LBL 1984) to develop heating and cooling coil loads from a simulation of a packaged single-zone (PSZ) system. The four exterior zones were each 30.5 m x 4.6 m, 139.4 m^2 (100 ft x 15 ft, 1500 ft^2). The interior zone was 30.5 m x 30.5 m, 929.4 m^2 (100 ft x 100 ft, 10,000 ft^2). The system simulation did not include the free-cooling effects of economizer systems—important in the relatively mild cooling climates of Canada. The weather data used in the simulations were Typical Meteorological Year (TMY) data (NCDC 1981), a set of statistically derived, hourly weather data. The TMY data set contains no Canadian locations.

3.2.3 Concerns about Using 90.1 Envelope Correlations for NECB

A number of concerns about using the Standard 90.1 envelope correlations had been identified including:

- The DOE-2.1B simulation program used to generate the coil loads was released in 1983. Subsequently, DOE-2.1E had been released with significant enhancements and improvements to the simulation of building envelopes. Probably most significant, the sky model was changed to an anisotropic model from the isotropic sky model in DOE-2.1B. Other improvements made it easier to obtain the data needed for the envelope correlation work.
- The heating and cooling coil loads of a PSZ system without economizer controls were simulated for the original envelope correlation data set. The LCC model that NRC developed required energy performance data to enable calculation of cost benefits from energy savings.
- No Canadian locations were among those used to develop the data set for the Standard 90.1 envelope correlations. Although many U.S. locations along the border have climates similar to those of Canadian locations, the coldest location used in the data set was Fairbanks, Alaska, with 8,000 heating degree-days base 18.3ºC (14,400 heating degree-days base 65ºF). This effectively limits use of the correlations to locations with fewer than 8333 heating degree-days base 18.3ºC (15,000 heating degree-days base 65ºF)—preventing the colder northern locations in Canada from being able to use the correlation methodology.
- The correlations did not cover the range of potential new envelope technologies (or even existing ones). High-performance windows are now available that are far better than any included during development of the correlations. This required extrapolating beyond the original correlation data set—with potentially inaccurate results.
- The correlations are complex and cannot be checked easily by manual calculations. Including the coefficients, the correlations extend for more than six pages in Standard 90.1. People questioned whether this complexity adds to the accuracy of the results. Also, the form of the equations do not reflect physical relationships or engineering-based calculations.
- In early 1992, while using the correlations in test cases, NRC staff found significant inconsistencies when comparing the correlation results against a simulation program. The heating loads predicted by the correlations appeared to be reasonable, but the cooling loads were twice as large as expected.

3.2.4 Predicted Heating and Cooling Loads from Envelope Correlations

As a way to test the importance of these concerns, the loads for a series of cases were calculated using the original correlations and Ottawa, Ontario weather data. Using an internal load of 21.5 W/m^2 (2 W/ft^2) and a range of U-values from 0.284 to 2.84 W/(m^2-K) (0.05 to 0.50 Btu/(h-ft^2-ºF)) along with a range of shading coefficients from 0.0 to 1.0, predicted heating and cooling loads were calculated using the correlations. The results are shown in a series of figures for the east, north, south, and west orientations and discussed below. Figure 3-1 shows the heating and cooling coil loads from the Standard 90.1 envelope correlations for the east orientation. Figure 3-2 shows the north orientation, Figure 3-3 the south orientation, and Figure 3-4 the west orientation.

The heating results are well ordered except in cases of low heat loss values (0.284, 0.568 W/(m^2-K); 0.05, 0.10 Btu/(h-ft^2-ºF)). In these cases, the predicted heating loads do not run parallel to the other values and quickly go off the scale as the shading coefficient is increased—the opposite of what would be expected. This shows that these data are beyond the range of the data set used for the correlations. Correlation-based methods should be limited to the range of the data set from which they were constructed.

3.2.5 New Prototypical Building Model for Envelope Correlations

A five-zone model similar to the one used in the SP 41 (Pacific Northwest Laboratory 1983) to develop the first set of regression equations was created to compare the predicted loads from the Standard 90.1 correlations with DOE-2.1E results. ASHRAE Standing Standard Project Committee (SSPC) 90.1 used a similar model to produce revised regression equations in 1986 (Berkeley Solar Group 1986; Wilcox 1991). In 1989 and 1990, Eley Associates (1990) used a variation of the same model in work for the SSPC 90.1 and the Primary Glazing Manufacturers Council. The California Energy Commission (CEC) used a similar model in setting requirements for its third-generation non-residential energy standards (CEC 1990).

This five-zone model was simplified to make it less an actual building than a model of thermal zones. The HVAC system type was changed to a packaged variable-air-volume system (PVAVS) which includes an outside air economizer. The core zone was removed from the simulation, leaving the four exterior zones. (As with the Standard 90.1 envelope correlations, the NECB used data from exterior zones only—the core zone was not needed.)

The revised model has four zones, each facing a cardinal direction, as shown in Figure 3-5. Each zone is 4.6 m x 30.5 m (15 ft x 100 ft), with areas of 139.4 m^2 (1500 ft^2) and a floor-to-floor height of 3.6 m (12 ft). The HVAC systems have been simplified, and each zone has an independent system. Cooling is scheduled off during unoccupied periods; heating is available whenever needed. Minimum ventilation rates were set to *ANSI/ASHRAE Standard 62-1989* (ASHRAE 1989b) requirements—189 l/s-person (20 CFM/person). Zone setpoint temperatures were 22.2°C (72°F) for heating and 23.9°C (75°F) for cooling, with a 12.8°C (55ºF) night setback for heating and unlimited setup for cooling. Fan power was set to be linear from 0 to 100 percent part-load. Cooling auxiliary equipment energy was set to zero. Heating and cooling equipment efficiencies were set to 1.0 in the model, allowing them to be adjusted later outside the envelope correlations.

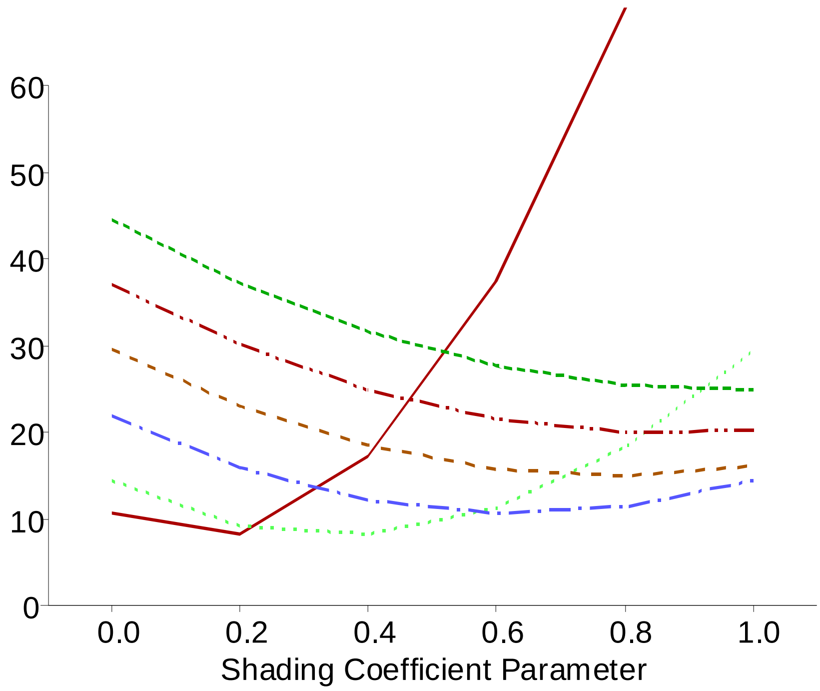
With these assumptions, monthly reports were created to present monthly energy loads for five end uses: heating, cooling, fans, lighting, and miscellaneous equipment.

3.2.6 **Predicted Heating and Cooling Loads using New Prototypical Building Model**

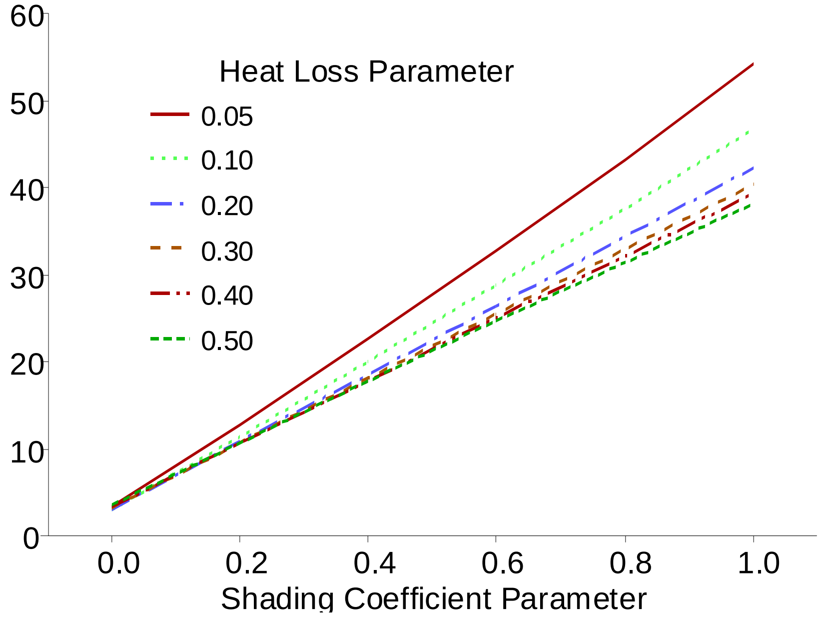
Using this new DOE-2.1E 4-zone model, simulations were run using the same thermal characteristics as for correlations shown in Figures 3-1 through 3-4 [internal load of 21.5 W/m^2 (2 W/ft^2), U-values from 0.284 to 28.4 $W/(m^2\text{-}K)$ (0.05 to 0.50 $Btu/(h\text{-}ft^2\text{-}°F)$), and glazing shading coefficients from 0.0 to 1.0]. The heat loss parameters shown on Figures 3-1 through 3-4 are U-values in $Btu/(h•ft^2•°F)$. To convert to $W/m^2•K$, multiply by 5.678.

Figure 3-6 shows the DOE-2.1E simulated coil loads for the south orientation. Note that unlike the data for the Standard 90.1 envelope correlations, these data are well-ordered and behave as expected. As the shading coefficient increases, cooling energy loads increase and heating energy loads decrease; as the heat loss parameter increases, the cooling decreases and the heating increases.

The heating loads predicted by the Standard 90.1 envelope correlations are of the same general magnitude and have the same general response as the DOE-2.1E simulation results. The cooling results from the correlations are as expected for the east, south, and west orientations, except that they are approximately twice the loads predicted by DOE-2.1E (Figure 3-6). This is attributed to the absence of economizer controls in the simulations



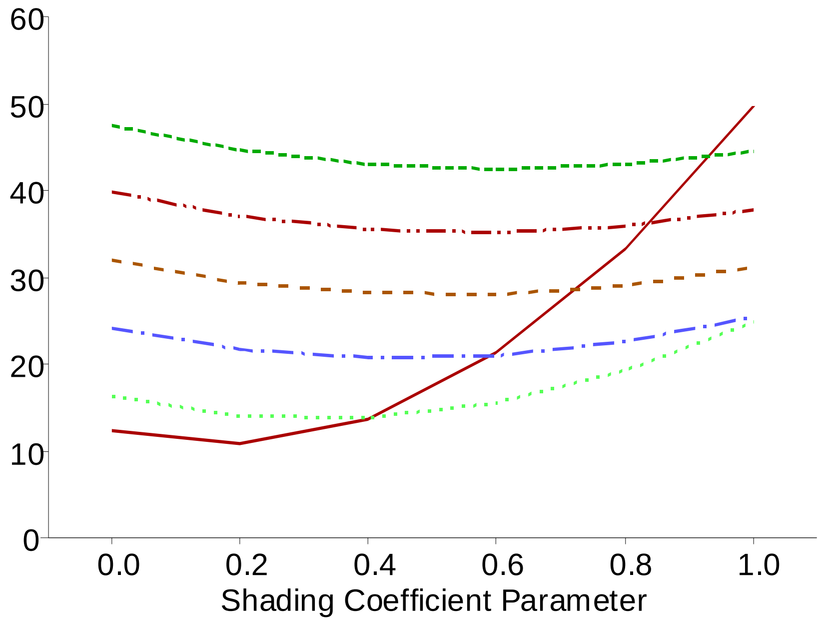
Heating



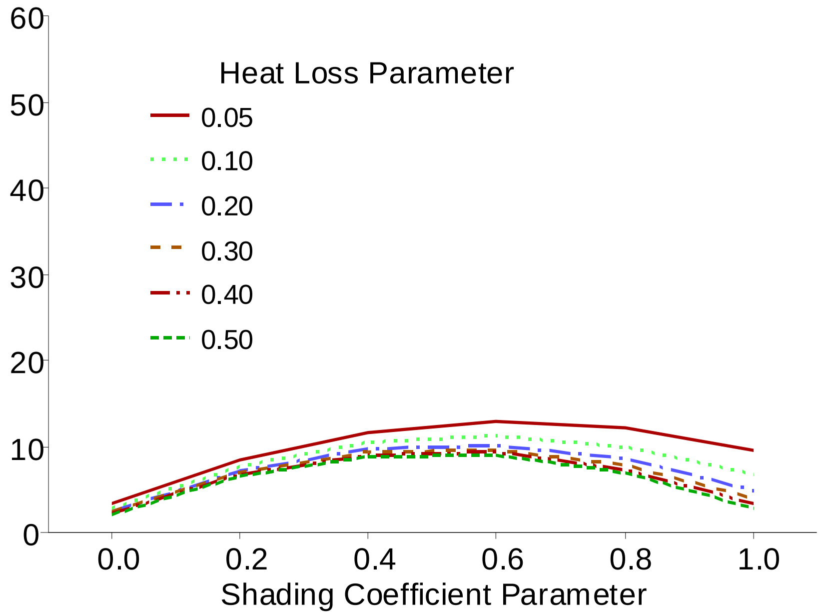
Cooling

Figure 3-1. Coil Loads for the East Orientation[2]

[2] The units for the Y-axis in each figure are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.



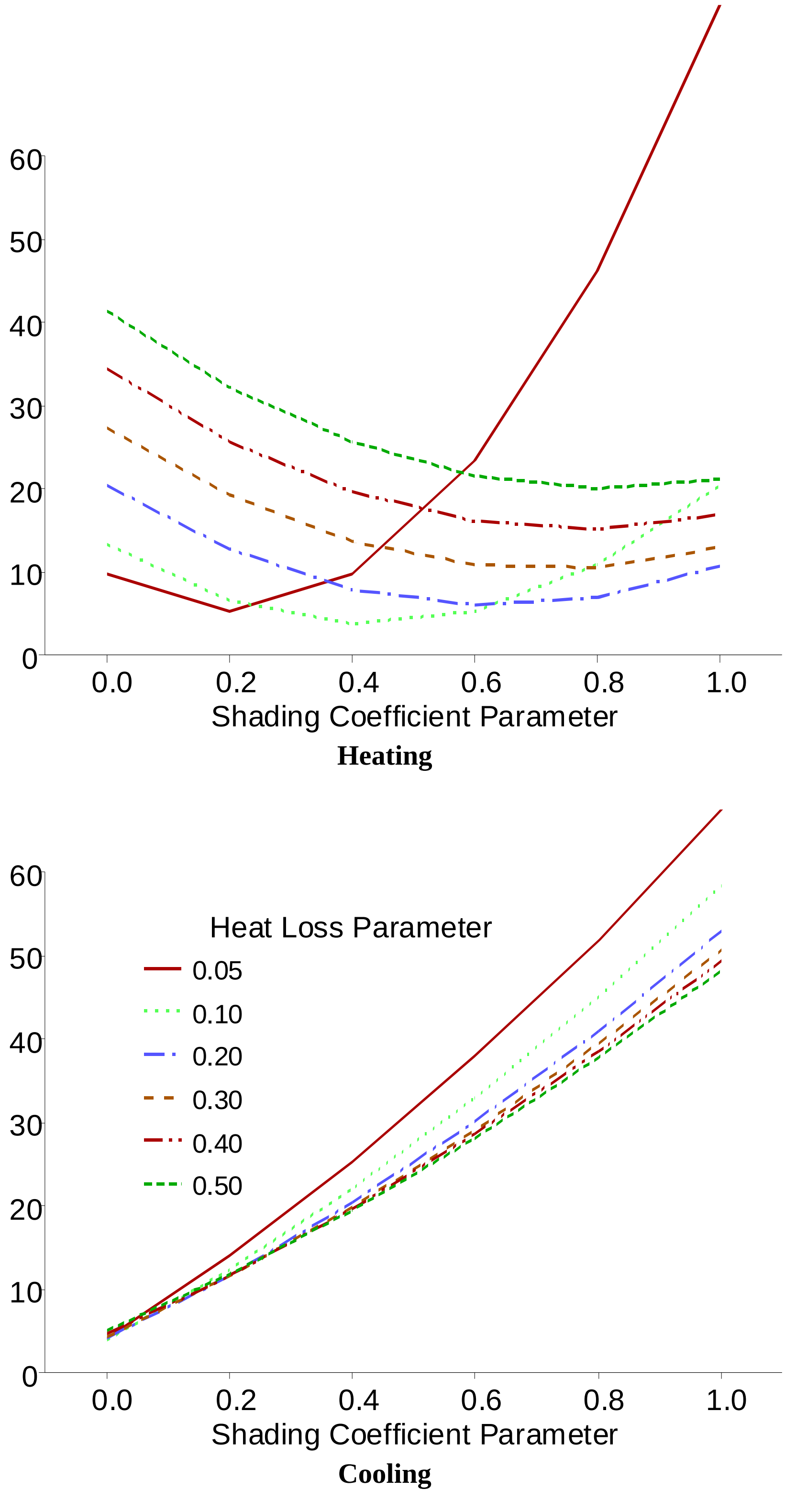
Heating



Cooling

Figure 3-2. Coil Loads for the North Orientation[3]

[3] The units for the Y-axis in each figure are in kWh/ft². To convert to kWh/m², multiply by 10.76; to convert to MJ/m², multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft²•°F). To convert to W/m²•K, multiply by 5.678.

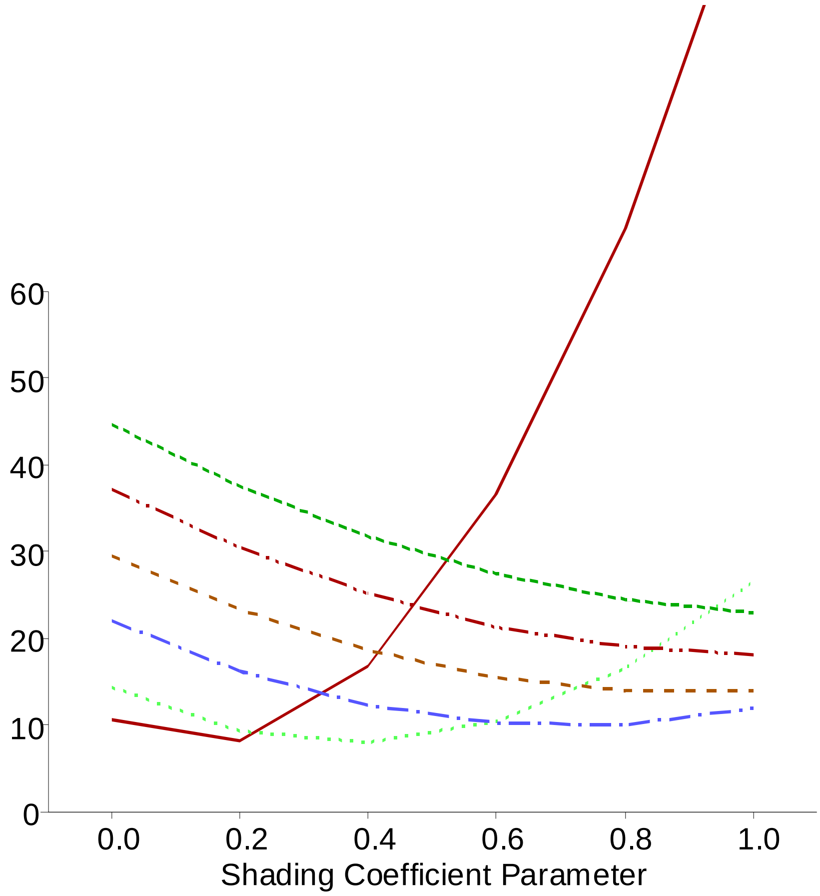


Heating

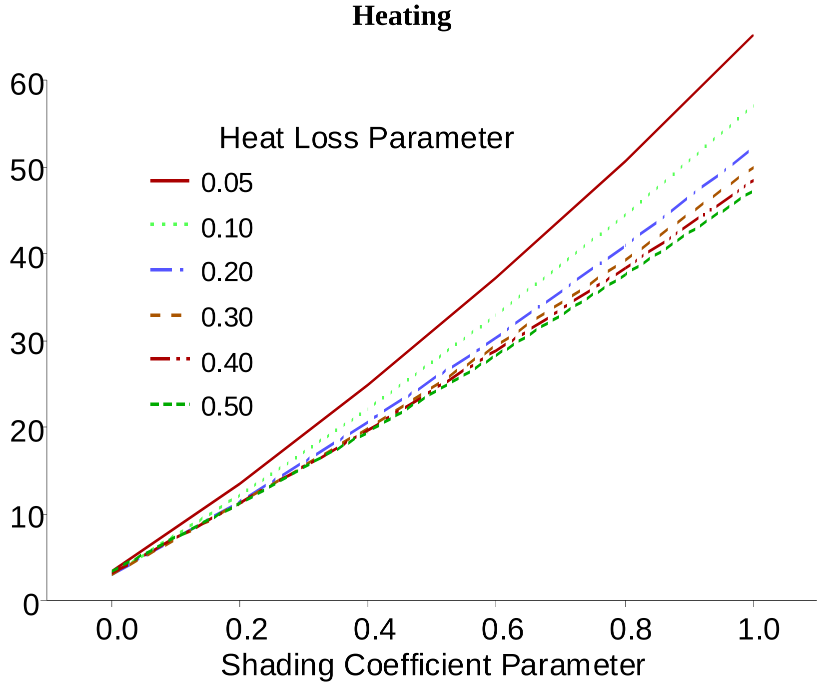
Cooling

Figure 3-3. Coil Loads for the South Orientation[4]

[4] The units for the Y-axis in each figure are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.



Heating



Cooling

Figure 3-4. Coil Loads for the West Orientation[5]

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[5] The units for the Y-axis in each figure are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.

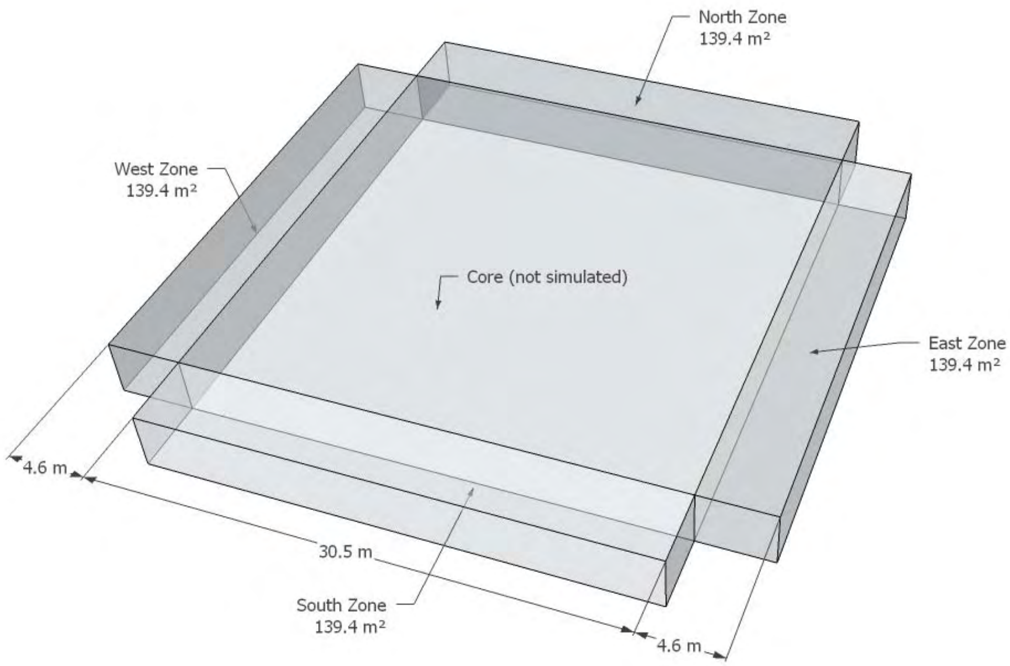

Figure 3-5. Diagram of Four-Zone DOE-2 Building Model

performed for the original envelope correlation data set. An economizer is particularly effective in reducing cooling loads in the relatively mild cooling climates of Canada. There is not a reasonable explanation for the north orientation results—as shown in Figure 3-2—the cooling loads for the north orientation continue to increase as the shading coefficient increases. These results show that using the Standard 90.1 correlations for Canadian constructions and climates could force them beyond the valid ranges of their use. Because of these identified shortcomings in the existing Standard 90.1 correlations, a new data set of DOE-2.1E heating and cooling results was developed for Canadian locations for use in deriving new envelope correlations. This work is described in the next section.

3.2.7 Design of Parametric Analyses for Envelope Correlations

The envelope correlations were intended to predict the energy consumption change that results from a change in envelope characteristics in a separate procedure that NRC developed. This procedure used construction cost and operating cost (including energy) to determine the combination of envelope components which gave the lowest energy costs at little or no increase in LCC.

This meant that the envelope correlations had to be capable of dealing with the broad range of envelope characteristics in commercial buildings throughout Canada—from the lowest to

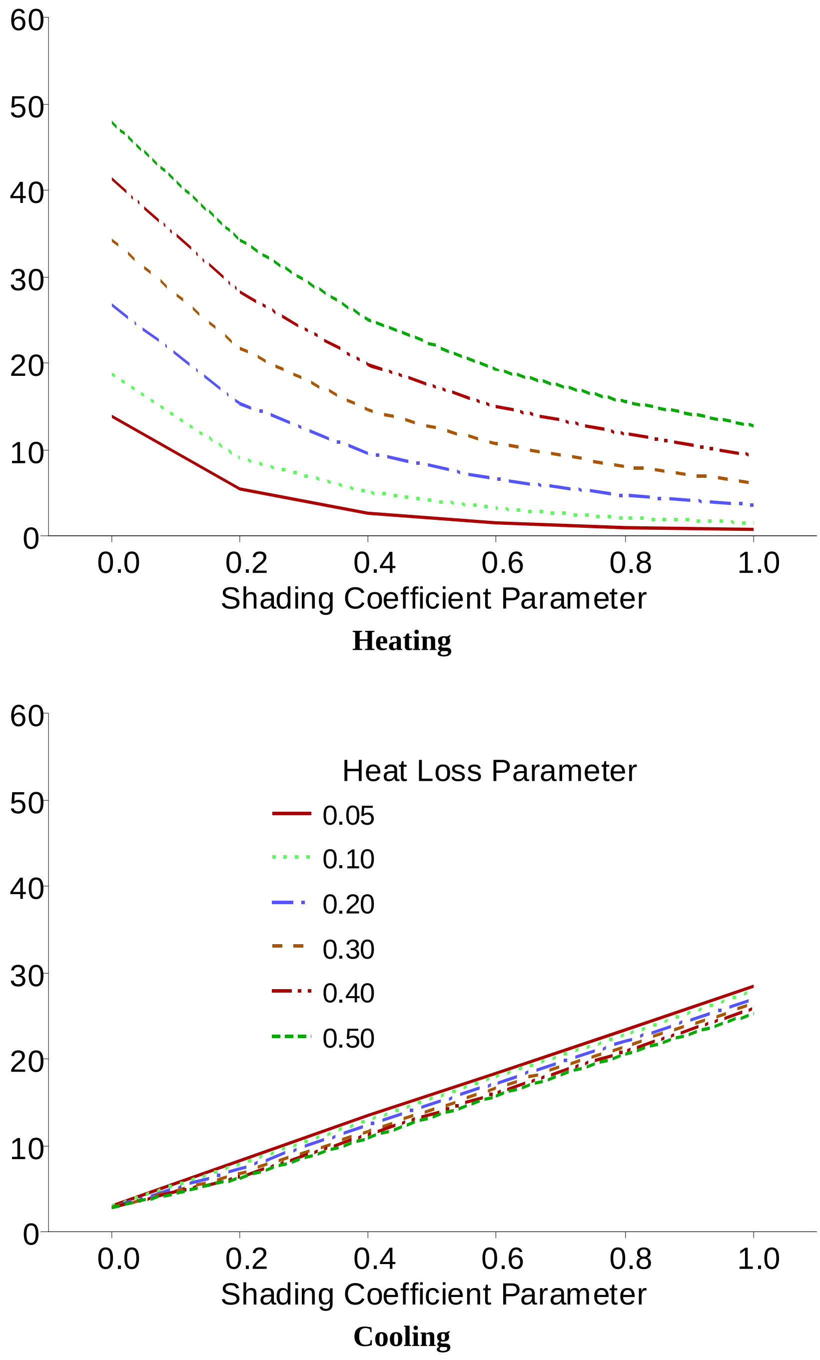

Figure 3-6. DOE-2.1E Results, Ottawa, South Orientation, 21.5 W/m^2 [6]

[6] The units for the Y-axis in each figure are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.

the highest level of internal loads; from virtually no- to all-glass buildings; from office to 24-hour operation.

Thus, it was important that the design of the parametric analyses for the new data set include the entire range of thermal envelope characteristics as well as thermal loads and amount of glazing. The first step was to select the envelope components that would be included in the parametric analyses, including effects of schedules, roofs, daylighting (sidelighting and toplighting), and other building components. The number of items in the parametric analyses would cause the number of simulations required to increase exponentially.

The first step was to test the impacts of varying the schedules from a typical office 10-hour, 5-day schedule to a 6-day, 7-day, and 24-hour, 7-day schedule. This showed that wide variations in schedules would not change the relative ranking of envelope requirements—only the absolute level of energy performance was affected. Because the LCC trade-off procedures were designed to compare the energy performance of options rather than absolute energy performance, a 10-hour, 6-day schedule typical of office and retail occupancy was selected for the parametric analyses based on these tests.

NRC decided to determine the impact of the roofs separately for use in the LCC and envelope trade-off procedures, rather than include them directly in the parametric analyses for the initial data. This simplified the data set that would be required. If roofs were included, then the simple model had to include the number of floors and different models for zones with roofs and zones without roofs.

An option considered in defining the scope of the analysis was to include daylighting or skylighting. As daylighting and skylighting involve interactions of envelope, lighting, and HVAC systems, however, it was decided not to include them in the data set. Their inclusion would have added another level of complexity for estimating construction costs and determining compliance trade-offs that was deemed beyond the scope of setting envelope requirements. This meant that prescriptive requirements derived using the LCC procedure would be limited to envelope components and would not include their interaction with other building systems (such as the lighting and load reduction impacts of daylighting/skylighting). For building designers interested in taking advantage of these interactions, the whole-building energy performance method would provide a better path. Combined, these decisions limited the scope of new envelope correlations to the exterior vertical surfaces of buildings.

Once the scope of the analysis was determined, the set of combined envelope characteristics that would be evaluated was studied. As the equations were intended to be realistic, a set of physics-based attributes was selected: heat loss/gain, solar gain, and internal gains. Each envelope component characteristic could then be defined in terms of a combination of these three variables. This made development of the parametric simulations simpler. The range of potential opaque wall and fenestration heat loss characteristics (U-values) was considered, and a range of 0 to 2.84 $W/m^2 \bullet K$ (0.05 to 0.5 $Btu/(h \bullet ft^2 \bullet °F)$) was selected. While more data points that were included in the data set would have increased the accuracy of the equations, it was found that six increments for the heat loss/gain cases would provide enough variation to ensure smooth curves. These six heat loss/gain cases are shown in Table 3-2. Similarly, for the solar gain cases, the first step was to look at the range of possible solar heat gain combinations from existing and projected windows. As DOE-2.1E takes shading coefficient as an input for windows, it was easy to define the solar gain cases as increments in shading coefficient ranging from 0.0 to 1.0. This would allow virtually any combination of window-to-wall ratio to be covered by the data set (and equations). As with the heat loss/gain cases, six cases were defined for the solar gain parametric cases, shown in Table 3-3. The last set of parametric cases was the internal gains, defined as the combination of building occupants, lights, and miscellaneous equipment. A range of 0.0 to 86.1 W/m^2 (0 to 8.0 W/ft^2) was selected to cover the range of internal gains within commercial building types with six cases set within that range as shown in Table 3-4.

Table 3-2. Heat Loss/Gain Parametric Cases

Case	UA/A, $W/m^2 \bullet K$ ($Btu/(h \bullet ft^2 \bullet °F)$)	WWR	U_g, $W/m^2 \bullet K$ ($Btu/(h \bullet ft^2 \bullet °F)$)	U_w, $W/m^2 \bullet K$ ($Btu/(h \bullet ft^2 \bullet °F)$)
0	0.227 (0.04)	0.4	0.568 (0.1)	0.001 (0.0001)
1	0.568 (0.1)	0.4	1.14 (0.2)	0.187 (0.033)
2	1.14 (0.2)	0.4	2.27 (0.4)	0.38 (0.067)
3	1.7 (0.3)	0.4	3.41 (0.6)	0.568 (0.1)
4	2.27 (0.4)	0.4	4.54 (0.8)	0.755 (0.133)
5	2.84 (0.5)	0.4	5.68 (1.0)	0.948 (0.167)

Table 3-3. Solar Gain Parametric Cases

Case	A_g/A_w x SC	WWR	Shading Coefficient
0	0.0	0.4	0.0
1	0.2	0.4	0.5
2	0.4	0.4	1.0
3	0.6	0.4	1.5
4	0.8	0.4	2.0
5	1.0	0.4	2.5

Table 3-4. Internal Gain Parametric Cases

Case (Internal Load)	Total Internal Loads, W/m^2 (W/ft^2)	People, latent[7], W/person (Btu/person)	Lights, W/m^2 (W/ft^2)	Equipment, W/m^2 (W/ft^2)
0	0 (0)	0 (0)	0 (0)	0 (0)
1	10.76 (1)	55.6 (190)	0 (0)	10.76 (1)
2	21.5 (2)	55.6 (190)	10.76 (1)	10.76 (1)
4	43.0 (4)	55.6 (190)	32.28 (3)	10.76 (1)
6	64.6 (6)	55.6 (190)	53.8 (5)	10.76 (1)
8	86.1 (8)	55.6 (190)	75.32 (7)	10.76 (1)

Window-to-wall ratio (WWR) was held constant as NRC had decided to set 40% glazing as the maximum allowable with standard double-pane glazing. If a building design team wanted to go beyond 40% glazing, then the trade-off procedure would require lower U-value and or shading coefficient to comply with the standard.

Together, these three parametric cases could be used to create an almost unlimited number of combinations of envelope and building characteristics without having to create a parametric case for each individual envelope characteristic. The three sets of 6 heat loss/gain cases, 6 solar gain, and 6 internal gain cases produce 216 combinations (6 x 6 x 6). The last part of setting up the parametric analyses was to select weather locations. With the wide range of climate conditions in Canada as well as ten provinces and two territories, it was important to cover the country efficiently. While more than 50 locations were available in the CWEC weather data set, it was found that 25 locations would cover both the geopolitical and climatic conditions. The 25 locations selected for use in developing the data sets for the new

[7] People sensible heat gains can be accounted for as part of the total internal gains.

envelope correlations are shown in Appendix A. This combination of 216 simulations per location and 25 locations produced a data set of 5,400 DOE-2.1E simulation results.

3.2.8 Development of Parametric Simulation Routines

The final critical part of developing the data sets for the new correlations was to automate the procedures for creating, ensuring input data quality, and running the parametric DOE-2 simulations, deriving the data needed for new correlations and compressing and storing the all resulting files. After several means of automating the process, including a program, were tested, a set of batch scripts was selected as the most flexible. These batch scripts automatically generated the 216 parametric combinations of DOE-2 input files. Because the input files were essentially identical for all locations, it was important to be able to distinguish the output files and results for each location. This was facilitated by extensive use of the PARAMETRIC, INCLUDE, and MACRO capabilities of the DOE-2 simulation program. Essentially this allows a user to create scripts within an input file, which were invoked by key parameters whose value was set at the beginning of the file. For this study, parametric values were created in the input files based on the values in the three tables above: internal gains, fenestration, and wall insulation. Thus, a single input file included the entire range of defined parameters needed for the study. This was important to allow quality assurance checking of the input data. Once the simulation for a single input file was complete, a second script automatically extracted the key summary data (heating, cooling, and fan loads) required for the new correlations. Because the scripts assembled data from multiple simulations into a single file, that data was plotted so that any outlying data was easily identified. The final step was to assemble the input, output, and weather data files into a single compressed file, which was then moved to the appropriate directory for the location. The batch scripts and parametric inputs were critical to dealing with this large data set from 5,400 simulations. The data set covers a wide range of building envelope component characteristics: U-values from 0 to 28.4 $W/m^2•K$ (0.05 to 0.5 $Btu/(h•ft^2•°F)$), shading coefficients from 0.0 to 1.0, and internal gains from 0.0 to 86.1 W/m^2. The results of the DOE-2.1E simulations which created the data sets are presented in Chapter 4.

3.3 Evaluating Performance Levels for Envelope Incentives in a New Building Construction Program

In 1993, the Province of Ontario adopted a new minimum energy efficiency code for commercial buildings based on *ASHRAE/IES Standard 90.1-1989* (ASHRAE 1989a) but modified to cover the broad spectrum of Ontario climates. To promote energy efficiency in new commercial construction and to aid in deploying the new energy code throughout the province, Ontario Hydro began using Standard 90.1 in April 1992 as the basis for a program of financial incentives that paid building owners and design teams that met or exceeded the requirements of Standard 90.1. This program was known as the Savings by Design New Building Construction Program.

In 1991 to 1992, Ontario Hydro defined and implemented basic incentives for meeting the requirements of the New Building Construction Program, and additional incentives for energy-efficient motors, interior lighting, and exit lighting, and for exceeding the requirements when using the energy cost budget method (whole-building performance method) of Standard 90.1. In late 1992, Ontario Hydro wanted to evaluate whether incentives for building envelopes that exceeded the requirements of the System/Component method of Standard 90.1 would be cost-effective.

Ontario Hydro was interested in promoting optimal levels of building insulation and fenestration assemblies for the current utility costs. Because their base standard (Standard 90.1) was developed using U.S. climatic conditions and cost-benefit calculations, they were unsure whether incremental increases in wall and roof insulation or improved glazing beyond the minimum prescriptive requirements[8] would be cost-effective in Ontario. This research was constructed so that, starting with the baseline of Standard 90.1, a series of incremental wall and roof insulation levels would be tested along with a series of leading edge fenestration technologies. This required compiling construction cost information for insulation for walls and roofs and fenestration assemblies, evaluating the value (energy and economic) to new building owners and Ontario Hydro of various levels of potential incentives, and finally, recommending incentive levels for various building envelope components[9]. This section describes the building model developed for the building envelope analysis and the design of the simulation set. The results of the analysis are described in Chapter 4.

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[8] Minimum prescriptive envelope requirements were developed as part of this work for Ontario locations and are shown in Appendix B. These prescriptive requirements were the baseline parameters for the building model described in the next section.

[9] Much of this was previously published in Crawley (1994).

3.3.1 Definition of Baseline Building Model

Because the New Building Construction Program offered incentives to design teams to meet the requirements of Standard 90.1, those wall and roof insulation requirements (Standard 90.1) were set as the baseline for the assessment. For fenestration, Ontario Hydro specified that clear double-pane glazing with aluminum frames was the baseline.

The four-zone building model described in Section 3.2 was selected for this analysis as it had been tested and tuned to Canadian climate conditions. This baseline building model has four zones, each facing a cardinal direction. Each zone is 4.6 m x 30.5 m (15 ft x 100 ft), floor area of 139.6 m^2 (1500 ft^2), a floor-to-floor height of 3.6 m (12 ft), and an independent packaged variable-air-volume (PVAVS) system.

The baseline U-values for fenestration, opaque walls, and roofs for the five locations are shown in Tables 3-5 and 3-6. The fenestration U-value is a double-pane, clear glazed, aluminum-frame window. The U-values for opaque walls and roofs are the minimum efficiency requirements set by Ontario Hydro for the climate zones.

3.3.2 Design of the Analysis for the Envelope Incentives

After the baseline model was established, the design of analysis was confirmed with Ontario Hydro. To test whether the impact of internal loads and fenestration area had a significant impact, two internal loads cases (21.5 and 43 W/m^2) and three cases of fenestration-to-wall area (FWR) (0.2, 0.4, and 0.6) were selected. The opaque wall options were to add 19 mm and 38 mm of rigid insulation in each location; roof options included 51 mm and 104 mm of insulation; fenestration options include double thermal-break frame, double vinyl frame, double low-e (e=0.4, 0.2, and 0.1), and Visionwall (shown in Table 3-7).

These baseline cases and the wall, roof, and fenestration options were then simulated using DOE-2.1E. CWEC weather files (WATSUN Simulation Laboratory 1992) were used in the simulations in five locations: Ottawa, Sault Ste. Marie, Schefferville, Toronto, and Windsor. In a way similar to the work for the NECB, a set of batch scripts were created to automate the creation of the DOE-2 input files and extract results from the output files for further analysis. Combining these scripts with the parametric input capability of DOE-2 made quality assurance and validation much easier. As each simulation completed, the scripts automatically compressed and combined the input and output files into a single file and moved them to a directory established for each location.

Table 3-5. Baseline Fenestration

Fenestration Assembly	Overall Fenestration U-Value, W/(m^2-K)	Description
Double-pane Aluminum Frame	3.92	double clear, 6 mm air space, center of glass U-Value = 3.24, aluminum spacer, fixed pane

Table 3-6. Baseline Wall and Roof Overall U-Values

Simplified Table[10]	City	Wall U-value, W/(m^2-K)	Roof U-value, W/(m^2-K)
8A-31	Windsor	0.449	0.278
8A-32	Toronto	0.426	0.278
8A-33	Ottawa	0.380	0.256
8A-36	Sault Ste. Marie	0.335	0.227
8A-38	Schefferville	0.261	0.210

Table 3-7. Fenestration Options

Fenestration Assembly	Overall Fenestration U-Value, W/(m^2-K)	Description
Double-pane Thermally Broken Frame	3.41	double clear, 6 mm air space, center of glass U-value = 3.24, thermal break spacer (butyl/metal), fixed pane
Double-pane Vinyl Frame	3.18	double clear, 6 mm air space, center of glass U-value = 3.24, wood/vinyl spacer, fixed pane
Double-pane Low-E (e=0.4)	2.84	double low-e clear, E=0.40 on A, 6 mm air space, center of glass U-value = 2.84, wood/vinyl spacer, fixed pane
Double-pane Low-E (e=0.2)	l.82	double low-e clear, E=0.20 on s3, argon, 13 mm air space, center of glass U-value = 1.7, wood/vinyl spacer, fixed pane
Double-pane Low-E (e=0.1)	l.65	double low-e clear, E=0.10 on s2, argon, 13 mm air space, center of glass U-Value = 1.53, wood/vinyl spacer, fixed pane
Visionwall[11]	0.79	quad low-e clear, E=0.10 on two films, krypton, 6 mm air space, center of glass U-value = 0.68, wood/vinyl spacer, fixed pane, equivalent to Visionwall VTI-C-88, VTI-C-77, or VTI-C-66

[10] This refers to the table in ASHRAE Standard 90.1-1989.
[11] Visionwall is the trademark product of Visionwall Technologies. It has two panes of glass, two low-e films, a krypton gas fill, and a well-constructed, thermally-broken frame.

Table 3-8. Fenestration Costs

Fenestration Assembly	Overall Fenestration U-value, $W/(m^2\text{-}K)$	Builder Cost, $\$/m^2$	Total Cost (Including Overhead and Profit), $\$/m^2$	Adjusted Cost[12], $\$/m^2$	Source	Notes
Double Aluminum Frame	3.92	--	$145.69	$145.69	Means 1993	commercial window glass, 13 mm, total in-place
Double Thermally Broken Frame	3.41	$80.00	----	$149.24	Enermodal Engineering Ltd. 1993	aluminum thermally broken, clear/air/clear, metal spacer
Double Vinyl Frame	3.18	$119.97	----	$223.92	Enermodal Engineering Ltd. 1993	vinyl picture, clear/air/clear, insulated spacer
Double Low-E (e=0.4)	2.84	$122.00	----	$227.57	Enermodal Engineering Ltd. 1993	vinyl picture, clear/air/low-e, metal spacer
Double Low-E (e=02)	l.82	$169.00	----	$315.27	Enermodal Engineering Ltd. 1993	vinyl picture, clear/argon/low-e, insulated spacer
Double Low-E (e=0.1)	l.65	$171.00	----	$319.03	Enermodal Engineering Ltd. 1993	foam-vinyl picture, clear/argon /low-e, insulated spacer
Visionwall	0.79	--	$376.60	$376.60	Visionwall Technologies 1993	phone conversation with Donald Holte, Visionwall Technologies, December 1993

[12] Adjusted cost = builder cost*[1 + (26.8% G&A overhead * 25% installation cost (labor) 10% profit * 7% GST for commercial retrofit)]. Approximately=builder cost*1.866.

Table 3-9. Wall Insulation Costs

Option	Cost, $/m^2	Cost Source	Notes
Add R-4	$10.87	Energy Building Group Ltd. 1993	assembly C-EWSH212, $14.42/m^2, 38 mm, R 1.05 type II EPS, estimate 3/4 cost for 19 mm
Add R-4	$8.82	Means 1993	Polystyrene, Extruded, 19 mm thick, R 1.05. 1.09 Toronto location cost multiplier and 1.07 GST multiplier
Add R-8	$14.42	Energy Building Group Ltd. 1993	assembly C-EWSH212, $14.42/m^2, 38 mm, R 1.05 type II EPS
Add R-8	$11.62	Means 1993	Polystyrene, Extruded, 38 mm thick, R1.05. 1.09 Toronto location cost multiplier and 1.07 GST multiplier

Table 3-10. Roof Insulation Costs

Option	Cost, $/m^2	Cost Source	Notes
Add R-10	$16.50	Energy Building Group Ltd. 1993	assembly C-EWSH231, 51 mm, R 1.41, type II EPS
Add R-10	$15.17	Means 1993	Polystyrene, Extruded, 51 mm thick, R 1.41. 1.09 Toronto location cost multiplier and 1.07 GST multiplier
Add R-20	$29.24	Energy Building Group Ltd. 1993	assembly C-RFSH300, 102 mm, R 2.82, type II EPS
Add R-20	$30.34	Means 1993	Polystyrene, Extruded, 51mm thick, R2.82, 2 layers. 1.09 Toronto location cost multiplier and 1.07 GST multiplier

The results of the simulations are described in more detail in Chapter 4 along with the energy and economic results. The costs calculated for each of the envelope incentives are shown in Tables 3-8, 3-9, and 3-10, respectively for the fenestration upgrades, wall insulation, and roof insulation.

3.4 Developing Models and Data Sets to Support Development of a National Voluntary Program for Existing Building Retrofits

In 1993, a new national voluntary program to promote building energy retrofits was being developed. This program, known as ENERGY STAR Buildings (ESB) (US EPA 1993), focused on improving the whole-building energy performance of existing buildings.

A central component of the ESB was a staged implementation of building retrofits—a series of upgrades structured to allows for direct measurement of the interactive system effects of individual measures. This provided the potential additional energy savings while lowering capital expenditures. The five stages are:

Stage 1: Green Lights,
Stage 2: Building Tune-Up,
Stage 3: Heating and Cooling Load Reductions,
Stage 4: Improved Fans and Air Handling Systems, and
Stage 5: Improved Heating and Cooling Plant.

By focusing first on loads-reduction and re-calibration in Stages 1 through 3, the size and cost of equipment associated with Stages 4 and 5 can be significantly reduced. Uncertainties in proper sizing of upgraded cooling equipment [chillers and direct-expansion (DX) units] are reduced, leading to potential equipment down-sizing and cost savings. Each stage is outlined in more detail below.

Stage 1: Green Lights focuses on retrofitting lighting systems for improved energy efficiency. In this Stage 1 analysis, the cooling load reduction and heating load impacts that result from the lighting upgrade should also be considered.

Stage 2: Building Tune-up has several components. First, historical energy data, drawings, maintenance logs, operating sequences and existing monitoring and control systems are reviewed to identify problem areas and opportunities to establish priorities within each subsequent stage. The second part of this stage is to identify energy savings that can be completed with minimal capital investment (e.g., re-calibrating controls, reducing excessive pressure in air and water systems). Finally, Stage 2 is completed by creating and implementing a comprehensive building preventative maintenance schedule.

Stage 3: Additional HVAC Load Reductions focuses on reducing the remaining heating and cooling loads such as building envelopes (e. g., high-efficiency windows, window films, or wall and roof insulation) and office equipment. In Stage 3, participants are encouraged to purchase only Energy Star compliant computer equipment to reduce plug load and related sensible heat gains.

Stage 4: Improved Fan Systems includes several steps: convert constant-air-volume systems to variable-air volume operation, reduce equipment size to meet lower peak loads, and variable speed motor controls to the fan systems.

Stage 5: Improved HVAC Plant takes advantage of the reduced loads on the central plant resulting from the retrofits of Stages 1 through 4 by measuring actual peak loads so that replacement equipment can be more accurately sized and capital costs reduced.

In the formative days of the ESB, building energy simulation was the core method for determining cost-effective pathways for building owners to upgrade their building systems—particularly building envelopes, fans, and central heating and cooling equipment. This section describes the series of simulation suites that were created to estimate potential savings of the ESB program and determine specific upgrade pathways in buildings envelopes, and chillers—and whether the weather data which was used mattered.

During a period of nine months, more than 25,000 DOE-2.1E simulations were completed for a series of research questions posed in support of the ESB program. Most of the work focused on distilling information from the thousands of simulations to provide key findings for briefing materials on the potential energy and environmental benefits of the ESB retrofit program and to support program marketing pieces.

3.4.1 Parametric Energy Simulation of ESB Staged Implementation Approach

To support the development of the ESB program, an extensive series of parametric simulations of three office buildings were performed in 18 climatic regions throughout the United States. The first set of parametric simulations is described in this section. The goal of this study was to determine potential energy savings and pollution prevention potential for each of the five stages and in aggregate for the ESB Program.

To begin this study, a baseline building or buildings needed to be developed. The ESB program was initially focused on larger office buildings—those with central heating and cooling systems, which could more readily take advantage of downsized airflow and heating and cooling equipment. Various sources of data about building energy performance were investigated to establish building prototypes that were representative of the building stock. Since 1979, the Energy Information Administration of US DOE has performed a regular survey of building energy consumption and characteristics known as CBECS—Commercial Building Energy Consumption Survey. At the time of this work, the latest survey was for 1992 (EIA 1994). While the CBECS does not cover many energy attributes, it did have the advantage of providing a snapshot of the entire commercial building sector with many buildings representing the larger data set. The 1992 CBECS showed that there were 678,514 office buildings in the United States comprising 1.1 billion m^2. The average office building had an area of 1,616 m^2 and 2 floors and was built in 1961 (33 years old at the time of the survey). CBECS also indicated that 41.5 percent of office buildings used all-electric heating systems with the remainder using natural gas or other fuels (58.5 percent). In terms of energy, the average office building used 339.9 kWh/m^2 at annual energy cost of \$16.03/m^2 or \$25,880.

The average office building, at 1,616 m^2 in size, also covered a wide range of office energy intensity and size. It was found that subdividing the CBECS data into quartiles would provide a broader range of commercial building types than focusing on the mean of the entire sector. Four categories based on size and construction methods were selected after some experimenting. The categories are: less than 2,323, up to 9,294, up to 46,468, and larger than 46,468 m^2 (25,000, 100,000, and 500,000 ft^2, respectively). Smaller buildings tend to use wood frame construction as opposed to steel or concrete. These four categories apportioned the total office building floor area into fractions of roughly 30, 26, 27, and 17 percent of the total floor area from the smallest to largest building. The smallest buildings, those under 2,323 m^2, were not part of the ESB or this study because of the predominance of packaged HVAC systems. The other three size categories primarily had central HVAC systems as shown in Table 3-11. Table 3-12 provides average building and energy characteristics for the four categories based on the 1992 CBECS data.

The next step was to create more detailed building descriptions for the three larger (central system) office building categories. Where data and characteristics were available from the 1992 CBECS, the mean value of the characteristic for the buildings within that size category was used. This included floor area, number of floors, and other key characteristics. The sizes and configurations selected are shown in Table 3-13. Yet this left undefined many assumptions required for modeling building energy performance. The remaining data needed for building simulation were collated based on typical practice from building standards, such as ASHRAE Standard 90.1 (ASHRAE 1989a). Table 3-14 summarizes equipment and operating assumptions for the three office building models.

3.4.1.1 Simulation Models for the Base Case Existing Office Buildings

From these data, three base office models were defined for the DOE-2.1E building energy simulation program (Winkelmann et al. 1993). Each of these DOE-2.1E models was calibrated to match the mean energy consumption of the buildings with that size category. A set of locations were selected to represent a spread of climate conditions. The diversity of weather condition throughout the United States, from the cold north of Alaska to the tropical warmth of Florida and Hawaii, required that enough locations were included to cover these distinctions. In the end, 18 locations around the U.S. were selected to represent a spread of climatic conditions, with larger cities in a climate zone being selected where possible.

The locations were: Anchorage, Alaska; Atlanta, Georgia; Boston, Massachusetts; Chicago, Illinois; Cleveland, Ohio; Fort Worth/Dallas, Texas; Honolulu, Hawaii; Los Angeles, California; Memphis, Tennessee; Miami, Florida; Minneapolis, Minnesota; New York, New York; Omaha, Nebraska; Phoenix, Arizona; San Antonio, Texas; San Francisco, California; Seattle, Washington; and Washington, D.C. For each location, current utility cost rates were obtained from the local electric and natural gas utilities. These rates were used to calculate annual energy costs for use in the energy savings and cost-effectiveness calculations. The three building models were then simulated with both all-electric and gas heating systems in the 18 locations using Weather Year for Energy Calculations weather data (ASHRAE 1985). Results from these simulations are shown in Chapter 4.

Table 3-11. Office Building Stock Categories

Building Area, thousand m^2	Number of U.S. Office Buildings	Total Office Building Floor Area, million m^2	Percent of Total Office Building Floor Area	Percent of Total Office Building Energy Consumption	Primary HVAC System Type
0-2.3	595,945	326	29.8%	30.54%	Packaged
2.3-9.3	64,075	283	25.8%	25.54%	Central
9.3-46.5	16,024	293	26.8%	27.74%	Central
>46.5	2,470	194	17.7%	16.19%	Central

Table 3-12. Office Building Stock Categories Characteristics

Building Area, thousands of ft^2	Average					
	Building Area, m^2	Year Built	Number of Floors	Annual Energy Consumption, kWh/m^2	Annual Energy Cost, $	Annual Energy Cost, $/$m^2$
0-2.3	548	1961	1.7	340	$9,158	$17.43
2.3-9.3	4,416	1960	3.2	345	$69,886	$16.46
9.3-46.5	18,316	1967	7.3	331	$312,060	$16.79
>46.5	78,398	1965	19.8	287	$1,056,684	$15.39

Table 3-13. Three Existing Office Building Models

Building Description	Floor Area, m^2	Number of Floors	Aspect Ratio (Length: Width)
Low-rise	4,461	3	2
Mid-rise	18,216	7	3
High-rise	78,067	20	3

Table 3-14 Base Case Assumptions: Building Equipment and Systems

Description	Equipment/System Assumptions
Lighting	24.75 W/m^2, T-12 fluorescent 4-lamp 600mm x 1200 mm (2 ft x 4 ft) fixtures, 3271 Equivalent Full-Load Hours (EFLH)
Office Equipment	10.76 W/m^2 (computers, laser printers, photocopiers, and facsimile machines), 2616 EFLH.
Envelope	40% WWR, glazing varies by location—primarily single-pane, tinted/reflective in southern locations; double-pane, tinted in northern locations.
Ventilation	9 l/s-person outside air (ASHRAE 1989b).
Air System	Inlet Vane VAV System, 178 mm W.C. supply static pressure, 30% oversized, outside air damper stuck at 40% open position.
Central Plant	Centrifugal chillers, CFC refrigerant, COP 3.9, 30% oversized chiller, cooling towers, and pumps, electric heat/reheat.

After the DOE-2.1E base case simulations were established for the existing office buildings, the next step was to create models for each of the 5 ESB stages. The goal was not only to demonstrate the overall energy and cost savings potential, but also to detail the system-specific energy savings (or penalties) associated with each step. For example, the modeling results showed not only the direct savings that result from a lighting upgrade, but also the net HVAC energy savings resulting from the reduced sensible heat load due to more efficient lighting (lower lighting power density). The modeling assumptions for each of the stages are described below.

Rather than creating DOE-2.1E files with embedded parametric cases as in the two previous studies, a more efficient ways was to subdivide the input files apart into the portions that were being studied—geometry, schedules, and outputs; location design conditions; internal loads; envelope; HVAC system; and HVAC plant. This allowed these segments of the total input file to be more carefully checked and cross-compared. For each study, the number of input file segments was approximately 15 depending on the focus of the study. For example, a study looking at chiller efficiency had fewer input file segments than a study looking at building envelope with variation in windows, and wall and roof insulation. This allowed these smaller portions of the input files to be carefully quality checked and cross-compared between locations and size cases. Separate versions of the sub-files were created for the base as well as each stage upgrade. A set of batch scripts then combined the individual portions of the input files into the full input file. Further batch scripts automated the simulation of the individual input files.

Because of the need to deal with the results from more than 25,000 simulations, scripts were constructed that automatically extracted energy performance, equipment size, peak demand, utility costs, and other key data from the DOE-2.1E simulations. The extracted data were written to comma-separated value (CSV) format to facilitate their use in spreadsheets. The final scripts compressed the completed simulation input, output, and extracted results into a combined file and moved it to the appropriate building type and location directory for storage.

Tasks were also automated in the cost-benefit summary results spreadsheet. Once simulations for a portion of the analysis were complete and results data extracted, a template spreadsheet for a building type and a second template for a location were constructed to test results presentation. The template spreadsheet contained a series of tables of summary results from LCC calculations as well as charts. The template spreadsheets were structured so that upgrade costs or other assumptions could be easily adjusted. Once the energy performance and cost data from the CSV results files were imported, formatted, presentation-ready tables and graphs were ready. Other template spreadsheets were linked to the building type and location spreadsheet to summarize and aggregate the results.

This approach of subdividing the input files into separate portions coupled with automation scripts and template results spreadsheets was carried into the subsequent chiller upgrade and weather analysis discussed below.

3.4.1.2 Stage 1: Lighting Upgrade

First, lighting experts were consulted and the products that were available in the market as typical lighting upgrades were identified. This showed that a typical office building lighting upgrade was from existing 4-lamp, T-12 fixtures to 2-lamp T-8 fixtures with electronic ballasts and occupancy sensor controls. Occupancy sensors were simulated by modifying the lighting schedules—reducing the equivalent full-load operating hours (EFLH) from 3271 to 2742. These upgrades resulted in reducing the lighting power density from 24.7 to 8.6 W/m^2

with an estimated upgrade cost of \$8.82 to \$12.05/m^2, depending on building size (\$12.05, \$9.25, and \$8.82/m^2 for low-rise, mid-rise, and high-rise office buildings, respectively.) The costs for Stages 1, 2, and 3 were based on cost data from Means (1993).

Some initial analysis found that for the all-electric low-rise office buildings in Anchorage, Seattle, Boston, and Minneapolis; the all-electric mid-rise office buildings in Minneapolis, and Seattle; and the natural gas-heated low-rise office in Seattle, the 8.6 W/m^2 lighting upgrade was not cost-effective because the energy savings from the lighting upgrade was more than offset by a substantial increase in heating loads. For those cases, an alternate upgrade of 12.80 W/m^2, 2-lamp, T-10 fluorescent fixtures was used with magnetic ballasts with a retrofit cost of \$4.20/m^2. (The cost-effectiveness target set for ESB was the prime rate [6 percent in 1993] plus 6 percent or 12 percent.)

3.4.1.3 Stage 2 Building Survey and Tune-up

For Stage 2, the goal was to do a comprehensive survey of existing building systems and equipment and to fix any immediately obvious operational or control problems. For this stage of the modeling, an obvious repair was assumed—an outside air damper that had been stuck at 40 percent open was repaired. This is but one example of typical tune-up problems found in commercial buildings—other typical problems include controls and sensors that no longer work properly or that are out of calibration. In addition, it was assumed that in inspecting filters and recalibrating air-side equipment, the static pressure across the fan could be reduced by 13 mm (from 165 mm to 152 mm). Finally, because of the ENERGY STAR program then underway, it was projected that a successful employee information campaign would provide 10 percent reduction in office equipment operating hours. For Stage 2, these improvements were estimated to cost \$1.08/m^2 for building survey and tune-up.

3.4.1.4 Stage 3 Loads Reduction

For Stage 3, the goal was to implement potential load reductions, such as ENERGY STAR Computers, and other improvements, such as building envelope upgrades. Three elements were included in the upgrades under Stage 3. First, window films were applied to the existing windows to reduce solar gains and cooling load. Second, it was assumed that the existing roof was leaking and in need of replacement (wet insulation, reduced R-value), and that the replacement insulation would have an R-value equal to current design practice as recommended in Standard 90.1 (ASHRAE 1989a). Finally, it was assumed that building owners and tenants would implement a new desktop computer procurement policy to purchase only ENERGY STAR-compliant computers (i.e., the computer and monitor each will use less than 30 Watts when not in active use). For the modeling analysis, this translated into 20 percent of the computer equipment upgraded to this ENERGY STAR Computer standard, and Energy Star equipment was available at no incremental cost. This reduced annual EFLH to 1942 due to low power idle time. The costs for Stage 3 changes were estimated to be $0 for Energy Star Computers, $5.38/m^2 for adding roof insulation at the next time the roof was replaced, and $21.52/m^2 for window films.

3.4.1.5 Stage 4 Air Distribution Systems

For Stage 4, the goals were to upgrade air systems with variable speed drive (VSD) controls on the VAV systems and recalculate reduced overall supply air requirements contributed from loads reductions in the first three stages. The upgrades that were collectively modeled for this stage included:

- Adjustment of fan system capacity to match the revised (and lower) peak airflow requirements, with a sizing margin of 10 percent.
- Installation of outside air economizer.
- Reduction of supply air static pressure from 152 mm WC to 102 mm WC (because of reduced airflow requirements).
- Installation of VSD to control fan motors and to greatly improve the operating efficiency of the fan system, especially at prevailing part-load conditions throughout the year.

The costs for these upgrades in Stage 4 were estimated at $500 per air handler for the air-side economizer, duct modifications, and controls and were a function of size for the VSD and high-efficiency motors. The curves of cost versus size are shown in Appendix B.

3.4.1.6 Stage 5 Central Plant

In the final stage, the ESB program could take advantage of significantly lower loads due to the Stage 1 to 4 upgrades, allowing an upgraded chiller or boiler to be significantly smaller. The upgrades that were collectively modeled for this stage include:

- Recalculate chiller and heating size required based on loads reductions from Stages 1, 2, 3, and 4.
- Replace 20- to 25-year-old (from late 1960s/early 1970s) centrifugal chiller (with CFC refrigerant) with new non-CFC high-efficiency chiller (COP 6.9) equipped with a

variable speed drive controlling the compressor motor. The chiller was sized to meet the significantly lower peak cooling loads, with a sizing margin of 10 percent.

- Add variable speed drives to chilled water and condenser water pumps.
- Upgrade cooling tower.
- In gas-heated buildings, install new high-efficiency, gas-fired boiler(s) (80 percent efficiency).

The upgrade costs in Stage 5 are a function of the size of the equipment being retrofitted or replaced. The cost curves used for non-CFC retrofit of existing chiller, new high-efficiency non-CFC centrifugal chiller, VSDs on pumps, and new high-efficiency, gas-fired boiler in Stage 5 are shown in Appendix B. As not all the proposed upgrades were cost-effective in all locations, they did vary by location and building size. See Table 3-15 for a key to the cost-effective plant upgrades that were applied in the simulations by location, heating energy source, and office building size. Table 3-16 summarizes the costs assumed for each of the modeled upgrades. The energy and economic results for the baseline buildings as well as the five stages are presented in Chapter 4.

3.4.2 Creating Energy Simulation Databases for Envelope Upgrades and Chiller Upgrades

After the base set of energy simulations for the ESB staged strategy was completed, further simulations were needed to provide more depth in several areas. First, more in-depth sets of independent building envelope upgrades for roof insulation, wall insulation, and fenestration options would provide a means for building owners to look up cost-effective envelope retrofits based on their location, building size, and existing envelope conditions. Second, as replacing CFC refrigerants in chiller systems was becoming important, a more in-depth study of the opportunities for chiller upgrades was also needed. This would validate building owners' decisions to replace their chillers to deal with CFC replacement—but also take advantage of substantially lower loads (and resulting lower chiller costs) offered by the ESB five-stage methods.

This new research on envelope upgrade simulation started with the three office buildings developed for the ESB staged strategy analysis described above—low-rise office, 4,461 m^2, 3 floors; mid-rise office, 18,216 m^2, 7 floors; and high-rise office, 78,067 m^2, 20 floors. As in the earlier work, two internal load levels were included to represent typical existing lighting systems (24.8 W/m^2) and cost-effective new lighting systems (8.6 W/m^2).

Table 3-15. Stage 5 Upgrades by Building Size and Location

Location	Low-Rise		Mid-Rise		High-Rise	
	All-Electric	Natural Gas Heat	All-Electric	Natural Gas Heat	All-Electric	Natural Gas Heat
Anchorage	C	C/B	C/PV	R	C/VSD/PV	C/VSD/PV/B
Atlanta	C	C	C/VSD/PV	C/VSD/PV	C/VSD/PV	C/VSD/PV/B
Boston	C	C/B	C/VSD/PV	C/VSD/PV/B	C/VSD/PV	C/VSD/PV/B
Chicago	C	C/B	C/VSD/PV	C/VSD/PV	C/VSD/PV	C/VSD/PV/B
Cleveland	C	C/B	C/VSD/PV	C/VSD/PV/B	C/VSD/PV	C/VSD/PV/B
Ft. Worth/Dallas	C	C	C/VSD/PV	C/VSD/PV/B	C/VSD/PV	C/VSD/PV/B
Honolulu	C	C	C/VSD/PV	C/VSD/PV	C/VSD/PV	C/VSD/PV
Los Angeles	C	C/B	C/VSD/PV	C/VSD/PV/B	C/VSD/PV	C/VSD/PV/B
Memphis	C	C/B	C/VSD/PV	C/VSD/PV/B	C/VSD/PV	C/VSD/PV/B
Miami	C	C/B	C/VSD/PV	C/VSD/PV/B	C/VSD/PV	C/VSD/PV/B
Minneapolis	C	C/B	R	C/VSD/PV/B	ER/PV	C/VSD/PV/B
New York	C	C/B	C/VSD/PV	C/VSD/PV/B	C/VSD/PV	C/VSD/PV/B
Omaha	C	C/B	C/VSD/PV	C/VSD/PV/B	C/VSD/PV	C/VSD/PV/B
Phoenix	C	C/B	C/VSD/PV	C/VSD/PV/B	C/VSD/PV	C/VSD/PV/B
San Antonio	C	C	C/VSD/PV	C/VSD/PV	C/VSD/PV	C/VSD/PV/B
San Francisco	C	C/B	C/VSD/PV	C/VSD/PV/B	C/VSD/PV	C/VSD/PV/B
Seattle	C	C	ER	R	ER	ER
Washington, D.C.	C	C/B	C/VSD/PV	C/VSD/PV/B	C/VSD/PV	C/VSD/PV/B

Key: **C -** Chiller Replacement/**R -** Chiller Retrofit/**ER -** Chiller Engineered Retrofit
PV - VSD on Pumps **VSD -** VSD on Chiller **B -** Boiler Replacement

Table 3-16. Upgrade Costs by Stage

Stage	Upgrade	Units	Cost[13]	Economic Life, years
Stage 1 Green Lights	Lighting System	$\$/m^2$	8.82	15
Stage 2 Building Survey and Tune-up	Building Survey and Tune-up	$\$/m^2$	1.08	3
Stage 3 Loads Reduction	ENERGY STAR Computers	$\$/m^2$		5
	Window Films	$\$/m^2$ window area	21.52	5
	Roof Insulation	$\$/m^2$ roof area	5.38	15
Stage 4 Air Distribution Systems	System Survey, Fixed Cost	$/building	200.00	15
	System Survey Costs per AHU	$/AHU	50.00	15
	Fan VSD Equipment	$/kW	90.79	15
	VSD Installation	$/motor	200.00	15
	High-Efficiency Motors	$/kW	33.11	15
	High-Efficiency Motors Installation	$/motor	90.00	15
Stage 5 Central Plant	Chiller Retrofit Costs	$/kW	165.93	30
	Chiller Replacement Costs	$/kW	634.19	30
	Net Chiller Costs	$/kW	292.46	30
	Pump VSD Equipment	$/kW	35.31	15
	VSD Installation	$/building	400.00	15

[13] Data from Means (1993) used for upgrade costs in Stages 1 through 3. See Appendix B for cost data sources for the Stage 4 and 5 upgrades.

The last step in defining the simulations was to select HVAC systems that would cover the range of potential system efficiency. As in the previous work, two different HVAC systems (constant volume reheat [CV] and inlet vane variable air volume reheat [VAV]) with and without reductions in required air flows through a fan motor pulley change-out were used. The following section describes the scope of the new envelope simulations.

3.4.2.1 Envelope Upgrades

The building envelope upgrades were envisioned as three independent sets—roof insulation, wall insulation, and fenestration options. These sets of building envelope upgrades were designed to cover the range of potential existing wall and roof conditions (roof insulation condition, thermal insulating value, and color) and fenestration glazing combinations.

For roofs, the insulation thickness (and effective thermal R-value) and roof color (light/dark) were varied. Polyurethane insulation (R-0.48/mm) was simulated but the results are transferrable to other insulation types by a simple ratio of the new insulation R-value per inch to the R-value per inch of the polyurethane insulation. The insulation thickness was varied in fifteen 13 mm increments (R 6.07 each) from no insulation to 178 mm (R-83.4). To simulate the light and dark roof colors, the roof absorptance was varied from 20 percent for light to 90 percent for dark roof colors. Wall insulation and fenestration remained constant for each location for the set of roof insulation simulations. This created 30 combinations of roof insulation and color.

Similar to the roof simulations, the insulation thickness for walls was varied in fifteen 13 mm increments (R-6.07 each) of polyurethane insulation (R-0.48/mm) from no insulation to 178 mm (R-83.4). Wall color was not changed in the wall simulations. The percent glazing or fenestration-to-wall ratio (FWR) was also varied, using 10 percent, 40 percent, and 70 percent glazing. Roof insulation and fenestration remained constant for each location for the set of wall insulation simulations. This yielded 45 wall insulation and FWR combinations.

For fenestration, a range of specific glazing was simulated using DOE-2.1E glass type codes. The equivalent U-values and shading coefficients (SC) for the glazing options are single clear, 1.57 W/m^2-K U-value and 0.84 SC; single gray, 1.57 W/m^2-K U-value and 0.83 SC; single green, 1.54 W/m^2-K U-value and 0.69 SC; double clear, 0.90 W/m^2-K U-value and 0.88 SC; double grey, 0.90 W/m^2-K U-value and 0.72 SC; double low-e, 0.88 W/m^2-K U-value and 0.58 SC; and double low-e, 0.88 W/m^2-K U-value and 0.55 SC. The FWR was also varied using 10 percent, 40 percent, and 70 percent glazing. Wall and roof insulation levels remained constant for each location for the fenestration simulations. This created 30 fenestration combinations.

Together, the combination of three building sizes, four HVAC systems, eight locations, and two levels of internal loads yielded 200 simulations per wall, roof, or fenestration option along with one base sizing simulation per location. The total number of simulations was 6,000 combinations for roofs, 9,000 for walls, and 6,000 fenestration options—a total of 21,000 DOE-2.1E simulations.

Scripts were used to extract energy performance and utility costs automatically from the simulation results for the roofs, walls, and fenestration data sets. Combining these data with upgrade costs in spreadsheets allowed easy calculation of cost-benefit results based on an existing building envelope. The spreadsheets were structured so that users can adjust upgrade costs or change the insulation type to match their specific situations more closely.

The estimated roof and wall insulation upgrade costs assume that owners would wait until planning a roof replacement or a major rehabilitation of exterior walls before considering increasing insulation levels. Effectively this limited upgrade costs to that of installing new insulation (no cost to replace the existing roof or the exterior wall). National average construction cost databases show installation costs for polyurethane insulation of approximately $0.25/m^2 per mm thickness (Means 1993). For a fan motor pulley change out (reducing air flow to meet the reduced loads) in the roof simulation set, it was assumed that only the pulley on the top floor would be changed. National average material and installation costs were estimated to be $250 per fan motor pulley (one per building). The energy and economic results and conclusions for the envelope upgrades are shown in Chapter 4.

3.4.2.2 Chiller Upgrades

To support EPA's work in CFC-replacement, another set of simulations was created to clearly lay out the benefits of combining a chiller replacement or engineered retrofit with the ESB upgrades. This set started with the same three existing office buildings and the 18 locations used earlier. This time, however, only the all-electric cases were simulated as the focus was on the electric chillers. Five cases were developed:

A – Baseline Chiller (3.9 COP)

B – Simple Chiller Retrofit (non-CFC retrofit, 3.5 COP)

C – Engineered Chiller Retrofit (resized to match load, 3.9 COP)

D – Chiller Replacement (resized to match load, 5.4 COP)

E – ENERGY STAR Buildings Program (new chiller, all ESB stages, 6.4 COP)

Together, this resulted in 6 simulations per location (a sizing base run plus five cases) or a total of 324 simulations. For each location and building size, a spreadsheet was created that combined simulation results (energy use, peak demand, chiller size) with cash-flow and other economic analyses. These results are presented in Chapter 4.

3.4.3 Which Weather Data to Use? [14]

Subsequent to the simulations for the ENERGY STAR Buildings work, several new, more robust data sets of weather data became available, including the TMY2 (NREL 1995), CTZ2 (CEC 1992), WYEC2 (ASHRAE 1997), CWEC (WATSUN 1992), and a 30-year data set for the United States known as SAMSON (NCDC 1993). As the analyses conducted for the ESB staged upgrades were based on the WYEC data set—the most robust weather data set available in the United States at the time—a question arose about which data were more appropriate, best represented the long-term record, and whether it made any difference to the simulation results.

The best way to determine which weather data to use was to compare the impacts of using the various typical year weather data in energy simulations, specifically looking at predicted energy performance, equipment sizing, and utility costs. The gas-heated low-rise office building described in Section 3.4.1.1 was used in simulations in eight U. S. locations (Denver, Los Angeles, Miami, Minneapolis, New York, Phoenix, Seattle, and Washington, D. C.). The building model was kept identical for all weather data sets with HVAC equipment sizing based on design conditions in the ASHRAE Handbook—Fundamentals (ASHRAE 1993).

The weather data sets used in this study include TRY (NCDC 1976), TMY (NCDC 1981), TMY2, WYEC (Crow 1980, 1983), WYEC2, and SAMSON. The TRY data are an actual historic year of weather, selected using a process in which years in the period of record (~1948-1975) which had months with extremely high or low mean temperatures were progressively eliminated until only one year remained. This tended to result in a particularly

[14] This work was previously published in an ASHRAE Transactions paper (Crawley 1998) and received a 1999 Symposium Paper Award as one of the best papers presented in a 1998 ASHRAE symposium.

mild year that, either by intention or default, excludes extreme conditions. TRY data are available for 60 locations in the United States. The TMY and TMY2 data were developed using a similar method to the TRY, but instead typical months were selected and an artificial year assembled. The TMY were from a similar period as the TRY, but for 234 U.S. locations; the TMY2 covered 1961-1990 for 239 U.S. locations. The WYEC and WYEC2 used a similar typical month selection process. The WYEC provided 46 locations in the U.S. and 5 locations in Canada; the WYEC2 comprised 77 locations—the original 51 WYEC locations with 26 U.S. locations with measured solar radiation. SAMSON are the data set for 1961-1990 used to derive the TMY2 data—239 U.S. locations with hourly recorded meteorological and mostly calculated solar radiation (except for 26 locations with measured solar radiation) for the period of record.

Eight locations were selected to represent a range of climatic conditions in the United States: Miami, Florida (hot humid); Phoenix, Arizona (hot dry); Denver, Colorado; Los Angeles, California (mild coastal); Minneapolis, Minnesota (cold); New York, New York (warm cool); Seattle, Washington (cool coastal); and Washington, D. C. (hot cool). First, all 30 years in the SAMSON were simulated for each location—something that would rarely occur when doing normal building simulation. As noted above, the equipment size for all simulations was held constant in the DOE-2.1E simulations—no automatically sized equipment. Then the simulations were repeated with the TRY, TMY, TMY2, WYEC, and WYEC2 (TMY and WYEC). The results for the SAMSON simulations and the weather data sets are shown and discussed in detail in Chapter 4.

3.5 Developing Building Models and Climate Data to Support Impact Analysis of Climate Change and Urban Heat Islands

During the past 15 years, the international scientific community (as organized through the Intergovernmental Panel on Climate Change [IPCC]) has focused significant effort to characterize the potential impacts of greenhouse gas emissions from human activities (anthropogenic) on the complex interactions of our global climate. IPCC Working Group I focused on creating atmosphere-ocean general circulation models (GCM), similar to models used to predict the weather, in which the physics of atmospheric motion are translated into equations that can be solved on supercomputers. The GCM predict climate at a relatively high level of spatial resolution (5 x 5 degrees latitude and longitude or several hundred kilometers). The four major GCM are HadCM3 (United Kingdom), which includes a finer spatial resolution for the British Isles, CSIRO2 (Australia), CGCM2 (Canada), and PCM

(USA) (IPCC 2001). In 2007, the IPCC released the fourth assessment report (AR4) (IPCC 2007). Rather than creating a new series of economic development scenarios or revising the results from the GCMs, the IPCC instead focused on the impacts of climate change, providing the strongest consensus to date on the potential impacts of climate change: "the net effect of human activities since 1750 has been one of warming." In this same report, the IPCC identifies buildings as the sector with the highest economic mitigation potential of any other energy sector.

The scenarios developed by the experts of the IPCC in 2001 represent the range of emissions of carbon dioxide and other pollutants based on specific economic and political conditions (described later). When these scenarios are then simulated within the 4 major GCMs, they result in 16 combinations of scenario and climate prediction. The range of potential annual average global temperature changes predicted by the GCM using the scenarios—from 1.5 to nearly 6°C—is shown in Figure 3-7.

Human-induced warming at the global scale is not the only change affecting our built environment. During the past 50 years, there has been a worldwide trend toward increasingly larger urban areas. This concentration of transportation infrastructure and buildings often results in a phenomenon labelled urban heat islands, where the average temperature within an urban area can be several degrees warmer than the surrounding, undeveloped countryside.

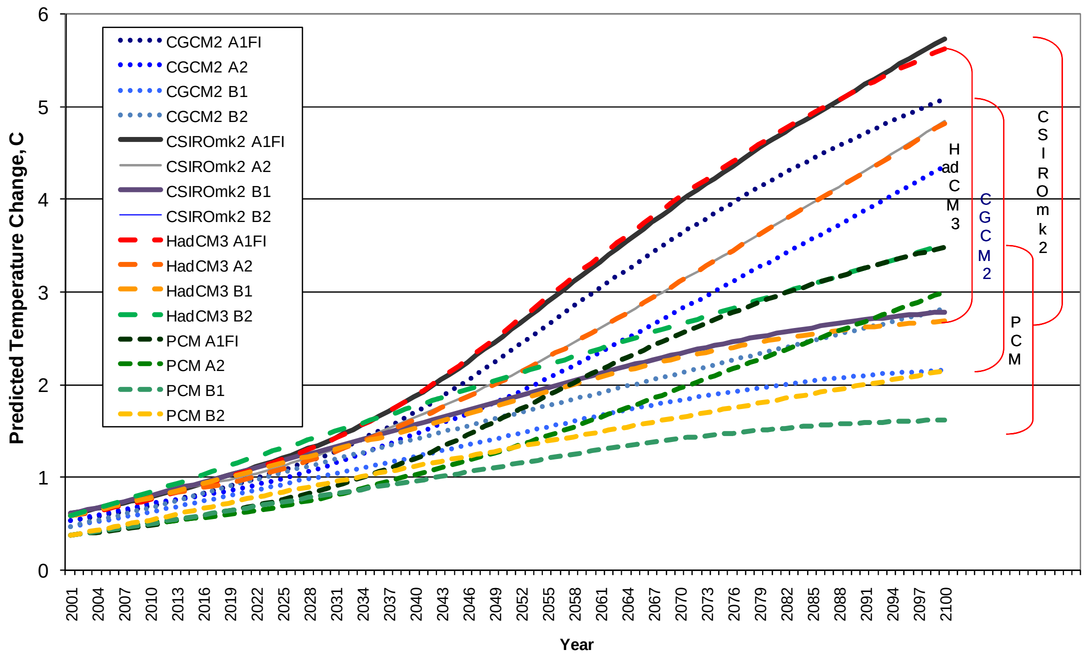

Figure 3-7. Global Annual Average Temperature Change Predicted by Four Major Global Climate Models

For example, the average temperatures at the airports of London Heathrow, Los Angeles, and Phoenix have increased by at least 1°C during the past 30 years.

To test the possible impacts on building performance of the GCM-predicted changes in climate, a study was constructed. This included determining a reasonable range of climate conditions—from among the typical and extreme meteorological weather data sets. Then the baseline data were modified to represent a range of predicted climate change and heat island scenarios for building simulation. Prototypical buildings were then created to represent typical, good, and low-energy practices around the world. When these prototype buildings were simulated, the results provide a snapshot view of the impact of the set of climate scenarios on building performance. These include location-specific responses of the prototype buildings including impacts on equipment use and longevity, fuel swapping as heating and cooling ratios change, impacts on environmental emissions, comfort issues, and the significant mitigation of low-energy building design incorporating renewable energy technologies on any potential climate variation.

3.5.1 What Are the Potential Impacts on the Built Environment?

Little of the scientific study has pursued the potential impact of climate change on the operating performance of buildings. The IPCC's Third Assessment Report (IPCC 2001) summarizes the impact on the built environment simply as "increased electric cooling demand and reduced energy supply reliability." This is essentially a top-down view of the entire building sector which ignores variability in climatic response seen among buildings from the poles to the equator. Buildings respond to their environments in complex ways—with time-varying interactions of local weather conditions with internal loads (people, lights, equipment, and appliances) and heating, ventilating, and cooling systems (natural or forced). This is seen in Figure 3-8, which compares the energy end-uses of commercial buildings in the United States and Europe. Typical European buildings use little or no cooling, while cooling is a significant portion of commercial building energy performance in the United States.

In the Third Assessment Report, Working Group II states:

> "The basis of research evidence is very limited for human settlements, energy, and industry. Energy has been regarded mainly as an issue for Working Group III, related more to causes of climate change than to impacts. . . . Impacts of climate

change on human settlements are hard to forecast, at least partly because the ability to project climate change at an urban or smaller scale has been so limited. As a result, more research is needed on impacts and adaptations in human settlements." (IPCC 2001)

From this, a number of questions arise about the impact of climate change or urbanization on the performance of buildings:

- What might be the potential impacts of climate change or urbanization on buildings?
- Will the changes predicted by the climate models and recent measurable temperature changes due to urbanization significantly change building energy use patterns and peak demand or cause cost shocks?
- Will increased demands on building heating and cooling equipment decrease life?
- What are the potential impacts on comfort?
- What other building performance impacts might be seen?

3.5.2 A Bottom-up Model for Evaluating Impacts of Climate Change

Attributing the changes in performance to the characteristics that are changing will be more instructive than using a top-down model of buildings. For this study, a process for creating a bottom-up model of potential changes in climatic conditions and the building sector is tested and a series of simulation cases developed. This process includes:

- Select baseline climate data and locations for testing.
- Translate scenarios (such as the IPCC Special Report on Emissions Scenarios [SRES] mentioned above or urban heat islands) into temporal climatic change based on a reference period.
- Define a building (or set of buildings) prototype to represent the building stock.
- Define a series of simulation cases to represent the range and combinations of scenarios and building response and evaluate the results.

This section describes how a set of baseline climate regions were developed, and how the climate change and heat island scenarios were translated into modified climate data which could be used within building simulation software. Finally, a series of prototype buildings are defined and simulated and the results are analyzed.

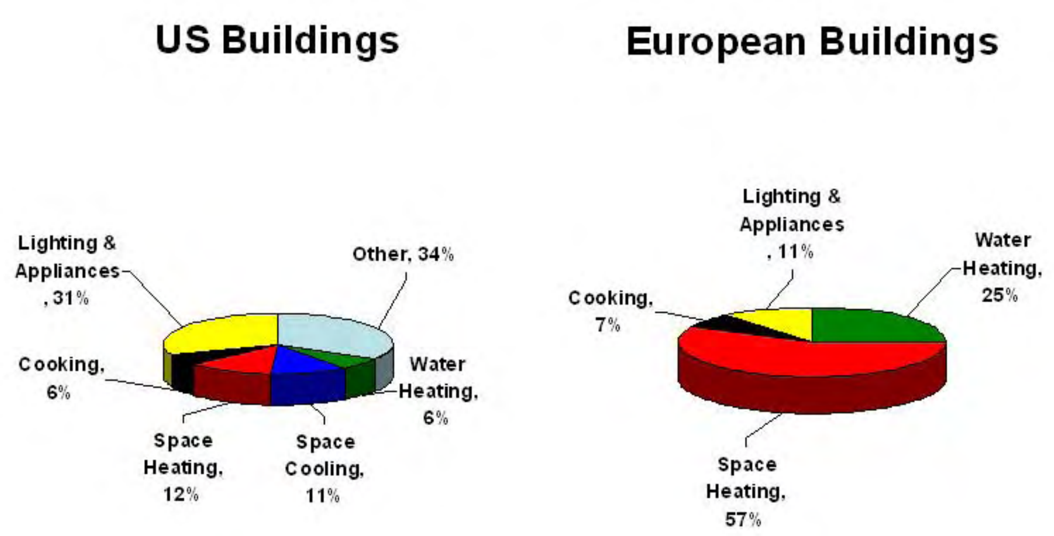

Figure 3-8. Commercial Building Energy End-Uses in the United States (EIA 2002) and Europe (EC 2000)

3.5.3 Selecting Weather Sources, Climate Regions, and Locations

All the widely used building simulation programs use some representation of weather conditions to simulate the response of a building. These data often are "typical" data derived from hourly observations recorded at a specific location by the national weather service or meteorological office. Examples of these typical data include TMY2 (NREL 1995) in the United States, CWEC (WATSUN Simulation Laboratory 1992) in Canada, TRY (CEC 1985) in Europe, and IWEC (ASHRAE 2001) worldwide. The TMY2, CWEC, and IWEC typical weather years contain more detailed solar radiation and illumination data than some older typical meteorological year data sets. Crawley (1998) showed that assembling months that are most typical of the period of record but that may be from different years (the typical month method used in the TMY2, CWEC, and IWEC data sets) results in synthetic weather years that better fit the long-term climate patterns.

For the work described here, an array of locations were needed to represent the range of climatic conditions around the world. Also, it was clear that the locations should have data with a reasonable source period of record—on the order of 15 years. Both the TMY2 and CWEC were derived from at least 30 years of weather data for all their locations, while IWEC locations have up to 19 years. But the periods of record vary—TMY2 covers 1961-2005 while CWEC covers ~1950-1999, and IWEC covers 1982-1999. Despite these varying periods of record, TMY2, CWEC, and IWEC were the most robust climatic data sources from which to select the range of climate regions for this work.

3.5.3.1 Climate Classification

Early in the 20th century, Vladimir Köppen (1918) proposed categorizing the climate regions of the world with a relatively straightforward schema, originally intended for agricultural use. During the past 90 years, this schema has been expanded to include polar and highland climates but remains much as Köppen originally proposed. The major Köppen climate classes are:

A – Tropical humid climates
B – Hot dry climates
C – Mild mid-latitude climates
D – Cold mid-latitude climates
E – Polar climates
H – Highland climates

These six major climate types are further subdivided into hot/cold and dry/wet—creating 20 regions that represent the range of climatic conditions worldwide. These climate classes are similar to other climate classification schemes that require more detailed data to determine which classes the locations belong in. Table 3-17 describes each of the 20 Köppen classes.

To select locations for this work, the TMY2, CWEC, and IWEC locations were first categorized into Köppen climate regions. Then a rank based on city population was added, derived from data from Brinkhoff (2007). Using this information as a starting point, the goal was to select at least one location within each climate class to represent that region. Generally, from the equator to approximately 40-50º latitude, the location within the TMY2, CWEC, or IWEC data set with the largest population was selected. For 5 Köppen climate regions where there were both major developed and emerging economy locations, a second location was selected to ensure that developed and emerging economy locations were represented. Ten of the 25 locations are among the top 25 largest population centers. For the colder climates, no population-based city rank is shown because there are not many cities with large populations. The twenty-five locations selected, their Köppen climate classes, and a few major climatological attributes based on the TMY2, CWEC, and IWEC typical files are shown in Table 3-18.

Table 3-17. Köppen Climate Classification System

Climate	Description
Af	Tropical wet (no dry season, rainforest, hot all year, lat. < 10°)
Am	Tropical monsoonal or tradewind-coastal (short dry season, lat. 5-25°)
Aw	Tropical savanna (pronounced wet & dry seasons, lat. 15-20°)
BSh	Hot subtropical steppe (lat. 15-30°N)
BSk	Mid-latitude dry semiarid (e.g. Great Plains of USA, lat. 15-60°N)
BWh	Subtropical hot desert (lat. 15-25°N)
Cfa	Humid subtropical (mild with no dry season, hot summer, lat. 20-35°N)
Cfb	Marine west coastal (warm summer, mild winter, rain all year, lat. 35-60°N)
Cfc	Marine west coastal (mild summer, cool winter, no dry season, lat. 35-60°S)
Csa	Mediterranean climate (dry hot summer, mild winter, lat. 30-45°S)
Csb	Mediterranean climate (dry warm summer, mild winter, lat. 30-45°S)
Dfa	Humid continental (hot summer, cold winter, no dry season, lat. 30-60°N)
Dfb	Moist continental (warm summer, cold winter, no dry season, lat. 30-60°N)
Dfc	Subarctic (cool summer, severe winter, no dry season, lat. 50-70°N)
Dwa	Humid continental (hot winter, cold dry winter, lat. 30-60°N)
Dwb	Moist continental (warm summer, dry severe winter, lat. 30-60°N)
Dwc	Subarctic (cool summer, dry severe winter, lat. 50-70°N)
Dwd	Subarctic (cool summer, severely cold dry winter, lat. 50-70°N)
ET	Polar (tundra, no true summer, latitude 60-75°)
H	Severely cold high altitude climate

3.5.3.2 Selecting Climate Years for Simulation

As Crawley (1998) showed when using a range of actual weather years, the annual energy consumption as predicted by building simulation software could vary as much as +-11%. It was important to capture this normal variation in climatic conditions in this study. Thus, in addition to the typical year from the TMY2, CWEC, or IWEC data sets, years of data from the period of records were needed to cover the range of climatic conditions, such as hottest/coldest.

An efficient way to gather data would be to determine which years result in the highest and lowest energy use, rather than attempting a brute force method of simulating up to 45 years of weather data for each location in addition to the climate scenarios. Initially, it was thought that a simple combination of climatic variables, such as highest and lowest heating and cooling degree days or solar radiation for each weather year, might be sufficient to pinpoint which years would result in the highest and lowest energy. To test this, a prototype office building was simulated using the EnergyPlus building energy simulation model (US DOE 2007) in three locations—an extreme cold, high-latitude location (Resolute, Nunavut, Canada), a temperate, mid-latitude location (Washington, D.C.-Sterling, Virginia, USA), and

Table 3-18. Selected Locations and Climate Characteristics

Köppen Climate	City Rank[15], D/E[16]	Location	Data Source[17] and Period of Record	Latitude	Longitude	Time Zone[18]	Elevation (m)	Design Conditions[19]			Annual CDD, base 10°C	Annual HDD, base 18°C
								Heating 99.6% DB, °C	Cooling 0.4% DB, °C	Cooling 0.4% MCWB, °C		
Af	65, D	Singapore, SGP	IWEC, 1982-1999	N 1° 22'	E 103° 58'	8	16	22.8	33	25.9	6374	0
Am	139, D	San Juan, PRI	TMY2, 1961-2005	N 18° 25'	W 66° 0'	-4	19	20.3	33.2	25	5904	0
Aw	57, D	Miami, FL, USA	TMY2, 1961-2005	N 25° 47'	W 80° 16'	-5	2	7.6	32.8	25.2	5225	64
BSh	12,E	Cairo, EGY	IWEC, 1982-1999	N 30° 7'	E 31° 23'	2	74	7	38	20.3	4276	390
BSk	145, D	Boulder, CO, USA	TMY2, 1961-2005	N 40° 1'	W 105° 15'	-7	1634	-19.7	33.8	15.3	1493	3322
BSk	3, E	Mexico City, MEX	IWEC, 1982-1993	N 19° 25'	W 99° 4'	-6	2234	4	29	13.8	2503	547
BWh	6, E	New Delhi, IND	IWEC, 1982-1999	N 28° 34'	E 77° 11'	5.5	216	6.6	41.7	22	5279	321
Cfa	1, D	Tokyo, JPN	IWEC, 1982-1999	N 36° 10'	E 140° 25'	9	35	-7	31.8	25.4	1911	2311
Cfa	7, E	Sao Paulo, BRA	IWEC, 1982-1999	S 23° 37'	W 46° 39'	-3	803	8.8	31.9	20.3	3607	252
Cfb	22,D	London (Gatwick), GBR	IWEC, 1982-1997	N 51° 9'	W 0° 10'	0	62	-5.6	26.4	18.4	864	2866
Cfb	38,E	Johannesburg, ZAF	IWEC, 1982-1999	S 26° 7'	E 28° 13'	2	1700	1	29	15.6	2216	1052
Cfc	-, E	Punta Arenas, CHL	IWEC, 1982-1999	S 53° 0'	W 70° 50'	-4	37	-5	17.8	12.5	96	4273
Csa	17, E	Buenos Aires, ARG	IWEC, 1982-1999	S 34° 49'	W 58° 31'	-3	20	-0.7	33.9	22.8	2524	1189
Csb	9, D	Los Angeles, CA, USA	TMY2, 1961-2005	N 33° 55'	W 118° 24'	-8	32	6.2	29.2	17.7	2433	720
Csb	48, E	Santiago, CHL	IWEC, 1982-1999	S 33° 22'	W 70° 46'	-4	476	-1.4	31.9	18.4	1784	1570
Dfa	35,D	Washington-Dulles, VA, USA	TMY2, 1961-2005	N 38° 57'	W 77° 26'	-5	82	-12.8	33.7	23.9	1939	2795
Dfb	60, D	Toronto, ON, CAN	CWEC, 1961-1999	N 43° 40'	W 79° 37'	-5	173	-19.9	30.3	21.8	1172	4089
Dfb	18, E	Moscow, RUS	IWEC, 1982-1999	N 55° 45'	E 37° 37'	3	156	-23.1	27.6	19.3	862	4655
Dfc	-, D	Whitehorse, YT, CAN	CWEC, 1961-1999	N 60° 43'	W 135° 4'	-8	703	-36.8	25	13.8	271	6946
Dwa	19, E	Beijing, CHN	IWEC, 1982-1999	N 39° 47'	E 116° 28'	8	32	-10.4	34.2	21.9	2321	2750
Dwb	-, D	The Pas, MB, CAN	CWEC, 1961-1999	N 53° 58'	W 101° 5'	-6	271	-35.3	28.1	18.6	790	6443
Dwc	-, D	Fairbanks, AK, USA	TMY2, 1961-2005	N 64° 49'	W 147° 52'	-9	138	-44	27.1	15.8	510	7715
Dwd	-,E	Yakutsk, RUS	IWEC, 1982-1999	N 62° 4'	E 129° 45'	9	103	-51.9	29.4	18.7	685	10032
ET	-, D	Resolute, NU, CAN	CWEC, 1963-1999	N 74° 43'	W 94° 58'	-6	67	-40.9	10.2	7.3	0	12571
H	224, E	La Paz, BOL	IWEC, 1982-1999	S 16° 31'	W 68° 10'	-4	4042	-4	17.3	6.6	6	4015

15 Rank of cities with population greater than 1 million. (Brinkhoff 2007)

16 D = Developed economy, E = Emerging economy

17 IWEC, International Weather for Energy Calculations, 1982-1999, (ASHRAE 2001). TMY2, Typical Meteorological Year 2 (NREL 1993), 1961-1990 period of record SAMSON (NCDC 1993), 1991-2005 period of record NSRDB (NREL 2007). CWEC, Canadian Weather for Energy Calculations (WATSUN Simulation Laboratory 1992), 1950-1999, here an intersecting portion of 1961-1999 used, CWEEDS (Environment Canada (2001).

18 Hours from Universal Coordinated Time.

19 ASHRAE Handbook of Fundamentals (ASHRAE 2005). DB = dry-bulb temperature, MCWB = mean coincident wet-bulb temperature, HDD = heating degree days, CDD= cooling degree days.

a tropical location (San Juan, Puerto Rico)—selected to represent the range of climate conditions. The prototype office building is described in Section 3.5.6 below. These three locations are part of the TMY2 and CWEC data sets with periods of record of 45 and 36 years, respectively. For each location, the same prototype building was simulated using weather data for each of the available years—from 1961 through 2005 for Washington and San Juan and from 1963 through 1999 for Resolute. HVAC equipment and systems were automatically sized using the ASHRAE 2005 Fundamentals design conditions (ASHRAE 2005).

Figure 3-9 shows all 45 years in the TMY2/SAMSON/NSRDB data set for Washington, D.C., ranking each year from coolest to warmest based on the combination of heating and cooling degree days, base 18 and 10°C, respectively. From Figure 3-9, one might presume that 1969—the warmest year—might result in the combination of highest cooling and lowest heating while 1990—the coolest year—would result in the combination of lowest cooling and highest heating in terms of energy. Yet, when the energy end-use results for these 45 annual simulations were assembled, this proved not to be the case. As shown in Figure 3-10, 1990 had the next to lowest energy use, but 2001 had the lowest energy use overall of the 45 simulated years, and a full third of the years yielded a higher annual energy consumption than1969. Similar comparisons are shown in Figures 3-11 and 3-12 for Resolute, Nunavut, Canada, and San Juan, Puerto Rico. Figure 3-11 shows for Resolute that the year with the lowest heating degree days (there were no cooling degree days for Resolute) was 1998 (warm), and the year with the highest heating degree days was 1972 (cool). The 1998 data result only in the third-lowest energy use, while 1972 corresponds to the highest annual energy use. Figure 3-12 shows that 1961 is the coolest year for San Juan, Puerto Rico, and the second-lowest energy use, while 1980 is both the warmest year and highest energy use.

From this test case of three locations, it can be concluded that selecting a year of weather data based on a single, simple climate descriptor, such as degree days, will not guarantee the lowest or highest energy for the period of record. Too many other variables, such as solar radiation and humidity, significantly affect how buildings perform and the resulting energy use. The most robust means of selecting years that result in high and low energy use was to run the prototype office through the complete set of years available for the 25 locations (a total of 707 simulations). A matrix of available simulation data for each of the 25 locations is shown in Table 3-19. The years which resulted in the highest and lowest energy use (shown in Table 3-20) were then used for the further analysis described next.

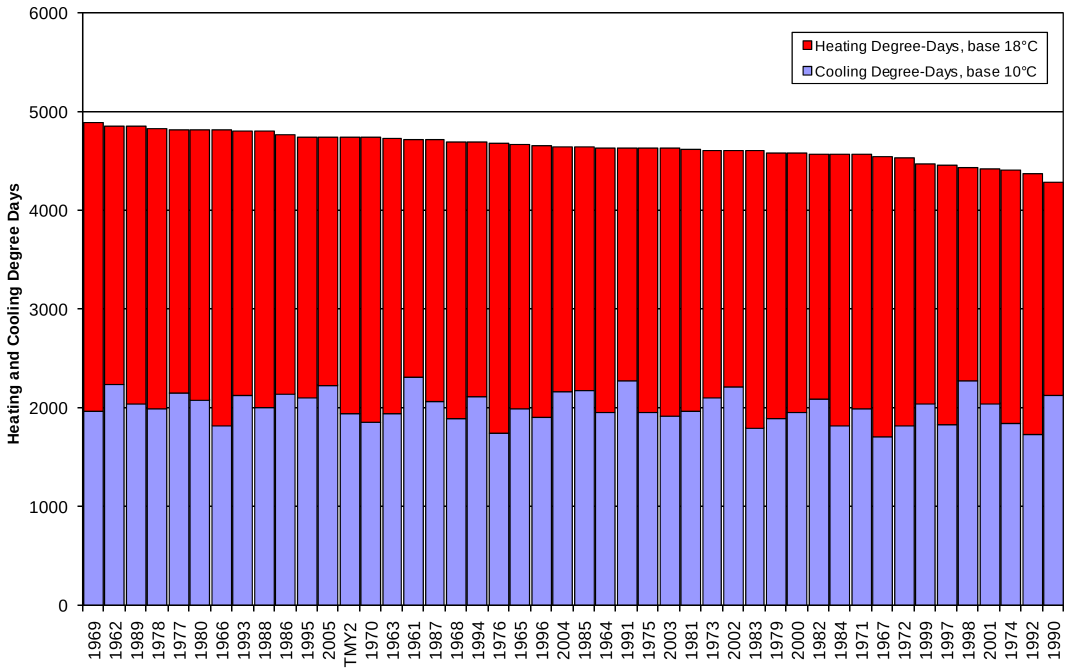

Figure 3-9. Washington, D. C., Summed Heating and Cooling Degree Days Ranked from Highest to Lowest

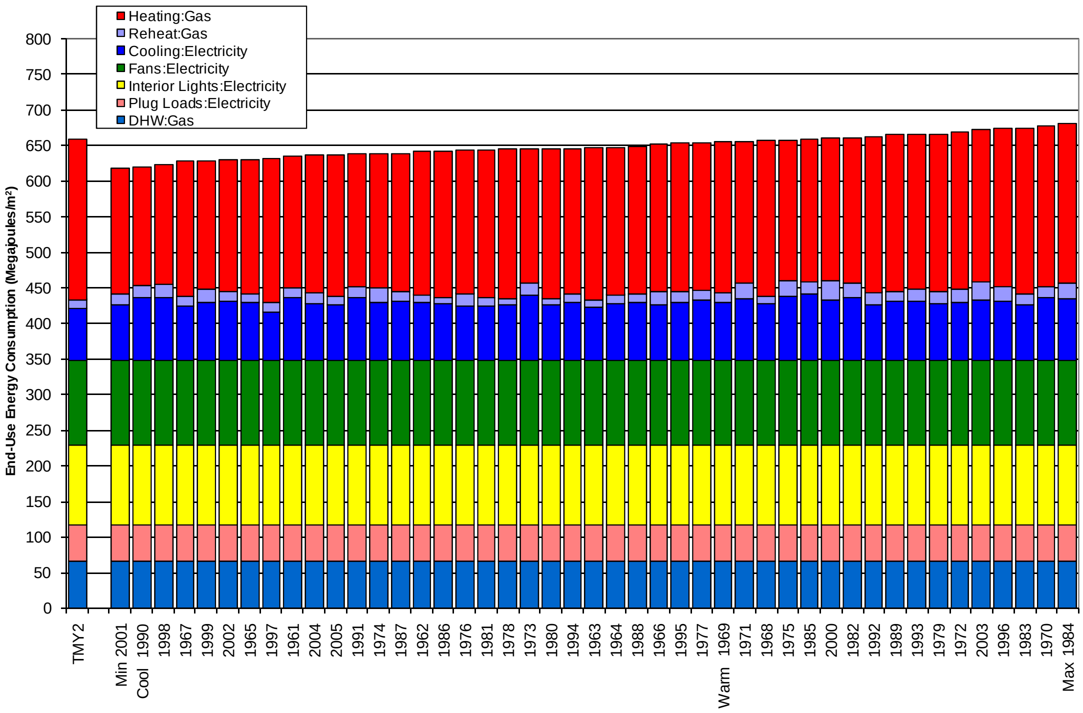

Figure 3-10. Washington, D. C., Energy End-Use Consumption for 550 m² Office Building

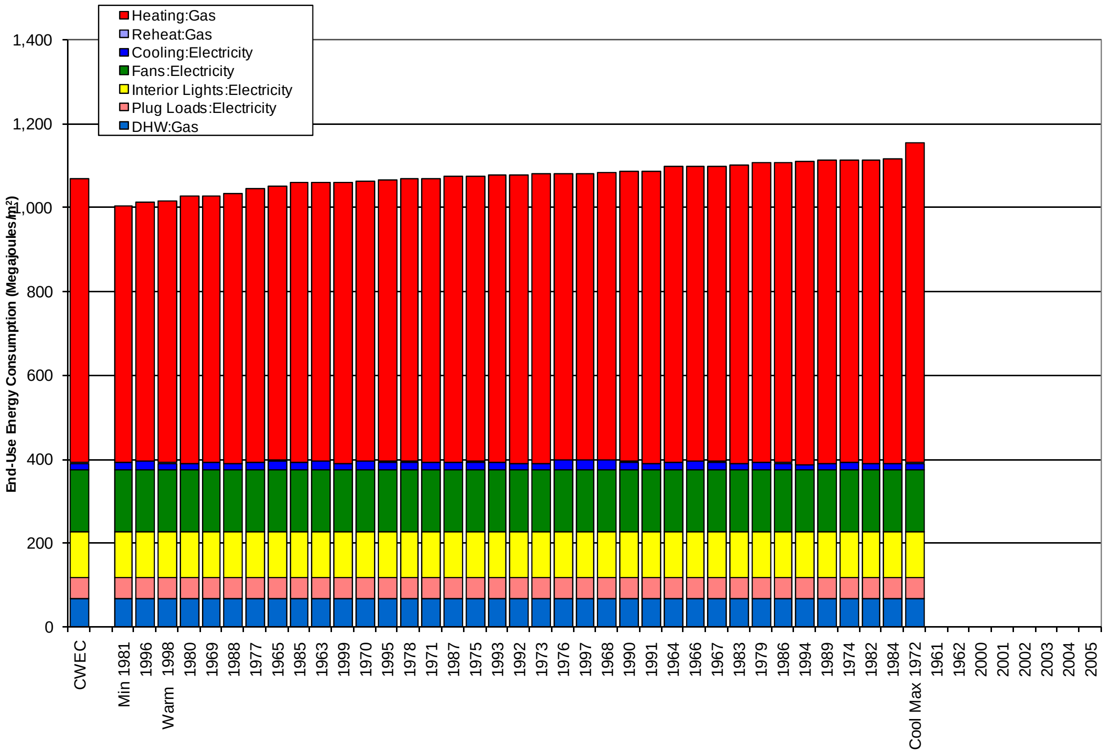

Figure 3-11. Resolute, Nunavut, Canada, Energy End-Use Consumption for 550 m^2 Office Building

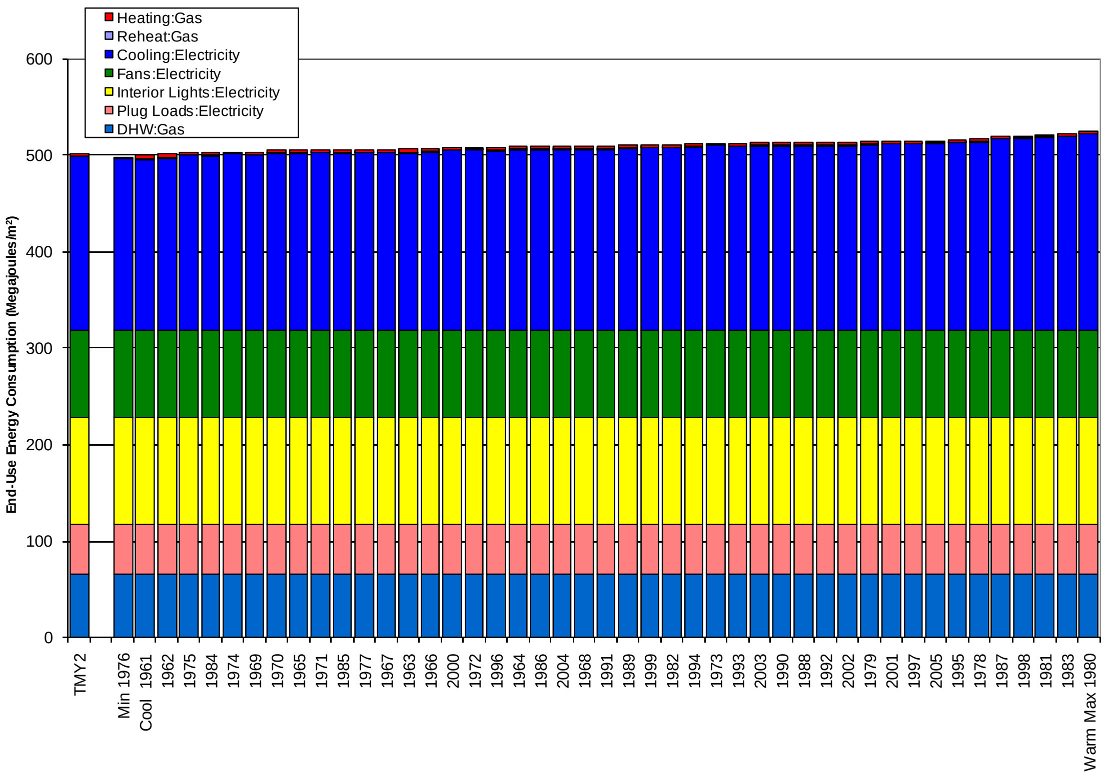

Figure 3-12. San Juan, Puerto Rico, Energy End-Use Consumption for 550 m^2 Office Building

3.5.4 Representing the Climate Change Scenarios

As mentioned previously, the four major storylines developed by IPCC WG III represent a potential range of different demographic, social, economic, technological, and environmental developments (IPCC 2000). Four of the storyline scenarios cover the range of annual average global temperature changes predicted by the GCM:

- A1—rapid economic and population growth; three groups of alternative energy system change: fossil intensive (A1FI), non-fossil sources, or balance among sources.
- A2—continuous population growth, but fragmented economic growth.
- B1—population peaks in mid-21st century; economic change toward service and information economy; clean and resource-efficient technologies at global level.
- B2—local solutions to economic, social, and environmental sustainability; intermediate population and economic development.

The GCM have a three-dimensional latitude and longitude grid, which vary by model; for example, the Hadley CM3 GCM uses a grid of 2.5° latitude by 3.75° longitude—up to 60 km—too wide an area when working with local climatic conditions. Through reanalysis of the Hadley CM3 GCM data sets, Mitchell (2003) created a dataset with a higher resolution of 0.5° x 0.5° latitude and longitude. These data are monthly grids of latitude and longitude covering the period 2001 through 2100. Mitchell reanalyzed five climatic variables from the larger IPCC data set: cloud cover, diurnal temperature range, precipitation, temperature, and vapor pressure. In the data set, there are 16 climate change scenarios—the four GCM with four SRES emissions scenarios each (A1FI, A2, B2, B1). Together, the 16 scenarios cover 93 percent of the possible range of future global warming estimated by the IPCC in their Third Assessment Report (2001). The HadCM3 data were selected to represent the four climate scenarios because, as seen in Figure 3-7, they provide the broadest range of predicted global average temperature change among the four GCM.

Using Mitchell’s denser global grid of the data, the predicted monthly change of the five climatic variables in a particular location could simply be looked up. Since the weather data used by EnergyPlus (and most energy simulation programs) does not include precipitation, these data were not used to modify existing weather data. Also because Mitchell calculated the change in vapor pressure in this data set to be quite small, it also was excluded.

The next step was to modify the existing weather data (typical as well as highest and lowest energy years) to account for the monthly predicted changes in diurnal temperature range, dry

Table 3-19. Available and Selected Weather Years for the 25 Locations

Location	Typical File Type	Years Available for Location																																												
		1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
ARG_Buenos.Aires	IWEC																															H					WL		C							
BOL_La.Paz	IWEC																							L	H		C												W							
BRA_Sao.Paolo	IWEC																					C															H		W	L						
CAN_MB_The.Pas	CWEC												HC															LW																		
CAN_NU_Resolute	CWEC												HC									L																	W							
CAN_ON_Toronto	CWEC												H						C																				WL							
CAN_YT_Whitehorse	CWEC																											LW					C				H									
CHL_Punta.Arenas	IWEC																								C			L				H							W							
CHL_Santiago	IWEC																						C										H	W			L									
CHN_Beijing	IWEC																								W	H										CL										
EGY_Cairo	IWEC																							C	L							H							W							
GBR_London.Gatwick	IWEC																									HC				W	L															
IND_New.Delhi	IWEC																								L		W											C	H							
JPN_Tokyo.Hyakuri	IWEC																								W								H	C			L									
MEX_Mexico.City	IWEC																						L			C						HW														
PRI_San.Juan	TMY2	C															L				HW																									
RUS_Moscow	IWEC																									HC				L	W															
RUS_Yakutsk	IWEC																						H					C								LW										
SGP_Singapore	IWEC																								C					L									HW							
USA_AK_Fairbanks	TMY2						C															LW																		H						
USA_CA_Los.Angeles	TMY2		C																							L												W								H
USA_CO_Boulder	TMY2																							CH			L													W						
USA_FL_Miami	TMY2						C	L																						H					W											
USA_VA_Sterling-Washington.Dulles	TMY2									C															H						W											L				
ZAF_Johannesburg	IWEC																									L		W									H			C						

IPCC Scenarios Reference Years (1961–1990)

H Highest energy
L Lowest energy
C Coolest year
W Warmest year

Table 3-20. Weather File Type and Years with Highest and Lowest Energy

Location	Typical File Type	Low	High
ARG_Buenos.Aires	IWEC	1996	1991
BOL_La.Paz	IWEC	1983	1984
BRA_Sao.Paolo	IWEC	1999	1996
CAN_MB_The.Pas	CWEC	1987	1972
CAN_NU_Resolute	CWEC	1981	1972
CAN_ON_Toronto	CWEC	1998	1972
CAN_YT_Whitehorse	CWEC	1987	1996
CHL_Punta.Arenas	IWEC	1987	1991
CHL_Santiago	IWEC	1996	1992
CHN_Beijing	IWEC	1995	1985
EGY_Cairo	IWEC	1984	1991
GBR_London.Gatwick	IWEC	1990	1985
IND_New.Delhi	IWEC	1984	1998
JPN_Tokyo.Hyakuri	IWEC	1996	1992
MEX_Mexico.City	IWEC	1982	1991
PRI_San.Juan	TMY2	1976	1980
RUS_Moscow	IWEC	1989	1985
RUS_Yakutsk	IWEC	1995	1982
SGP_Singapore	IWEC	1989	1998
USA_AK_Fairbanks	TMY2	1981	1999
USA_CA_Los.Angeles	TMY2	1985	2005
USA_CO_Boulder	TMY2	1986	1983
USA_FL_Miami	TMY2	1967	1989
USA_VA_Sterling-Washington.Dulles	TMY2	2001	1984
ZAF_Johannesburg	IWEC	1985	1996

bulb temperature, and cloud cover effects on solar radiation. A program was created to read in the existing weather file and the four GCM monthly variable changes. It then recalculated the hourly dry bulb temperature based on both the temperature change and the reduced diurnal temperature range, recalculated the humidity ratio based on relative humidity, and recalculated the hourly global, direct normal, and diffuse horizontal solar radiation based on the change in cloud cover. The equations for modifying the dry bulb temperature, dew point temperature, and relative humidity are shown below. For the modified dry bulb temperature, the equations add the predicted change in dry bulb temperature and diurnal dry bulb temperature range to the existing dry bulb temperature in the typical weather data. As discussed in the IPCC report (2001), the change in diurnal temperature range was usually a compression of the data. In most cases, the change in diurnal temperature range was small. The modified dew point temperature was calculated in a similar way. For the relative humidity, the predicted change in relative humidity was added to the existing relative humidity.

Modified dry bulb temperature:

If DB > DBdailyave then DBmod = DB + ΔDB + 0.5 * ΔDBdiurnal (1)

If DB ≤ DBdailyave then DBmod = DB + ΔDB - 0.5 * ΔDBdiurnal (2)

Where:

DB = dry bulb temperature

ΔDB = change in dry bulb temperature from the climate change scenario

DBdailyave = daily average dry bulb temperature

DBmod = modified dry bulb temperature

ΔDBdiurnal = change in diurnal dry bulb temperature from the climate change scenario

Modified dew point temperature:

If DB > DBdailyave then DPmod = DP + ΔDB + 0.5 * ΔDBdiurnal (3)

If DB ≤ DBdailyave then DPmod = DP + ΔDB - 0.5 * ΔDBdiurnal (4)

Where:

DB = dry bulb temperature

DP = dew point temperature

ΔDB = change in dry bulb temperature from the climate change scenario

DBdailyave = daily average dry bulb temperature

DPmod = modified dew point temperature

ΔDBdiurnal = change in diurnal dry bulb temperature range from the climate change scenario

Modified relative humidity:

RHmod = RH + ΔRH (5)

Where:

RH = relative humidity

ΔRH = change in relative humidity from the climate change scenario

RHmod = modified relative humidity

The humidity ratio and wet bulb temperature were then recalculated using standard psychrometric equations based on the modified dry bulb temperature, dew point temperature, and relative humidity.

To estimate the effects of changes in solar radiation, solar radiation was recalculated twice using the Zhang and Huang solar model—once for the existing cloud cover and a second time using the modified cloud cover (Zhang and Huang 2002; Krarti et al 2006). To modify the cloud cover, the monthly change in cloud cover from the climate change scenarios was added to the existing hourly cloud cover. To determine the modified solar radiation, the existing solar radiation data was multiplied by the ratio between the recalculated solar radiation with the modified cloud cover and the existing solar radiation with the existing cloud cover. (Note: the cloud cover in the IPCC climate change scenarios often was little changed, resulting in almost no change in the solar radiation.)

Figure 3-13 shows an example of the average hourly temperatures for December in Washington, D.C.. Note that for this one day, the diurnal temperature range is slightly compressed for all the scenarios (almost imperceptible in Figure 3-13).

3.5.5 Representing the Urban Heat Island

That urban conditions are different from rural has been recorded for more than 2,000 years. In Neuman's historical review of heat islands (1979), he notes that the effects of pollution and heat islands have been known for thousands of years. That the air pollution and temperature in Rome differed from the countryside was noted in the odes of Quintus Horatius Flaccus in 24 B.C. From the Middle Ages, larger cities such as London were known for their often health-threatening pollution. King Edward I banned the burning of sea coal in 1306; two centuries later Queen Elizabeth I banned the burning of coal during sessions of Parliament. Even in the 19th and 20th centuries, people of means left for the countryside to escape the summer heat and the pollution of the city.

In the early 1800s, Luke Howard first described the altered meteorological conditions caused by pollution in London as "city fog" (Howard 1833). Howard also measured the temperature differences between the urban center and the countryside for a number of years, publishing his initial findings in 1820. In a footnote to his table of mean monthly temperature differences, Howard wrote: “night is 3.70º warmer and day 0.34º cooler in the city than in the country,” recognizing what today is called the heat island effect.

More recently, Mitchell (1953, 1961) measured the extent and intensity of the heat island phenomenon. Oke (1988) and Runnells and Oke (2000) were the first to develop diagrams to explain the diurnal and seasonal patterns of the heat island. Their diagrams were confirmed by the temperature measurements by Streuker (2003) and Morris and Simmonds (2000). Specifically, Streuker’s measurements reinforced Oke’s findings (1973) that heat island intensity depends on urban concentration (population density), vegetation, and surface albedo. Streuker went further in his thesis to demonstrate the influence bodies of water and other geographic features affected the size and shape of the urban heat island.

The US EPA’s Heat Island Reduction Initiative estimates that the heat island effect is in the range of 1-5ºC (US EPA 2007). But this is a range of potential impacts, not an annual, monthly, or even a daily average. Rather than focus on the impacts, most discussions in the literature focus on mitigating heat island effects through green roofs, increased vegetation, light roof colors, and reduction of hard surfaces. Some research has focused on measuring the resultant air temperatures, but there is little documentation of how urban heat islands affect the operating performance of buildings.

In reviewing the measured data and Oke’s diagrams, one could see that heat islands could be represented as a change to the diurnal temperature patterns. The heat island diurnal pattern shown in Oke’s diagram was transformed into the equations shown below. For heat islands, this included modifying only dry bulb temperatures and recalculating the humidity ratio in an existing weather file.

If sun is down: $$DBmod = DB + \Delta DB \quad (6)$$

If hour is first or last hour of daylight: $$DBmod = DB + 0.5*\Delta DB \quad (7)$$

If hour is second or next to last hour of daylight: $$DBmod = DB + 0.25*\Delta DB \quad (8)$$

If hour is third or second to last hour of daylight: $$DBmod = DB + 0.075*\Delta DB \quad (9)$$

All other hours when sun is up: $DBmod = DB - 0.1*\Delta DB$ (10)

Where:

DB = dry bulb temperature

ΔDB = change in dry bulb temperature for heat island scenario

DBmod = modified dry bulb temperature

An example for the hourly average dry bulb temperatures in April is shown in Figure 3-14. Because the US EPA estimates that the heat island effect is in the range of 1 to 5ºC, these values were selected to represent the range of heat island modification—except for colder climates (>48 degrees latitude) where lower populations limit the heat islands, here represented by a range of 1 to 3 ºC. The result was a set of new weather files representing a range of heat island impacts based on the typical weather file and the high- and low-energy years for each of the 25 locations described above.

3.5.6 Representing Building Stock

As noted earlier, the Commercial Building Energy Consumption Survey (CBECS) provides a statistical snapshot of the U.S. commercial building stock and energy consumption characteristics and is updated every four years. For this work, the 1999 CBECS data (EIA 2002) were evaluated to identify possible reasonable groups of building types and sizes. Table 3-21 summarizes the building floor area, number of buildings, and energy use by building type from the 1999 CBECS.

The building types in Table 3-22 are in rank order of total floor area. From this table, one can see that the top three building types (office, warehouse, and retail) represent nearly half of the building floor area (48.9 percent). If the next four building types were included (education, public assembly, lodging and health care), another 30 percent of the floor area is represented—or nearly 80 percent. Similarly the top three building types represent 43.1 percent of the number of buildings and 39 percent of the total energy consumption. While not shown in this table, these three building types also represent 45 percent of the electricity of the commercial building sector. Thus, with a few building types one could represent much of the building stock and new construction.

Yet the average belies the wide range of building sizes and energy consumption among and within the principal building activities. Table 3-22 further subdivides the office, warehouse,

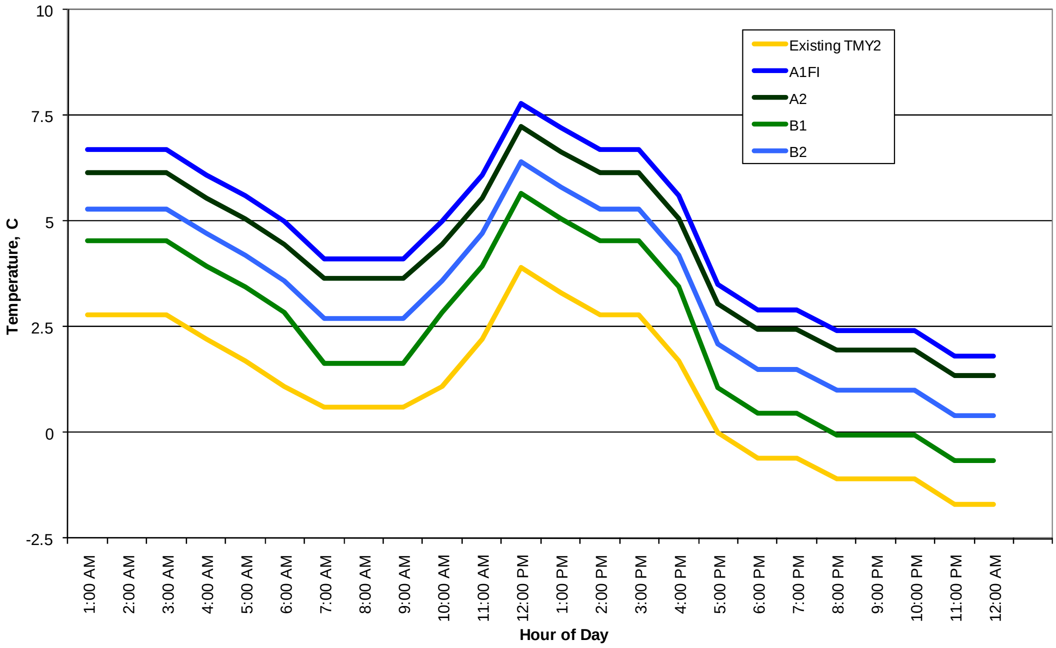

Figure 3-13. Example TMY2 and Climate Change Scenario Dry Bulb Temperatures for December in Washington, D.C.

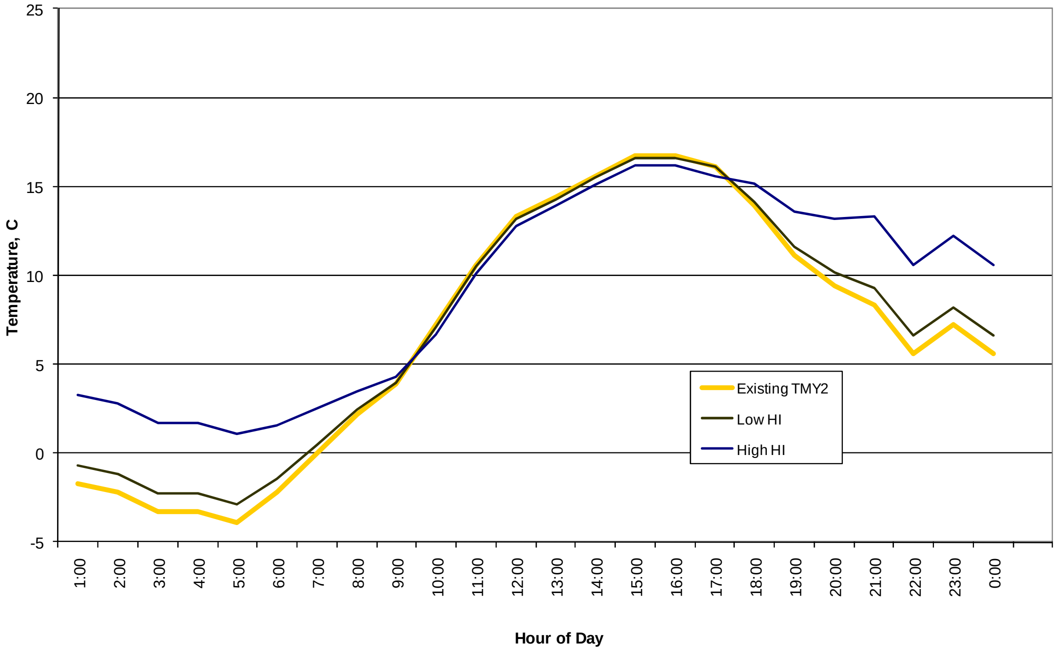

Figure 3-14. Example TMY2 and Heat Island Dry Bulb Temperatures for April in Washington, D.C.

and retail sectors into different sizes or categories. The data are presented based on these subdivisions: office buildings are broken into roughly equal thirds of floor area; the warehouses are divided into refrigerated and non-refrigerated; and the retail sector is broken into small shopping malls, enclosed shopping malls, and other retail. The totals for each building type are shown in bold. Thus, for the office buildings the average size of smaller buildings is 550 m^2. Note that the energy use varies significantly among the subdivisions of the sectors. For example, refrigerated warehouses use nearly three times as much energy as non-refrigerated warehouses but represent only 1.5 percent of the total commercial building consumption. Prototype buildings could then be defined for each of these eight buildings based on the average floor area and number of floors. Table 3-23 shows the basic definitions for the prototype buildings.

Because the focus of this thesis is on the structure and framework of building simulation for policy analysis rather than the impacts of climate change on the commercial building sector, only the small office building was used for the subsequent analyses described here and in Chapter 5. Having the additional building performance results would not contribute to demonstrating the policy framework. In the survey data, a two-story building of 550 m^2 was the average size for the smallest third of office building floor area. Thus, this small office building represents approximately 33 percent of U. S. office buildings. The office building model has the following characteristics (see the schematic in Figure 3-15):

- 550 m^2
- two stories
- 14 m^2/person
- typical office occupancy schedules
- office equipment at 8 W/m^2
- natural gas heating and hot water
- packaged rooftop electric DX cooling units
- lighting power at 11 W/m^2
- opaque building envelope and windows and equipment efficiencies equivalent to current minimum regulations [Standard 90.1-2004 (ASHRAE 2004)]

Two models with the same shape and floor area were also created:

- Low-energy building that includes photovoltaic power cells on the roof as well as shading overhangs (see Figure 3-16), using less than 50 percent of the energy of the base small office building model. When combined with the 87.5 kW photovoltaic panels, these building are often net-zero energy in total consumption.

- Building similar to the base building, but which has thermo-physical characteristics more typical of locations without an energy code or of developing economies, hereafter called the developing case.

Tables 3-24 through 3-26 show the minimum thermal envelope requirements for the base standard, developing, and low-energy cases. These are based on ASHRAE Standard 90.-2004 for the base standard, Carlo and Lamberts (2001) and Signor (1999) for the developing case, and Griffith et al (2007) for the low-energy case. For both the developing and low-energy cases, none of the sources provided complete information suitable for use in the building simulation, and judgment was used. Table 3-27 shows the latitude for the locations—used for setting the tilt of the photovoltaic panels simulated in the low-energy case. Tables 3-28 through 3-30 show the minimum HVAC and SWH equipment efficiency requirements. These are taken from Standard 90.1-2004 for the base standard and from the previously cited sources for the developing and low-energy cases. Outside air rates are based on Standard 62.1-2004 (ASHRAE 2004b). The schedules for the HVAC system operation, lighting and plug loads, occupancy, and SWH were derived from the schedules in Section 13 of Standard 90.1-1989 (ASHRAE 1989a).

3.5.7 Design of the Simulation Study

The small office building was then simulated for each of the 25 locations. For each location, a combination of typical year data (TMY2, CWEC, or IWEC) and high- and low-energy weather years were used as the baseline. Then, for each of these (typical/high/low), weather files were created to represent four IPCC climate change scenarios (A1FI, A2, B1, and B2) and two levels of heat island (1 and 5 °C or 1 and 3 °C in high-latitude locations). Heating and cooling design conditions from Chapter 28 of the Handbook of Fundamentals (ASHRAE 2005) were used in all cases—essentially using 2005 design conditions for HVAC equipment and system sizing. EnergyPlus (US DOE 2007) was used to calculate building thermal flows given the varying weather data sets.

Similar to the previous study, the input files were subdivided into parts that could be mixed and matched to create the appropriate full input files. The parts include:

- a base heading file with geometry, schedules, and other information that did not change among the locations or cases;

Table 3-21. Commercial Building Floor Area, Number of Buildings, Energy Consumption and Other Characteristics by Principal Building Activity

Principal Building Activity	Total Floor Area, m^2	Percent of Total Floor Area	Number of Buildings	Percent of Total Number of Buildings	Average Size, m^2	Average Number of Floors	Average Year Constructed	Major Fuels		
								Percent of Total Consumption	Energy Use, kWh/m^2-yr)	Energy Cost, $/$m^2$
Office/Professional	1,119,333,799	17.89	738,743	15.86	1,515	1.91	1965	19.00	285.23	15.92
Warehouse	973,655,871	15.56	603,314	12.96	1,614	1.20	1969	8.04	126.85	5.60
Retail	966,323,044	15.44	667,018	14.32	1,449	1.57	1958	12.63	230.50	13.88
Education	803,973,693	12.85	327,314	7.03	2,456	1.55	1963	11.32	236.51	10.01
Public Assembly	408,291,411	6.52	305,152	6.55	1,338	1.62	1958	6.26	257.75	12.48
Lodging	356,697,606	5.70	127,640	2.74	2,795	2.79	1965	6.33	298.14	13.23
Health Care	334,590,906	5.35	152,574	3.28	2,193	1.96	1972	10.49	319.07	16.03
Religious Worship	316,467,676	5.06	307,216	6.60	1,030	1.83	1955	1.91	101.59	4.73
Service	314,892,872	5.03	478,210	10.27	658	1.35	1962	7.35	392.19	14.74
Food Sales/Service	264,491,423	4.23	523,054	11.23	506	1.42	1966	11.30	719.75	37.66
Vacant	177,327,659	2.83	252,577	5.42	702	1.58	1943	0.53	50.57	2.04
Public Order/Safety	108,588,723	1.74	72,163	1.55	1,505	2.13	1968	1.77	273.98	11.30
Other	74,193,436	1.19	74,955	1.61	990	1.32	1967	1.19	269.32	16.36

Table 3-22. Office, Warehouse, and Retail Sectors Subdivisions

Principal Building Activity	Percent of Total Floor Area	Percent of Total Number of Buildings	Average Size, m^2	Average Number of Floors	Average Year Constructed	Major Fuels		Percent of Total Electric Consumption	Percent of Total Natural Gas Consumption
						Percent of Total Consumption	Energy Use, kWh/m^2-yr		
Office	**17.89**	**15.86**	**1,515**	**1.91**	**1965**	**19.00**	**285.23**	**24.75**	**10.85**
Small	5.96	14.31	559	1.61	1964	5.02	226.28	6.09	3.96
Medium	5.94	1.33	5,998	3.56	1971	6.82	308.20	8.85	4.20
Large	5.99	0.22	35,893	11.18	1971	7.09	317.82	9.70	2.66
Warehouse	**15.56**	**12.96**	**1,614**	**1.20**	**1969**	**8.04**	**126.85**	**7.10**	**11.36**
Non-Refrigerated	14.26	12.66	1,513	1.20	1969	6.50	122.40	5.21	10.06
Refrigerated	1.30	0.29	5,934	1.35	1959	1.54	318.35	1.89	1.30
Retail	**15.44**	**14.32**	**1,449**	**1.57**	**1958**	**12.63**	**230.50**	**16.82**	**9.18**
Strip Shopping Mall	5.87	2.81	2,809	1.33	1972	5.35	244.69	7.67	3.28
Enclosed Mall	2.50	0.06	56,391	2.62	1958	1.28	137.85	2.03	0.47
Other Retail	7.08	11.46	830	1.62	1955	6.00	227.51	7.12	5.43

Table 3-23. Definitions of Eight Commercial Building Prototypes Based on CBECS

Principal Building Activity	Floor Area, m^2	Floors	Length, m	Width, m	Zones per Floor	Floor-to-Floor Height, m	Window-to-Wall Ratio	Total Number of People	Lighting Power Density, W/m^2	Equipment Power Density, W/m^2
Office										
Small	550	2	25	11	2	3.7	0.4	24	14.0	7.5
Medium	6,000	4	60	25	5	4.0	0.4	235	14.0	8.1
Large	36,300	11	110	30	5	4.0	0.4	1302	14.0	8.6
Warehouse										
Non-Refrigerated	1,500	1	50	30	1	5.5	0.1	4	13.0	1.1
Refrigerated	6,000	1	100	60	2	4.6	0.1	16	13.0	1.1
Retail										
Strip Shopping Mall	2,800	1	140	20	3	3.8	0.4	110	20.0	2.7
Enclosed Mall	56,400	3	140	135	5	4.6	0.2	2427	20.0	2.7
Other Retail	832	2	26	16	1	3.4	0.4	30	20.0	2.7

Table 3-24. Base Standard (Standard 90.1-2004) Wall, Roof, and Fenestration Envelope Requirements

Location	Standard 90.1-2004 Climate Zone	Standard 90.1-2004 Building Envelope Table	Roof Assembly Maximum U-Value, W/m²•K	Roof Insulation Minimum R-Value, m²•K/W	Wall Assembly Maximum U-Value, W/m²•K	Wall Insulation Minimum R-Value, m²•K/W	Fenestration Assembly Maximum U-Value, W/m²•K	Fenestration SHGC All
PRI_San.Juan	1A	5.5-1	0.358	2.64	0.704	2.29	6.93	0.25
SGP_Singapore	1A	5.5-1	0.358	2.64	0.704	2.29	6.93	0.25
USA_FL_Miami	1A	5.5-1	0.358	2.64	0.704	2.29	6.93	0.25
CHL_Santiago	3C	5.5-3	0.358	2.64	0.704	2.29	6.93	0.34
CHN_Beijing	3C	5.5-3	0.358	2.64	0.704	2.29	6.93	0.34
USA_CA_Los.Angeles	3C	5.5-3	0.358	2.64	0.704	2.29	6.93	0.34
USA_VA_Sterling-Washington.Dulles	3C	5.5-3	0.358	2.64	0.704	2.29	6.93	0.34
ZAF_Johannesburg	3C	5.5-3	0.358	2.64	0.704	2.29	6.93	0.34
ARG_Buenos.Aires	4A	5.5-4	0.358	2.64	0.704	2.29	3.24	0.39
BRA_Sao.Paulo	4A	5.5-4	0.358	2.64	0.704	2.29	3.24	0.39
CHL_Punta.Arenas	4C	5.5-4	0.358	2.64	0.704	2.29	3.24	0.39
EGY_Cairo	4B	5.5-4	0.358	2.64	0.704	2.29	3.24	0.39
GBR_London.Gatwick	4C	5.5-4	0.358	2.64	0.704	2.29	3.24	0.39
IND_New.Delhi	4B	5.5-4	0.358	2.64	0.704	2.29	3.24	0.39
JPN_Tokyo.Hyakuri	4C	5.5-4	0.358	2.64	0.704	2.29	3.24	0.39
MEX_Mexico.City	4B	5.5-4	0.358	2.64	0.704	2.29	3.24	0.39
USA_CO_Boulder	5B	5.5-5	0.358	2.64	0.477	2.96	3.24	0.39
BOL_La.Paz	6B	5.5-6	0.358	2.64	0.477	2.96	3.24	0.39
CAN_ON_Toronto	6A	5.5-6	0.358	2.64	0.477	2.96	3.24	0.39
RUS_Moscow	6A	5.5-6	0.358	2.64	0.477	2.96	3.24	0.39
CAN_MB_The.Pas	7	5.5-7	0.358	2.64	0.363	3.61	3.24	0.49
CAN_YT_Whitehorse	7	5.5-7	0.358	2.64	0.363	20.5	0.57	0.49
CAN_NU_Resolute	8	5.5-8	0.273	3.52	0.363	20.5	0.46	No requirement
RUS_Yakutsk	8	5.5-8	0.273	3.52	0.363	20.5	0.46	No requirement
USA_AK_Fairbanks	8	5.5-8	0.273	3.52	0.363	20.5	0.46	No requirement

Table 3-25. Developing Standard Wall, Roof, and Fenestration Envelope Assumptions

Location	Standard 90.1-2004 Climate Zone	Standard 90.1-2004 Building Envelope Table	Roof Assembly Maximum U-Value, $W/m^2•K$	Roof Insulation Minimum R-Value, $m^2•K/W$	Wall Assembly Maximum U-Value, $W/m^2•K$	Wall Insulation Minimum R-Value, $m^2•K/W$	Fenestration Assembly Maximum U-Value, $W/m^2•K$	Fenestration SHGC All
PRI_San.Juan	1A	5.5-1	0.358	2.64	0.704	2.29	6.93	0.69
SGP_Singapore	1A	5.5-1	0.358	2.64	0.704	2.29	6.93	0.69
USA_FL_Miami	1A	5.5-1	0.358	2.64	0.704	2.29	6.93	0.69
CHL_Santiago	3C	5.5-3	0.358	2.64	0.704	2.29	6.93	0.69
CHN_Beijing	3C	5.5-3	0.358	2.64	0.704	2.29	6.93	0.69
USA_CA_Los.Angeles	3C	5.5-3	0.358	2.64	0.704	2.29	6.93	0.69
USA_VA_Sterling-Washington.Dulles	3C	5.5-3	0.358	2.64	0.704	2.29	6.93	0.69
ZAF_Johannesburg	3C	5.5-3	0.358	2.64	0.704	2.29	6.93	0.69
ARG_Buenos.Aires	4A	5.5-4	0.358	2.64	0.704	2.29	3.24	0.69
BRA_Sao.Paulo	4A	5.5-4	0.358	2.64	0.704	2.29	3.24	0.69
EGY_Cairo	4B	5.5-4	0.358	2.64	0.704	2.29	3.24	0.69
IND_New.Delhi	4B	5.5-4	0.358	2.64	0.704	2.29	3.24	0.69
MEX_Mexico.City	4B	5.5-4	0.358	2.64	0.704	2.29	3.24	0.69
CHL_Punta.Arenas	4C	5.5-4	0.358	2.64	0.704	2.29	3.24	0.69
GBR_London.Gatwick	4C	5.5-4	0.358	2.64	0.704	2.29	3.24	0.69
JPN_Tokyo.Hyakuri	4C	5.5-4	0.358	2.64	0.704	2.29	3.24	0.69
USA_CO_Boulder	5B	5.5-5	0.358	2.64	0.477	2.96	3.24	0.81
CAN_ON_Toronto	6A	5.5-6	0.358	2.64	0.477	2.96	3.24	0.81
RUS_Moscow	6A	5.5-6	0.358	2.64	0.477	2.96	3.24	0.81
BOL_La.Paz	6B	5.5-6	0.358	2.64	0.477	2.96	3.24	0.81
CAN_MB_The.Pas	7	5.5-7	0.358	2.64	0.363	3.61	3.24	0.81
CAN_YT_Whitehorse	7	5.5-7	0.358	2.64	0.363	3.61	3.24	0.81
CAN_NU_Resolute	8	5.5-8	0.273	3.52	0.363	3.61	2.61	0.81
RUS_Yakutsk	8	5.5-8	0.273	3.52	0.363	3.61	2.61	0.81
USA_AK_Fairbanks	8	5.5-8	0.273	3.52	0.363	3.61	2.61	0.81

Table 3-26. Low-Energy Case Wall, Roof, and Fenestration Envelope Assumptions

Location	Standard 90.1-2004 Climate Zone	Standard 90.1-2004 Building Envelope Table	Roof Assembly Maximum U-Value, $W/m^2•K$	Roof Insulation Minimum R-Value, $m^2•K/W$	Wall Assembly Maximum U-Value, $W/m^2•K$	Wall Insulation Minimum R-Value, $m^2•K/W$	Fenestration Assembly Maximum U-Value, $W/m^2•K$	Fenestration SHGC All
SGP_Singapore	1A	5.5-1	0.358	2.64	0.704	2.29	6.93	0.43
PRI_San.Juan	1A	5.5-1	0.358	2.64	0.704	2.29	6.93	0.43
USA_FL_Miami	1A	5.5-1	0.358	2.64	0.704	2.29	6.93	0.43
ZAF_Johannesburg	3C	5.5-3	0.358	2.64	0.704	2.29	6.93	0.43
CHL_Santiago	3C	5.5-3	0.358	2.64	0.704	2.29	6.93	0.43
USA_CA_Los.Angeles	3C	5.5-3	0.358	2.64	0.704	2.29	6.93	0.43
USA_VA_Sterling-Washington.Dulles	3C	5.5-3	0.358	2.64	0.704	2.29	6.93	0.43
CHN_Beijing	3C	5.5-3	0.358	2.64	0.704	2.29	6.93	0.43
EGY_Cairo	4B	5.5-4	0.358	2.64	0.704	2.29	3.24	0.43
MEX_Mexico.City	4B	5.5-4	0.358	2.64	0.704	2.29	3.24	0.43
IND_New.Delhi	4B	5.5-4	0.358	2.64	0.704	2.29	3.24	0.43
BRA_Sao.Paulo	4A	5.5-4	0.358	2.64	0.704	2.29	3.24	0.43
JPN_Tokyo.Hyakuri	4C	5.5-4	0.358	2.64	0.704	2.29	3.24	0.43
GBR_London.Gatwick	4C	5.5-4	0.358	2.64	0.704	2.29	3.24	0.43
CHL_Punta.Arenas	4C	5.5-4	0.358	2.64	0.704	2.29	3.24	0.43
ARG_Buenos.Aires	4A	5.5-4	0.358	2.64	0.704	2.29	3.24	0.43
USA_CO_Boulder	5B	5.5-5	0.358	2.64	0.477	2.96	3.24	0.455
CAN_ON_Toronto	6A	5.5-6	0.358	2.64	0.477	2.96	3.24	0.455
RUS_Moscow	6A	5.5-6	0.358	2.64	0.477	2.96	3.24	0.455
BOL_La.Paz	6B	5.5-6	0.358	2.64	0.477	2.96	3.24	0.455
CAN_YT_Whitehorse	7	5.5-7	0.358	2.64	0.363	3.61	3.24	0.455
CAN_MB_The.Pas	7	5.5-7	0.358	2.64	0.363	3.61	3.24	0.455
USA_AK_Fairbanks	8	5.5-8	0.273	3.52	0.363	3.61	2.61	0.455
RUS_Yakutsk	8	5.5-8	0.273	3.52	0.363	3.61	2.61	0.455
CAN_NU_Resolute	8	5.5-8	0.273	3.52	0.363	3.61	2.61	0.455

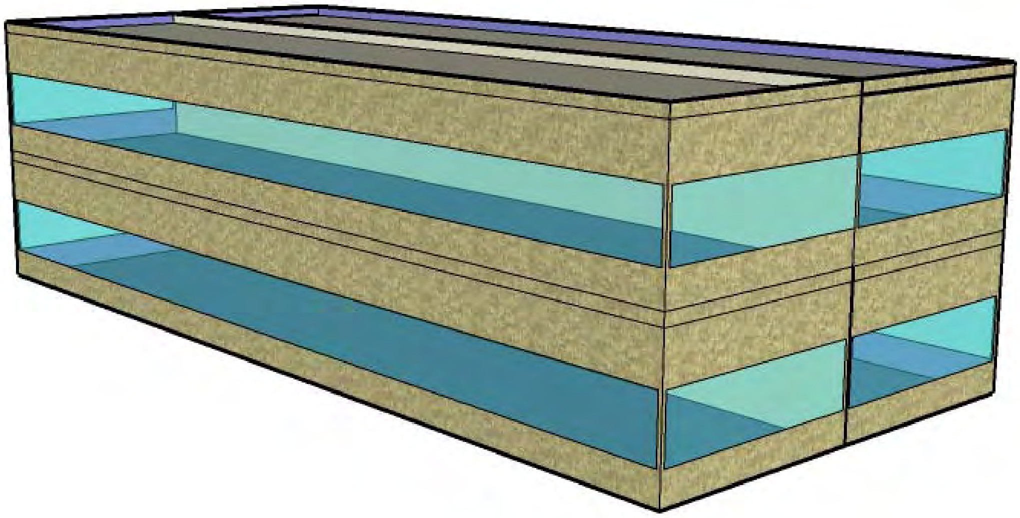

Figure 3-15. Schematic of Small Office Building

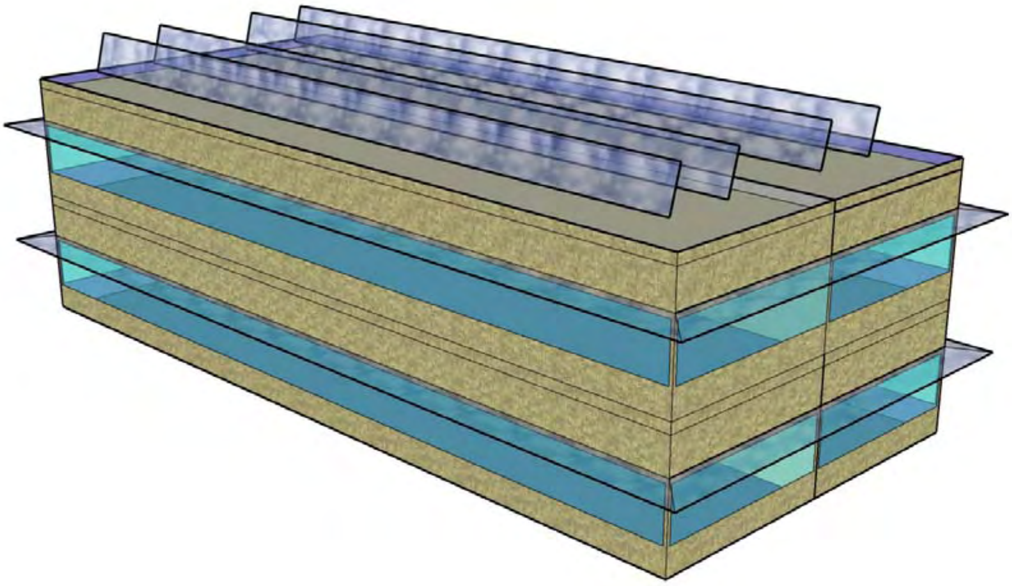

Figure 3-16. Schematic of Low-Energy Building

Table 3-27. Low-Energy Case Photovoltaic System Tilt Angles

North Latitude Locations	Tilt Angle (same as latitude)
CAN_NU_Resolute	74.717
USA_AK_Fairbanks	64.817
RUS_Yakutsk	62.067
CAN_YT_Whitehorse	60.717
RUS_Moscow	55.750
CAN_MB_The.Pas	53.967
GBR_London.Gatwick	51.150
CAN_ON_Toronto	43.667
USA_CO_Boulder	40.017
CHN_Beijing	39.783
USA_VA_Sterling-Washington.Dulles	38.950
JPN_Tokyo.Hyakuri	36.167
USA_CA_Los.Angeles	33.917
EGY_Cairo	30.117
IND_New.Delhi	28.567
USA_FL_Miami	25.783
MEX_Mexico.City	19.417
PRI_San.Juan	18.417
SGP_Singapore	1.367

South Latitude Locations	Tilt Angle (same as latitude)
BOL_La.Paz	16.517
BRA_Sao.Paulo	23.617
ZAF_Johannesburg	26.117
CHL_Santiago	33.367
ARG_Buenos.Aires	34.817
CHL_Punta.Arenas	53.000

Table 3-28. Base Standard HVAC and SWH Equipment Efficiency

Equipment Type	Minimum Efficiency
Unitary Air Conditioner, Cooling Mode	3.52 COP
Warm Air Furnace, Gas Fired	80% Et
Gas Instantaneous Water Heaters	80% Et

Table 3-29. Developing Standard HVAC and SWH Equipment Efficiency

Equipment Type	Minimum Efficiency
Air Cooled, Cooling Mode	2.64 COP
Warm Air Furnace, Gas Fired	75% Et
DHW Water Heater, Gas Fired	70% Et

Table 3-30. Low-Energy Building HVAC and SWH Equipment Efficiency

Equipment Type	Minimum Efficiency
Air Conditioners, Air Cooled, Split System	5.27 COP
Warm Air Furnace	97% Et
DHW efficiency	97% Et

- three different envelopes—standard, developing, and low-energy for each location;
- three different end files containing the output variables and reports as well as the HVAC systems and equipment efficiency for each case (standard, developing, and low-energy); and
- a photovoltaic system file for the low-energy case with panel tilt set to the latitude for each location.

For this study, all available output variables that were available for reporting (more than 400) were requested at aggregation of hourly, daily, monthly, and annual time steps. In addition, standardized reports and meters also reported were requested. This resulted in output files that were larger than 60 megabytes each. For each simulation, available results include:

- surface temperature and conduction and radiation through the building envelope;
- zone sensible, latent, convective, and radiant heating gains and losses;
- zone air and mean radiant temperature, relative humidity, and humidity ratio;
- HVAC equipment runtime fraction, heating and cooling rates, part-load ratios, and temperature and humidity;
- energy consumption and demand by zone, system, and plant equipment;
- energy end-uses, consumption and demand by energy source; and
- atmospheric emissions by pollutant type and equivalent carbon.

Because there were hundreds of 60+ megabyte results files to review, a series of scripts were constructed to extract relevant data and organize it into CSV files of similar results. The CSV files were easily imported into spreadsheets or databases and the inputs verified and the performance results checked for anomalies. The CSV files for each case and location include:

- external environment (temperature, humidity, wind speed and direction, solar radiation);
- envelope conduction, temperatures, and solar gains;
- window conduction, temperatures, and solar gains;
- zone and system temperature and humidity conditions;
- HVAC equipment consumption and sizing;
- HVAC system node conditions;
- HVAC plant components;
- domestic hot water;
- total energy consumption;
- end-use energy consumption;

- photovoltaic power production and system operating attributes (low-energy case only);
- water use and demand; and
- atmospheric emissions.

Another key to dealing with all the data was to establish naming conventions to distinguish among the many input and output files. The file naming convention for this study has the form of:

prototype_building_location_weather_scenario

Where:

prototype is SmOff (for Small Office)

building is either:

Std (for the standard building),
Dev (for the developing building), or
LowEn (for the low-energy building)

location is weather data location name beginning with a three-letter country abbreviation:

ARG_Buenos.Aires
BOL_La.Paz
BRA_Sao.Paulo
CAN_MB_The.Pas
CAN_NU_Resolute
CAN_ON_Toronto
CAN_YT_Whitehorse
CHL_Punta.Arenas
CHL_Santiago
CHN_Beijing
EGY_Cairo
GBR_London.Gatwick
IND_New.Delhi
JPN_Tokyo.Hyakuri

MEX_Mexico.City
PRI_San.Juan
RUS_Moscow
RUS_Yakutsk
SGP_Singapore
USA_AK_Fairbanks
USA_CA_Los.Angeles
USA_CO_Boulder
USA_FL_Miami
USA_VA_Sterling-Washington.Dulles
ZAF_Johannesburg

weather is:

TMY2, CWEC, or IWEC (typical weather data);
High (selected high-energy weather data year); or
Low (selected low-energy weather data year.

scenario is:

blank if the base case;
A1FI (IPCC A1FI scenario)
A2 (IPCC A2 scenario)
B1 (IPCC B1 scenario)
B2 (IPCC B2 scenario)
HtIsHi (high heat island case—5°C or 3°C if high latitudes)
HtIsLo (low heat island case—1°C)

Thus, SmOff_LowEn_USA_VA_Sterling-Washington.Dulles_TMY2_A1FI is the small office prototype with low-energy features with Washington, D.C., weather data and design conditions using the TMY2 typical weather data modified to the IPCC A1FI climate change scenario. This file name convention made it easy to sort and distinguish among the many hundreds of files.

The last part of the simulation design was the construction of scripts to automatically:

- uncompress the appropriate weather file;
- assemble the specific input file;

- control and run the individual simulations;
- run the appropriate data extraction scripts;
- compile and compress the related input, output, and CSV files into a single archive; and
- move the archive to the location directory.

For this study, the simulations took approximately six weeks to run—all automatically controlled by the scripts described above. The results of the analysis for the small office building are described in Chapter 5.

3.6 References

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Chapter 4
Using Building Simulation to Define and Evaluate Building Energy Standards

> A great building must begin with the unmeasurable, must go through measurable means when it is being designed, and in the end must be unmeasurable.
>
> Louis Kahn

4.1 Introduction

This chapter presents and discusses the simulation results for the building standards analyses described and established in Chapter 3:

- Section 4.2 describes and summarizes the simulation results for defining and evaluating the new envelope correlations for the Canadian standard described in Section 3.2.
- Section 4.3 summarizes the analyses, results, and conclusions relating to cost-effective envelope upgrade options that utilities could incentivize financially. Section 3.3 provides the building models, cost data, and design of the analysis.
- Section 4.4 provides an overview of the retrofit staging, savings potentials, and simulation results for the national program for energy savings in commercial buildings. Section 3.4 presented the models and the structure of the analysis.

Implications of the results for policy and the decisions made as a result are presented at the end of this chapter.

4.2 Defining Equivalent Performance Relationships for Building Envelopes in an Energy Code

As described in Section 3.2, a national building energy standard was under development for Canada. That work required the creation of a new data set for use in creating correlations of heating and cooling coil loads as a function of envelope characteristics. The building model definitions and a description of the analysis structure are presented in Section 3.2.

The new envelope correlations were designed to cover the exterior vertical surfaces of buildings, using three building and envelope characteristics: heat loss/gain, solar gain, and internal gains. This allowed most buildings to be defined in terms of a combination of those three terms. Parametric DOE-2.1E simulations were then created with these cases: heat loss/gain of 0.284 to 2.84 W/(m^2-K) (0.05 to 0.5 Btu/(h•ft^2•°F)); solar gain defined in terms of shading coefficient from 0.0 to 1.0; and internal gains defined as the combination of building occupants, lights, and miscellaneous equipment with a range of 0.0 to 86.1 W/m^2.

Together, these three parametric cases provide an almost unlimited number of combinations of envelope and building characteristics without requiring the creation of a parametric case for each individual envelope characteristic. The three sets of 6 heat loss/gain cases, 6 solar gain, and 6 internal gain cases (shown in Tables 3-2, 3-3, and 3-4) produce 216 combinations (6 x 6 x 6). Twenty-five simulation locations were selected to cover the wide range of climate conditions in Canada as well as the ten provinces and two territories and are shown in Appendix A.

4.2.1 Envelope Performance Data Set

Figure 4-1 shows an example of one internal load condition from the data set for Ottawa, Ontario. The heating and cooling energy loads for the south orientation, 21.5 W/m^2 internal loads case are shown, similar to those shown for the Standard 90.1 envelope correlations in Section 3.2. Note that unlike the data for the Standard 90.1 envelope correlations (shown in Section 3.2), these data are well ordered and behave as expected. As the shading coefficient increases, cooling energy loads increase and heating energy loads decrease; as the heat loss parameter increases, cooling decreases and heating increases.

Figure 4-1 is but a single sample of the data developed for Ottawa. The heating portion of Figure 4-1 shows parallel lines of U-value from 0.284 to 2.84 W/(m^2-K) as a function of shading coefficient. For any combination of shading coefficient and U-value, a value of heating coil load can be read from the Y-axis. The cooling portion of Figure 4-1 shows a similar relationship, but the Y-axis value is cooling coil load. In contrast to heating and cooling loads predicted by the Standard 90.1 equations shown in Figures 3-1 through 3-4, Figure 4-1 shows well-ordered, parallel values throughout the entire range of the data set. Appendix A contains figures presenting the entire heating, cooling, and fan energy load data set—six internal loads cases for the four orientations for Ottawa. Appendix A represents but a subset of the data set developed (only the annual data) for the NECB. Similar data, both annual and monthly, were created for each of 25 Canadian locations (weather locations listed in Appendix A).

4.2.2 Creating Envelope Performance Correlations from the Data Set

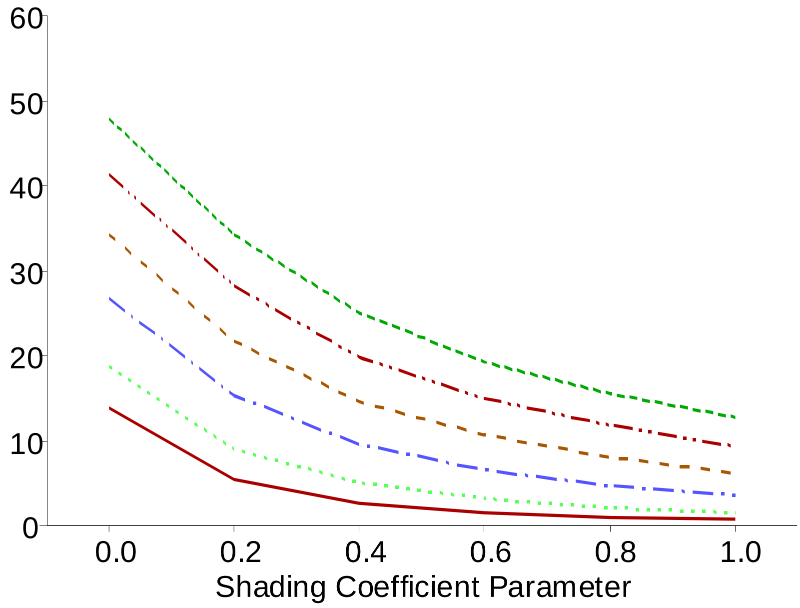
The next step was to correlate the heating and cooling loads with the climatic response and thermal envelope characteristics. As mentioned in Section 3.2, it was important that new correlations be easily understood, easily calculated, and based on the physics involved. NRC selected an internal and solar gain utilization approach similar to the one developed by Barakat and Sander (1982, 1986) for the form of the new correlation-based equations from the data set of DOE-2 simulations. These equations, developed by NRC, form the basis of the NECB as the trade-off procedure and for setting prescriptive envelope requirements. These were described by Sander et al. (1993) and are contained in the National Energy Code for Buildings 1995 (NRCC 1994a) and the Trade-Off Compliance for Buildings (NRCC 1994b).

The requirements of the energy model for these purposes were that it be quick and simple to use, while accurately predicting changes in heating/cooling energy due to changes in envelope characteristics. It was not intended to predict building energy consumption; therefore, its absolute accuracy in predicting energy consumption was not as important as its sensitivity to envelope variations. It also was deemed desirable to derive simpler, more rational equations (the correlations and coefficients cover more than nine pages of Standard 90.1).

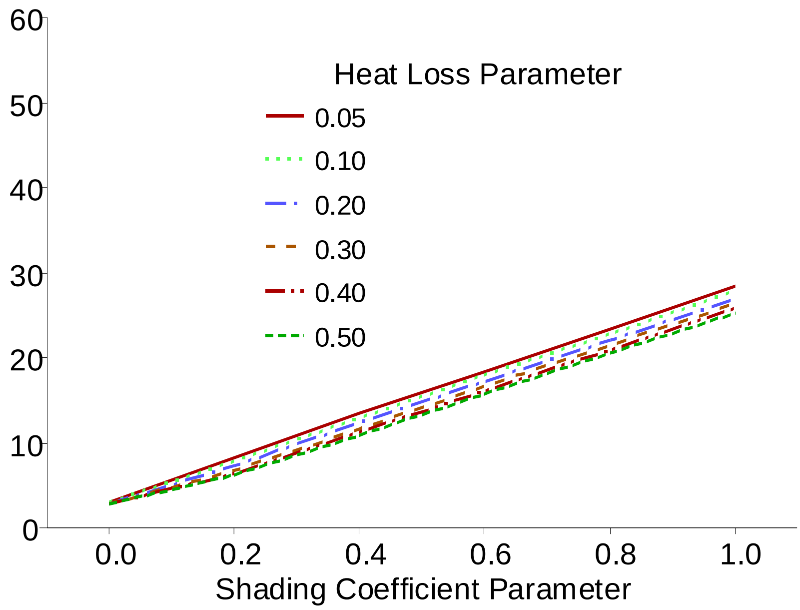
The correlations were developed as location specific with location-specific coefficients, and the form of the equation was the same for all locations rather than fitting all potential locations. The correlations focused on the monthly and annual values for both peak demand and energy consumption due to heating, cooling, and fans, by orientation. The heating and cooling values are coil loads, i.e., they do not include plant efficiencies—NRC accounted for plant efficiencies external to the envelope equations.

Figure 4-2 shows the cooling energy calculated using the equations and coefficients for Ottawa against the original DOE-2.1E simulation results for the east orientation in Ottawa. This graph contains the entire range of parametric values for heat loss/gain, solar gain, and internal gain as shown in Tables 3-1 through 3-3. This simple model produces results that are within 10 percent of the DOE-2 simulations, except at the very lowest values of cooling.

Figure 4-3 shows heating energy calculated using the equations and coefficients for Ottawa compared with the DOE-2.1E simulation results for the east orientation in Ottawa. The



Heating



Cooling

Figure 4-1. DOE-2.1E Results, Ottawa, Ontario, Canada, South Orientation, 21.5 W/m^2 [1]

[1] The units for the Y-axis in each figure are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft2•°F). To convert to W/m2•K, multiply by 5.678.

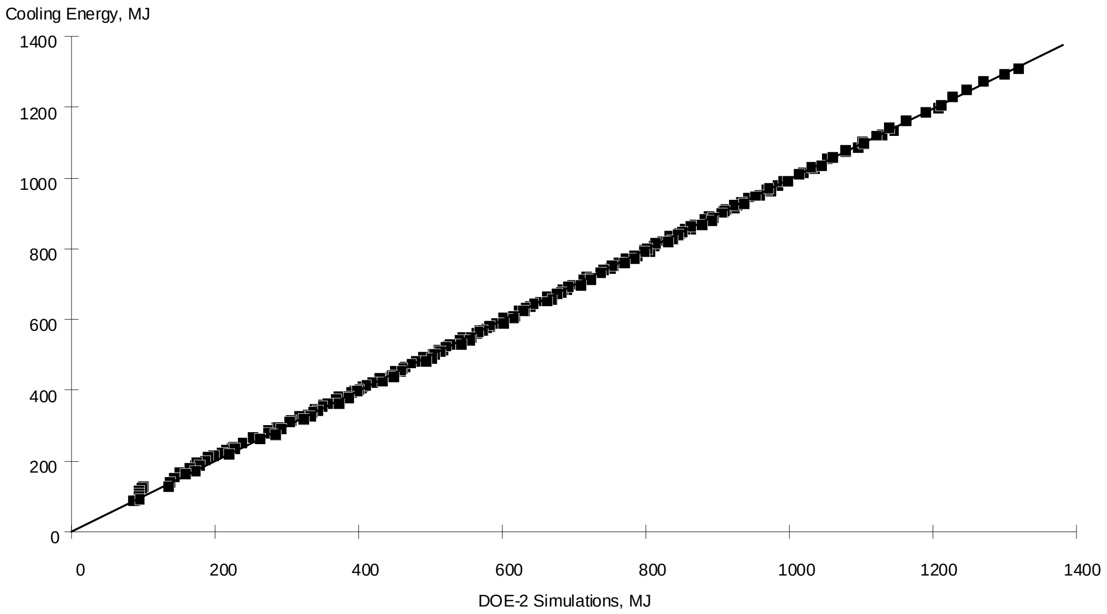


Figure 4-2. Predicted Cooling Energy for Correlation v. DOE-2.1E Simulations for East Orientation in Ottawa

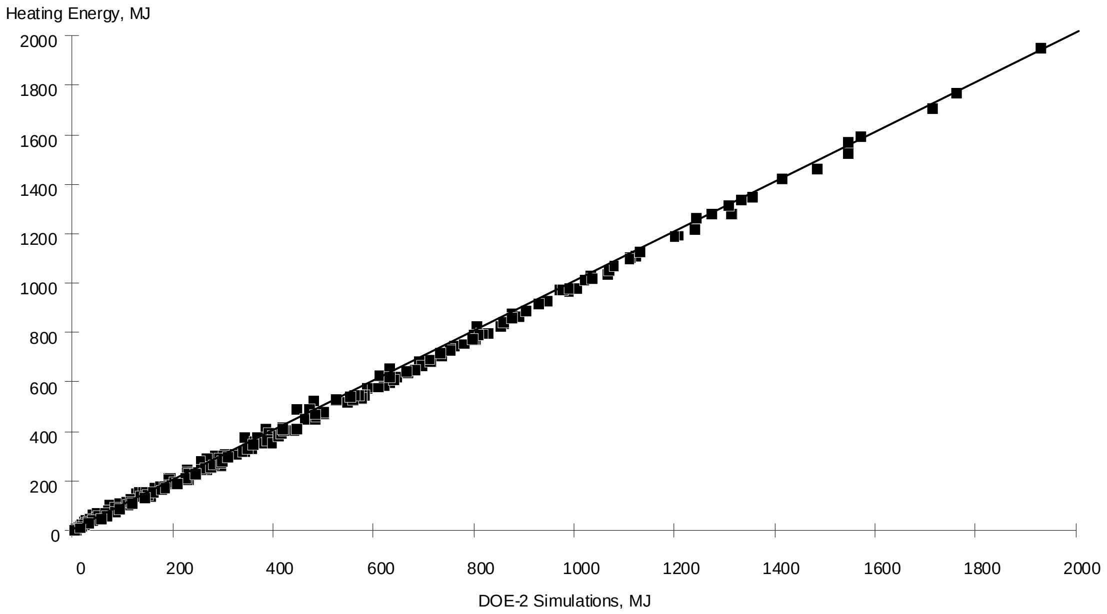


Figure 4-3. Predicted Heating Energy for Correlation v. DOE-2.1E Simulations for East Orientation in Ottawa

points on the graphs represent the entire range of parametric values for heat loss/gain, solar gain, and internal gain. The simple model for heating also produces results that are within 10 percent of the DOE-2 simulations, except at very lowest values of heating.

4.2.3 Conclusions

A simple model of heating coil, cooling coil, and fan energy was developed by NRC (Sander et al (1993)) to satisfy the needs of the Canadian energy code for fast, simple, but accurate prediction of changes in heating, cooling, and fan energy due to changes in envelope thermal characteristics. This model is based on the energy performance predicted by thousands of DOE-2.1E simulations of specific building envelope configurations and characteristics described in this thesis. These correlations were not intended to estimate the absolute energy consumption of a building but instead to compare the energy impact of variations in envelope thermal characteristics. This heating and cooling coil load model requires location-specific coefficients.

Energy simulation played a key role in the development and operation of the NECB, not only in the performance path, but also in the other two compliance paths—prescriptive (tabular) and envelope trade-off compliance tool. The prescriptive values in the code were set at the life-cycle cost optimum, taking into account specific costs and economic assumptions for each region of Canada using energy simulation results. This analysis required calculating construction and energy costs for a large number of combinations—further emphasizing the need for a simple energy model. A simple energy model was also needed as the basis for comparison of energy characteristics in an envelope trade-off compliance tool, which was intended to be an interactive tool widely distributed to users of the code.

It was important that the data set covered the range of potential heat gain/loss, internal gain, and solar gain parameters in commercial buildings. In the context of this thesis, that required a strict input file structure along with automated creation and extraction of the required data. By combining this structure with file naming conventions, this ensured that the input, output, and extracted data from the 5,400 simulations were easily verified and identifiable.

4.3 Defining Envelope Incentives for an Electric Utility

As described in Section 3.3, the electric utility in Ontario, Canada, was interested in determining whether cost-effective improvements to building envelopes beyond the requirements of Standard 90.1were possible. A building model and range of technologies was defined and a set of proposed envelope improvements were evaluated for energy and economic performance. The incremental cost and energy savings were calculated using the DOE-2.1E hourly energy simulation program (Winkelmann et al. 1993) for increased wall and roof insulation levels as well as a variety of fenestration assemblies (shown in Tables 3-5 and 3-6) for five Ontario locations: Ottawa, Sault Ste. Marie, Schefferville, Toronto, and Windsor. Tables 3-7, 3-8, and 3-9 show the incremental wall and roof insulation and fenestration assembly costs.

4.3.1 Energy Performance of Envelope Options

Tables 4-1, 4-2, and 4-3 (opaque walls, roofs, and fenestration, respectively) show sample results for a portion of the DOE-2.1E simulations for Toronto. Appendix B shows summary tables of all the DOE-2.1E energy performance results.

Table 4-1. Simulation Results for Wall Insulation Options in Toronto with 21.5 W/m^2 Internal Loads and 0.4 FWR

Insulation Added, mm	Annual Energy Performance	
	kWh	kWh/m^2
Baseline	149,063	269.11
19 mm (R 0.7)	146,477	264.47
38 mm (R 1.4)	144,875	261.60

Table 4-2. Simulation Results for Roof Insulation Options in Toronto with 21.5 W/m^2 Internal Loads and 0.4 FWR

Insulation Added, mm	Annual Energy Performance	
	kWh	kWh/m^2
Baseline	165,513	298.60
51 mm (R 1.76)	159,961	288.65
102 mm (R 3.52)	157,210	283.71

Table 4-3. Simulation Results for Fenestration Options in Toronto with 21.5 W/m^2 Internal Loads and 0.4 FWR

Fenestration Option	Annual Energy Performance	
	kWh	kWh/m^2
Aluminum Frame	149,063	269.11
Thermally Broken Frame	148,588	268.26
Vinyl Frame	148,209	267.57
Low-E (e=0.4)	143,332	258.83
Low-E (e=0.2)	127,182	229.87
Low-E (e=0.1)	121,409	219.51
Visionwall	110,791	200.47

4.3.2 Economic Performance of Envelope Options

Annual energy cost savings and simple payback were calculated using the annual energy simulation results from DOE-2.1E and the estimated cost for each option. Ontario Hydro specified an electricity cost of $0.075/kWh for calculating energy cost savings. Cost savings for heating systems were based on Means (1993)—a rule-of-thumb of $145/kW of baseboard, perimeter heating multiplied by the city adjustment of 1.09 for Toronto yields $158.05/kW of installed heating reduced. All dollars shown in this section are Canadian dollars.

The results presented below have been simplified in two ways. First, the results are presented only for the 21.5 W/m^2 case (the 43.0 W/m^2 case yields similar results). Second, the 0.4 FWR case is omitted—only the 0.2 and 0.6 cases are shown, as the performance results for the 0.4 FWR case falls exactly midway between the 0.2 and 0.6 cases. Tables 4-4 and 4-5 summarize the energy and economic results for the wall and roof insulation cases, respectively. Tables 4-6 through 4-10 show the results for the fenestration cases for the five locations.

4.3.3 Conclusions from the Evaluation of Potential Envelope Incentives

This analysis evaluated potential incentives for increased levels of wall and roof insulation and improved fenestration (glazing and framing), using the requirements of Standard 90.1-1989 as a baseline. As shown in Tables 4-4 through 4-10, simple payback periods for wall insulation ranged from 11 to 40 years, roof insulation payback from 20 to 43 years, and fenestration options ranged from 6 to more than 400 years. Many of the advanced glazing options ranged in payback from 7 to 35 years. At the project outset, Ontario Hydro indicated that they would implement envelope incentives if simple payback periods for a technology level were 3 years or less. Since all of the payback periods were at least twice that, Ontario Hydro did not include envelope incentives in the New Building Construction Program. Thus, results from this building simulation analyses were a key input to the incentive program for Ontario Hydro.

This study showed that a structured analysis using building simulation could support decision-making in the context of building incentives for a utility. The key attributes of the framework for this analysis include automating the creation of the input files and simulation scripts, and extraction of results data.

4.4 Energy and Economic Evaluation of Existing Building Retrofits

In 1993, a new national voluntary program to promote building energy retrofits, known as the Energy Star Buildings program, was being developed. As described in Section 3.4, building energy simulation was used to identify cost-effective pathways for building owners to upgrade their building systems—particularly building envelopes, fans, and central heating and cooling equipment. This section summarizes the energy and cost-effectiveness results for a series of simulation suites created to estimate potential savings of the ESB program, determine specific upgrade pathways in building envelopes and chillers, and determine whether weather data source influenced outcomes. Appendix C provides the summary results from the 25,000 simulations.

4.4.1 Results of Parametric Energy Simulation of ESB Staged Implementation Approach

This section presents the simulation results for the parametric energy simulations of the five ESB stages. The results include the energy savings and pollution prevention potential for each of the five stages and in aggregate for the ESB Program for three existing office building models (Table 4-11). Section 3.4.1 describes the baseline assumptions for the three models. Table 4-12 shows the energy performance, energy costs, peak demand, chiller load, and fan supply air and motor size as calculated by DOE-2.1E for the 18 locations for the gas-heated, low-rise, office building. Appendix C shows similar results for the mid-rise and high-rise office buildings.

Table 4-4. Energy and Economic Results for Wall Insulation Options

Fenestration to Wall Ratio	Wall Insulation Added, mm	U-value Difference from Baseline	kWh Savings per m^2 Wall Area	Annual Savings per m^2 Wall Area	Cost Difference per m^2 Wall Area	Heating Watt Savings per m^2 Wall Area	Heating Watt Cost Difference per m^2 Wall Area	Payback, Years
Ottawa								
0.2	19 mm (R 0.7)	0.108	5.97	$ 0.699	$ 10.87	3.3356	$ 0.538	14.77
	38 mm (R 1.4)	0.131	9.81	$ 1.151	$ 14.42	5.5952	$ 0.893	11.76
0.6	19 mm (R 0.7)	0.108	2.88	$ 0.334	$ 10.87	1.7216	$ 0.269	31.35
	38 mm (R 1.4)	0.131	4.75	$ 0.560	$ 14.42	2.7976	$ 0.441	25.08
Sault Ste. Marie								
0.2	19 mm (R 0.7)	0.062	4.81	$ 0.560	$ 10.87	3.6584	$ 0.581	18.28
	38 mm (R 1.4)	0.108	8.06	$ 0.947	$ 14.42	6.1332	$ 0.979	14.24
0.6	19 mm (R 0.7)	0.062	2.28	$ 0.269	$ 10.87	1.7216	$ 0.269	39.59
	38 mm (R 1.4)	0.108	3.85	$ 0.452	$ 14.42	2.7976	$ 0.441	30.96
Schefferville								
0.2	19 mm (R 0.7)	0.040	4.72	$ 0.549	$ 10.87	2.7976	$ 0.441	18.82
	38 mm (R 1.4)	0.068	8.19	$ 0.958	$ 14.42	4.7344	$ 0.753	14.24
0.6	19 mm (R 0.7)	0.040	2.29	$ 0.269	$ 10.87	1.3988	$ 0.226	39.57
	38 mm (R 1.4)	0.068	3.97	$ 0.463	$ 14.42	2.2596	$ 0.355	30.25
Toronto								
0.2	19 mm (R 0.7)	0.097	6.39	$ 0.753	$ 10.87	3.8736	$ 0.624	13.67
	38 mm (R 1.4)	0.159	10.32	$ 1.205	$ 14.42	6.1332	$ 0.979	11.11
0.6	19 mm (R 0.7)	0.097	3.07	$ 0.355	$ 10.87	1.9368	$ 0.312	29.46
	38 mm (R 1.4)	0.159	4.96	$ 0.581	$ 14.42	3.1204	$ 0.484	23.96
Windsor								
0.2	19 mm (R 0.7)	0.108	6.26	$ 0.732	$ 10.87	5.5952	$ 0.893	13.59
	38 mm (R 1.4)	0.174	8.87	$ 1.044	$ 14.42	8.1776	$ 1.291	12.63
0.6	19 mm (R 0.7)	0.108	2.92	$ 0.344	$ 10.87	2.2596	$ 0.355	30.73
	38 mm (R 1.4)	0.174	4.71	$ 0.549	$ 14.42	3.6584	$ 0.581	25.04

Table 4-5. Energy and Economic Results for Roof Insulation Options

Fenestration to Wall Ratio	Roof Insulation Added, mm	U-value Difference from Baseline	kWh Savings per m^2 Roof Area	Annual Savings per m^2 Roof Area	Cost Difference per m^2 Roof Area	Heating Watt Savings per m^2 Roof Area	Heating Watt Cost Difference per m^2 Roof Area	Payback, Years
Ottawa								
0.2	51 mm (R 1.76)	0.080	4.907	$ 0.366	$ 16.46	3.44	$ 0.538	43.27
	102 mm (R 3.52)	0.122	9.975	$ 0.753	$ 29.27	5.16	$ 0.818	38.00
0.6	51 mm (R 1.76)	0.080	9.200	$ 0.689	$ 16.46	3.44	$ 0.538	23.08
	102 mm (R 3.52)	0.122	14.010	$ 1.054	$ 29.27	5.16	$ 0.818	27.07
Sault Ste. Marie								
0.2	51 mm (R 1.76)	0.065	8.178	$ 0.707	$ 16.46	3.55	$ 0.570	25.91
	102 mm (R 3.52)	0.101	12.708	$ 0.958	$ 29.27	5.60	$ 0.882	29.79
0.6	51 mm (R 1.76)	0.065	7.661	$ 0.570	$ 16.46	3.55	$ 0.570	27.65
	102 mm (R 3.52)	0.101	11.922	$ 0.893	$ 29.27	5.60	$ 0.882	31.76
Schefferville								
0.2	51 mm (R 1.76)	0.040	7.769	$ 0.581	$ 16.46	3.01	$ 0.484	27.42
	102 mm (R 3.52)	0.068	12.621	$ 0.947	$ 29.27	4.84	$ 0.764	30.11
0.6	51 mm (R 1.76)	0.040	7.532	$ 0.570	$ 16.46	2.47	$ 0.398	28.40
	102 mm (R 3.52)	0.068	12.159	$ 0.915	$ 29.27	3.98	$ 0.624	31.39
Toronto								
0.2	51 mm (R 1.76)	0.092	10.265	$ 0.775	$ 16.46	3.55	$ 0.484	20.66
	102 mm (R 3.52)	0.137	15.989	$ 1.194	$ 29.27	5.38	$ 0.764	23.71
0.6	51 mm (R 1.76)	0.092	9.469	$ 0.710	$ 16.46	3.44	$ 0.398	22.40
	102 mm (R 3.52)	0.137	14.203	$ 1.065	$ 29.27	5.06	$ 0.624	26.73
Windsor								
0.2	51 mm (R 1.76)	0.092	9.028	$ 0.678	$ 16.46	4.63	$ 0.732	23.24
	102 mm (R 3.52)	0.137	13.461	$ 1.011	$ 29.27	6.99	$ 1.108	27.90
0.6	51 mm (R 1.76)	0.092	7.026	$ 0.527	$ 16.46	3.98	$ 0.624	30.10
	102 mm (R 3.52)	0.137	11.180	$ 0.839	$ 29.27	5.92	$ 0.936	33.81

Table 4-6. Energy and Economic Results for Fenestration Options for Ottawa

Fenestration to Wall Ratio	Fenestration Option[2]	U-value Difference from Baseline	kWh Savings per m^2 Window Area	Annual Savings per m^2 Window Area	Cost Difference per m^2 Window Area	Heating Watt Savings per m^2 Window Area	Heating Watt Cost Difference per m^2 Window Area	Payback, Years
0.2	Thermal Break Frame	0.51	0.463	$6.241	$3.55	2.260	$0.355	6.86
	Vinyl Frame	0.74	0.839	$11.083	$78.23	4.519	$0.710	92.95
	Low-E (e=0.4)	l.08	3.067	$40.888	$81.88	17.969	$2.841	25.80
	Low-E (e=0.2)	2.10	11.545	$153.868	$169.58	69.510	$11.018	13.74
	Low-E (e=0.1)	2.27	13.450	$179.369	$173.34	78.440	$12.439	11.96
	Visionwall	3.13	17.872	$238.226	$230.91	109.860	$17.410	11.95
0.6	Thermal Break Frame	0.51	0.151	$1.937	$3.55	0.753	$0.118	23.03
	Vinyl Frame	0.74	0.269	$3.551	$78.23	1.506	$0.237	289.32
	Low-E (e=0.4)	l.08	2.475	$33.033	$81.88	15.279	$2.432	32.06
	Low-E (e=0.2)	2.10	10.028	$133.639	$169.58	64.237	$10.190	15.90
	Low-E (e=0.1)	2.27	12.557	$167.426	$173.34	73.598	$11.664	12.88
	Visionwall	3.13	17.259	$230.156	$230.91	103.834	$16.463	12.43

[2] All fenestration options are double-pane glazing. Visionwall has two panes of glass, two low-e films, a krypton gas fill, and a well-constructed, thermally broken frame.

Table 4-7. Energy and Economic Results for Fenestration Options for Sault Ste. Marie

Fenestration to Wall Ratio	Fenestration Option[3]	U-value Difference from Baseline	kWh Savings per m^2 Window Area	Annual Savings per m^2 Window Area	Cost Difference per m^2 Window Area	Heating Watt Savings per m^2 Window Area	Heating Watt Cost Difference per m^2 Window Area	Payback, Years
0.2	Thermal Break Frame	0.51	0.495	$6.564	$3.55	3.34	$0.538	6.11
	Vinyl Frame	0.74	0.904	$12.051	$78.23	5.60	$0.893	85.82
	Low-E (e=0.4)	l.08	3.120	$41.641	$81.88	21.30	$3.379	25.12
	Low-E (e=0.2)	2.10	11.685	$155.805	$169.58	82.96	$13.149	13.39
	Low-E (e-0.1)	2.27	13.375	$178.401	$173.34	94.15	$14.924	11.84
	Visionwall	3.13	17.894	$238.657	$230.91	135.58	$21.498	11.70
0.6	Thermal Break Frame	0.51	0.161	$2.152	$3.55	1.08	$0.183	21.12
	Vinyl Frame	0.74	0.291	$3.766	$78.23	2.26	$0.355	272.72
	Low-E (e=0.4)	l.08	2.475	$33.033	$81.88	15.28	$2.432	32.04
	Low-E (e=0.2)	2.10	10.276	$136.975	$169.58	70.26	$11.137	15.43
	Low-E (e=0.1)	2.27	12.460	$166.134	$173.34	79.95	$12.675	12.89
	Visionwall	3.13	17.463	$232.846	$230.91	117.28	$18.593	12.16

[3] All fenestration options are double-pane glazing. Visionwall has two panes of glass, two low-e films, a krypton gas fill, and a well-constructed, thermally broken frame.

Table 4-8. Energy and Economic Results for Fenestration Options for Schefferville

Fenestration to Wall Ratio	Fenestration Option[4]	U-value Difference from Baseline	kWh Savings per m^2 Window Area	Annual Savings per m^2 Window Area	Cost Difference per m^2 Window Area	Heating Watt Savings per m^2 Window Area	Heating Watt Cost Difference per m^2 Window Area	Payback, Years
0.2	Thermal Break Frame	0.51	0.818	$10.975	$3.55	5.60	$0.893	3.25
	Vinyl Frame	0.74	1.496	$19.906	$78.23	10.11	$1.603	51.41
	Low-E (e=0.4)	l.08	5.003	$66.712	$81.88	20.23	$3.196	15.73
	Low-E (e=0.2)	2.10	19.454	$259.316	$169.58	81.78	$12.966	8.05
	Low-E (e=0.1)	2.27	20.799	$277.285	$173.34	85.22	$13.504	7.69
	Visionwall	3.13	27.470	$366.270	$230.91	121.05	$19.185	7.71
0.6	Thermal Break Frame	0.51	0.269	$3.551	$3.55	1.08	$0.183	12.59
	Vinyl Frame	0.74	0.484	$6.456	$78.23	1.83	$0.301	160.76
	Low-E (e=0.4)	l.08	3.970	$52.939	$81.88	21.63	$3.432	19.75
	Low-E (e=0.2)	2.10	17.259	$230.156	$169.58	93.83	$14.860	8.96
	Low-E (e=0.1)	2.27	19.529	$260.392	$173.34	103.83	$16.463	8.03
	Visionwall	3.13	26.459	$352.713	$230.91	139.34	$22.090	7.89

[4] All fenestration options are double-pane glazing. Visionwall has two panes of glass, two low-e films, a krypton gas fill, and a well-constructed, thermally broken frame.

Table 4-9. Energy and Economic Results for Fenestration Options for Toronto

Fenestration to Wall Ratio	Fenestration Option[5]	U-value Difference from Baseline	kWh Savings per m^2 Window Area	Annual Savings per m^2 Window Area	Cost Difference per m^2 Window Area	Heating Watt Savings per m^2 Window Area	Heating Watt Cost Difference per m^2 Window Area	Payback, Years
0.2	Thermal Break Frame	0.51	0.398	$5.272	$3.55	2.260	$0.355	8.00
	Vinyl Frame	0.74	0.732	$9.684	$78.23	4.519	$0.710	106.73
	Low-E (e=0.4)	1.08	2.787	$37.230	$81.88	14.526	$2.313	28.51
	Low-E (e=0.2)	2.10	10.136	$135.146	$169.58	49.281	$7.812	15.96
	Low-E (e=0.1)	2.27	12.051	$160.754	$173.34	56.060	$8.888	13.64
	Visionwall	3.13	16.958	$226.175	$230.91	77.364	$12.256	12.89
0.6	Thermal Break Frame	0.51	0.129	$1.722	$3.55	0.753	$0.118	26.06
	Vinyl Frame	0.74	0.237	$3.120	$78.23	1.076	$0.183	329.24
	Low-E (e=0.4)	1.08	2.260	$30.128	$81.88	12.374	$1.958	35.40
	Low-E (e=0.2)	2.10	8.780	$117.069	$169.58	54.876	$8.705	18.32
	Low-E (e=0.1)	2.27	11.341	$151.286	$173.34	60.579	$9.598	14.44
	Visionwall	3.13	15.796	$210.681	$230.91	84.789	$13.439	13.77

[5] All fenestration options are double-pane glazing. Visionwall has two panes of glass, two low-e films, a krypton gas fill, and a well-constructed, thermally broken frame.

Table 4-10. Energy and Economic Results for Fenestration Options for Windsor

Fenestration to Wall Ratio	Fenestration Option[6]	U-value Difference from Baseline	kWh Savings per m^2 Window Area	Annual Savings per m^2 Window Area	Cost Difference per m^2 Window Area	Heating Watt Savings per m^2 Window Area	Heating Watt Cost Difference per m^2 Window Area	Payback, Years
0.2	Thermal Break Frame	0.51	0.344	$4.627	$3.55	3.336	$0.538	8.71
	Vinyl Frame	0.74	0.613	$8.178	$78.23	6.671	$1.065	125.91
	Low-E (e=0.4)	1.08	2.507	$33.464	$81.88	17.969	$2.841	31.53
	Low-E (e=0.2)	2.10	8.769	$116.854	$169.58	68.326	$10.835	18.11
	Low-E (e=0.1)	2.27	11.083	$147.735	$173.34	64.990	$10.308	14.71
	Visionwall	3.13	15.301	$204.010	$230.91	82.960	$13.149	14.23
0.6	Thermal Break Frame	0.51	0.108	$1.506	$3.55	0.753	$0.118	31.33
	Vinyl Frame	0.74	0.194	$2.582	$78.23	1.506	$0.237	398.17
	Low-E (e=0.4)	1.08	2.098	$27.976	$81.88	12.697	$2.012	37.99
	Low-E (e=0.2)	2.10	7.597	$101.252	$169.58	58.642	$9.297	21.10
	Low-E (e=0.1)	2.27	10.448	$139.342	$173.34	64.237	$10.190	15.61
	Visionwall	3.13	14.827	$197.769	$230.91	89.631	$14.214	14.61

[6] All fenestration options are double-pane glazing. Visionwall has two panes of glass, two low-e films, a krypton gas fill, and a well-constructed, thermally broken frame.

Simulation models were created for each of the 5 ESB stages beyond the base case simulations for the existing office buildings. Section 3.4 shows the modeling assumptions for each of these stages, including the estimated cost of the retrofit for each stage.

Figures 4-4 through 4-6 and Tables 4-13 through 4-20 show sample data from the DOE-2.1E simulation results in one location. Figure 4-4 compares the end-use energy performance for each of the five stages for the mid-rise office building with gas heat in Washington, D.C. Figure 4-5 compares the end-use energy performance for the existing building and Energy Star buildings upgrade cases for the three office buildings in Washington, D.C. Figure 4-6 compares the total energy performance for the existing buildings and Energy Star building upgrades case in eight selected locations. Appendix C shows similar data to that shown in Figures 4-4 and 4-5 for all energy sources and building sizes.

Tables 4-13 through 4-20 show example simulation results for one case—the mid-rise office building with gas heat in Washington, D.C. While similar data for the other 107 cases (three building sizes, two energy sources, 18 locations) were created, they are not included here for the sake of brevity.

Summary results from all the energy simulations and economic calculations are shown in Tables 4-21 and 4-22. Table 4-21 shows the average reduction in predicted energy use, energy costs, peak electrical demand, and equipment loads as well as the calculated internal rate of return for the three office buildings in all 18 locations. Table 4-22 shows similar information separately for the three office buildings. Appendix C includes similar summary results for each of the 18 locations.

The simulations showed the potential to reduce overall energy consumption by up to 60 percent in existing buildings while realizing an average rate of return of 54 percent on the investments. The staged implementation strategy was the key factor in these overall savings and economic returns—upgrading HVAC systems to match significantly reduced peak loads were substantially lower in cost.

As shown by these simulation results, the potential for high rates of return and energy savings in the existing office building stock from the Energy Star Buildings Program was quite significant:

- Annual energy savings of over 25 percent are easily obtained—savings up to 60 percent are possible in some locations.
- Energy cost savings of greater than 26 percent can be obtained throughout the United States for office buildings, with potential savings of up to 59 percent in some locations.
- Internal rates of return average 58 percent.
- Peak electric demand reductions average 45 percent.
- Peak cooling loads (chiller requirements) are reduced on average 47 percent.
- Fan supply air requirements are reduced on average 34 percent; reducing fan motor size required an average of 64 percent.

A few observations about the simulation results from each of the stages follow.

Table 4-11. Three Existing Office Building Models

Building Description	Floor Area, m^2	Number of Floors	Aspect Ratio (Length: Width)
Low-Rise	4,461	3	2
Mid-Rise	18,216	7	3
High-Rise	78,067	20	3

Table 4-12. DOE-2.1E Simulation Results for Gas-Heated Existing Low-Rise Office Building (4, 461 m^2, 3 floors)

Location	Annual Energy, kWh/m^2	Annual Energy Cost, $\$/m^2$	Peak Demand, kW	Peak Chiller Load, kW	Fan Supply Air, l/s	Fan Motor Size, kW
Anchorage	376	17.75	289	197	20,071	50
Atlanta	314	18.40	422	608	32,054	77
Boston	353	21.95	390	513	25,969	65
Chicago	375	23.03	399	542	26,996	66
Cleveland	369	24.32	385	499	27,100	66
Ft. Worth/Dallas	299	17.86	444	672	30,006	73
Honolulu	285	43.90	405	556	27,525	69
Los Angeles	257	30.02	384	478	28,974	72
Memphis	304	23.24	437	665	28,205	69
Miami	294	23.89	450	707	31,046	77
Minneapolis	423	17.43	395	542	27,131	66
New York	341	41.53	405	563	26,625	66
Omaha	363	20.44	427	615	27,540	66
Phoenix	298	26.47	452	703	36,089	87
San Antonio	314	17.00	458	710	35,826	87
San Francisco	249	32.39	338	341	25,902	64
Seattle	295	9.36	352	387	27,333	67
Washington, D.C.	317	23.13	443	661	27,395	67

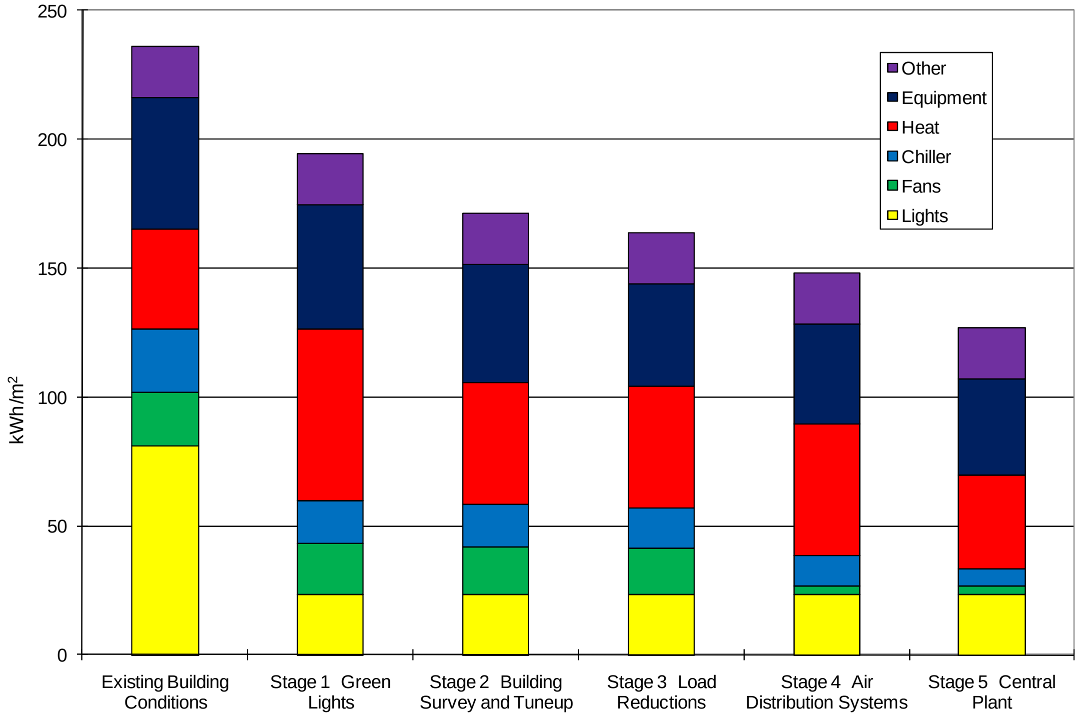


Figure 4-4. Energy End-Use by Stage for Mid-Rise Office Building with Gas Heat in Washington, D.C.

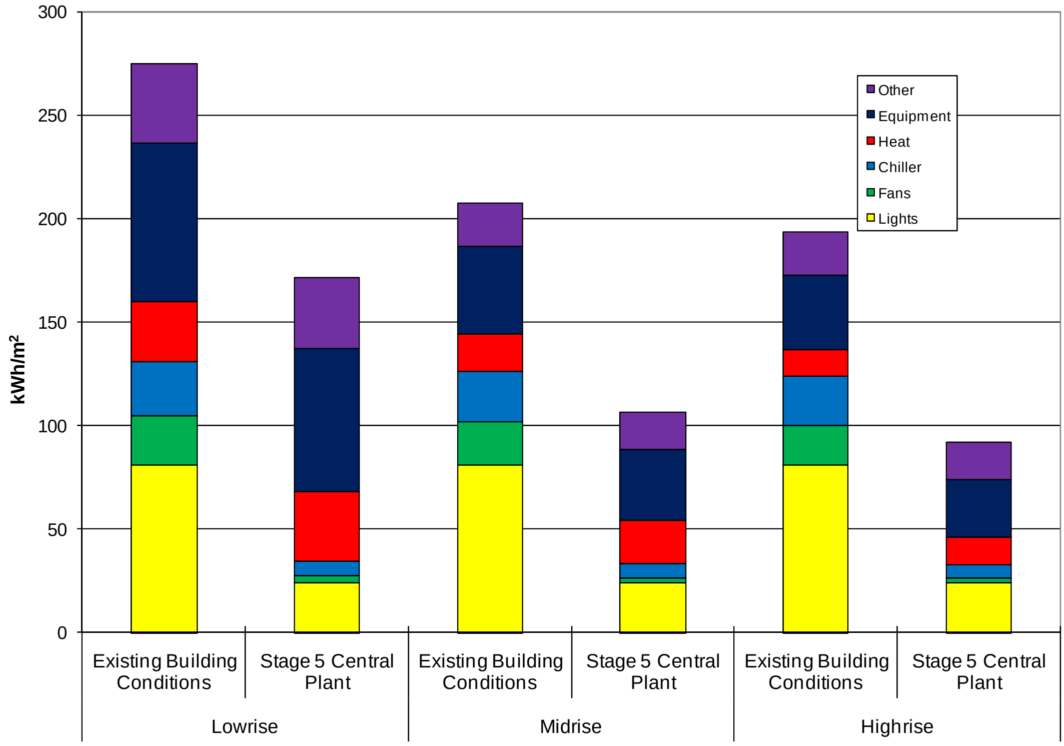


Figure 4-5. Comparison of Energy End-Uses for Existing Buildings and Energy Star Buildings Upgrade for the Three Office Building Sizes in Washington, D.C.

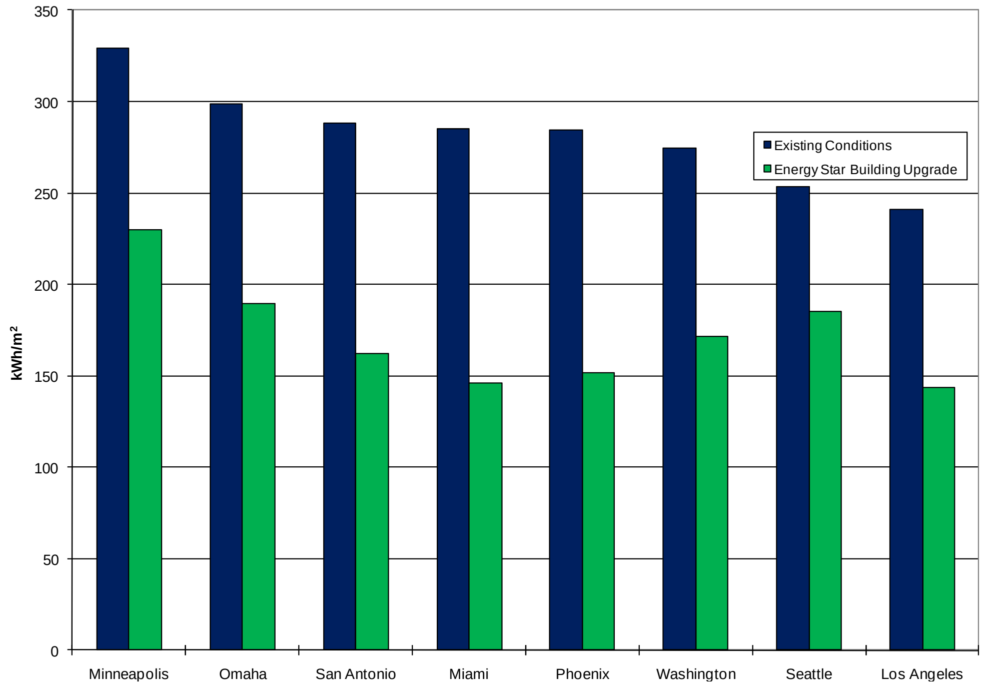


Figure 4-6. Comparison of Existing Buildings and Energy Star Building Upgrades for Eight Locations

Table 4-13. Energy Performance of the Five Stages for the Mid-Rise Office with Gas Heat in Washington, D.C.

Stage	Annual Total Energy Cost, $	Annual Total Energy Cost, $/m^2	Annual Total Natural Gas, MJ	Annual Total Electricity, kWh	Annual Total Energy, thousands of kWh/m^2	Annual Peak Demand, kW	Summer Peak Demand, kW
Existing Building	324,072	17.75	3,860	3,228,074	236.0	1,452	1,452
Stage 1	236,810	13.02	5,660	2,010,903	196.6	1,053	1,053
Stage 2	215,926	11.84	4,399	1,931,704	173.0	903	903
Stage 3	205,870	11.30	4,374	1,800,941	165.4	870	870
Stage 4	176,994	9.68	4,645	1,440,656	150.0	761	761
Stage 5	152,368	8.39	3,663	1,318,467	128.3	587	587

Table 4-14. End-Use Energy Performance of the Five Stages for the Mid-Rise Office with Gas Heat in Washington, D.C.

Stage	Lights, kWh	Fans, kWh	Chiller, kWh	Heat, GJ	Reheat, kWh	Service Hot Water, GJ	Office Equipment and Other, kWh
Existing Building	1,474,622	378,424	445,897	2,568	27,334	1,293	929,131
Stage 1	429,985	357,875	304,219	4,367	41,428	1,293	877,396
Stage 2	429,985	332,780	299,578	3,107	34,736	1,293	834,625
Stage 3	429,985	325,074	282,465	3,081	34,181	1,293	729,236
Stage 4	429,985	51,971	221,531	3,353	36,513	1,293	700,656
Stage 5	429,985	51,971	124,702	2,371	24,811	1,293	686,998

Table 4-15. Calculated Major HVAC Equipment Sizes of the Five Stages for the Mid-Rise Office with Gas Heat in Washington, D.C.

Stage	Installed Cooling, kW	Peak Cooling, kW	Installed Heating, MJ	Peak Heating, MJ	Installed Fan Supply Air, l/s	Installed Fan Motor Size, kW
Existing Building	2,395	2,434	10,797	7,296	98,043	242
Stage 1	2,395	2,107	10,797	7,475	98,043	242
Stage 2	2,395	1,607	10,797	5,388	98,043	224
Stage 3	2,395	1,569	10,797	5,335	98,043	224
Stage 4	2,395	1,414	10,797	4,934	63,911	87
Stage 5	1,333	1,210	5,546	4,934	63,911	87

Table 4-16. Energy Savings of the Five Stages for the Mid-Rise Office with Gas Heat in Washington, D.C.

Stage	Annual Total Energy Cost, $	Annual Total Energy Cost, $/m^2	Annual Total Natural Gas, GJ	Annual Total Electricity, kWh	Annual Total Energy, kWh/m^2	Annual Peak Demand, kW	Summer Peak Demand, kW
Existing Building	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Stage 1	87,262	N/A	N/A	N/A	N/A	400	400
Stage 2	20,884	4.842	-1,800	1,217,171	39.4	150	150
Stage 3	10,056	1.184	1,261	79,199	23.6	33	33
Stage 4	28,876	0.538	25	130,763	7.6	109	109
Stage 5	24,626	1.614	-271	360,285	15.8	175	175
Totals	171,704	1.399	982	122,189	21.7	866	866
	53%	53%	5%	59%	46%	60%	60%

Table 4-17. End-Use Energy Savings of the Five Stages for the Mid-Rise Office with Gas Heat in Washington, D.C.

Stage	Lights, kWh	Fans, kWh	Chiller, kWh	Heat, GJ	Reheat, kWh	Service Hot Water, GJ	Office Equipment and Other, kWh
Existing Building	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Stage 1	1,044,637	20,549	141,678	-1,800	-14,094	0	51,735
Stage 2	0	25,095	4,641	1,261	6,692	0	42,771
Stage 3	0	7,706	17,113	25	555	0	105,389
Stage 4	0	273,103	60,934	-271	-2,332	0	28,580
Stage 5	0	0	96,829	982	11,702	0	13,658
Totals	1,044,637	326,453	321,195	197	2,523	0	242,133
	71%	86%	72%	8%	9%	0%	26%

Table 4-18. Calculated Major HVAC Equipment Size Reductions of the Five Stages for the Mid-Rise Office with Gas Heat in Washington, D.C.

Stage	Installed Cooling, kW	Peak Cooling, kW	Installed Heating, MJ	Peak Heating, MJ	Installed Fan Supply Air, l/s	Installed Fan Motor Size, kW
Existing Building	N/A	N/A	N/A	N/A	N/A	N/A
Stage 1	0	327	0	-179	0	0
Stage 2	0	503	0	2,088	0	17
Stage 3	0	39	0	53	0	0
Stage 4	0	155	0	411	34,132	138
Stage 5	1,062	200	5,240	0	0	0
Totals	1,062	1,220	5,240	2,372	34,132	155
	44%	50%	49%	32%	35%	64%

Table 4-19. Economic Analysis of the Five Stages for the Mid-Rise Office with Gas Heat in Washington, D.C.

Stage	Total Upgrade Cost, $	Upgrade Cost, $/m^2	Internal Rate of Return, %	30-Year Net Present Value[7], $	Percent of Total Energy Cost Savings	Percent of Total Energy Savings
Existing Building	N/A	N/A	N/A	N/A	N/A	N/A
Stage 1	168,560	9.254	52%	$439,840	51%	64%
Stage 2	19,600	1.076	91%	$72,314	12%	4%
Stage 3	14,000	0.753	66%	$49,286	6%	7%
Stage 4	23,786	1.291	121%	$178,773	17%	19%
Stage 5	130,159	7.102	19%	$60,001	14%	6%
Totals	356,105	19.583	47%	$800,214	100%	100%

Table 4-20. Atmospheric Pollution Reduction of the Five Stages for the Mid-Rise Office with Gas Heat in Washington, D.C.

Stage	Sulfur Dioxide, SO_2, tonnes	Nitrogen Oxides, NO_x, tonnes	Carbon Dioxide, CO_2, tonnes
Existing Building	N/A	N/A	N/A
Stage 1	9.981	2.739	789.013
Stage 2	0.650	0.504	123.570
Stage 3	1.072	0.346	96.222
Stage 4	2.955	0.873	247.250
Stage 5	1.002	0.550	140.167
Totals	15.659	5.011	1,396.222

[7] Net Present Value is the discounted sum of 30 years of cash flows for capital, energy, and maintenance. A discount rate of 12% was used in this analysis. The calculation includes subsequent capital costs for equipment and systems with an economic life shorter than 30 years.

Table 4-21. Average Energy Savings, Economic Returns, and Load Reductions for All Three Office Buildings and All Locations

	Percent Reduction or Return **Average** (Min/*Max*)						
Fuels	Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Electrical Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels[8]	**44%** (23/*59*)	**47%** (24/*61*)	**58%** (16/*157*)	**45%** (4/*61*)	**47%** (35/*64*)	**34%** (29/*43*)	**64%** (61/*69*)
All-Electric	**44%** (25/*59*)	**41%** (24/*59*)	**63%** (16/*157*)	**31%** (4/*56*)	**46%** (35/*64*)	**34%** (29/*43*)	**64%** (61/*69*)
Gas Heat	**44%** (23/*58*)	**51%** (29/*61*)	**54%** (21/*157*)	**54%** (39/*61*)	**47%** (35/*64*)	**34%** (29/*40*)	**64%** (61/*67*)

Table 4-22. Average Energy Savings, Economic Returns, and Load Reductions for the Three Office Buildings and All Locations

Size/Fuels		Percent Reduction or Return **Average** (Min/*Max*)						
		Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
Low-Rise	All Fuels	**37%** (23/*48*)	**40%** (24/*51*)	**53%** (26/*127*)	**40%** (14/*51*)	**46%** (35/*55*)	**31%** (29/*33*)	**63%** (61/*64*)
	Electric	**37%** (25/*48*)	**35%** (24/*48*)	**61%** (26/*127*)	**29%** (14/*44*)	**45%** (35/*51*)	**31%** (29/*33*)	**62%** (61/*64*)
	Gas Heat	**37%** (23/*47*)	**44%** (29/*51*)	**47%** (27/*127*)	**48%** (39/*51*)	**46%** (35/*55*)	**32%** (29/*33*)	**63%** (61/*64*)
Mid-Rise	All Fuels	**46%** (26/*57*)	**50%** (33/*59*)	**58%** (16/*135*)	**47%** (4/*60*)	**47%** (35/*61*)	**35%** (31/*37*)	**64%** (62/*65*)
	Electric	**47%** (35/*57*)	**44%** (33/*58*)	**61%** (16/*135*)	**32%** (4/*54*)	**46%** (35/*61*)	**34%** (31/*37*)	**64%** (62/*65*)
	Gas Heat	**46%** (26/*56*)	**54%** (43/*59*)	**56%** (21/*135*)	**57%** (49/*60*)	**47%** (42/*61*)	**35%** (32/*37*)	**64%** (63/*65*)
High-Rise	All Fuels	**50%** (38/*59*)	**53%** (36/*61*)	**67%** (21/*157*)	**48%** (17/*61*)	**48%** (43/*64*)	**37%** (34/*43*)	**66%** (64/*69*)
	Electric	**51%** (40/*59*)	**47%** (36/*59*)	**71%** (21/*157*)	**33%** (17/*56*)	**48%** (43/*64*)	**38%** (34/*43*)	**66%** (64/*69*)
	Gas Heat	**50%** (38/*58*)	**57%** (48/*61*)	**64%** (24/*157*)	**59%** (51/*61*)	**48%** (43/*64*)	**37%** (34/*40*)	**66%** (64/*67*)

[8] The averages of building size are weighted based on the existing office building stock. The averages across locations are not weighted.

4.4.1.1 Stage 1 Green Lights

For locations with significant cooling requirements (such as Fort Worth, Honolulu, Los Angeles, Memphis, Miami, Omaha, Phoenix, San Antonio, and Washington, D.C.), the T-8 (8.61 W/m^2) fluorescent lighting upgrade results in high energy savings of 13 to 37 percent, energy cost savings of 11 to 35 percent, and internal rates of return of 19 to 84 percent.

Savings are greater in larger, more internally load-dominated buildings (mid-rise and high-rise). For locations where cooling is not the predominant load (Anchorage, Minneapolis, and Seattle), this upgrade removes beneficial, offsetting heating, causing heating to increase substantially. For the low-rise all-electric offices in these locations, alternative upgrades of 1.19 W/ft^2 were cost-effective. For all three building office sizes in Minneapolis and Seattle, energy savings of 6 to 31 percent, energy cost savings of 3 to 25 percent, and internal rates of return of 12 to 18 percent were observed. The larger buildings tend to be on the higher end of the ranges. Due to the low cost of electricity (~$0.04/kWh), Seattle tends to be at the lowest end of the ranges.

4.4.1.2 Stage 2 Building Survey and Tune-up

Due to the relatively low estimated cost ($1.076/$m^2$) for building survey and tune-up in Stage 2, internal rates of return are high. Re-commissioning may yield lower or greater savings, depending on the specific problems found. Energy savings range from 1 to 16 percent, energy costs are reduced in the range of 1 to 26 percent, and internal rates of return are from 17 to 488 percent. The lowest savings and rates of return are for Seattle where the stuck outside air damper helps offset cooling (becoming essentially a fixed outside air economizer giving free cooling). Fixing the damper problem increased the cooling load that must be met by the chiller.

4.4.1.3 Stage 3 Loads Reduction

Buying Energy Star computers was essentially a no-cost upgrade. Combining this with lower (but generally cost-effective) savings from adding roof insulation the next time the roof is replaced, yielded good rates of return. In the low-rise offices in Minneapolis and Seattle, an upgrade of the roof insulation was not cost-effective and not included in the Stage 3 simulations. Energy savings range from 1 to 4 percent, energy costs are reduced in the range of 1 to 4 percent, and internal rates of return are from 12 to 213 percent. Overall the results are more consistent between locations than for previous stages.

4.4.1.4 Stage 4 Air Distribution Systems

Upgrading the VAV system from inlet vane controls to VSDs and installing air-side economizers in Stage 4 yields consistently high savings of energy and costs and high internal rates of return. The savings and returns are 30 to 50 percent higher in the largest, most internal-load dominated buildings (high-rise) than in the smaller, more envelope-dominated low-rise buildings. Energy savings range from 7 to 12 percent, energy costs are reduced in the range of 4 to 12 percent, and internal rates of return are from 37 to 223 percent.

4.4.1.5 Stage 5 Central Plant

Because Stage 5 concentrates on upgrading the cooling portion of the plant (in the all-electric building), the greatest savings are in locations where cooling is a predominant load. Where cooling requirements are significant (Atlanta, Fort Worth, Honolulu, Los Angeles, Memphis, Miami, Phoenix, San Antonio, and Washington, D.C.), Stage 5 results in energy savings of 3 to 6 percent, energy cost savings of 3 to 11 percent, and internal rates of return of 12 to 313 percent. Savings are higher in larger, more internally load-dominated buildings (mid-rise and high-rise). Where heating is the predominant load (Anchorage, Minneapolis, Omaha, and Seattle), upgrade costs are not offset by as much energy cost savings. In those locations—for the all-electric building—the cost-effectiveness is limited: energy savings of 1 to 3 percent, energy cost savings of 1 to 2 percent, and internal rates of return of 12 to 31 percent. Larger buildings tend to be at the higher end of the ranges. The natural gas-fired boiler upgrade tends to be most cost-effective in the colder climates.

4.4.1.6 ESB Results Summary

Energy and economic performance varies widely among regions due to variations in heating and cooling requirements, utility costs, and conditions (such as stuck outside air damper). Using the staged approach reduces loads substantially leading to capital cost savings when downsizing or replacing equipment in subsequent stages. The results of this study are not surprising. The study was intended to show quantitatively that the ESB staged approach with engineered resizing of fans and chillers would yield more savings than would retrofits. Chiller replacement cost savings result from offsetting retrofit costs for non-CFC refrigerants and significantly downsized chiller loads. Cost-effectiveness of retrofit options for each stage will vary by region and building type. Only those measures that are profitable become part of the Energy Star Building Upgrade. The staged strategy of the EPA Energy Star Building Program offers a number of advantages for building energy-efficiency upgrades and can result in higher levels of energy savings than other approaches, such as a la carte measure selection or a modeling approach that does not incorporate field confirmation of engineering calculations. Tables 4-23 through 4-28 show summary data used in ESB program materials. These data aggregate major U.S. regions from the 18 locations based on weightings from the CBECS.

Table 4-23. Average Annual Energy Savings for All-Electric Office Buildings

Building Size	U. S. Region				Entire U.S.
	Northeast	Midwest	South	West	
Low-Rise	31.0%	33.3%	40.4%	37.7%	36.2%
Mid-Rise	41.5%	40.5%	50.0%	47.8%	45.6%
High-Rise	45.5%	45.0%	53.2%	52.2%	49.5%
All Offices	38.6%	39.0%	47.3%	45.2%	43.1%

Table 4-24. Average Annual Energy Cost Savings for All-Electric Office Buildings

Building Size	U. S. Region				Entire U.S.
	Northeast	Midwest	South	West	
Low-Rise	31.0%	31.3%	37.6%	35.3%	34.3%
Mid-Rise	38.0%	37.0%	46.6%	46.0%	42.5%
High-Rise	41.0%	39.8%	49.4%	50.2%	45.7%
All Offices	36.2%	35.6%	44.0%	43.1%	40.3%

Table 4-25. Average Annual Energy Savings for Gas-Heated Office Buildings

Building Size	U.S. Region				Entire U.S.
	Northeast	Midwest	South	West	
Low-Rise	35.5%	37.8%	36.6%	36.5%	36.6%
Mid-Rise	43.0%	44.3%	47.2%	44.5%	45.0%
High-Rise	45.5%	46.8%	51.6%	49.8%	48.8%
All Offices	40.9%	42.5%	44.4%	42.9%	42.9%

Table 4-26.Average Annual Energy Cost Savings for Gas-Heated Office Buildings

Building Size	U. S. Region				Entire U.S.
	Northeast	Midwest	South	West	
Low-Rise	44.5%	42.5%	45.0%	42.7%	43.8%
Mid-Rise	54.5%	52.5%	55.8%	52.8%	54.1%
High-Rise	57.0%	55.5%	59.0%	57.2%	57.4%
All Offices	51.5%	49.6%	52.6%	50.2%	51.1%

Table 4-27. Average Annual Energy Savings for All Office Buildings

Building Size	U. S. Region				Entire U.S.
	Northeast	Midwest	South	West	
Low-Rise	34.0%	36.3%	37.8%	36.9%	36.5%
Mid-Rise	42.5%	43.0%	48.1%	45.6%	45.2%
High-Rise	45.5%	46.2%	52.1%	50.6%	49.1%
All Offices	40.1%	41.3%	45.3%	43.6%	43.0%

Table 4-28. Average Annual Energy Cost Savings for All Office Buildings

Building Size	U. S. Region				Entire U.S.
	Northeast	Midwest	South	West	
Low-Rise	40.1%	38.8%	42.6%	40.3%	40.7%
Mid-Rise	49.1%	47.4%	52.8%	50.6%	50.3%
High-Rise	51.8%	50.4%	55.9%	54.9%	53.6%
All Offices	46.5%	45.0%	49.8%	47.9%	47.6%

4.4.2 Simulation Results for Detailed Envelope Upgrades

As described in Section 3.4.2, a series of potential building envelope upgrades were simulated to provide a look-up table solution for various existing thicknesses of wall and roof insulation. Similarly, a set of specific fenestration assemblies were simulated with a variety of fenestration-to-wall ratios (FWR). Energy performance results from this set of more than 21,000 DOE-2.1E simulations (combination of building size, HVAC system, location, and internal loads) yielded 200 simulations per wall, roof, or fenestration option (three building sizes, four HVAC systems, eight locations, two internal loads, and one base sizing simulation per location) were combined with upgrade costs. The following tables and figures present a subset of the energy results from the roof insulation, wall insulation, and fenestration simulations.

Tables 4-29, 4-30, and 4-31 present a sample subset of the results for a CV reheat system with fan motor pulley change out and high lighting levels (24.75 W/m^2) in Washington, D.C. Table 4-29 displays results for 25 mm existing roof insulation; Table 4-30, 25 mm existing wall insulation; and Table 4-31, single-pane existing glazing.

Figure 4-7 presents annual energy cost savings for four locations (Los Angeles, Miami, Minneapolis, and Washington, D.C.) for a CV system, changing the roof color from dark to light, fan motor pulley change out, and high internal loads (lighting power density of 24.75

W/m^2). The annual energy cost savings are presented in terms of dollars saved per m^2 of roof area. The bar shows the effect of adding 51 mm roof insulation for cases where the existing roof has from none to 165 mm of insulation. As can be seen in all cases, the highest energy cost savings are for the lowest levels of existing roof insulation.

Figure 4-8 shows similar annual energy cost savings for two lighting power densities (24.75 and 8.61W/m^2) and two HVAC systems (CV and VAV) in Washington, D.C. Annual energy cost savings for the lower lighting power density are slightly lower than for the higher lighting power density case in Washington, D.C. More significant are the differences in savings between the CV and VAV systems. Because these data are the result of multiple changes to building characteristics, impacts of individual changes in characteristics are shown in the figures that follow.

Figures 4-9, 4-10, 4-11, and 4-12 present cost-effectiveness results in terms of simple payback period for the same combinations of energy cost savings shown in Figure 4-8. In all cases, there are significant opportunities for upgrading roof insulation when there is little or no insulation to start with. In most cases, payback periods of less than 10 years are possible for added insulation, even when the roof is already heavily insulated. The 0 curve is always near the bottom of the charts–where no insulation is currently in place.

In Figures 4-13 through 4-16, the impacts of various building characteristics are shown, using a single starting point for existing roof insulation—25 mm. One of the most significant factors in cost-effectiveness is roof color, as shown in Figure 4-13. An existing dark-colored roof when changed to a light color provides the highest predicted savings for both CV and VAV systems. Leaving a roof dark yields the lowest potential savings. If the roof is already a light color, solar gains are already reduced and insulation upgrades are not as effective overall.

Figure 4-15 shows the effect of lighting power density on cost-effectiveness for the CV and VAV systems. For Washington, D.C., there is a slightly higher cost-effectiveness for CV systems with the higher level of lighting. In reviewing data for other locations, internal load level plays only a slight role in cost-effective of roof insulation upgrades. For VAV systems, lighting power density is even less significant in determining whether insulation upgrades are cost-effective. There is little difference in relative results among internal load levels.

Table 4-29. Example Results for Dark Roof with 25 mm Existing Roof Insulation in Washington, D.C.

Roof Upgrade Option			Energy and Economic Analyses					
Add Insulation, mm	Roof Color	Fan Motor Option	Upgrade Cost, $/m^2$ Roof Area	Internal Rate of Return, %	Simple Payback Period, Years	Annual Energy Savings		
						$/m^2$ Roof Area	kWh/m^2	%
0	Light	Pulley Change Out	$0.00	NA	0.0	$2.58	8.61	2.04%
13			$3.23	119%	0.8	$3.87	14.96	3.52%
25			$6.46	71%	1.4	$4.63	18.61	4.39%
38			$9.68	52%	1.9	$5.06	20.87	4.91%
51			$12.91	41%	2.4	$5.38	22.70	5.34%
64			$16.14	35%	2.9	$5.60	23.89	5.63%
76			$19.37	29%	3.3	$5.81	24.75	5.84%
89			$22.60	25%	3.8	$5.92	25.50	6.01%
102			$25.82	22%	4.2	$6.13	26.15	6.17%
114			$29.05	20%	4.7	$6.24	26.68	6.28%
127			$32.28	18%	5.1	$6.35	27.12	6.40%
140			$35.51	16%	5.6	$6.35	27.44	6.47%
152			$38.74	14%	6.0	$6.46	27.76	6.53%

Table 4-30. Example Results for 25 mm Existing Wall Insulation with 0.4 FWR and Fan Motor Pulley Change-out in Washington, D.C.

Existing Wall	Wall Upgrade	Energy and Economic Analyses					
Insulation Thickness, mm	Add Insulation, mm	Upgrade Cost, $/m^2$ Wall Area	Internal Rate of Return, %	Simple Payback Period, Years	Annual Energy Savings		
					$/m^2$ Wall Area	kWh/m^2	%
25	13	$3.44	61%	1.6	$1.51	5.918	1.54%
	25	$6.67	50%	2.0	$2.47	9.469	2.44%
	38	$9.90	41%	2.4	$3.01	11.621	3.00%
	51	$13.13	35%	2.8	$3.44	13.127	3.40%
	64	$16.36	31%	3.2	$3.77	14.311	3.71%
	76	$19.58	28%	3.5	$3.98	15.279	3.96%
	89	$22.81	25%	3.9	$4.20	16.032	4.15%
	102	$26.04	22%	4.3	$4.41	16.678	4.33%
	114	$29.27	20%	4.7	$4.52	17.324	4.48%
	127	$32.50	18%	5.0	$4.63	17.754	4.60%
	140	$35.72	17%	5.4	$4.84	18.184	4.72%
	152	$38.95	15%	5.7	$4.95	18.615	4.82%

Table 4-31. Example Results for Single-Pane Glazing with 0.4 FWR and Fan Motor Pulley Change-out in Washington, D.C.

Existing Fenestration	Fenestration Upgrade Option	Energy and Economic Analyses					
Glazing U-Value (W/m²-K), Color, and SC	Glazing U-Value (W/m²-K), Color, and SC	Upgrade Cost, $/m² Glazing Area	Internal Rate of Return, %	Simple Payback Period, Years	Annual Energy Savings $/m² Glazing Area	Annual Energy Savings kWh/m²	Annual Energy Savings %
5.17 Clear 0.84	5.17 Grey 0.83	$3.55	10%	7.6	$0.22	0.753	0.2
	5.05 Green 0.69	$5.70	151%	0.7	$4.20	14.418	3.3
	2.95 Clear 0.88	$12.16	95%	1.1	$5.60	23.995	5.5
	2.95 Grey 0.72	$14.31	153%	0.7	$10.54	41.534	9.4
	2.90 Low-E 0.58	$27.22	111%	0.9	$14.63	55.522	12.6
	2.90 Low-E 0.55	$30.45	104%	1.0	$15.28	57.889	13.1

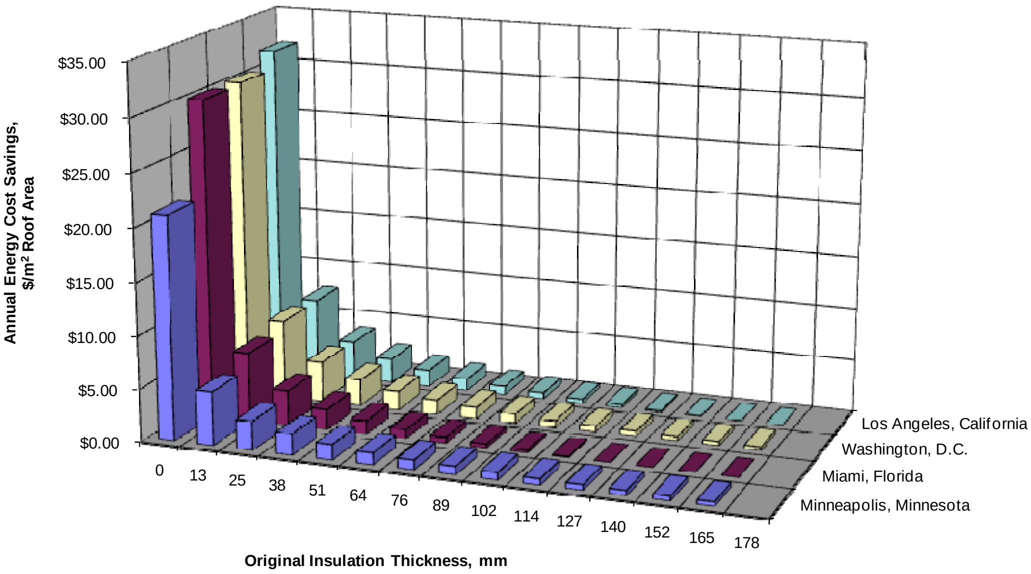


Figure 4-7. Annual Energy Cost Savings for Adding 13 mm Roof Insulation with Constant Volume Reheat and High Lighting (24.75 W/m²) in Four Locations

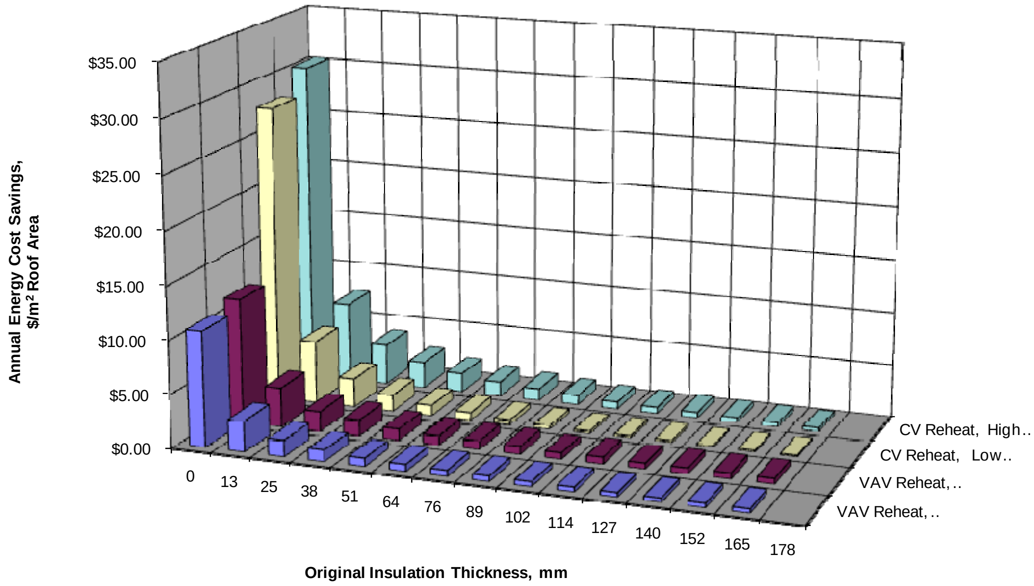


Figure 4-8. Annual Energy Cost Savings for Adding 13 mm Roof Insulation in Washington, D.C.

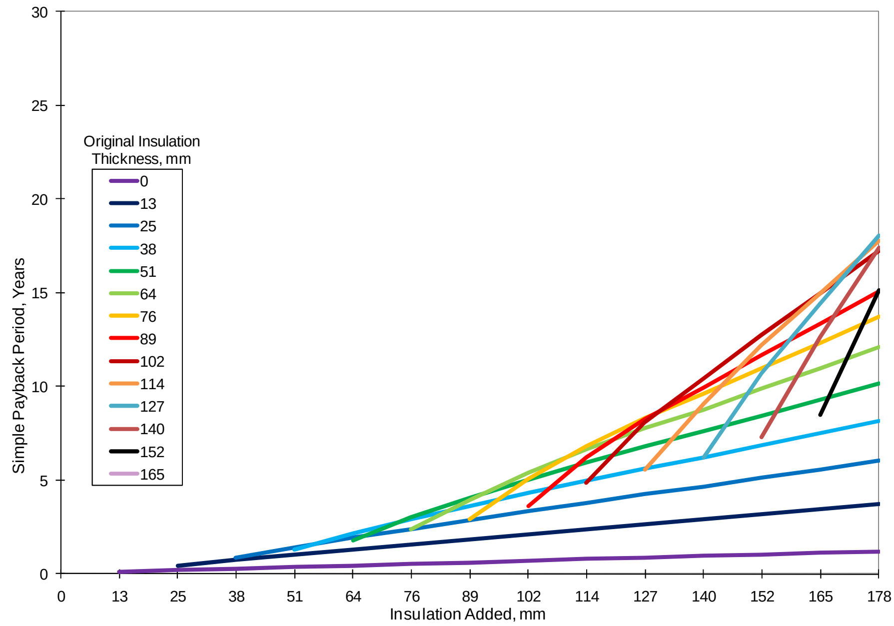


Figure 4-9. Cost-Effectiveness Results for Roof Insulation Upgrades with CV Reheat System and High Lighting in Washington, D.C.

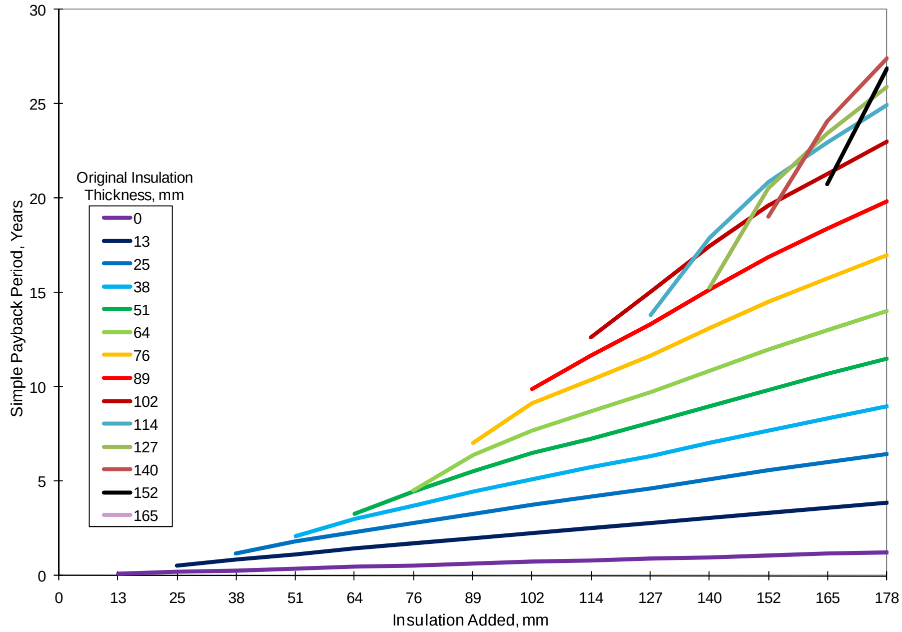


Figure 4-10. Cost-Effectiveness Results for Roof Insulation Upgrades with CV Reheat System and Low Lighting in Washington, D.C.

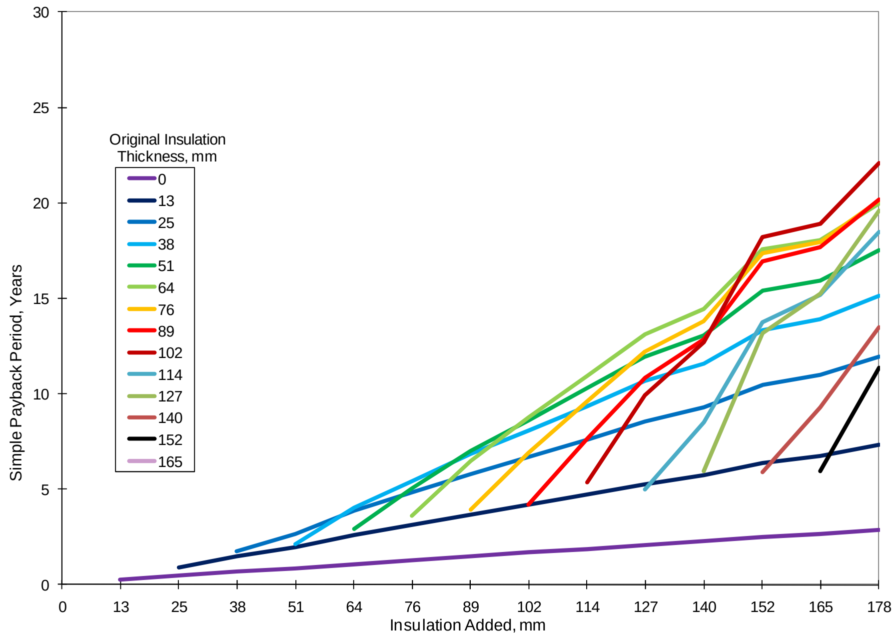


Figure 4-11. Cost-Effectiveness Results for Roof Insulation Upgrades with VAV Reheat System and High Lighting in Washington, D.C.

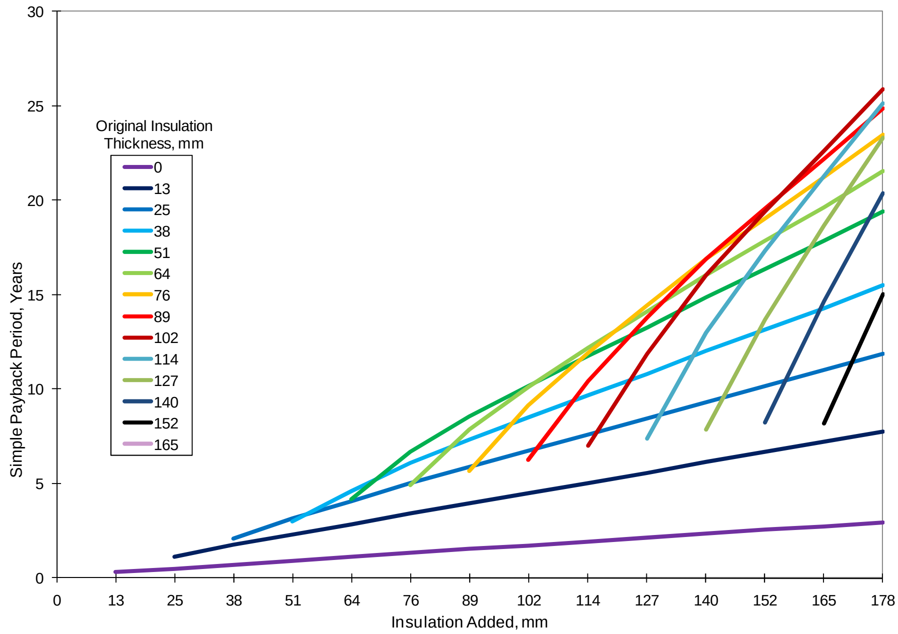


Figure 4-12. Cost-Effective Results for Roof Insulation Upgrades with VAV Reheat System and Low Lighting in Washington, D.C.

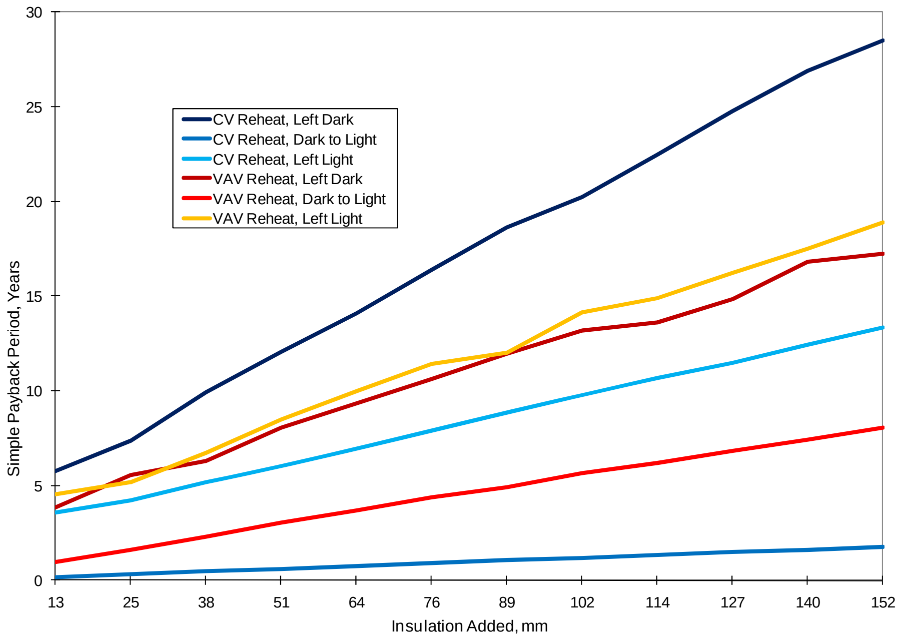


Figure 4-13. Effect of Roof Color and System Type on Roof Insulation Upgrade Cost-Effectiveness for Washington, D.C.

To single out the effect of reducing airflow to meet the reduced loads through a fan motor pulley change out, Figure 4-16 compares two cases (with and without pulley change) for CV and VAV systems. For CV systems, the pulley change out has significantly lower payback period while there is no significant difference between the two cases for VAV systems. VAV systems are inherently more efficient—they automatically reduce supply airflow to meet whatever load is present; changing the pulley does not provide significant advantages.

A number of observations may be made from the analysis of the databases of potential roof insulation upgrades:

- It is always cost-effective to add insulation to a roof that has little or no existing insulation (or wet insulation)—up to twice current practice or energy codes. In many cases, it is cost-effective to add insulation even when insulation levels in an existing roof assembly are already significant.
- Changing from a dark to a light-color roof provides the most significant savings potential—with highest savings in locations with high cooling loads. Light-color roofs can actually increase heating loads in colder locations.
- The level of internal loads plays only a small role in cost-effectiveness of insulation upgrades.
- HVAC system efficiency plays an important role in the savings equation for insulation upgrades. In a less efficient CV system, changing out fan motor pulleys to match reduced loads significantly increases the cost-effectiveness of adding insulation (lowest simple payback). This can mean that insulation upgrades that would not be cost-effective (or even more insulation) become cost-effective.
- For more efficient HVAC systems (VAV system), increased roof insulation is not as cost-effective. In most cases, changing out the fan motor pulley on VAV systems does not significantly improve the cost-effectiveness for added insulation.
- In general, there are greater opportunities for cost-effective changes for roof insulation than for wall insulation or fenestration (and roofs are replaced more frequently than are walls or windows).

An important conclusion learned from the databases was that buildings with large internal areas relative to exterior zones have a greater potential for roof insulation upgrades than do externally dominated buildings (low-rise/mid-rise).

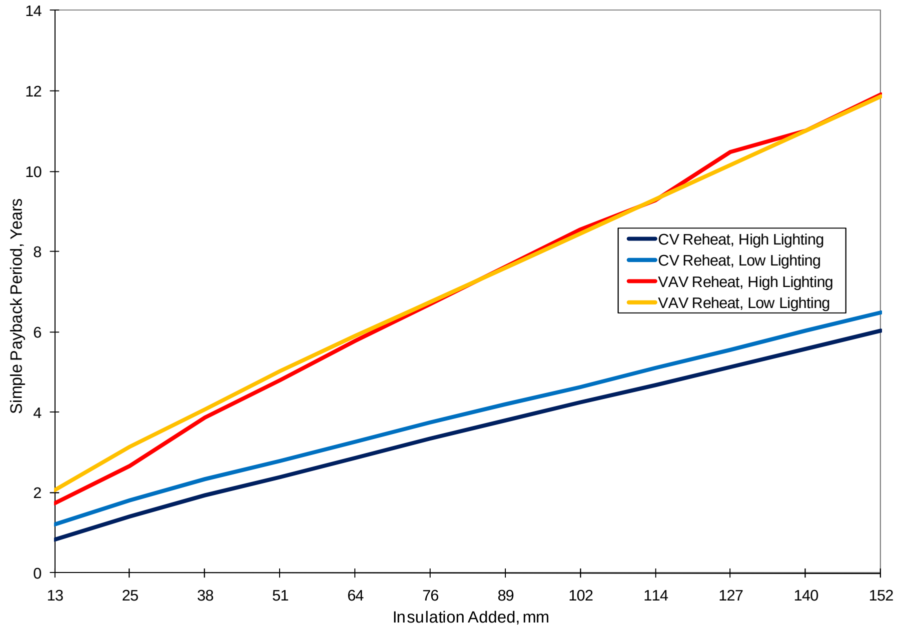


Figure 4-14. Effect of Internal Loads (Lighting) and System Type on Roof Insulation Upgrade Cost-Effectiveness for Washington, D.C.

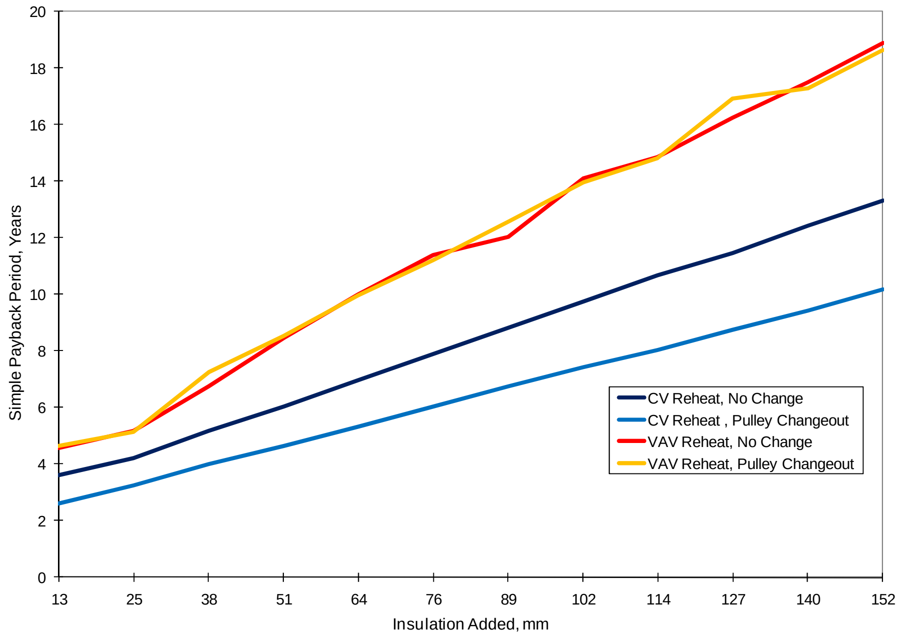


Figure 4-15. Effect of Fan Motor Pulley Change-out and System Type on Roof Insulation Upgrade Cost-Effectiveness for Washington, D.C.

These data sets can quickly provide information on the potential cost-effective upgrades for roof insulation, wall insulation, and fenestration options. The spreadsheets which summarize the cost-effectiveness results facilitate changing basic assumptions—upgrade costs, average utility costs, and insulation type—allowing a user to customize the results to the specific building characteristics . Once a user determines that potential cost-effective upgrades exist, more detailed engineering analyses can be performed.

4.4.3 Chiller Upgrade Results

A further series of DOE-2.1E simulations was performed to identify the benefits of combining a chiller replacement or engineered retrofit with the ESB upgrades. The results for the five cases are summarized next for Washington, D.C. For each location and building size, a spreadsheet that combined simulation results (energy use, peak demand, chiller size) with cash-flow and other economic analyses was created. This information was used in ESB promotional material—papers and articles on the economic benefits of upgrading chillers coupled with other energy efficiency improvements. Examples of the tabular data and charts for the mid-rise office in Washington, D.C. are shown in Table 4-32 and Figure 4-16. These simulations demonstrated that an extra investment in improving the overall energy efficiency of the building at the time of the chiller CFC-retrofit could result in significantly lower chiller replacement costs and overall lower operating costs. For this case, the size of the chiller could be cut by more than half through proper sizing and energy efficiency in the rest of the building, altogether resulting in cutting energy costs by half as well as achieving a simple payback of less than two years and an internal rate of return of 53 percent, an attractive economic return for a building owner. Similar data were created for the other 54 cases (building size and location).

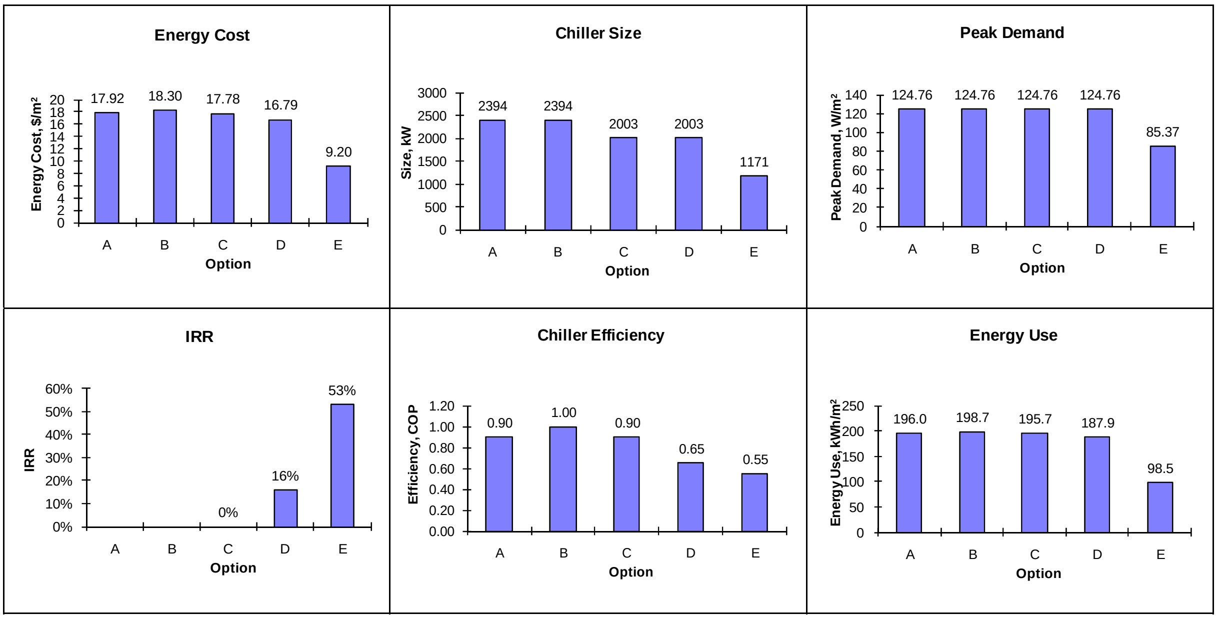
4.4.4 Weather Data Comparison Results

Section 3.4.3 described a series of simulations constructed to test a hypothesis that constructed weather years would offer equivalent energy performance to the mean of long-term weather data. Eight locations were simulated to represent a range of climatic conditions in the United States: Miami, Florida (hot humid); Phoenix, Arizona (hot dry); Denver, Colorado; Los Angeles, California (mild coastal); Minneapolis, Minnesota (cold); New York, New York (warm cool); Seattle, Washington (cool coastal); and Washington, D. C. (hot cool). Thirty years of weather data were simulated for each location and compared to the constructed weather files.

Table 4-32. Chiller Upgrade Simulation Results for All-Electric Mid-Rise Office Building in Washington, D.C.

		Simple Retrofit	Engineered Retrofit	Chiller Replacement	Energy Star Buildings Program
Project Cost, Upgrade		$56,385	$84,578	$128,095	$285,805
Chiller Size, kW		2395	2005	2005	1171
Peak Demand, W/m^2		124.8	124.8	124.8	85.0
Chiller Efficiency, COP		3.52	3.91	5.41	6.39
Energy Use, kWh/m^2		198.74	195.66	187.98	98.56
Energy Cost, $\$/m^2$		18.29	17.75	16.79	9.25
Energy Savings, %		-1.38	0.19	4.12	49.73
Simple Payback, Years		N/A	31.99	6.19	1.80
IRR, %		N/A	N/A	16%	53%
Pollution Prevented, kg/m^2	SO_2	-2172	293	6,491	78,339
	NO_x	-688	93	2,060	24,838
	CO_2	-192088	26,019	574,731	6,933,496

Baseline Chiller: 2,395 kW
3.91 COP
$18.29/m^2$ energy cost



Option Key: A – Baseline Chiller
B – Simple Retrofit
C – Engineered Retrofit
D – Chiller Replacement
E – Energy Star Buildings Program

Figure 4-16. Chiller Upgrade Simulation Results for All-Electric Mid-Rise Office Building in Washington, D.C.

Examples of the simulation results are shown in Figures 4-17 and 4-18—end-use energy consumption by year and energy costs by year. Table 4-33 presents the average, minimum, and maximum annual energy consumption and costs along with average, minimum, and maximum annual peak electric demand, and annual peak cooling and heating loads. Buildings in locations that are either heating-dominated (Minneapolis) or have a significant amount of both heating and cooling (Denver, New York, Seattle, and Washington, D.C.) exhibit a higher relative variation in annual energy consumption year to year. Milder or cooling-dominated climates (Los Angeles, Miami, and Phoenix) demonstrate relatively less overall variation in year-to-year energy consumption.

However, as the summary data in Table 4-33 shows, the range of annual energy performance across the eight locations varies only from –11 percent to 7 percent for the SAMSON 30-year period of record. Local utility rates weight electricity consumption and peak demand differently, depending on which is more expensive to the utility. Throughout the eight locations, the annual energy costs vary widely, from a low of $\$4.52/m^2$ for Denver to a high of $\$22.81/m^2$ for New York. Overall, the year-to-year variation in annual energy cost for the eight locations is less than half the variation in energy consumption noted above, only –4.6 percent to 3.6 percent. Interestingly, annual peak electrical demand variation is similar to that for energy costs, -4.7 percent to 4.9 percent. Similar to annual energy consumption, the least variation is apparent in cooling-dominated climates (Miami and Phoenix). But climates with a mix of heating and cooling (Denver, New York, Seattle, and Washington) showed less variation in peak demand. Unlike energy consumption, peak demand varies considerably more in Los Angeles, a location with relatively mild but variable weather conditions. Similar to Los Angeles, Seattle has higher variation in electric demand. Because the simulated building is gas heated, electrical demand variation is less than that of energy consumption in heating-dominated climates such as Minneapolis.

Figures 4-19 and 4-20 compare similar results for the weather data sets in terms of energy performance and energy cost for Washington, D.C. The weather data type sets are contrasted with average, minimum, and maximum values shown in Table 4-33 (from the SAMSON 30-year simulations in Figures 4-17 and 4-18). Figure 4-19 shows total energy performance (kWh/m^2-yr) for each of the weather data file types. The three lines are the maximum, average, and minimum energy performance from the SAMSON simulations (Table 4-33 and Figures 4-17 and 4-18). Figure 4-20 shows the total annual energy costs ($\$/m^2$-yr) as simulated for the weather data file types. As with Figure 4-19, the three lines show the

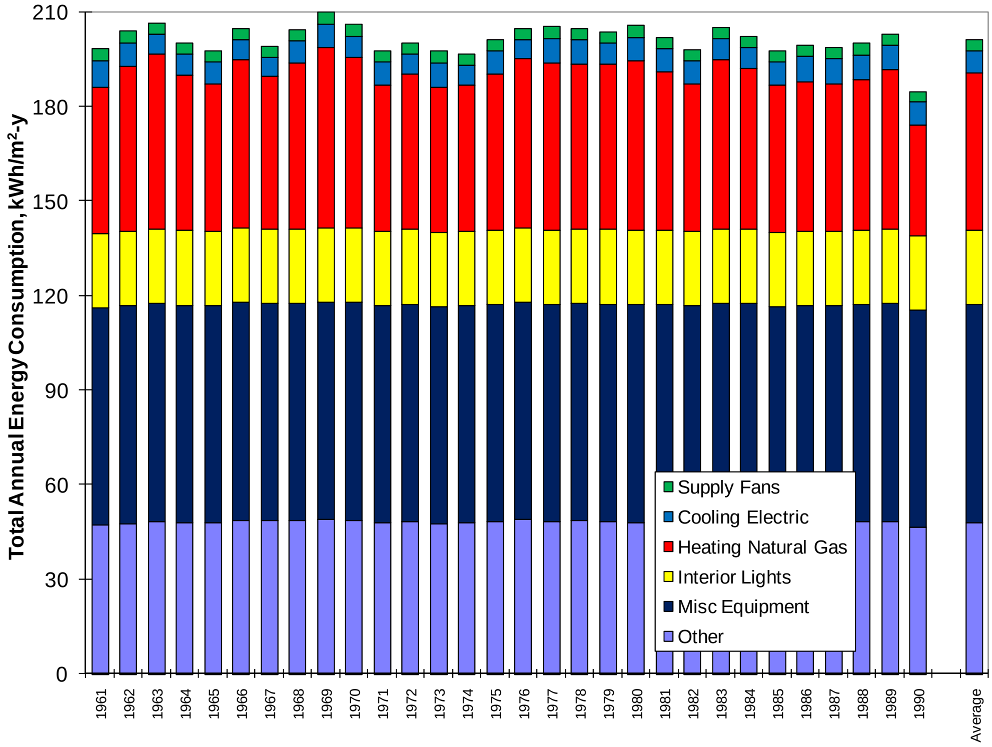


Figure 4-17. Annual End-Use Energy Consumption for a Gas-Heated Low-Rise Office Building in Washington, D.C.

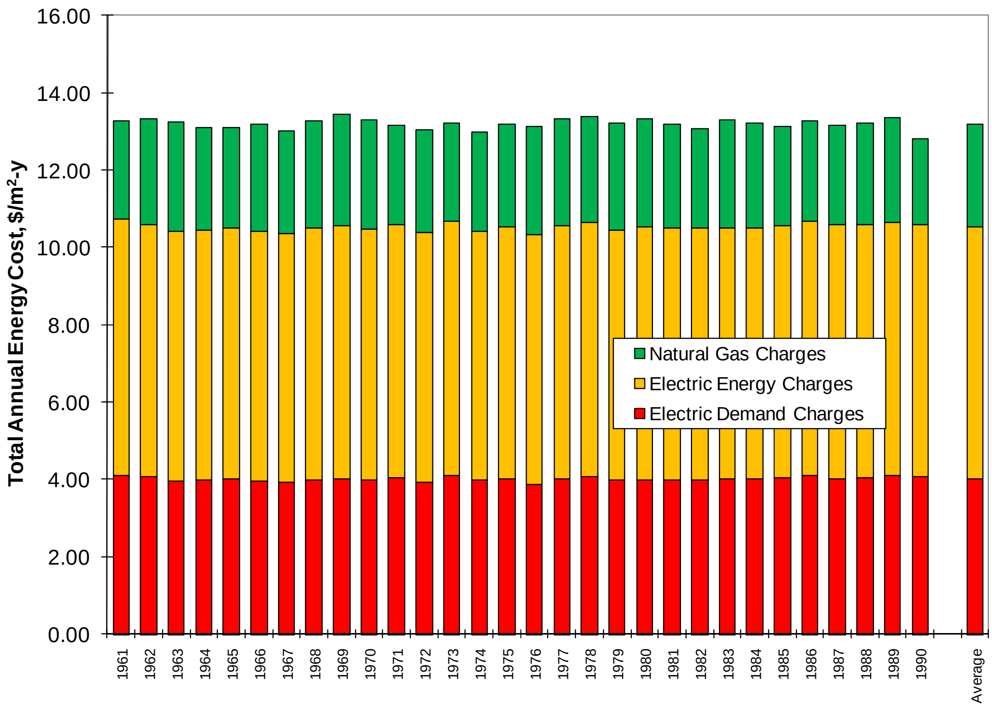


Figure 4-18. Annual Energy Costs by Year for a Gas-Heated Office Building in Washington, D.C.

Table 4-33. Variation in Simulated Annual Energy Consumption, Energy Costs, Peak Electric Demand, and Peak Loads for SAMSON Weather Data

Location	Average (Min/*Max* percent change from average)				
	Total Annual Energy		Annual Peak		
	Consumption, kWh/m^2-yr	Costs, \$/m^2-yr	Electric Demand, W/m^2	Cooling Load, W/m^2	Heating Load, W/m^2
Denver, Colorado	208.4 (-7.7%/*6.7%*)	4.52 (-4.6%/*3.3%*)	44.1 (-2.3%/*1.4%*)	55.5 (-8.8%/*9.0%*)	102.4 (-16.1%/*8.9%*)
Los Angeles, California	157.4 (-3.0%/*4.0%*)	17.11 (-1.7%/*1.7%*)	44.1 (-4.7%/*4.9%*)	61.5 (-21.2%/*34.1%*)	63.3 (-21.7%/*21.4%*)
Miami, Florida	158.6 (-1.8%/*1.8%*)	11.94 (-2.1%/*1.9%*)	50.6 (-1.1%/*1.0%*)	88.2 (-8.2%/*8.9%*)	49.2 (-74.8%/*75.3%*)
Minneapolis, Minnesota	256.7 (-11.0%/*7.0%*)	9.90 (-4.4%/*2.6%*)	47.3 (-4.5%/*2.2%*)	75.6 (-18.7%/*19.5%*)	116.3 (-6.4%/*11.9%*)
New York, New York	211.3 (-8.7%/*4.0%*)	22.81 (-1.5%/*1.6%*)	47.3 (-2.3%/*2.0%*)	75.6 (-11.9%/*15.2%*)	100.8 (-13.5%/*14.9%*)
Phoenix, Arizona	165.2 (-2.3%/*2.9%*)	14.10 (-2.1%/*2.1%*)	50.6 (-1.7%/2.6%)	88.2 (-7.6%/*10.7%*)	61.1 (-54.9%/*34.5%*)
Seattle, Washington	201.5 (-3.9%/*6.5%*)	6.24 (-2.3%/*3.6%*)	43.0 (-3.5%/*2.1%*)	57.0 (-17.8%/*18.5%*)	81.0 (-11.3%/*19.5%*)
Washington, D.C.	201.2 (-8.1%/*4.3%*)	13.23 (-3.0%/*2.0%*)	48.4 (-3.7%/*1.7%*)	77.2 (-14.4%/*16.7%*)	96.4 (-13.6%/*13.4%*)

maximum, average, and minimum energy costs from the simulations of 30 years of SAMSON data. For Washington, D.C., as seen in Figures 4-19 and 4-20, the WYEC2 data appear to most closely match the average of the SAMSON data. However, overall the TMY2 data match the average of the SAMSON data more often than any other weather data type.

The variation of energy consumption for the weather data types for all locations is less than that shown for the 30-year period of record. The range of variation across the eight locations is -2.3 percent to 5.4 percent; excluding the TRY results, and the range of variation among the weather data types is -1.9 percent to 3.2 percent. Because the TRY period of record (~1945-1973) and the SAMSON period of record (1961-1990) differ, TRY data could include years that are either hotter or colder than those in the SAMSON data. For example, the TRY data for Minneapolis resulted in significantly higher energy consumption and costs. In fact, the energy costs were outside the range of values from the SAMSON data. The TRY data had a winter design condition below that of all the SAMSON data and solar data on the low end of the range as well. Similarly, the energy costs exhibit a relatively higher range of variability, but the variation is still small, ranging from –2.2 percent to 3.3 percent, including the TRY data. With the exception of Washington, D.C., the TMY2 data set consistently provides the closest match to the average energy consumption of the SAMSON data. With a few exceptions (New York, Seattle, and occasionally WYEC and WYEC2), simulations using the typical weather data sets under-predict the energy consumption and energy costs.

Figure 4-21 presents another aspect of the impact of weather selection on energy performance simulation: annual peak cooling and heating loads. Figure 4-21 compares the variation in peak annual cooling and heating loads from the simulations using the 30 years of SAMSON data and the weather data file types for Washington, D.C. The left graph of each figure shows the annual peak-cooling load as a fraction of the average annual peak-cooling load for the 30 years. The right side shows similar information for the annual peak-heating load. The horizontal line shown on each graph is the calculated peak design size based on the design conditions (2-1/2 percent for cooling and 99 percent for heating) for the location from the 1993 Fundamentals (ASHRAE 1993). For the SAMSON simulations (1961-1990), the mean of the annual peak loads is shown as a diamond near the center of the left-hand vertical line on the figure. The vertical line represents the range of annual peak loads for the SAMSON simulations—maximum to minimum. The loads from the weather data sets are shown as a fraction of the mean of the annual peak loads from the SAMSON simulations. The values for the weather data files types are shown as a scatter of diamonds to the right of the SAMSON vertical line.

As would be expected, annual peak cooling and heating load vary more than either the annual energy consumption (summed hourly energy) or the annual energy costs (monthly peak demand and summed hourly energy consumption). The peaks depend on how much the building is affected by the hourly temperature fluctuation and incident solar radiation. The range of percentage variation of the peak loads as a function of the design sizing (see above) is shown in the two right-hand columns of Table 4-34.

A few observations about the peak cooling and heating loads become apparent from the results of the simulation. First, the heating design size values are generally higher than the peak heating loads of both the 30-year data set and the typical weather data sets; cooling design size is generally close to or less than the peak cooling loads. This pattern seems to be caused by the use of the more conservative 99 percent design conditions for heating and the more generous sizing allowed for heating by the commercial building energy standards such as Standard 90.1-1989 (ASHRAE 1989). Standard 90.1 allows designers to size heating

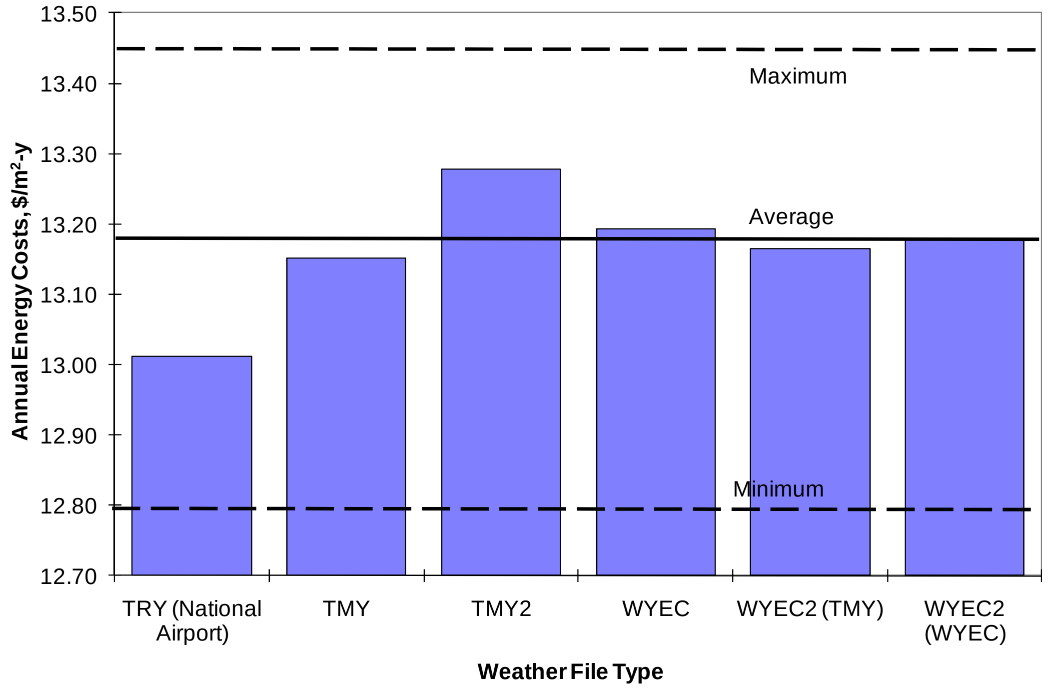


Figure 4-19. Comparison of Annual Energy Consumption for Weather File Types and SAMSON Weather Data in Washington, D.C.

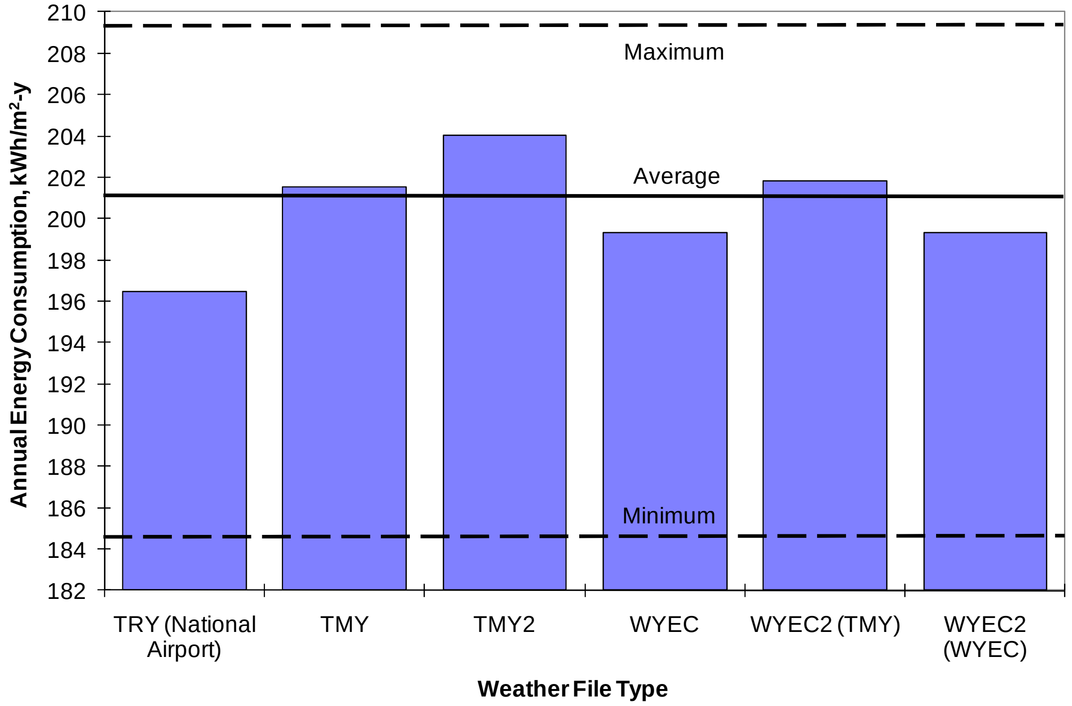


Figure 4-20. Comparison of Annual Energy Costs for Weather File Types and SAMSON Weather Data in Washington, D.C.

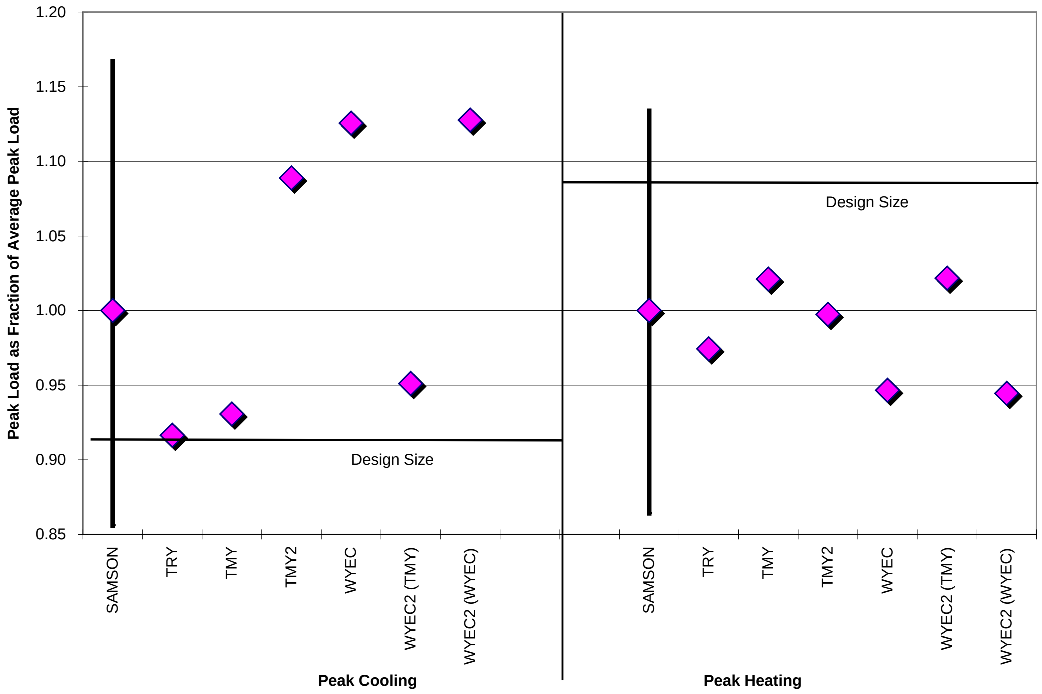


Figure 4-21. Comparison of Annual Peak Loads in Washington, D.C.

equipment up to 40 percent larger than the annual peak-heating load calculated based on the design conditions. On the other hand, Standard 90.1 only allows cooling equipment to be sized up to 20 percent larger than the calculated annual peak-cooling load. For cooling, the combination of less conservative 2-1/2 percent design conditions and the lower over sizing allowance means that for a few hours every year, the cooling equipment may not be able to meet the load.

Overall, the variation in annual peak cooling load ranged from 11.5 percent below the design size to 30.5 percent above. Note that in all the locations, the range of cooling loads from the SAMSON simulations was greater than that of the weather data sets. The variation among the weather data sets for annual peak heating loads ranges from 48.5 percent below the design size to 3.2 percent above. The locations with the greatest heating over sizing were those with relatively low heating loads—Los Angeles, Miami, and Phoenix.

As described above, the range of annual energy consumption and costs and peak cooling and heating loads due to actual weather variation over a 30-year period can be significant—in this case, the SAMSON data set. For the eight locations in this study,

- annual energy consumption varied as much as –11.0 percent to 7.0 percent,

- annual energy cost varied from –4.6 percent to 3.6 percent,
- annual peak electrical demand varied from –4.7 percent to 4.9 percent,
- annual peak cooling loads ranged from 11.5 percent below the design size to 30.5 percent above, and
- annual peak heating loads ranged from 48.5 percent below the design size to 3.2 percent above.

Of the six weather data types studied in this work (TRY, TMY, TMY2, WYEC, and WYEC2 [TMY and WYEC]), TRY showed the most variation, higher and lower (except in mild Los Angeles and hot Miami). This result is demonstrated in the annual energy costs for Minneapolis where the TRY values exceed the maximum from the SAMSON simulations. Another example is Washington, D.C., where both the annual energy consumption and energy costs are lower than all the other weather types even though they are still within the 30-year range shown for SAMSON. Because the method for selecting months for WYEC is limited to matching dry-bulb temperature, the resulting data set is not as representative of the period of record. Simulations using the TMY2 data set more consistently match the simulation results for the SAMSON 30-year period than any other data set. Users of energy simulation programs should avoid using single year, TRY-type weather data. No single year can represent the typical long-term weather patterns. More comprehensive methods that attempt to produce a synthetic year to represent the temperature, solar radiation, and other variables within the period of record are more appropriate and will result in predicted energy consumption and energy costs that are closer to the long-term average. Further, the single year weather file should be broadened beyond the typical (average) to include variations such as cold/cloudy or hot/sunny.

Which weather data should you use for simulating commercial buildings? This study found that the TMY2-type data provides users with energy simulation results that most closely represent typical weather patterns. Alternatively, multiple weather data files to represent a broader range of conditions for a particular locations such as hot/sunny, cold/cloudy, wet, dry, or windy. Even probabilistic methods could be used to determine the appropriate climatic sequences for a range of conditions in a location as robust source climate data sets become available.

Table 4-34. Comparison of Simulated Annual Energy Consumption, Energy Costs, Peak Electric Demand, and Peak Loads for Weather Data Files Types and SAMSON Weather Data

Location	Weather File Type	Total Annual Energy		Annual Peak		
		Consumption, kWh/m^2-yr (Percent of SAMSON Average)	Costs, \$/m^2-yr (Percent of SAMSON Average)	Electric Demand, W/m^2 (Percent of SAMSON Average)	Cooling Load, W/m^2 (Percent of Design Size)	Heating Load, W/m^2 (Percent of Design Size)
Denver, Colorado	SAMSON Average	208.4	4.519	44.1	6.1%	-9.2%
	Design Size	--	--	--	52.3	112.8
	TRY	--	--	--	--	--
	TMY	-0.7%	-2.2%	-0.6%	-0.3%	-0.3%
	TMY2	-0.9%	-1.7%	0.4%	7.6%	-9.2%
	WYEC	-1.9%	-2.2%	-0.1%	1.4%	-7.0%
	WYEC2 (TMY)	--	--	--	--	--
	WYEC2 (WYEC)	-1.2%	-1.7%	0.4%	2.9%	-7.5%
Los Angeles, California	SAMSON Average	157.4	17.108	44.1	14.2%	-25.6%
	Design Size	--	--	--	53.9	85.4
	TRY	0.4%	-0.2%	-0.1%	5.9%	-32.9%
	TMY	-0.2%	-0.4%	0.3%	17.0%	-35.6%
	TMY2	-0.8%	-0.5%	-0.3%	7.1%	-32.0%
	WYEC	1.2%	0.1%	2.0%	30.5%	-37.0%
	WYEC2 (TMY)	--	--	--	--	--
	WYEC2 (WYEC)	1.2%	-0.1%	1.3%	22.8%	-35.5%
Miami, Florida	SAMSON Average	158.6	11.944	50.6	11.1%	-43.5%
	Design Size	--	--	--	79.4	86.7
	TRY	-0.2%	0.2%	-0.1%	13.6%	-43.7%
	TMY	-0.8%	-0.9%	-0.3%	7.9%	-22.2%
	TMY2	-0.6%	-0.3%	0.6%	16.3%	-23.7%
	WYEC	-0.8%	-0.7%	-0.5%	8.8%	-37.5%
	WYEC2 (TMY)	-0.6%	-0.6%	0.1%	10.5%	-21.8%
	WYEC2 (WYEC)	-0.8%	-0.7%	-0.4%	6.9%	-38.5%
Minneapolis, Minnesota	SAMSON Average	256.7	9.899	47.3	13.2%	-4.3%
	Design Size	--	--	--	66.8	121.6
	TRY	5.4%	3.3%	0.6%	22.6%	-2.8%
	TMY	2.3%	1.2%	1.4%	20.9%	-0.7%
	TMY2	-0.4%	-0.6%	-2.2%	-1.5%	-7.3%
	WYEC	1.6%	1.4%	-1.0%	2.4%	-5.1%
	WYEC2 (TMY)	--	--	--	--	--
	WYEC2 (WYEC)	1.4%	1.2%	-1.8%	-0.8%	-5.8%
New York, New York	SAMSON Average	211.3	22.811	47.3	12.4%	-3.7%
	Design Size	--	--	--	67.1	104.6
	TRY	-1.4%	-0.9%	-0.8%	8.4%	-11.2%
	TMY	1.1%	-0.9%	-3.1%	-3.3%	-7.0%
	TMY2	0.2%	-0.6%	0.2%	11.7%	3.2%
	WYEC	3.2%	1.2%	-0.7%	9.0%	-1.6%
	WYEC2 (TMY)	1.6%	-1.9%	-6.1%	-11.6%	0.1%
	WYEC2 (WYEC)	3.2%	1.1%	-0.7%	8.5%	-1.6%

Location	Weather File Type	Total Annual Energy		Annual Peak		
		Consumption, kWh/m^2-yr (Percent of SAMSON Average)	Costs, $\$/m^2$-yr (Percent of SAMSON Average)	Electric Demand, W/m^2 (Percent of SAMSON Average)	Cooling Load, W/m^2 (Percent of Design Size)	Heating Load, W/m^2 (Percent of Design Size)
Phoenix, Arizona	SAMSON Average	165.2	14.096	50.6	9.3%	-33.3%
	Design Size	--	--	--	81.0	91.7
	TRY	1.0%	-1.3%	0.7%	15.3%	-15.6%
	TMY	0.2%	-1.0%	-0.4%	4.5%	-26.5%
	TMY2	-0.1%	-0.4%	-0.6%	8.4%	-27.7%
	WYEC	0.2%	-0.6%	-0.2%	8.5%	-46.3%
	WYEC2 (TMY)	0.0%	-1.2%	-0.8%	2.5%	-28.1%
	WYEC2 (WYEC)	0.0%	-0.9%	-0.2%	7.3%	-48.5%
Seattle, Washington	SAMSON Average	201.5	6.241	43.0	12.3%	-15.3%
	Design Size	--	--	--	50.7	95.5
	TRY	3.9%	1.9%	1.0%	19.6%	-14.0%
	TMY	2.5%	1.4%	-0.6%	7.6%	-18.5%
	TMY2	-0.2%	-0.1%	-0.3%	5.3%	-20.6%
	WYEC	2.8%	1.5%	-0.9%	5.3%	-14.0%
	WYEC2 (TMY)	2.5%	1.4%	-0.7%	7.3%	-17.8%
	WYEC2 (WYEC)	2.7%	1.5%	-1.4%	2.0%	-16.5%
Washington, D. C.	SAMSON Average	201.2	13.235	48.4	9.8%	-7.0%
	Design Size	--	--	--	70.3	103.7
	TRY	-2.3%	-1.3%	-1.4%	0.6%	-9.4%
	TMY	0.2%	-0.3%	-0.7%	2.2%	-5.1%
	TMY2	1.4%	0.7%	1.5%	19.6%	-7.3%
	WYEC	-0.9%	0.1%	0.9%	23.6%	-12.0%
	WYEC2 (TMY)	0.3%	-0.2%	-0.5%	4.4%	-5.0%
	WYEC2 (WYEC)	-0.9%	-0.1%	0.7%	23.8%	-12.2%

4.4.5 Conclusions from ESB Analyses

The summary level information developed from the ESB analyses provided confidence that significant opportunities in existing building retrofit were available. Based on these results, the ESB program moved forward with the staged approach to ESB retrofit—that there were large energy and environmental benefits available at cost-attractive economic returns for building owners. The information from the ESB simulations was used to further support program marketing materials. Building energy simulation was key to convincing US EPA decision makers to launch the ESB program with a staged approach.

From the perspective of this thesis, the large number (more than 22,000) and diversity (staged approach, envelope upgrades, chiller retrofit, and weather data) of simulations required to support the ESB analysis required a very structured approach. This required a file naming convention, data storage, and management structure for the input, output, and extracted data files as well as the summary material. This allowed the input and output results to be easily and quickly identified, verified, retrieved, and summarized.

4.5 Summary

The results from three examples of using building performance simulation to develop, test, and evaluate building standards, utility incentives, or retrofit programs have been presented in this chapter. In the first case, building energy simulation was used to study changes in building envelope thermo-physical characteristics for a specific climate. This study allowed the building energy standard developers to evaluate and set the level of prescriptive envelope requirements and related whole-building energy performance requirements. For the utility incentive evaluation, building simulation confirmed that, for the current envelope upgrade costs and utility costs, the thermal envelope requirements were already at or near the economic optimum. In the third case, an extensive series of energy simulations provided key insights into how buildings work. This study allowed a national building retrofit program to confidently move forward with a staged, structured approach. Pre-simulating many of the potential cases reduced the uncertainty and identified the paths that yield the highest energy savings at the highest economic return.

From these three research studies, additional key attributes for large multi-simulation policy studies include:

- Clear structure comprising data structure and management, and automated quality assurance for input and output, and
- Study design to include scope of the parameters to be studied, resulting performance data, and structure of the results.

4.6 References

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Chapter 5
Evaluating Climate Change and Heat Islands Impacts on Buildings

Everybody talks about the weather, but nobody does anything about it.

Charles Dudley Warner

5.1 Introduction

As described in Chapter 3, weather files that represent changes in temperature, humidity, and cloud cover based on International Panel on Climate Change (IPCC) climate change scenarios were created from existing representative and extreme meteorological weather data. Similar weather files were created to represent a range of urbanization or heat island effects. For each location, a combination of typical year data (TMY2, CWEC, or IWEC) and high- and low-energy weather years were used as the baseline. Then, for each of these cases (typical/high/low), weather files were created to represent four IPCC climate change scenarios (A1FI, A2, B1, and B2) and two levels of heat island (1 and 5°C or 1 and 3°C in high-latitude locations). An office building with three distinct energy performance levels (standard practice, low energy, and developing) was defined and a series of simulations performed for 25 locations around the world. Heating and cooling design conditions from Chapter 28 of the *Handbook of Fundamentals* (ASHRAE 2005) were used in all cases; using 2005 design conditions to auto-size HVAC equipment and systems. EnergyPlus (US DOE 2007) was used to calculate building thermal flows given the various weather data. For each simulation, results available from the annual simulations include:

- energy end-uses, consumption and demand by energy source;
- energy consumption and demand by zone, system, and plant equipment;
- surface temperature and conduction and radiation through the building envelope;
- zone-sensible, latent, convective, and radiant heating gains and losses;
- zone-air and mean-radiant temperature, relative humidity, and humidity ratio;
- HVAC equipment runtime fraction, heating and cooling rates, part-load ratios, and temperature and humidity; and
- atmospheric emissions by pollutant type and equivalent carbon.

Development of the climate change scenario and heat island weather files and the prototype office building was described in Section 3.5. This chapter summarizes the energy performance results and findings from that analysis. Although the data shown in the thesis is usually source or primary energy, CO_2 building performance results were also available. But the quality of the CO_2 data are limited by the availability of CO_2 data and conversion factors. Annual average CO_2 conversion factors are available for most countries and occasionally for sub-national regions such as electric grid regions, states or provinces. As the fuel mix for the electrical plants changes with time of day and year, it is difficult to determine what CO_2 can be attributed to the energy delivered to the building.

5.2 Annual Energy Performance Results

Annual energy performance results from the EnergyPlus simulation of the climate change scenario and heat island cases for Washington, D.C. are shown in Figures 5-1 through 5-3. These figures show the annual energy consumption by end-use for the small office building in Washington, D.C., USA (Köppen region Dfa, wet all seasons, hot summer). The energy end-uses include heating, reheat, cooling ,fans, lights, plug loads, and service hot water (SHW). Scripts and procedures created for this study and described in Chapter 3 automatically extracted results data, which then could be imported into the location template spreadsheets and graphs and tables that had been automatically created. Note that all the remaining figures in this chapter use source or primary energy, which relates more directly to the energy costs and environmental impacts of the various energy sources.

Figures 5-2 and 5-3 have sets of three columns: low, TMY2, and high. The low and high cases are the years from the period of record that result in the lowest and highest energy use for the standard building; TMY2 is the typical-year weather file. Figure 5-2 compares the results for the standard small office building with the four IPCC climate-change scenarios (A1FI, A2, B1, and B2) using source or primary energy—taking into account all the energy flows from the source energy into the power plants. Figure 5-3 compares the results of the standard building with those of the two heat island cases (1 and 5°C), again with source or primary energy.

Figures 5-1 through 5-3 show a small increase in total source energy across the various scenarios. For the climate change scenarios, cooling increases are offset by decreases in heating. In contrast, total site energy consumption—what is measured by utilities at the

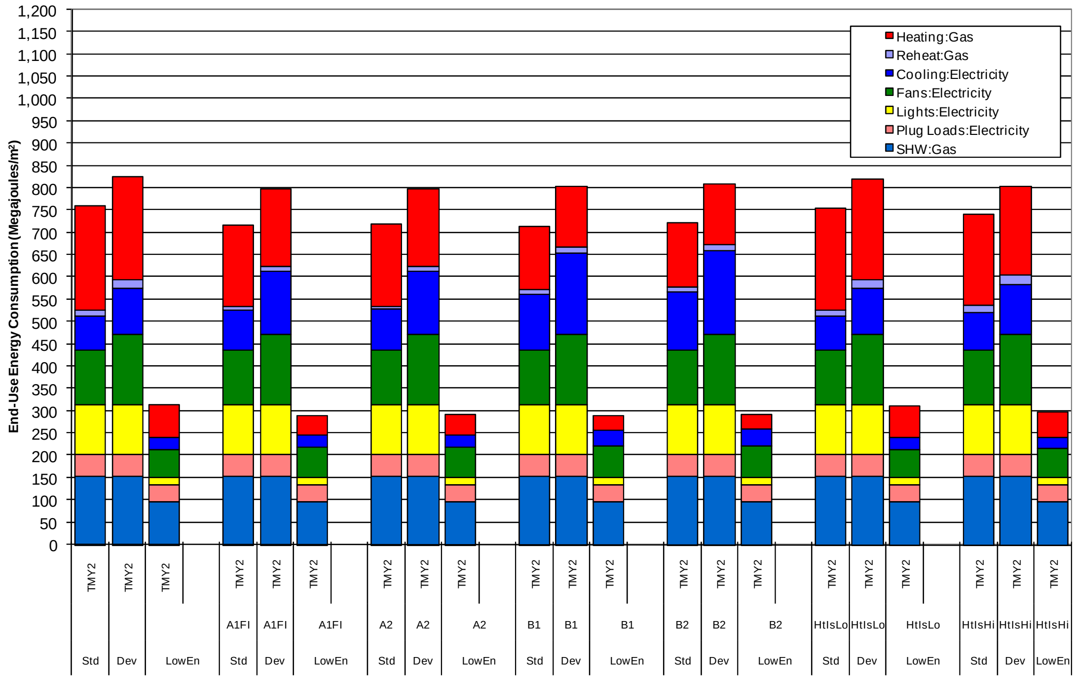

Figure 5-1. Annual Site Energy End-Use Consumption, in MJ/m^2, in Washington, D.C., USA for Standard, Developing, and Low-Energy Buildings Using Typical Year, Climate Change Scenarios, and Heat Island Cases Using Typical Weather Data

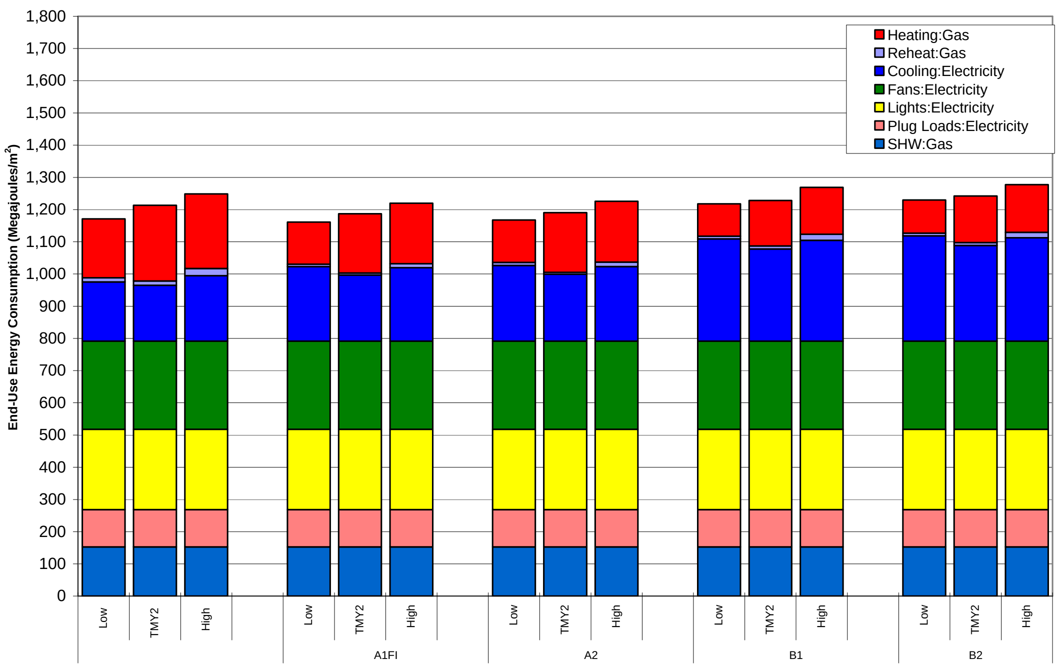

Figure 5-2. Annual Source Energy End-Use Consumption, in MJ/m^2, in Washington, D.C., USA for Standard Building and Four Climate Change Scenarios Using Typical Weather

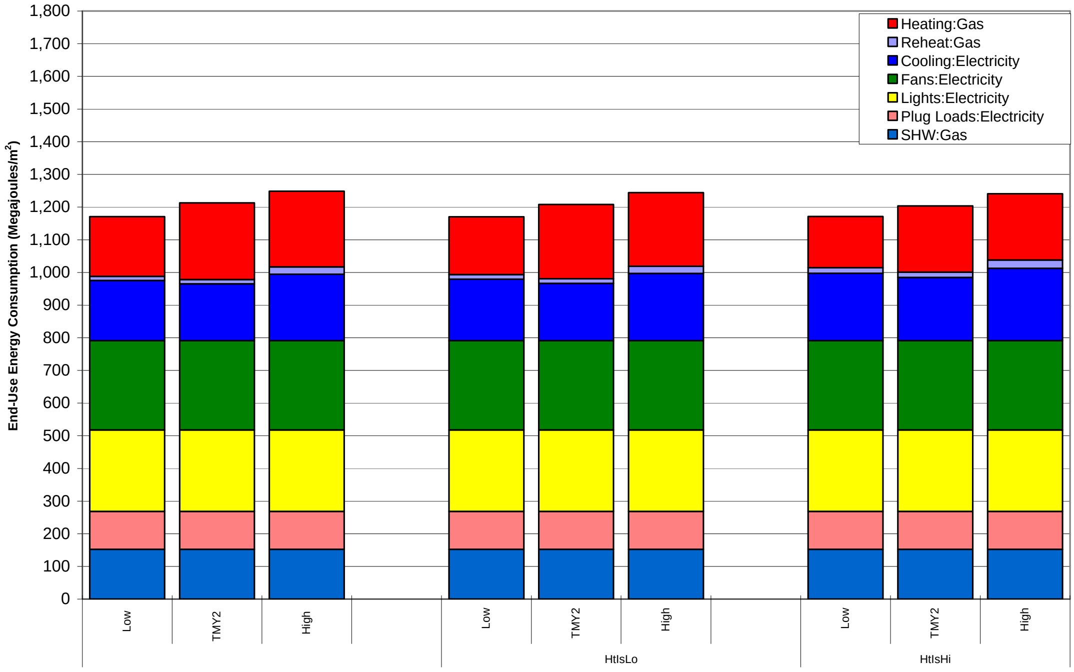

Figure 5-3. Annual Source Energy End-Use Consumption, in MJ/m^2, in Washington, D.C., USA for Standard Building and High and Low Heat Island Cases Using Typical Weather

building site—for the small office in Washington, D.C. declines slightly over the range of scenarios and for the two heat island cases, despite the predicted increase in temperature (see Appendix D for figures showing this trend). This is due to significant decreases in less-efficient, natural gas-fired heating while the more efficient electric cooling increases slightly. This fuel swapping results in roughly equivalent total site energy consumption over the range of scenarios.

5.3 Monthly End-Use Energy Performance Results

Figures 5-4 and 5-5 show the monthly source energy end-use consumption for the climate change scenarios in the standard and developing office buildings in Washington. The swapping between heating and cooling mentioned above for the annual energy consumption can be clearly seen in the monthly data in Figures 5-4 and 5-5. For the base weather data, the substantial portion of the cooling occurs primarily between May and September. With the climate change scenarios, the cooling season is extended throughout the year, with substantial cooling from March through October. For the developing building case (Figure 5-5), the end-use swapping is even more apparent, with larger decreases in heating and cooling now nearly year-round in Washington. The more severe A1FI and A2 climate change scenarios normally result in higher energy use than do the B1 and B2 scenarios—except as described in Section 3.5.4 and seen in Figure 3-14, for Washington the predicted temperature changes for the A1FI and A2 scenarios are smaller than those for the B1 and B2 scenarios. The impacts of this smaller temperature change is seen in Figures 5-4 and 5-5 where the monthly energy use for B1 and B2 is greater than A1FI and A2.

For the small office building designed to the energy standard, the largest difference is 7 percent; while for the low-energy office building, the largest difference is 5 percent. Similar reduction in the spread of results is seen (but not included in this chapter) among the high, low, and typical cases. This suggests that the low-energy office building, while already significantly reducing energy consumption by 50 percent over the baseline energy standard, also reduces the variation in energy performance due to year-to-year variation in climatic conditions. This also shows that the characteristics can have as large or larger an impact on energy use than the apparent changes due to predicted climate change. For the developing case, the climate scenarios result in more than a 15 percent change in monthly energy performance for a few cases, much higher than either the standard or low-energy buildings. The difference for the low-energy office building is that the variation between the baseline and the climate change scenarios or heat island cases is significantly less.

Similar results for the heat island cases in the standard, low-energy, and developing building are shown in Figures 5-6, 5-7, and 5-8, respectively. While the end-use swapping (heating to cooling) is also apparent in the heat island cases, it is not as pronounced as in the climate change scenarios.

The remaining figures in this chapter show monthly source end-use energy consumption of the standard and low-energy versions of the small office building for San Juan (Figures 5-9 through 5-12) and Resolute (Figures 5-13 through 5-16). Only the monthly energy consumption is shown here as it reveals more about the changes in energy use patterns for these two locations than does the annual energy performance data.

For San Juan, a similar pattern to Washington emerges—increases in cooling causing an overall increase in energy use due to the climate scenarios. Unlike Washington, San Juan has little heating for end-use swapping. Thus, the overall result is a net increase in annual energy use. But as with Washington, the low-energy building case (Figures 5-10 and 5-12) shows the least impacts due to either climate change or the heat island impact. The developing

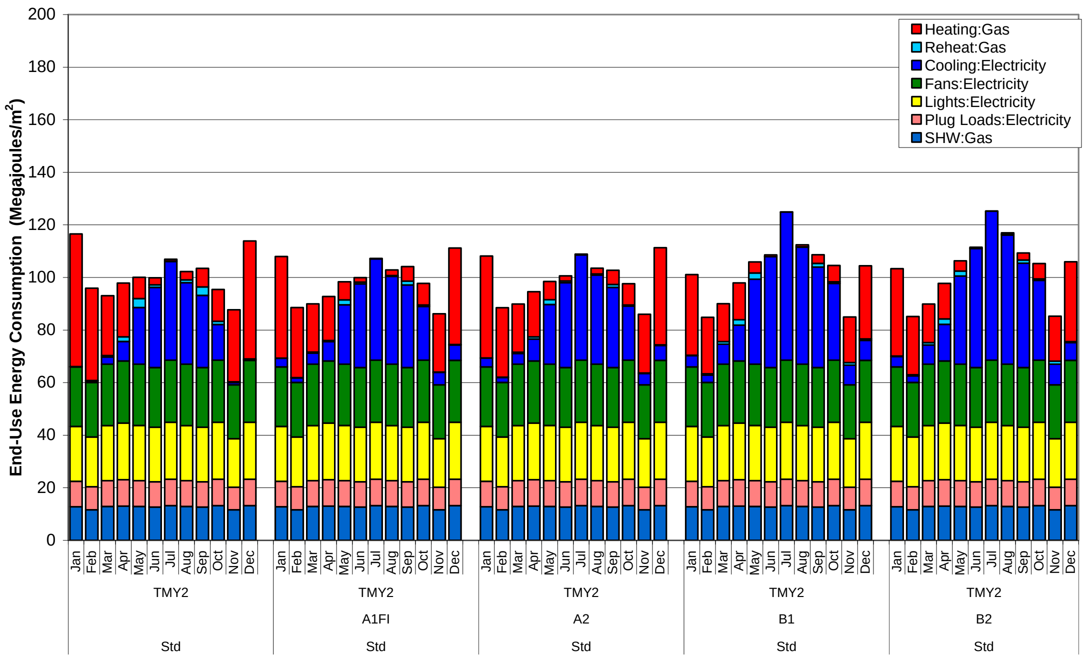

Figure 5-4. Monthly Source Energy End-Use Consumption, in MJ/m^2, in Washington, D.C., USA for Standard Building and Four Climate Change Scenarios Using Typical Weather

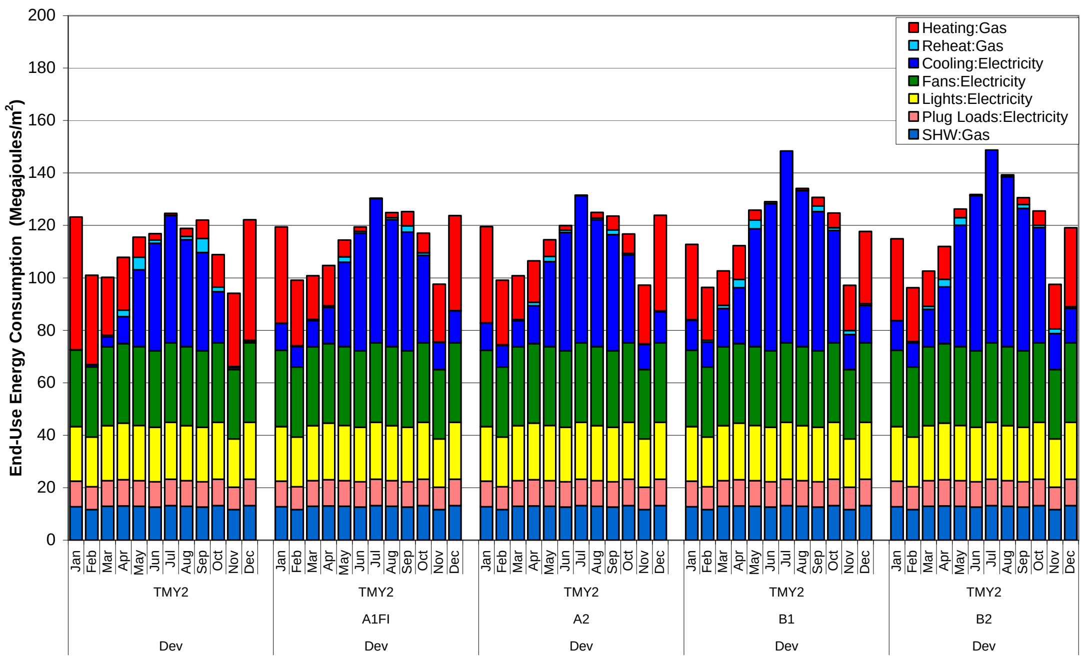

Figure 5-5. Monthly Source Energy End-Use Consumption, in MJ/m^2, in Washington, D.C., USA for Developing Building and Four Climate Change Scenarios Using Typical Weather

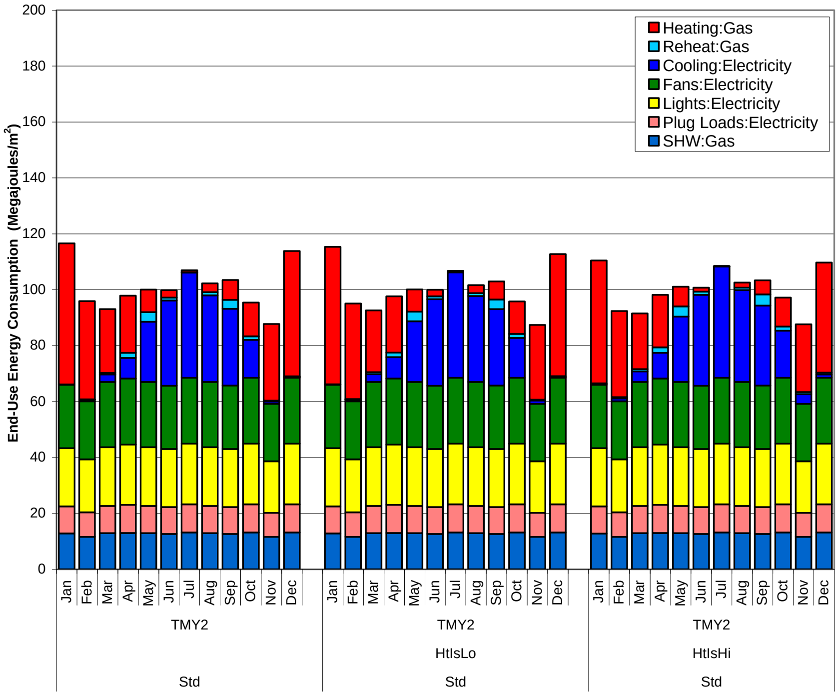

Figure 5-6. Monthly Source Energy End-Use Consumption, in MJ/m^2, in Washington, D.C., USA for Standard Building and High and Low Heat Island Cases Using Typical Weather

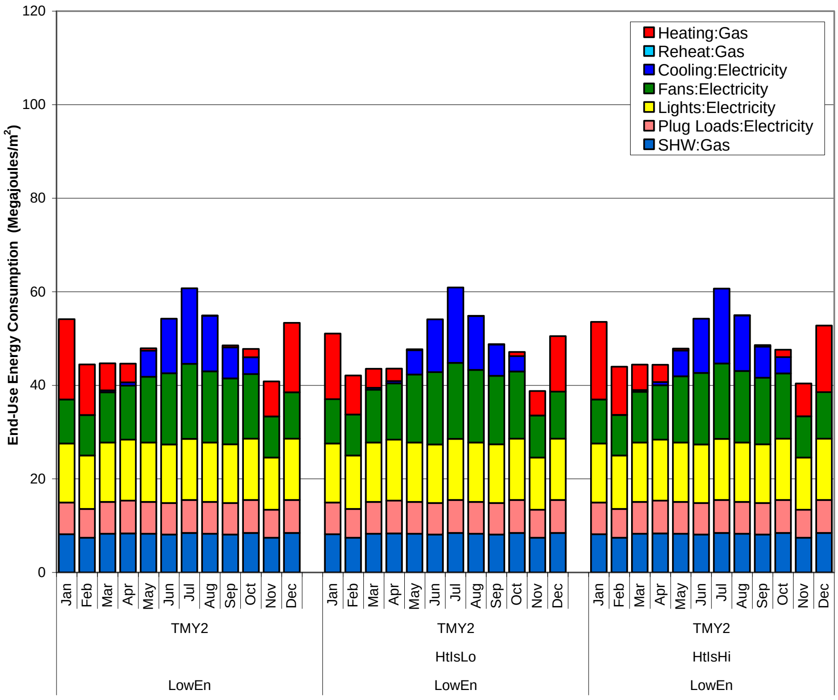

Figure 5-7. Monthly Source Energy End-Use Consumption, in MJ/m^2, in Washington, D.C., USA for Low Energy Building and High and Low Heat Island Cases Using Typical Weather

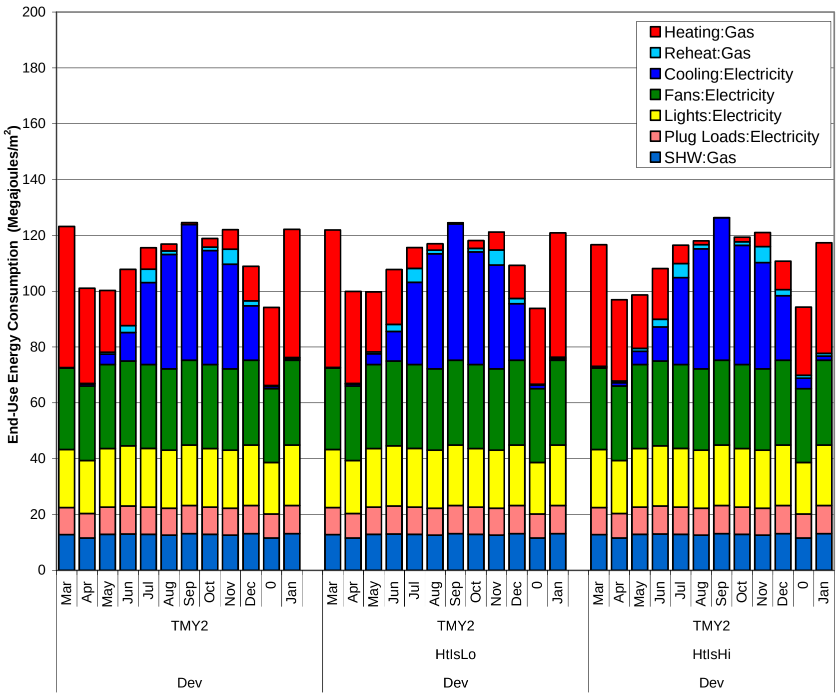

Figure 5-8. Monthly Source Energy End-Use Consumption, in MJ/m^2, in Washington, D.C., USA for Developing Building and High and Low Heat Island Cases Using Typical Weather

building case (see further results in Appendix D) shows significant increases in monthly energy consumption—in some cases approaching 20 percent or more.

For Resolute, a similar pattern occurs, but a different result: significant reductions in heating due to the climate scenarios. But with almost no cooling load, the result is a significant overall decrease in energy use. As with San Juan and Washington, the low-energy buildings (Figures 5-14 and 5-16) see almost no impacts for the climate scenarios while the developing building case sees monthly energy use and variability twice as large.

5.4 Variation in Energy Performance Results Due to Different Weather Years

Sections 5.2 and 5.3 showed only the results for the typical weather and the modifications for the climate change scenarios and heat island cases. This section adds the high- and low-energy years from the period of record. Table 5-1 compares the ranges of decreases and increases for the base weather years (1961-1990); the A1FI, A2, B1, and B2 climate change cases; and the two urban heat island cases—1°C (low) and 5°C (high) for the 25 locations. Looking again at Washington, San Juan, and Resolute, definite trends appear. For

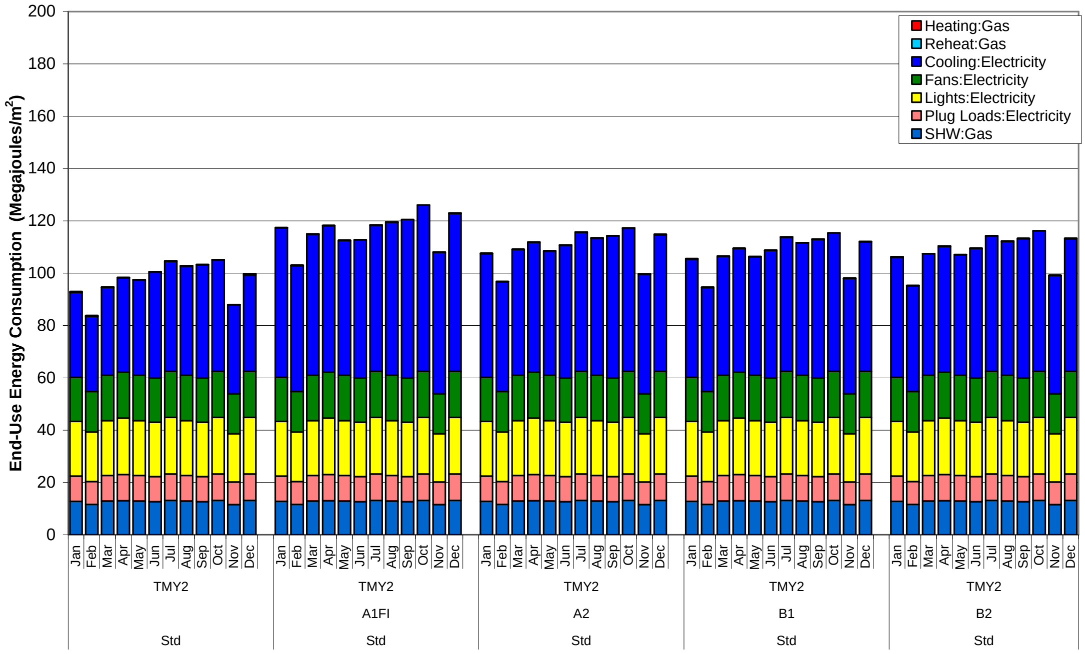

Figure 5-9. Monthly Source Energy End-Use Consumption, in MJ/m^2, in San Juan, Puerto Rico for Standard Building and Four Climate Change Scenarios Using Typical Weather

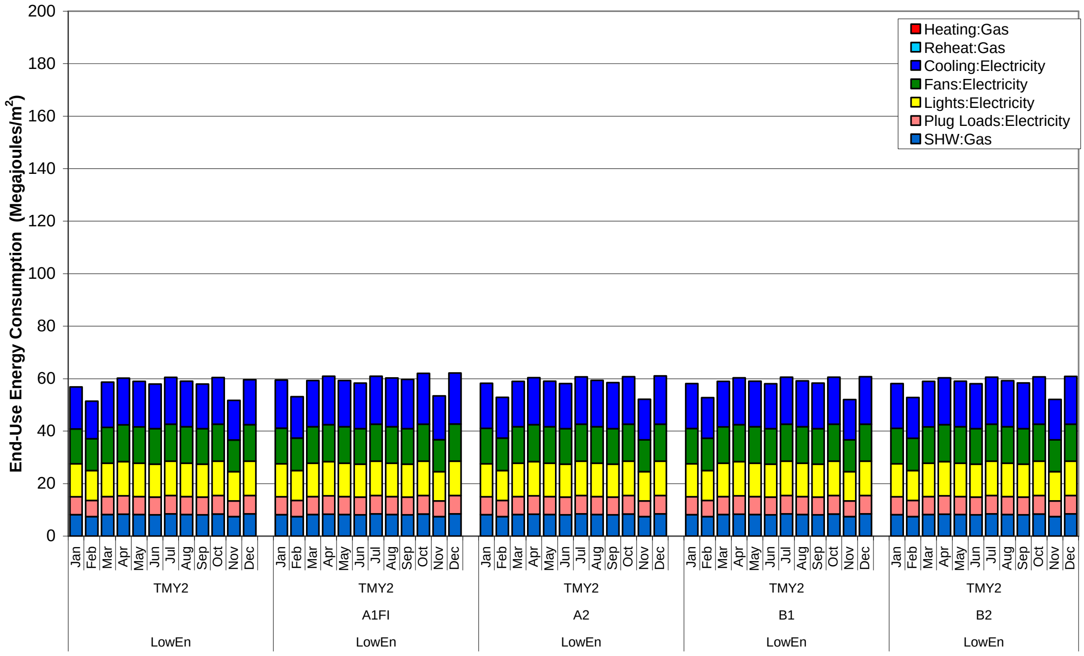

Figure 5-10. Monthly Source Energy End-Use Consumption, in MJ/m^2, in San Juan, Puerto Rico for Low Energy Building and Four Climate Change Scenarios Using Typical Weather

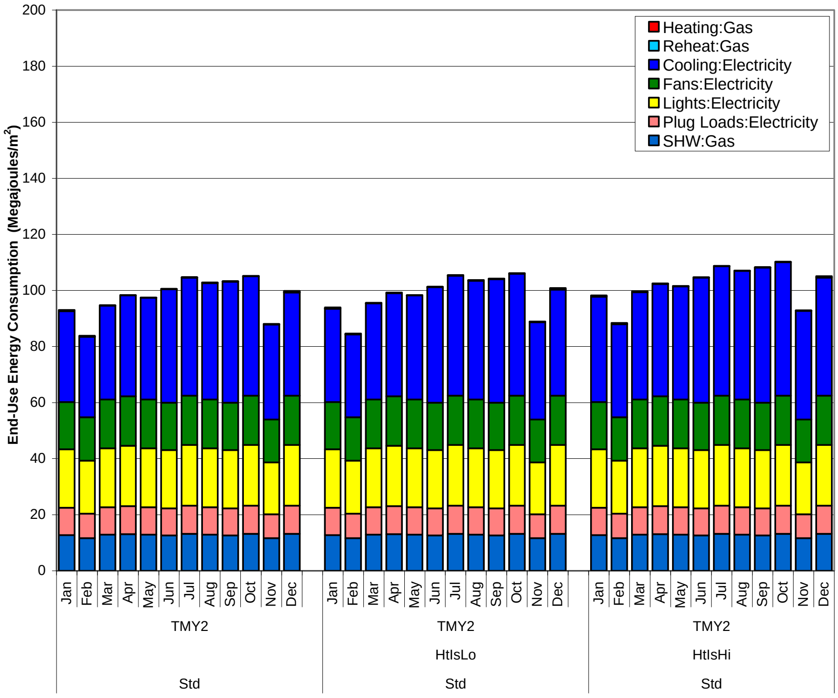

Figure 5-11. Monthly Source Energy End-Use Consumption, in MJ/m^2, in San Juan, Puerto Rico for Standard Building and High and Low Heat Island Cases Using Typical Weather

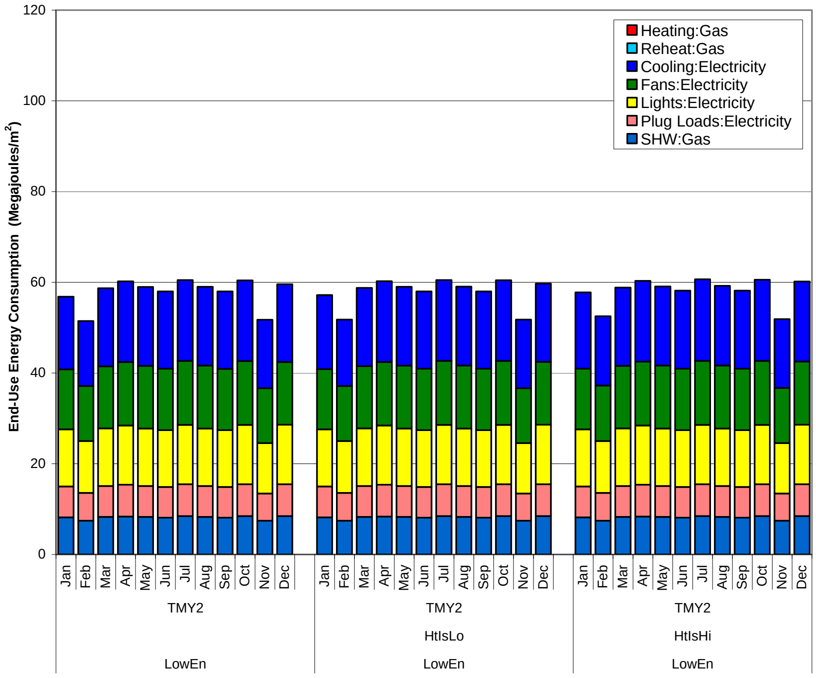

Figure 5-12. Monthly Source Energy End-Use Consumption, in MJ/m^2, in San Juan, Puerto Rico for Low Energy Building and High and Low Heat Island Cases Using Typical Weather

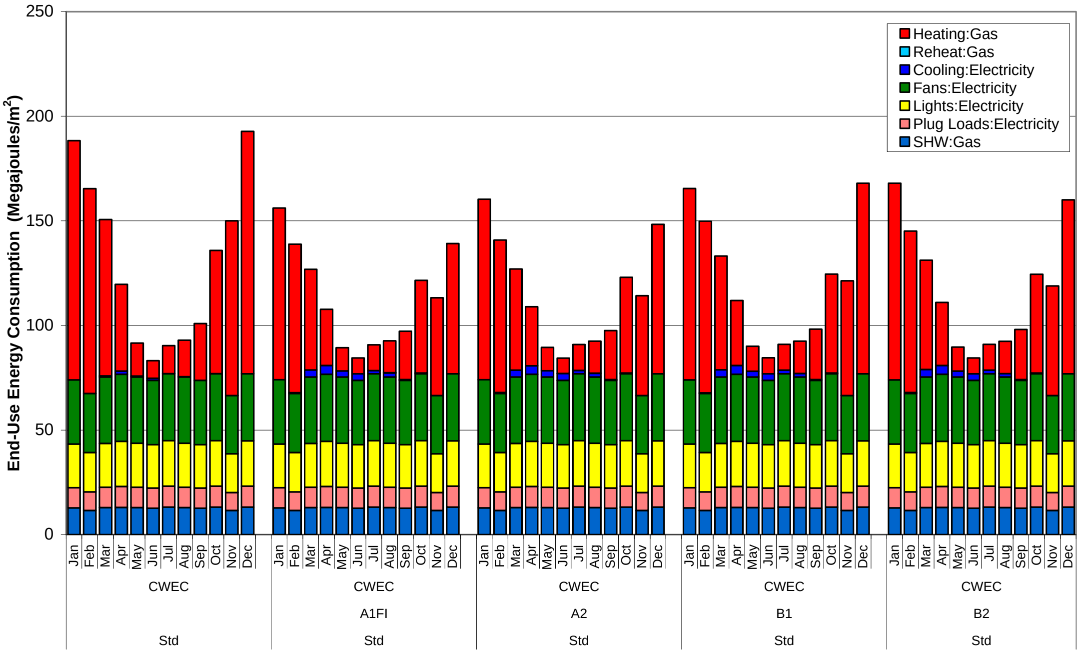

Figure 5-13. Monthly Source Energy End-Use Consumption, in MJ/m^2, in Resolute, Nunavut, Canada for Standard Building and Climate Change Scenarios Using Typical Weather

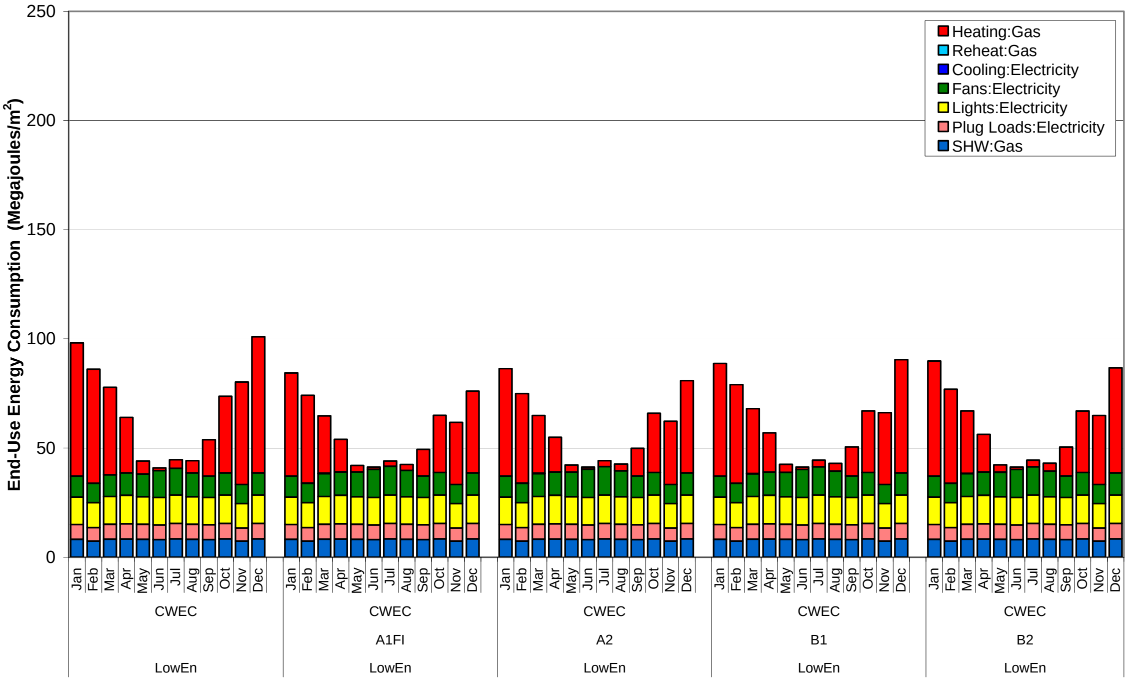

Figure 5-14. Monthly Source Energy End-Use Consumption, in MJ/m^2, in Resolute, Nunavut, Canada for Low Energy Building and Climate Change Scenarios Using Typical Weather

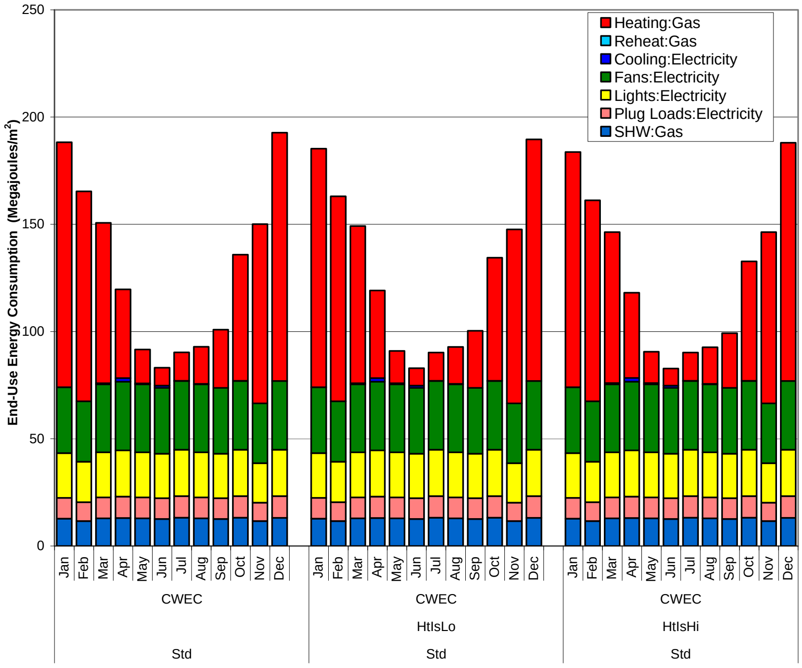

Figure 5-15. Monthly Source Energy End-Use Consumption, in MJ/m^2, in Resolute, Nunavut, Canada for Standard Building and Heat Island Cases Using Typical Weather

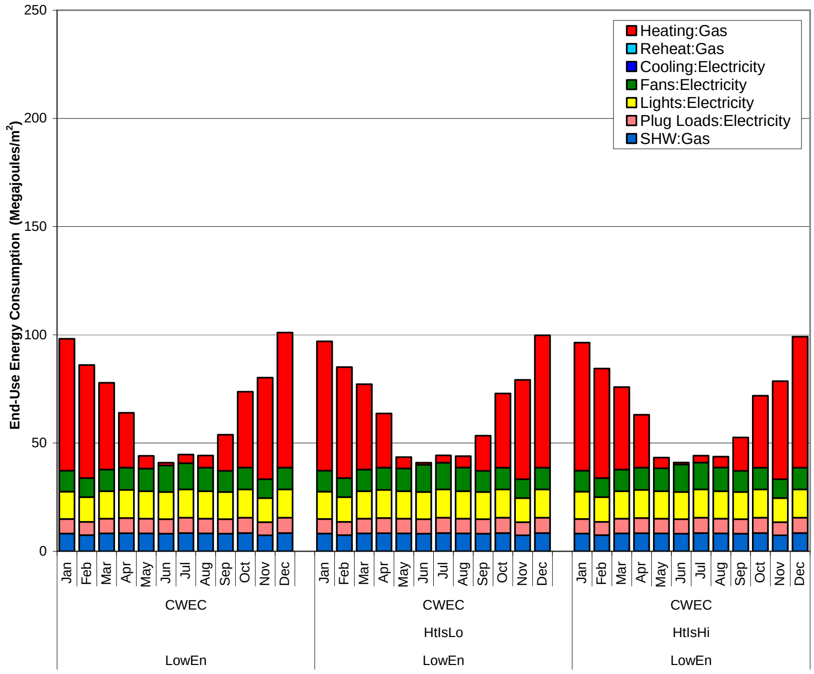

Figure 5-16. Monthly Source Energy End-Use Consumption, in MJ/m^2, in Resolute, Nunavut, Canada for Low Energy Building and Heat Island Cases Using Typical Weather

Washington, D.C. and San Juan, the range of energy performance between the years with lowest and highest energy use decreases for all the modified climate cases. For Resolute, the ranges increase slightly for the developing building model, between 0.1 and 1 percent, but decrease slightly for the standard and low-energy models.

In Washington, D.C., the annual energy consumption for the developing case small office building varied by 9.2 percent between the years with the highest and lowest energy use, with the typical year falling roughly in the middle of the range. For the standard case, the variation between the highest and lowest energy years was smaller at 8.8 percent. But the low-energy building had a similar pattern for the base year-to-year variation in weather patterns, with a range of variation from high to low of less than 9.1 percent. Interestingly for the results in Washington, D.C., the ranges were slightly less for the extreme climate change scenario (A1FI): 7.5 percent, 9.4 percent, and 5.8 percent, respectively for the developing, standard, and low-energy cases.

Results for the heat island cases are somewhat different due to the different diurnal temperature patterns extending high daytime temperatures into the evening hours and depressing daytime temperatures till later in the day. For Washington, D.C., the range of variation among years for the low (1°C) urban heat island case was similar to the baseline weather years: 9.1 percent, 8.3 percent, and 4.9 percent, respectively for the developing, standard, and low-energy building cases. When the high (5°C) urban heat island cases are applied in Washington, D.C., the variation is compressed somewhat: 8.7 percent, 8.2 percent, and 4.3 percent between the years with the highest and lowest energy use, respectively again for the developing, standard, and low-energy building models. In all cases, the energy performance of the low-energy building model was the least affected by year-to-year variation, predicted climatic changes for 2100, or urban heat islands.

The annual energy use in San Juan for the developing case small office building ranged 4.7 percent between the years with the highest and lowest energy use, lower than either the Washington, D.C. or Resolute results. For the standard case, the variation between the highest and lowest energy years was a bit larger at 5.3 percent. But the low-energy building was almost insensitive to the year-to-year variation in climate conditions, with range from low to high of only 0.5 percent. In San Juan, the ranges decreased slightly for the standard building under the extreme climate change scenario (A1FI), while the developing and low-energy models increased: 4.9 percent, 4.8 percent, and 2.1 percent, respectively for the developing, standard, and low-energy cases.

Results for the heat island cases in San Juan are similar to the base weather data despite the change in diurnal temperature patterns. The range of variation among years for the low (1°C) urban heat island case was similar to the baseline weather years: 4.8 percent, 5.3 percent, and 0.4 percent, respectively for the developing, standard, and low-energy building cases, with similar results for the high (5°C) urban heat island cases: 4.9 percent, 5.1 percent, and 0.4 percent between the years with the highest and lowest energy use. In all cases, the energy performance of the low-energy building model was again the least affected by year-to-year variation, predicted climatic changes for 2100, or urban heat islands.

Resolute demonstrates the greatest variability of the locations shown in this thesis, generally around 10 percent from the high to low years among all the cases. The annual energy performance for the developing model varied by 11.5 percent between the highest and lowest energy use years. For the standard case, the variation between the highest and lowest energy years was similar at 11.2 percent, but the low-energy building had a slightly lower range of energy use for the base year-to-year variations of 9.71 percent. For Resolute, the results for the extreme climate change scenario (A1FI) saw increased ranges of variability: 12.4 percent, 11.0 percent, and 11.2 percent, respectively for the developing, standard, and low-energy cases.

Results for the heat island cases are close to the base weather data results, with only the standard model reducing the range of variation slightly (11.2 to 11.0 percent). For Resolute, the range of variation among years for both the low (1°C) and high (3°C) urban heat island cases is almost unchanged from the standard weather data: 11.5 percent, 11.0 percent, and 9.5 percent, respectively for developing, standard, and low-energy building models.

In general, the low-energy building model shows the least change in energy performance in response to variations in climatic conditions. It also usually results in annual energy performance in the range of 50-60 percent less than the standard model. In addition, the photovoltaic system often meets or exceeds the remaining energy use, making these building net-zero energy. In contrast, the developing building model shows a substantial increase (around 10-20 percent) in annual energy performance over that of the standard building. When the climate change scenarios are applied, this increases by another 10 percent.

Table 5-1. Ranges of Percent Change in Energy Performance for the Low and High Energy Years in Comparison with Typical Weather Data Arranged by Köppen Climate Type (Hot Tropical to Severely Cold)

Location	Köppen Climate Type	Building	Base Weather Data (1961-1990 and Typical)	Climate Change Scenario				Urban Heat Island	
				A1FI	A2	B1	B2	Low (1 C)	High (3 or 5C)
Singapore, SGP	Af	Standard	-1.66 to 2.25	-1.53 to 2.17	-1.53 to 2.24	-1.53 to 2.23	-1.48 to 2.24	-1.67 to 2.2	-1.58 to 2.14
		Developing	-1.64 to 2.4	-1.66 to 2.63	-1.61 to 2.67	-1.55 to 2.7	-1.52 to 2.7	-1.62 to 2.4	-1.62 to 2.46
		Low-Energy	0.04 to 0.11	-0.3 to 0.78	-0.19 to 0.57	-0.05 to 0.29	-0.07 to 0.32	0.01 to 0.12	-0.06 to 0.27
San Juan, Puerto Rico	Am	Standard	-0.9 to 4.4	-0.66 to 4.23	-0.42 to 4.41	-0.3 to 4.46	-0.31 to 4.44	-0.93 to 4.36	-0.97 to 4.2
		Developing	-0.69 to 4.	-0.62 to 4.27	-0.37 to 4.25	-0.2 to 4.29	-0.26 to 4.28	-0.82 to 3.96	-1.02 to 3.9
		Low-Energy	0.14 to 0.48	-0.2 to 1.93	0.14 to 1.16	0.18 to 0.88	0.18 to 0.98	0.11 to 0.41	-0.04 to 0.33
Miami, Florida, USA	Aw	Standard	0.32 to 2.68	-1.4 to 1.48	-1.31 to 1.77	-1.09 to 2.03	-1.05 to 2.06	0.18 to 2.39	-0.13 to 1.61
		Developing	-0.32 to 2.13	-2.4 to 1.06	-2.31 to 1.35	-2.14 to 1.52	-2.13 to 1.49	-0.53 to 1.75	-0.7 to 1.09
		Low-Energy	0.31 to -2.19	0.15 to -1.11	0.15 to -1.54	0.18 to -1.89	0.2 to -1.88	0.31 to -2.17	0.22 to -2.1
Cairo, Egypt	BSh	Standard	-2.76 to 1.13	-2.62 to -1.23	-2.85 to -1.22	-2.77 to -0.54	-2.81 to -1.06	-3.16 to 0.64	-3.24 to 0.45
		Developing	-2.61 to 1.18	-2.49 to -1.48	-2.72 to -1.51	-2.67 to -0.82	-2.68 to -1.38	-2.92 to 0.68	-2.99 to 0.32
		Low-Energy	-0.3 to 0.45	-0.4 to -0.38	-0.68 to -0.47	-0.65 to 0.2	-0.73 to -0.23	-0.34 to 0.37	-0.67 to 0.01
Boulder, Colorado, USA	BSk	Standard	-4.01 to 2.81	-0.46 to -1.08	-0.86 to -0.53	-1.34 to 0.11	-1.37 to -0.08	-3.87 to 2.75	-2.98 to 2.54
		Developing	-2.92 to 2.23	-0.08 to -2.86	-0.36 to -2.43	-0.69 to -1.87	-0.71 to -2.05	-3.54 to 2.23	-1.87 to 1.94
		Low-Energy	-2.92 to 4.89	-0.52 to 1.01	-0.95 to 1.7	-1.3 to 2.47	-1.32 to 2.3	-2.88 to 4.61	-2.7 to 3.63
Mexico City, Mexico	BSk	Standard	-2.29 to 1.66	-0.09 to -0.24	0.14 to -0.14	-0.81 to 0.05	-0.41 to 0.0	-2.2 to 1.8	-2.1 to 1.28
		Developing	-1.59 to 1.57	0.08 to -0.49	0.35 to -0.52	-0.65 to -0.37	-0.28 to -0.44	-1.7 to 1.41	-1.65 to 0.7
		Low-Energy	0.64 to -0.05	0.84 to -0.04	0.96 to -0.06	1.04 to -0.14	1.06 to -0.04	0.85 to 0.13	1.16 to 0.29
New Delhi, India	BWh	Standard	-2.25 to 3.41	-2.54 to 2.26	-3.19 to 2.27	-3.12 to 2.28	-3.14 to 2.47	-2.38 to 3.36	-2.39 to 3.1
		Developing	-2.22 to 2.95	-2.3 to 1.68	-2.73 to 1.75	-2.76 to 1.73	-3.01 to 1.74	-2.24 to 3.11	-2.2 to 2.78
		Low-Energy	0.41 to -0.17	-0.44 to -0.01	-0.48 to -0.23	-0.45 to -0.34	-0.49 to -0.38	0.45 to -0.19	0.42 to -0.2
Tokyo, Japan	Cfa	Standard	-4.15 to 0.49	-1.75 to -1.41	-2.2 to -1.62	-2.99 to -2.78	-2.52 to -2.18	-4. to 0.19	-4.01 to 0.53
		Developing	-5.06 to 1.06	-1.47 to -1.65	-2.37 to -1.94	-3.09 to -2.71	-2.29 to -2.34	-4.85 to 0.54	-4.63 to 1.04
		Low-Energy	-3.66 to -2.2	-1.79 to 0.48	-2.07 to 0.04	-2.08 to -0.7	-2.07 to -0.4	-3.51 to -2.2	-3.06 to -2.61

Location	Köppen Climate Type	Building	Base Weather Data (1961-1990 and Typical)	Climate Change Scenario				Urban Heat Island	
				A1FI	A2	B1	B2	Low (1 C)	High (3 or 5C)
Sao Paulo, Brazil	Cfa	Standard	-3.06 to -2.61	-1.05 to -1.68	-1.31 to -1.56	-1.16 to -0.99	-1.3 to -0.98	-1.93 to 1.36	-2.53 to 0.06
		Developing	-2.12 to 1.54	-0.85 to -2.57	-1.19 to -2.45	-0.99 to -1.65	-1.11 to -1.83	-1.93 to 0.98	-2.5 to -0.67
		Low-Energy	0.54 to -1.85	0.14 to -0.51	0.1 to -0.61	-0.27 to -1.42	-0.13 to -1.18	0.52 to -1.83	0.48 to -1.87
London, England, UK	Cfb	Standard	-3.71 to 4.16	-2.32 to 1.92	-3.04 to 1.54	-3.74 to 2.64	-3.8 to 2.35	-3.76 to 4.02	-3.14 to 3.6
		Developing	-4.17 to 4.34	-2.39 to 2.46	-2.98 to 2.02	-3.65 to 3.27	-3.89 to 3.02	-4.03 to 4.36	-3.52 to 4.01
		Low-Energy	-3. to 2.07	-0.59 to 2.63	-0.69 to 1.92	-1.66 to 1.59	-1.42 to 1.6	-2.87 to 2.12	-2.43 to 2.32
Johannesburg, South Africa	Cfb	Standard	-2.54 to 5.25	-0.67 to 2.41	-0.59 to 2.38	-1.46 to 2.91	-0.88 to 3.01	-2.66 to 5.1	-2.45 to 5.64
		Developing	-2.31 to 4.45	-0.5 to 2.07	-0.47 to 2.07	-1.32 to 2.1	-0.73 to 2.52	-2.4 to 4.15	-2.17 to 4.36
		Low-Energy	-0.61 to 1.14	0.48 to 0.01	0.39 to -0.21	-0.07 to -0.05	0.08 to -0.31	-0.5 to 0.82	-0.24 to 0.23
Punta Arenas, Chile	Cfc	Standard	-1.57 to 3.11	-2.75 to -100.	-2.66 to -100.	-2.23 to -100.	-2.36 to -100.	-1.77 to 3.01	-2.08 to 2.86
		Developing	-2.72 to 3.27	-3.23 to -100.	-3.18 to -100.	-2.94 to -100.	-3.03 to -100.	-2.82 to 3.22	-3.1 to 3.14
		Low-Energy	-1.85 to 3.52	-1.61 to -100.	-1.64 to -100.	-1.79 to -100.	-1.8 to -100.	-1.85 to 3.51	-1.82 to 3.49
Buenos Aires, Argentina	Csa	Standard	-0.4 to 3.82	0.32 to 1.17	0.07 to 1.69	-0.15 to 1.83	-0.03 to 1.51	-0.2 to 3.82	0.26 to 3.06
		Developing	-0.11 to 4.05	0.48 to 0.64	0.11 to 1.22	-0.51 to 1.35	-0.12 to 1.17	-0.27 to 3.65	0.02 to 2.74
		Low-Energy	1.69 to 0.62	0.53 to -0.08	0.69 to 0.02	1.32 to 0.11	0.99 to 0.04	1.66 to 0.59	1.44 to 0.52
Los Angeles, California, USA	Csb	Standard	-6.39 to 5.7	-2.29 to 2.43	-2.75 to 2.74	-3.53 to 3.44	-3.39 to 3.22	-5.8 to 5.6	-4.48 to 4.28
		Developing	-6.69 to 6.74	-2.22 to 2.15	-2.76 to 2.83	-3.59 to 3.71	-3.36 to 3.36	-6.34 to 6.64	-4.84 to 5.58
		Low-Energy	0.45 to 0.83	-0.68 to -0.66	-0.32 to -0.38	0.03 to -0.01	0.03 to -0.09	0.42 to 0.7	0.19 to 0.28
Santiago, Chile	Csb	Standard	-3.82 to 2.22	-3.32 to 1.83	-3.19 to 1.73	-4.09 to 2.14	-3.67 to 2.	-4.23 to 2.11	-4.23 to 1.84
		Developing	-3.35 to 2.14	-7.77 to 1.52	-3.26 to 1.47	-3.83 to 1.8	-3.51 to 1.66	-3.64 to 2.21	-3.74 to 1.87
		Low-Energy	-1.07 to 0.67	-0.32 to 0.48	-0.25 to 0.27	-0.43 to 0.31	-0.34 to 0.26	-0.97 to 0.64	-0.72 to 0.43
Washington, D.C., USA	Dfa	Standard	-6.31 to 2.47	-5.64 to 2.83	-5.31 to 3.06	-3.95 to 3.6	-4.06 to 3.05	-5.88 to 2.58	-5.3 to 2.92
		Developing	-5.49 to 3.67	-4.52 to 3.03	-4.04 to 3.51	-2.8 to 3.85	-2.86 to 3.65	-5.18 to 3.88	-4.43 to 4.24
		Low-Energy	-6.39 to -1.35	-5.36 to 0.24	-5.45 to 0.2	-3.16 to 1.11	-3.38 to 1.16	-6.22 to -1.35	-5.56 to -1.17
Toronto, Ontario, Canada	Dfb	Standard	-6.76 to 2.07	-2.67 to -0.88	-3.22 to -0.37	-4.99 to 1.18	-4.88 to 0.71	-6.76 to 2.21	-6.03 to 2.86
		Developing	-5.54 to 3.21	-0.15 to -0.55	-0.7 to 0.1	-2.87 to 1.87	-2.67 to 1.56	-5.44 to 3.43	-4.78 to 3.94
		Low-Energy	-7.71 to -3.71	-3.43 to -1.95	-4.26 to -2.87	-4.77 to -4.06	-4.84 to -3.85	-7.6 to -3.75	-7. to -3.68

Location	Köppen Climate Type	Building	Base Weather Data (1961-1990 and Typical)	Climate Change Scenario				Urban Heat Island	
				A1FI	A2	B1	B2	Low (1 C)	High (3 or 5C)
Moscow, Russia	Dfb	Standard	-3.57 to 4.49	-2.16 to 4.83	-1.72 to 4.77	-1.71 to 5.67	-1.12 to 5.46	-3.48 to 4.35	-3.35 to 4.
		Developing	-3.18 to 4.14	-0.93 to 4.83	-0.09 to 5.28	-0.85 to 6.14	-0.06 to 5.53	-3.18 to 4.07	-3.09 to 3.69
		Low-Energy	-3.99 to 3.95	-4.39 to 2.99	-3.89 to 2.72	-3.7 to 3.37	-3.96 to 3.37	-4.04 to 3.98	-4.13 to 4.05
White Horse, Yukon, Canada	Dfc	Standard	-7.92 to 4.57	-7.08 to 3.36	-7.07 to 3.31	-7.18 to 2.57	-7.13 to 2.63	-7.89 to 4.55	-7.92 to 4.65
		Developing	-8.14 to 4.5	-7.38 to 2.61	-7.32 to 2.5	-7.42 to 1.94	-7.36 to 2.01	-8.13 to 4.48	-8.15 to 4.58
		Low-Energy	-7.08 to 2.24	-7.32 to -0.42	-7.08 to -0.52	-6.93 to -0.59	-6.97 to -0.61	-7.17 to 2.27	-7.34 to 2.41
Beijing, China	Dwa	Standard	-3.27 to 1.74	-1.09 to 2.56	-1.41 to 1.85	-1.56 to 1.49	-1.7 to 1.39	-3.08 to 1.78	-2.86 to 2.69
		Developing	-3.22 to 1.88	-0.59 to 2.84	-0.82 to 2.12	-1.25 to 1.64	-1.22 to 1.67	-3.04 to 1.99	-2.66 to 3.06
		Low-Energy	-0.75 to 0.09	0.5 to 1.13	0.44 to 0.93	0.15 to 0.92	0.25 to 0.95	-0.7 to 0.17	-0.5 to 0.4
The Pas, Manitoba, Canada	Dwb	Standard	-5.23 to 7.5	-3.25 to 5.67	-3.03 to 5.56	-2.64 to 6.78	-2.66 to 6.55	-5.12 to 7.38	-4.92 to 7.48
		Developing	-4.75 to 7.43	-2.58 to 4.87	-2.18 to 4.85	-1.64 to 6.27	-1.73 to 5.87	-4.65 to 7.35	-4.53 to 7.41
		Low-Energy	-4.65 to 6.03	-2.42 to 5.67	-2.8 to 5.05	-2.85 to 5.61	-2.94 to 5.48	-4.69 to 6.03	-4.77 to 6.05
Fairbanks, Alaska, USA	Dwc	Standard	-8.07 to 9.51	-4.01 to 7.61	-5.22 to 7.43	-6.26 to 8.31	-6.35 to 7.83	-7.44 to 9.58	-7.3 to 9.67
		Developing	-10.33 to 10.14	-6.47 to 8.92	-7.48 to 8.75	-8.32 to 9.38	-8.45 to 8.92	-9.76 to 10.22	-9.71 to 10.43
		Low-Energy	-11.08 to 10.34	-9.83 to 13.34	-9.44 to 13.37	-9.51 to 13.24	-9.49 to 13.4	-10.53 to 10.4	-10.57 to 10.52
Yakutsk, Russia	Dwd	Standard	-5.43 to 6.44	-3.63 to 6.64	-3.51 to 6.58	-4.11 to 6.76	-3.93 to 6.72	-5.36 to 6.49	-5.32 to 6.58
		Developing	-5.59 to 6.45	-4.7 to 7.04	-4.57 to 6.85	-4.94 to 6.92	-4.81 to 6.93	-5.59 to 6.49	-5.61 to 6.51
		Low-Energy	-4.57 to 5.28	-5.21 to 5.81	-5.34 to 5.73	-5.41 to 5.69	-5.37 to 5.74	-4.6 to 5.3	-4.66 to 5.36
Resolute, Nunavut, Canada	ET	Standard	-4.57 to 6.54	-3.92 to 6.85	-3.87 to 6.91	-4.1 to 6.81	-4.01 to 6.86	-4.51 to 6.53	-4.5 to 6.52
		Developing	-4.94 to 6.54	-4.93 to 7.5	-4.85 to 7.45	-4.94 to 7.2	-4.93 to 7.26	-4.93 to 6.56	-4.93 to 6.59
		Low-Energy	-3.92 to 5.56	-4.73 to 6.5	-4.54 to 6.41	-4.45 to 6.07	-4.45 to 6.13	-3.9 to 5.58	-3.9 to 5.61
La Paz, Bolivia	H	Standard	-1.63 to 2.2	0.99 to -1.05	0.62 to -1.12	-0.13 to 0.76	0.23 to 0.28	-1.63 to 1.95	-1.31 to 0.69
		Developing	-1.57 to 1.82	2.45 to -2.37	2.53 to -2.66	2.37 to -1.68	2.42 to -2.02	-1.58 to 1.62	-1.34 to 0.33
		Low-Energy	-1.86 to 2.75	1.57 to 0.08	0.93 to 0.06	0.16 to 0.62	0.35 to 0.4	-1.83 to 2.61	-1.49 to 2.06

Interestingly, as described above, the significant switchover from heating to cooling in Resolute results in a reduction in annual energy use due to the climate scenarios. At the other extreme, in the data shown here for San Juan, the developing building model changes from being 13 percent higher than the standard model to more than 33 percent higher in the A1FI climate change scenario. Similar variability can be seen throughout the 25 locations.

The colder continental climates experience the greatest range in year-to-year weather conditions and, thus, variability. The Pas, Manitoba, Canada and Fairbanks, Alaska, USA both have a variation often exceeding 10 percent between the highest and lowest energy use, with an occasional rise to 20 percent. In contrast, Mexico City has the least variation among the data. Note that Mexico City also has the fewest years available in the data set: 12 years (see Table 3-13). Hot humid, tropical climates, such as Singapore, San Juan, and Miami also see lower year-to-year variability, typically less than 5 percent. Temperatures in these locations tend to stay closer to the operating temperatures of buildings. The hot dry or monsoon locations (Cairo, New Delhi) also have lower year-to-year variability in energy consumption, as do marine locations such as Sao Paulo, Johannesburg, Punta Arenas, Buenos Aires, and Los Angeles.

5.5 Potential Energy Performance Impacts of Heat Islands and Climate Change Scenarios for the Small Office Building

The previous discussion has provided an indication of the direction and magnitude of the potential energy performance impacts of the IPCC climate change scenarios and the heat island cases. Figure 5-17 shows the percent change by climate change scenario and heat island case for source energy performance in Washington, D.C. While the A1FI and A2 climate change scenarios are usually the most extreme (greatest increase in temperature) , in Washington, D.C., there is little predicted temperature change in the warmest months—resulting in lower overall total annual energy performance. As noted above, such decreases are due to energy end-use swapping between heating and cooling (decreased heating and increased cooling). In this case, the developing building (least energy-efficient case) has increases in energy use across all climate change scenarios, but small decreases for heat islands.

Contrast Figure 5-17 with similar results for San Juan, Puerto Rico in Figure 5-18 and Resolute, Nunavut, Canada in Figure 5-19. In all cases for San Juan, the net change is always

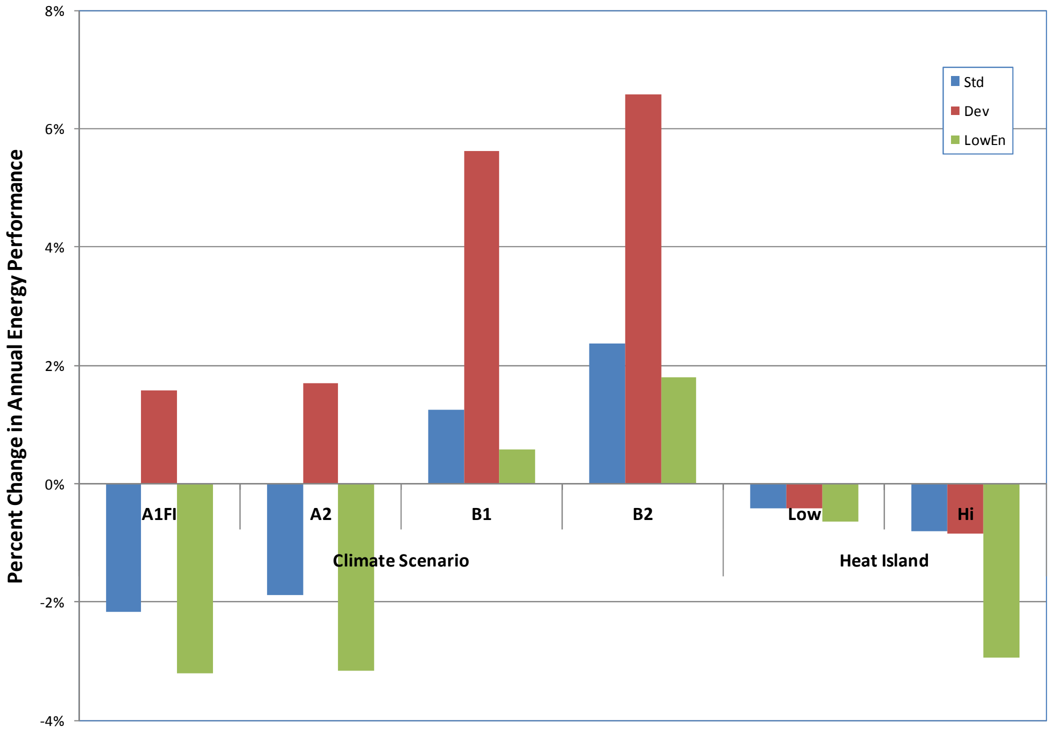

Figure 5-17. Percent Change in Annual Energy Consumption from the Typical Weather Data for Climate Change and Heat Island Cases in Washington, D.C., USA

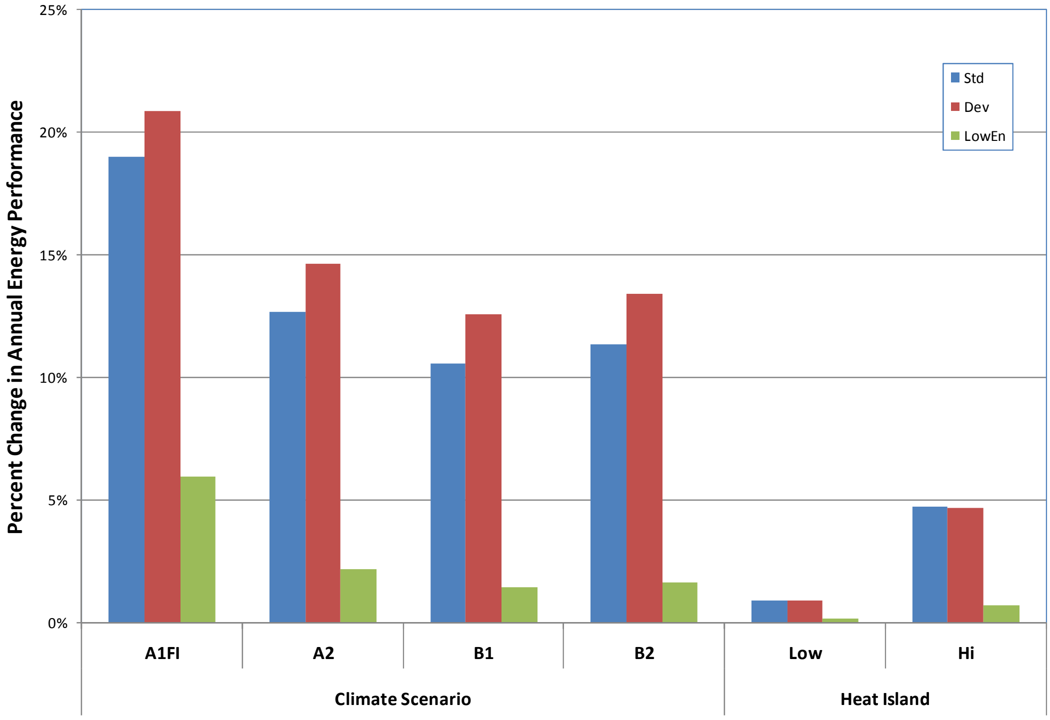

Figure 5-18. Percent Change in Annual Energy Consumption from the Typical Weather Data for Climate Change and Heat Island Cases in San Juan, Puerto Rico

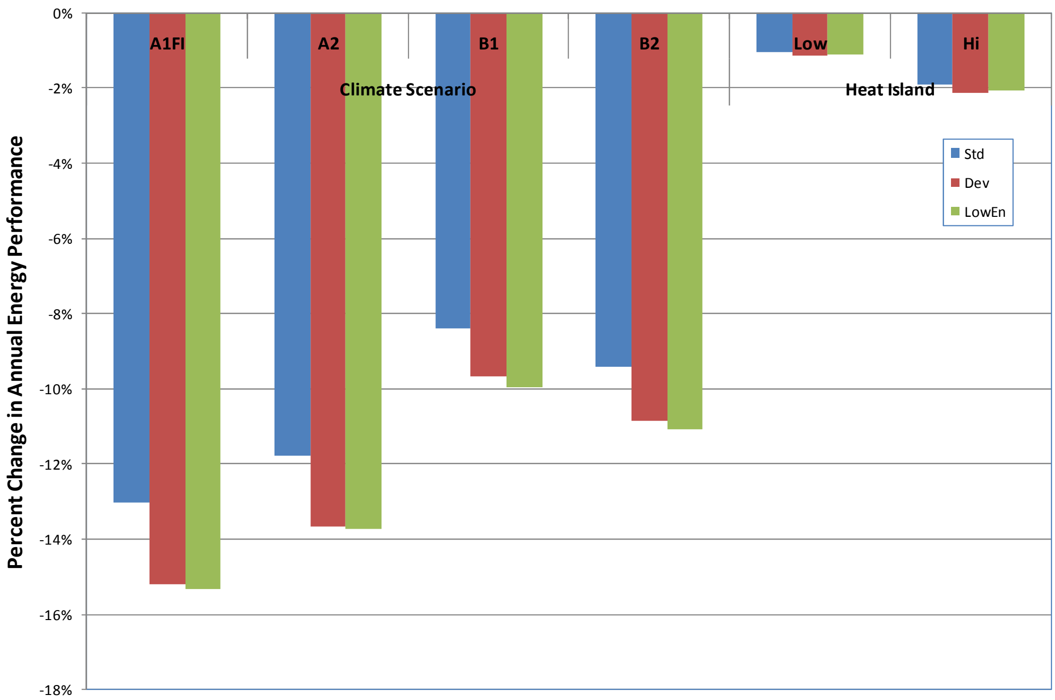

Figure 5-19. Percent Change in Annual Energy Consumption from the Typical Weather Data for Climate Change and Heat Island Cases in Resolute, Nunavut, Canada

an increase in annual energy consumption. The San Juan low-energy building case has the lowest increase of approximately 25 percent of the standard or developing buildings. Resolute in Figure 5-19 shows the opposite: the net change is always a decrease in annual energy consumption. For San Juan, there is little heating to trade off against cooling and so the net is an increase in total annual energy. For Resolute, the climate change and heat island cases all contribute to reducing the largest end use—heating. Detailed results and tables for Washington, D. C., San Juan, and Resolute are presented in Appendix D.

5.6 Summary

A few other observations (for which data are shown in Appendix D): locations that were heating dominated (little or no cooling—such as Resolute) or had a balance of heating and cooling energy usually saw decreases in annual energy consumption when the climate change scenarios were applied. Warmer regions with significantly less heating, such as New Delhi or Singapore, showed significant overall increases in total site energy consumption. Because heating consumption in these cooling-dominated regions is small, there is little to reduce to offset increased cooling energy. In addition, locations with a relative balance between heating and cooling show significant swapping of cooling for heating—especially in winter and spring/fall months. For example, Boulder, Colorado, which has relatively cold winters, shows significant decreases in heating energy while cooling energy appears in fall and spring months where previously no cooling was required. The developing case with the least effective building envelope and least efficient HVAC equipment is the most sensitive to normal climate variation or to climate change.

In cold climates, the net change to annual energy use due to climate change will be positive—reducing energy use on the order of 10 percent or more. For tropical climates, buildings will see an increase in overall energy use due to climate change, with some months increasing by more than 20 percent from current conditions. Temperate, mid-latitude climates will see the largest change, but it will be a swapping from heating to cooling, including a significant reduction of 25 percent or more in heating energy and up to a 15 percent increase in cooling energy. Buildings that are built to current standards, such as Standard 90.1 (ASHRAE 2004), will still see significant increases in electricity demand over the 21st century. Low-energy buildings designed to minimize energy use will be the least affected, with impacts in the range of 5-10 percent. If the buildings can indeed achieve net-zero energy, they will experience little or no net energy impacts from either urbanization or climate change. Unless the way buildings are designed, built, and operated changes significantly in coming decades, building owners will experience substantial operating cost increases and possible disruptions in an already strained energy supply system.

The analysis of the small office building prototype showed that building performance simulation can be used to answer policy questions such as:

- location-specific responses to potential scenarios;
- impacts on equipment use and longevity;
- fuel swapping as heating and cooling change;
- emissions impacts;
- comfort impacts; and
- means to improve building energy efficiency and incorporate renewable energy while mitigating potential changes.

This chapter presents a fraction of the building performance data available from this study. How heat island and climate change scenarios affect annual source energy performance are presented for three of the 25 locations in this Chapter. Further data and results are provided in Appendix D.

Today's building energy performance simulation tools provide data at a variety of time slices—from annual to monthly, weekly, daily, and hourly, down to the time-step (10 minutes for this study) for all surfaces, components, spaces, zones, equipment, and systems within the building.

Data for this study were reported at significantly higher temporal resolution than the previous three—from annual and monthly to hourly—for all the data listed in Section 5.1. This resulted in large data files of up to 600 megabytes. For this reason, an automated process for managing the simulations and the storage of all the files became critical. The results data were assembled across the simulations in pre-constructed spreadsheets which automatically generated graphs and tables for a location. Because of the volume of the results data, these were extracted into separate files for further analysis, organized by topic: energy consumption, energy end-use consumption, domestic hot water, envelope conduction and solar gain, emissions, equipment consumption and sizing, photovoltaic power and production (for the low-energy case), water, zone, and system conditions and loads.

In this research study, the key attributes for the policy framework include:

- Clear structure comprising data structure, management, and compression, and automated quality assurance for input and output, and
- Study design to include scope of the parameters to be studied, resulting performance data, and pre-constructed summary spreadsheets to automate structure and presentation of the results.

5.7 References

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Chapter 6
Summary and Conclusions

> If we knew what it was we were doing, it would not be called research, would it?
>
> Albert Einstein

6.1 Research Summary

The research documented here highlights how simulation can be used to inform, influence, and drive building-related policy. A series of studies demonstrate how building performance simulation informs and defines building-related policy for standards, utility incentive programs, energy-efficiency programs, and the determination of climatic influence and sensitivity on building operating performance. These studies show how decision-makers have used building performance simulation to craft voluntary and mandatory programs for building energy efficiency. Without building simulation in these studies, policy-makers would not have been able to provide as much design flexibility in energy standards, determined which glazing options or insulation improvements were economically justified in utility incentives, created a demonstrable pathway for upgrading an existing office buildings for reduced energy use, or determine the relative impacts of real or predicted climatic variability on energy use.

Chapter 3 described the process for establishing baseline models of representative buildings. These were structured either as a simple model that applied a wide range of thermo-physical characteristics excursions, or as prototype models representative of an entire building stock. Two of the studies used a simple four-zone model to enable research into the difference in building performance response rather than the absolute level of energy performance. The other two studies created prototypes representative of real buildings. In the first, three office building models of various sizes were derived from a national survey of building stock. The energy performance of these office building models was calibrated to the survey consumption data. In the last study, the size and configuration of a small office building were again determined from a national survey of building stock characteristics and energy performance. The energy performance of this small office model was calibrated to current construction practices and the minimum performance levels of the then-prevailing building energy standard. A second version of the small office building model was adjusted to account for construction practices in developing countries that did not have a minimum building energy standard. A third version was based on "state-of-the-shelf" low-energy and renewable-energy building technologies, resulting in energy performance of less than half that of the standard building. When the energy performance of the solar photovoltaic system is taken into account, these buildings become net producers of energy.

Chapter 3 also presented the design of parametric analyses and how these were constructed to ensure that the range of technologies and systems were adequately covered. For the envelope standard data set, this included a set of parametric cases for heat loss/gain, solar gain, and internal gains. The range of parameter values were set to cover the entire range of characteristics observed in commercial buildings. For example, the heat loss/gain cases went from very low to very high U-values for glazing (0.1 to 5.68 W/(m^2•K)) and walls (0.0001 to 0.95 W/(m^2•K)). For the study of envelope incentives for the Utility program, the analyses were designed around real products—glazing systems and thicknesses of insulation—coupled with market construction costs. In the ESB study, the simulation design focused on a staged approach to building retrofit: lighting, building survey and tune-up, loads reduction, air distribution systems, and central plant. Three other studies were also conducted for the ESB: constructing energy and cost databases for envelope and chiller upgrades and determining which weather data was most appropriate and best represented the long-term record. For the fourth research project design described in Chapter 3, weather files that represent changes in temperature, humidity, and cloud cover based on IPCC climate change scenarios were created from existing representative and extreme meteorological weather data. Similar weather files were created to represent a range of urbanization or heat island effects. The key attributes of the four studies in terms of the research focus and parameters, building model, and building performance data use were summarized in Table 3-1.

Chapter 4 presents results and findings from three of the studies. In the first study for the envelope requirements of the building energy standard, results from more than 5,400 combinations of building envelope characteristics comprised a database of heating, cooling, and fan loads. The simple, physics-based model derived from these loads data allows building designers to trade-off envelope component characteristics in the performance path of the building energy standard. The equations were also used to set cost-effective prescriptive levels of envelope components. In the second project, the energy and cost performance of building envelope upgrades beyond the minimum building energy standard was evaluated for potential utility incentives. The study found that the envelope upgrades all had economic paybacks of seven years or more—beyond the three-year target of the utility. The third study in Chapter 4 shows the results of the ESB research, focusing on the economic benefits of a staged program for reducing the energy use of existing buildings. The building performance simulation results showed a significant potential for reducing the overall energy consumption of existing office buildings: 25 to 60 percent energy savings with internal rates of return averaging 58 percent. A separate study of building envelope upgrades showed that it was always cost-effective to add insulation to roofs. The similar study on upgrading chillers showed that combining a chiller replacement with the ESB staged upgrades could reduce energy use and costs by half and significantly decrease the cost of the new chiller. Together these required more than 22,000 simulation runs.

Chapter 5 summarizes the simulation results from the climate change and urban heat island simulations. This study found that the low-energy building model is the least sensitive to variation in climatic conditions, with changes in the range of 0-10 percent, and with many locations having virtually no change in energy use among the years. The low-energy building has an annual energy performance of 50-60 percent less than the standard building. In contrast, the developing building model shows an increase (10-20 percent) in annual energy consumption over that of the standard building and substantially more sensitivity to climate change or heat island effects—up to another 20 percent. Among the three buildings, the climate change scenarios caused significant increases in cooling that could be offset by decreases in heating. If the climate is heating dominated, the net effect is an overall decrease in energy use. In temperate locations, predicted energy use could be little changed; in hot and tropical locations, overall energy use is expected to increase significantly. Similar but smaller impacts of the urban heat island were seen throughout all the locations.

6.2 Policy Implications of the Simulation Studies

This research crafted models and analyses that provided simulation results to support decisions on the structure of programs affecting many buildings. For the development of the National Energy Code for Buildings in Canada, energy simulation played a key role in its development and operation. The prescriptive values in the code were set at the life-cycle cost optimum taking into account specific costs and economic assumptions for each region of Canada using energy simulation results. Equations derived from a database of heating, cooling and fan loads (from simulation) established the envelope trade-off performance model. This analysis required calculating construction and energy costs for a large number of combinations—further emphasizing the need for a simple energy model.

In the study of potential envelope incentives, the utility planned to implement envelope incentives if simple payback periods for a technology were three years or less. This depended entirely on the outcome of the energy and cost simulations. In the end, none of the envelope options had paybacks less than seven years and no envelope incentives were included in the New Building Construction Program.

For the ESB program, energy simulation played a key role in verifying that the planned staged approach to building retrofit would substantially reduce loads, which could lead to capital cost savings when, in subsequent stages, equipment is down-sized or replaced. The energy results revealed that the cost-effectiveness of retrofit options for each stage varies by region and building type. This allowed the ESB program to ensure that only those measures that are profitable were introduced in the program. Building performance simulation demonstrated to the agency that a staged strategy offers clear advantages for building energy efficiency upgrades, and can result in higher levels of energy savings than other approaches, such as *a la carte* measure selection, or a modeling approach that does not incorporate field confirmation of engineering calculations.

For the climate change and urban heat island study, building simulation revealed that building performance would be affected quite differently depending on location, building configuration, and baseline energy performance. For heating-dominated locations with little or no cooling, simulation showed decreases in overall energy consumption. Hot and tropical regions with little heating, such as New Delhi or Singapore, showed significant overall increases in total site energy consumption. Where locations experience a relative balance between heating and cooling, there is significant swapping of cooling for heating—extending the cooling season into the Spring and Fall months—where previously no cooling was required.

In cold climates, the net change to annual energy use due to climate change will be positive—reducing energy use on the order of 10 percent or more. For tropical climates, buildings will see an increase in overall energy use due to climate change, with some months increasing by more than 20 percent from current conditions. Temperate, mid-latitude climates will see the largest change but it will be a swapping from heating to cooling, including a significant reduction of 25 percent or more in heating energy and up to a 15 percent increase in cooling energy. Buildings that are built to current standards, such as Standard 90.1, will still see significant increases in energy demand over the 21st century if climate change progresses as predicted. The developing building, with the least efficient building envelope and HVAC systems, is the most sensitive to normal climate variation or to climate change. Low-energy buildings designed to minimize energy use will be the least affected, with maximum increases of 5-10 percent. Unless the way buildings are designed, built, and operated changes significantly in coming decades, building owners will experience substantial operating cost increases and possible disruptions in an already strained energy supply system.

The analysis of the small office building prototype showed that building performance simulation can be used to answer policy questions such as:

- location-specific responses to potential scenarios;
- impacts on equipment use and longevity;
- fuel swapping as heating and cooling change;
- emissions impacts;
- comfort impacts; and
- the means to improve building energy efficiency and incorporate renewable energy while mitigating potential changes.

Table 6-1 builds on the key attributes from Table 3-1, adding analysis structure, performance data, and QA to the policy structure based on the four studies.

6.3 Conclusions

If buildings were simple, simulation would not be needed to provide insight into the complex interactions among climate, building operation, and thermo-physical characteristics. As shown in Chapter 5, sensitivity of building to climate is completely dependent on configuration and level of efficiency. One year may see the highest energy use in one building while it may be a moderate year in another building.

The largest challenge of the work presented here was dealing with the immense amount of data that building performance simulation programs can create. For example, a single

Table 6-1. Key Attributes of Analysis Structure and Output Data for the Four Studies

Parameter	Research Study			
	Envelope Standard (Sections 3.2 and 4.2)	Envelope Utility Incentives (Sections 3.3 and 4.3)	Voluntary Energy Efficiency Program (Sections 3.4 and 4.4)	Impact of Climate Change on Commercial Building Performance (Section 3.5 and Chapter 5)
Analysis Structure	216 simulations per location. File naming conventions for input, output, and extracted data. 5,400 total simulations.	3 cases each of wall and roof insulation at 2 FWR; 7 cases of fenestration. File naming conventions for input and output. 19 simulations per location. 95 total simulations.	3 office buildings, gas and electric heat options with existing building and five stages (648 simulations). 3 office buildings, 4 HVAC systems, 8 locations, and 2 lighting power levels for 105 combinations of wall insulation, roof insulation and fenestration (more than 21,000 simulations). Chiller retrofit 5 cases, 3 office buildings, 4 locations (60 simulations). 8 locations, 6 typical weather data and 30 observed weather data (288 simulations). File naming convention, data storage and management structure for input files, different cases, and output. 22,000 total simulations.	1 office building, 25 typical weather and 681 observed weather years, 706 simulations. 3 office buildings (typical, developing, and low-energy), 25 typical, high and low weather years, base, 4 climate change scenarios, 2 heat island scenarios, 525 simulations. File naming convention, data storage and management structure for locations, different cases, output data. 1231 total simulations.
Performance data	Annual heating, cooling, and fan energy	Annual energy performance and electric cost	Annual energy performance, energy cost, peak heating and cooling loads, electric demand, and equipment size.	Annual and monthly energy end-uses, consumption and demand by energy source; energy consumption and demand by zone, system, and plant equipment; surface temperature and conduction and radiation through the building envelope; zone-sensible, latent, convective, and radiant heating gains and losses; zone-air and mean-radiant

Parameter	Research Study			
	Envelope Standard (Sections 3.2 and 4.2)	Envelope Utility Incentives (Sections 3.3 and 4.3)	Voluntary Energy Efficiency Program (Sections 3.4 and 4.4)	Impact of Climate Change on Commercial Building Performance (Section 3.5 and Chapter 5)
				temperature, relative humidity, and humidity ratio; HVAC equipment runtime fraction, heating and cooling rates, part-load ratios, and temperature and humidity; and atmospheric emissions by pollutant type and equivalent carbon.
Quality assurance methods	Batch scripts automatically assembled and named input files from multiple files. Specific case set by fixed parameters at beginning of each file. Input values and output verified graphically in pre-constructed spreadsheets to easily compare results—anomalous data easily identified.	Specific case set by fixed parameters at beginning of each file. Input values and output verified in spreadsheets from automatically extracted data. Batch scripts automated creation of input files, and automated simulation scripts and extracted results data.	Batch scripts automatically assembled and named the input files, ran the simulations, and extracted the results. Results spreadsheets constructed before simulating cases to verify input data and results as simulations finished. Performance results from multiple simulations combined in spreadsheets for data presentation and visualization.	Batch scripts automatically assembled and named the input files, executed the simulations, extracted the performance data, compressed related files and stored them by location. Pre-constructed summary results spreadsheets automated the structure, validation of results, and presentation of the data.

simulation with 10-minute time step output for one of the climate change cases produced more than 600 megabytes of data. With hundreds or thousands of simulations, it is easy to become overwhelmed. It is critical to carefully plan and design the entire simulation—the representative building being modeled, the analyses to be performed, the analysis of the output, and how multi-simulation data will be presented.

Because of the range of scale, scope, and research focus of the four studies, a generalized framework of building-related policy research can be derived. Table 6-2 organizes the key attributes of the four studies from Tables 3-1 and 6-1 into three categories: research and policy focus, building model, and analysis structure and output data. For research and policy focus, the key attributes are existing or new, and single or multiple buildings. The sector-wide technology or performance studies focus on multiple buildings or extrapolating results to the entire stock (new or existing buildings) and the baseline building model becomes a representation of real buildings. Further, in existing building retrofit work, matching existing building performance using observed weather data may become important.

The analytic design requires a structure based on the policy focus and research parameters. The more buildings and parameters, the more important that a carefully crafted parametric structure and data plan is created. This is also true as the volume of data increases—data management and storage becomes more important. Finally QA procedures for automatically verifying input and output data and ensuring quality results become increasingly critical as the complexity of the simulation study increases (more buildings, locations, parameters, and temporal resolution of the data).

Performance simulation is one of the most important tools available to building designers and policy makers today. It reduces uncertainty about policy and program decisions by allowing the evaluation of many scenarios that affect capital and operating costs, as well as energy performance and demand. Building performance simulation is best used to compare the relative performance of two alternatives: different envelope configurations, HVAC system and plant efficiency, or even renewable technologies. And this is exactly what policy makers need—the relative value of two competing technologies, systems, or costs. But building performance simulation is captive to the inputs and assumptions made by the user. To paraphrase Brand from Chapter 1: “Every simulation is a forecast. Every forecast is wrong.” Every building has varying hours of operation, intensity and density of internal equipment, and building controls which do not operate perfectly. Only a carefully calibrated

Table 6-2. Generalized Framework for Policy Analysis Using Building Performance Simulation

Parameters			Policy Study: Minimum Building Energy Standard Development	Policy Study: Utility Incentives Beyond Minimum Standards	Policy Study: Upgrading Existing Buildings	Policy Study: Sector-Wide Technology or Performance Study
Research and Policy Focus						
Research Focus	Existing Building	Single Building			•	
Research Focus	Existing Building	Multiple Buildings or Stock			•	•
Research Focus	New building	Single Building	•	•		
Research Focus	New building	Multiple Buildings or Stock				•
Research Parameters	Building Envelope (walls, roofs, fenestration)		•	•	•	•
Research Parameters	Lighting		•	•	•	•
Research Parameters	Internal loads		•		•	•
Research Parameters	HVAC		•	•	•	•
Research Parameters	Renewable Technologies			•	•	•
Building Model						
Climate Data	Climatic Design Conditions		•	•	•	•
Climate Data	Typical meteorological data		•	•	•	•
Climate Data	Observed hourly data				•	•
Baseline Model	Simple prototype thermo-physical model		•	•		
Baseline Model	Existing Building Prototypes Based on Building Stock				•	•
Baseline Model	New Building Prototypes Based on Minimum Standards and Building Stock					•
Baseline Model	Low-Energy Prototypes including Renewable Technologies					•

Parameters		Policy Study			
		Minimum Building Energy Standard Development	Utility Incentives Beyond Minimum Standards	Upgrading Existing Buildings	Sector-Wide Technology or Performance Study
Analysis Structure and Output Data					
Analysis Structure	Parametric modelling structure and data	•	•	•	•
	Performance Data Automatically Extracted			•	•
	Data Storage and Management			•	•
Performance Data	Annual building energy performance and energy-uses	•	•	•	•
	Annual energy costs	•	•	•	•
	Peak heating and cooling loads			•	•
	Peak electric demand			•	•
	Plant equipment sizing			•	•
	Monthly building energy performance and end-uses				•
	Loads, energy performance and demand by zone, system, and plant				•
	Surface temperature, conduction, and solar radiation				•
	Temperature and comfort measures				•
Quality Assurance Methods	Numerically verified and well-documented input data sources	•	•	•	•
	Graphically verify input and performance data			•	•
	Automate performance data extraction and graphic display			•	•
	Baseline models calibrated against existing building performance			•	•

building simulation would match actual building conditions and performance—something very difficult in practice.

The studies presented here did not directly evaluate human comfort, illumination, or other building performance attributes, but the same building performance simulation tools can provide insights into these issues as well as environmental impacts. This allows policy setters and program designers to focus on establishing regulations, programs, and policies at the most financially and environmentally beneficial levels for individuals and the public.

It is cheaper to simulate many thousands of buildings than to build a single building that does not operate well.

6.4 Future Work

In the context of building standard development, regulators need structured methods that can allow them to expeditiously evaluate changes in efficiency levels. The studies presented here and the others cited in Chapter 2 all required simulation experts to construct representative buildings, evaluate climate regions, perform simulations, and calculate cost-benefit results. High-level tools that automatically perform the simulations and summarize the results will allow regulators to focus on achieving the most beneficial regulations for the public good. Such tools would include predefined representative building climate data and cost data, and then automatically summarize the results.

For program and policy development, the substantial time required to set up the analyses would be reduced by having predefined building prototypes that represent current building stock and new buildings (based on current energy standards). Then program development could focus on technical, economic, and marketing issues rather than worrying about running simulations.

The analysis conducted in Chapter 5 on the potential impacts of climate change provide a global view through all 20 climate zones of the potential impacts on energy performance of three variants of an office building (low-energy, standard practice, and developing). Further work should be considered to expand this analysis in several ways. The existing results should be evaluated to summarize impacts on building operation, environmental emissions, and costs as well as operating conditions. Rather than the single office building, a broader set of representative buildings should be used to have a more comprehensive view of potential impacts throughout the sector.

A recurrent theme in this section is the need for building models, expressed in simulation input format, that have been reviewed, tested, validated, and well documented. These prototypes must be sufficiently detailed to allow use by studies that focus on single elements of a building, such as lighting, envelope, HVAC systems, renewable energy technologies, or operation, as well as high-level, multi-building policy studies. Documentation of the models is critical and must clearly state where this input is derived from, whether it is based on a survey of a few buildings or an entire sector, or if it is based on professional judgment. While building energy standards are useful to help define some building attributes for these models, they do not cover all energy-using systems in buildings. Similarly, building surveys often omit data critical to simulation. In the case of the CBECS, data are available on the number of floors and the total floor area, but no building dimensions, shape, or fenestration percentage is available. These data sources must be supplemented with other data. It is also important for users to be able to understand the models and what performance levels they represent; requiring the documentation to include more than just details of the inputs. This prototype documentation should include summaries of energy performance, water use, comfort, and other metrics, such as energy demand, costs, and environmental emissions. Having such representative building models would allow policy studies to more robustly address the policy issues under consideration rather than focusing on the intricate inputs required by today’s building performance simulation programs.

Appendix A
Weather Data and Data Sets for Envelope Correlations

A.1 Weather Data

Part of the work to develop data sets for the new Canadian energy code for buildings (described in Chapters 3 and 4) involved selecting appropriate weather data that could be used with DOE-2.1E. A new set of typical weather years suitable for use with energy simulation programs recently had been created for more than 50 locations in Canada, called Canadian Weather for Energy Calculations, or CWEC (WATSUN Simulation Laboratory 1992). To ensure adequate coverage of Canadian climatic regions, 25 locations from among the CWEC were selected for use in developing the data sets for the new envelope correlations. Summary climatic statistics for the 25 CWEC locations are shown in Table A-1. These data were compiled from NRCC (1990) and ASHRAE (1989).

In Table A-2, the first five CWEC locations are compared against other weather file types with locations available for Canada. The five locations were Fredericton, Ottawa, Toronto, Vancouver, and Winnipeg. These are compared with three other weather file types: CTMY (NRCC 1983), WYEC (Crow 1980; 1983), and WYEC2 (ASHRAE 1990).

A.2 Data Sets for New Envelope Correlations

The data set developed for use in the new envelope correlations (described in Chapter 4) for Ottawa, Ontario, is shown through a series of figures in this appendix. The data set is presented in terms of the six internal load cases (0, 10.8, 21.5, 43.0, 64.6, 86.1 W/m^2) (0, 1, 2, 4, 6, and 8 W/ft^2) for east, north, south, and west orientations. For each orientation, a three-part figure is presented—cooling, heating, and fan energy. The data are the heating and cooling coil loads and fan energy for 139.4 m^2 (1500-ft^2) (zones 4.57 m (15 ft) by 30.49 m (100 ft)), all in kWh/ft^2.[1] Similar data were developed for the other 24 locations listed in Table A-1. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.

[1] The units for the Y-axis in each figure are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75.

Figures A-1 through A-4 are for the 0-W/ft^2 (0-W/m^2) internal loads case (Figure A-1 for the east orientation, A-2 for the north orientation, A-3 for the south orientation, and A-4 for the west orientation). Figures A-5 through A-8 are for the 1.0-W/ft^2 (10.8 W/m^2) case (with orientations in the same order as the 0-W/ft^2 case); Figures A-9 through A-12 are for the 2.0-W/ft^2 (21.5 W/m^2) case; Figures A-13 through A-16 are for the 4.0-W/ft^2 (43.0 W/m^2) case; Figures A-17 through A-20 are for the 6.0-W/ft^2 (64.6 W/m^2) case; and Figures A-21 through A-24 are for the 8.0-W/ft^2 (86.1 W/m^2) case.

A.3 References

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Table A-1. Comparison of Statistics for Four Weather Data Formats

City and Weather Data Format	HDD18	CDD18	Max. Temp., C	Min. Temp., C	Average Daily Direct Normal Solar, W	Average Daily Total Vertical Solar, W				Design Dry-Bulb Temperature, C	
						N	E	S	W	Summer 2.5%	Winter 2.5%
Fredericton, New Brunswick											
CTMY	4851.9	112.8	32.8	-35.0	1043.9	363.5	739.3	1019.6	701.4	27.8	-27.2
CWEC	4916.1	125.8	34.4	-32.8	1103.9	378.5	607.4	1041.9	901.8	28.3	-24.4
Ottawa, Ontario											
CTMY	4660.3	203.1	32.2	-27.8	1162.8	368.2	782.9	1045.4	737.9	27.8	-22.2
CWEC	4809.4	159.2	32.8	-24.4	1188.8	384.6	794.3	1067.4	777.7	27.8	-21.1
Toronto, Ontario											
CTMY	4430.8	203.6	32.8	-22.2	1038.1	385.1	751.6	980.6	740.3	28.9	-17.8
WYEC	4192.8	206.4	33.9	-23.3	1202.5	387.2	808.8	1016.2	765.3	28.9	-16.1
WYEC2	4236.9	178.9	32.8	-22.2	1088.3	406.6	890.0	1021.3	684.4	27.8	-16.1
CWEC	4267.8	195.8	32.8	-18.9	1087.0	388.2	788.4	985.6	737.9	28.9	-16.1
Vancouver, British Columbia											
CTMY	3231.9	6.4	27.8	-11.1	1094.9	349.7	679.7	951.7	743.8	22.2	-7.2
WYEC	3185.6	18.3	25.6	-7.8	1106.1	350.2	672.9	947.1	751.8	22.8	-4.4
WYEC2	3319.4	12.8	25.0	-7.2	1052.2	354.0	732.5	964.9	687.0	22.2	-3.9
CWEC	3176.9	4.7	26.1	-7.2	1119.2	350.6	691.3	943.1	753.0	22.8	-2.2
Winnipeg, Manitoba											
CTMY	6231.1	138.9	36.1	-40.0	1425.2	379.2	852.3	1207.0	808.3	28.9	-33.9
WYEC	6041.1	136.1	33.3	-36.1	1429.5	375.8	858.4	1187.2	794.6	28.3	-31.7
CWEC	5933.9	170.3	35.6	-34.4	1439.3	380.9	852.9	1185.8	829.9	29.4	-30.6

Key:

CTMY—Canadian TMY, developed by NRC using single-year (1970) weather data
CWEC—Canadian Weather for Energy Calculations
WYEC—Weather Year for Energy Calculations
WYEC2—Weather Year for Energy Calculations 2

Table A-2. Location Climatic Data

City, Province	Latitude	Longitude	Elevation, m	Time Zone	Winter Design Day: 99% Design Dry-Bulb, C	Winter Design Day: 99% Design Dewpoint, C	Summer Design Day: 2.5% Design Dry-Bulb, C	Summer Design Day: 2.5% Design Dewpoint, C	Summer Design Day: Mean Coincident Wet-Bulb, C
Alberta									
Calgary	51.12	114.02	1077	-7	-32.8	-35.6	27.8	14.4	16.1
Medicine Hat	50.02	110.72	717	-7	-33.9	-36.7	32.2	16.1	18.3
British Columbia									
Fort St. John	56.23	120.73	695	-8	-37.8	-40.6	25.6	14.4	16.7
Penticton	49.47	119.60	344	-8	-17.8	-20.6	32.2	15.6	18.3
Prince Rupert	54.30	130.43	34	-8	-16.1	-18.9	17.2	13.3	13.9
Vancouver	49.18	123.17	3	-8	-8.9	-11.7	24.4	16.7	18.3
Manitoba									
Churchill	58.73	94.07	28	-6	-41.1	-43.9	25.0	15.6	17.2
Winnipeg	49.90	97.23	239	-6	-35.0	-37.8	30.0	20.6	21.7
New Brunswick									
Fredericton	45.87	66.53	16	-4	-27.2	-30.0	29.4	20.0	20.6
Newfoundland									
St. John’s	47.62	52.73	134	-4	-16.1	-18.9	24.4	18.3	18.3
Nova Scotia									
Sable Island	43.93	60.02	4	-4	-18.9	-21.7	19.4	17.8	17.8
Shearwater	44.63	63.50	51	-4	-17.8	-20.6	25.0	18.9	18.3
Northwest Territories									
Resolute	74.72	94.98	67	-6	-45.0	-47.8	11.1	5.6	7.8
Yellowknife	62.47	114.45	205	-7	-45.0	-47.8	25.0	14.4	16.1
Ontario									
Ottawa	45.32	75.67	116	-5	-27.2	-30.0	30.0	21.1	21.7
Sault Ste. Marie	46.48	84.50	187	-5	-27.8	-30.6	28.3	20.6	21.1
Toronto	43.67	79.63	173	-5	-20.0	-22.8	30.6	21.7	22.2
Windsor	42.27	82.97	190	-5	-17.8	-20.6	31.1	22.2	22.8
Prince Edward Island									
Charlottetown	46.28	63.13	48	-4	-22.2	-25.0	26.1	20.0	20.6
Quebec									
Montreal	45.47	73.75	31	-5	-26.1	-28.9	28.3	21.1	21.7
Quebec	46.80	71.38	70	-5	-27.8	-30.6	28.3	21.1	21.7
Schefferville	45.52	73.42	27	-5	-40.0	-42.8	22.8	14.4	14.4
Saskatchewan									
Estevan	49.22	102.97	572	-6	-33.9	-36.7	31.7	19.4	20.0
North Battleford	52.77	108.25	548	-6	-36.1	-38.9	28.9	17.2	18.3
Yukon Territory									
Whitehorse	60.72	135.07	703	-8	-42.8	-45.6	24.4	15.6	13.9

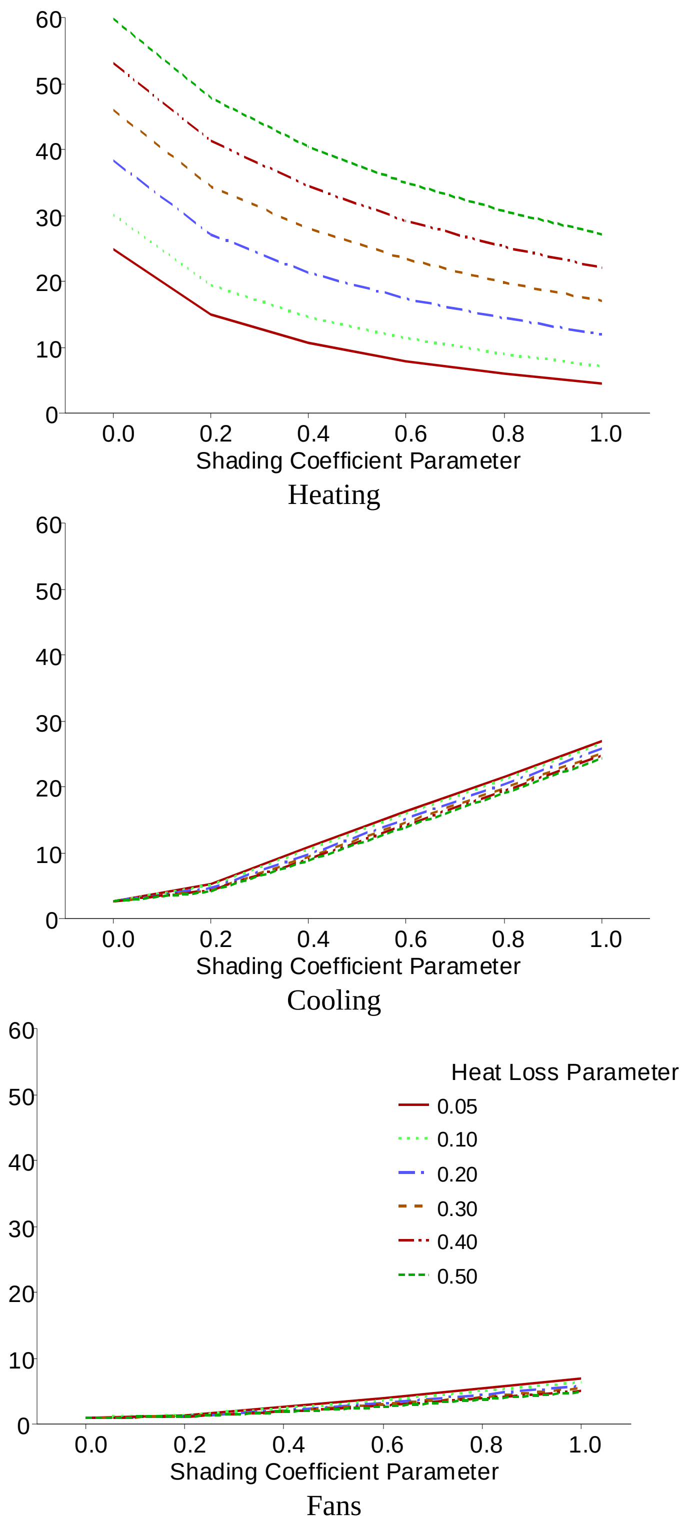
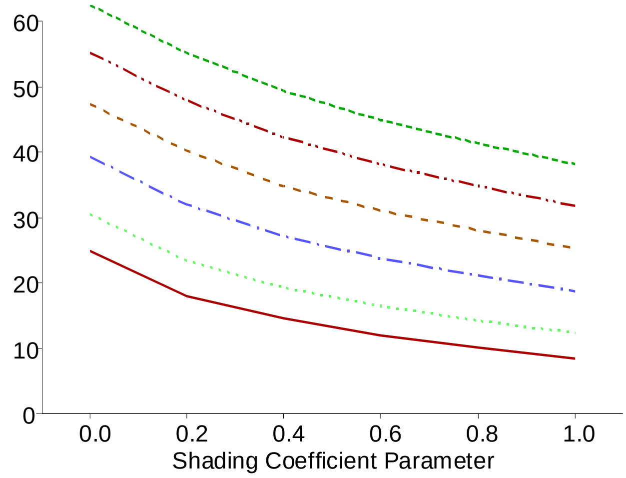


Figure A-1. East Orientation, 0 W/m² (0 W/ft²) Internal Loads[2]

[2] The units for the Y-axis are in kWh/ft². The heat loss parameters are U-values in Btu/(h•ft²•°F). To convert to W/m²•K, multiply by 5.678. To convert to kWh/m², multiply by 10.76; to convert to MJ/m², multiply by 38.75.



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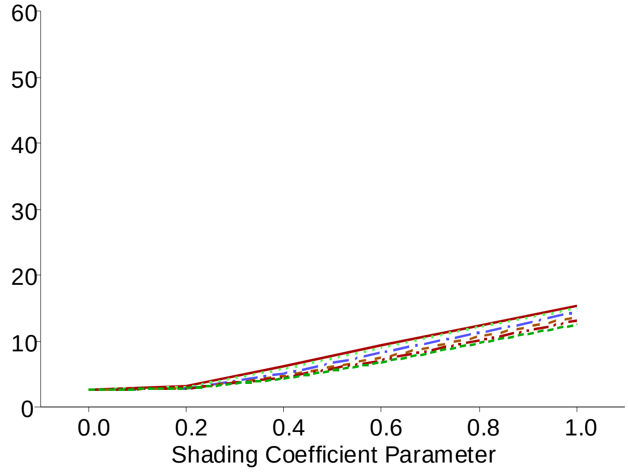

Cooling

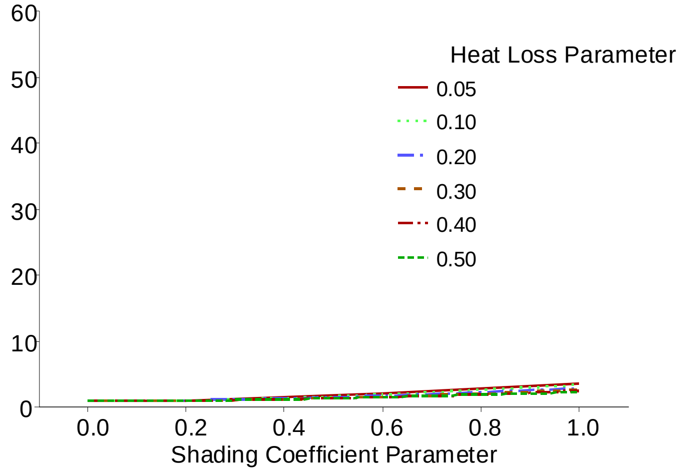

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Figure A-2. North Orientation, 0 W/m^2 (0 W/ft^2) Internal Loads[3]

[3] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.

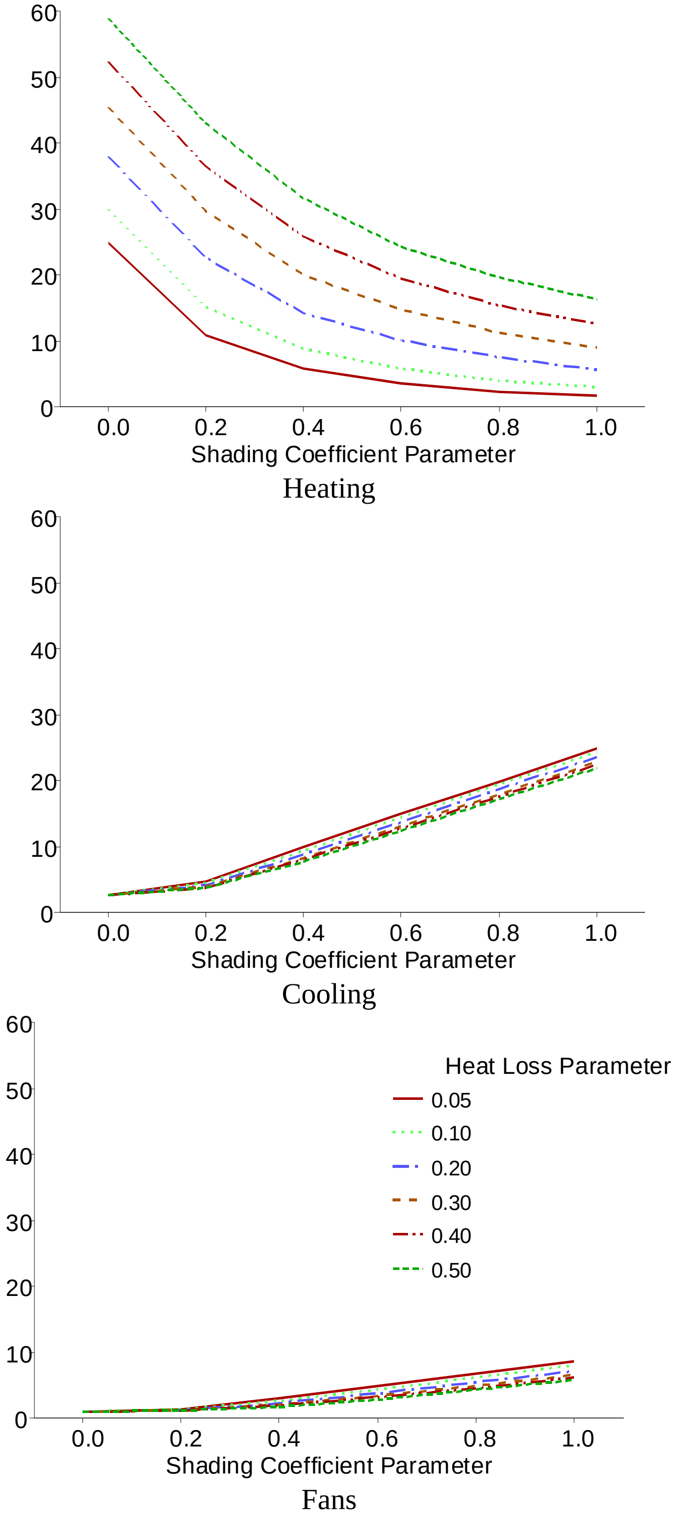
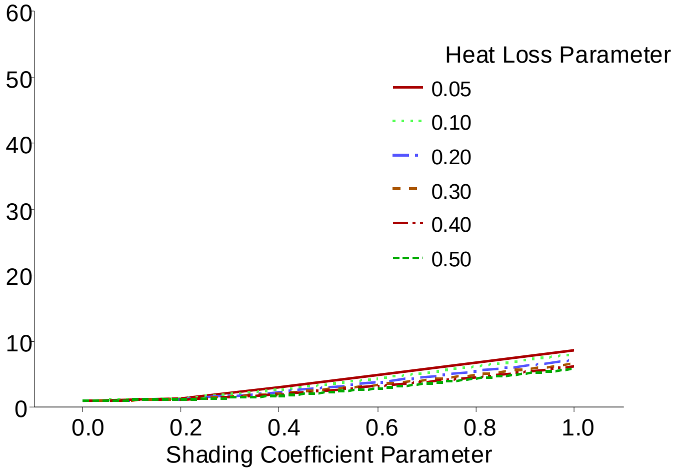


Figure A-3. South Orientation, 0 W/m^2 (0 W/ft^2) Internal Loads[4]

[4] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.



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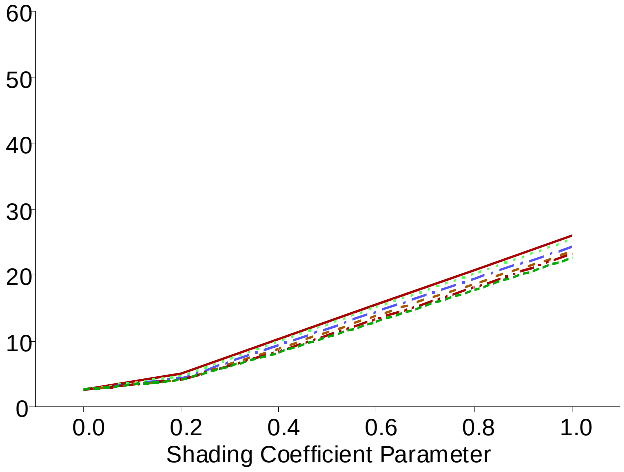

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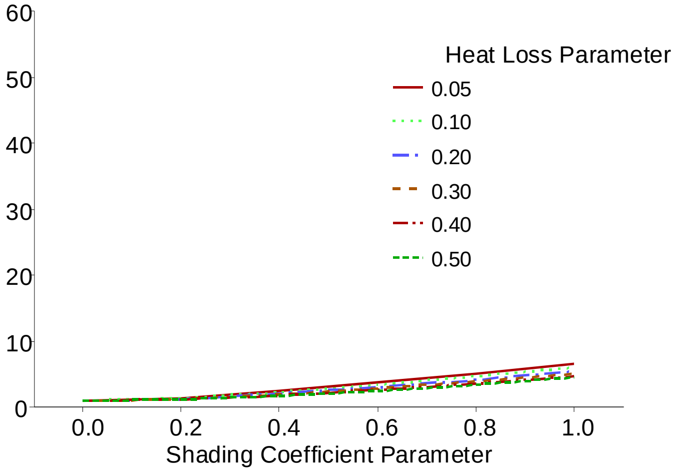

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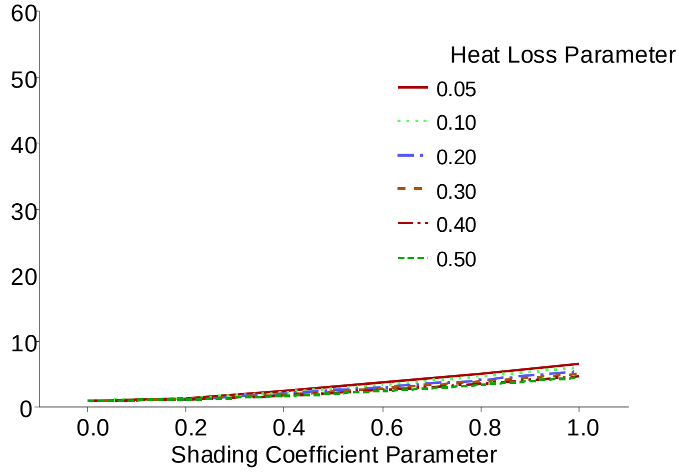
Figure A-4. West Orientation, 0 W/m^2 (0 W/ft^2) Internal Loads[5]

[5] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.



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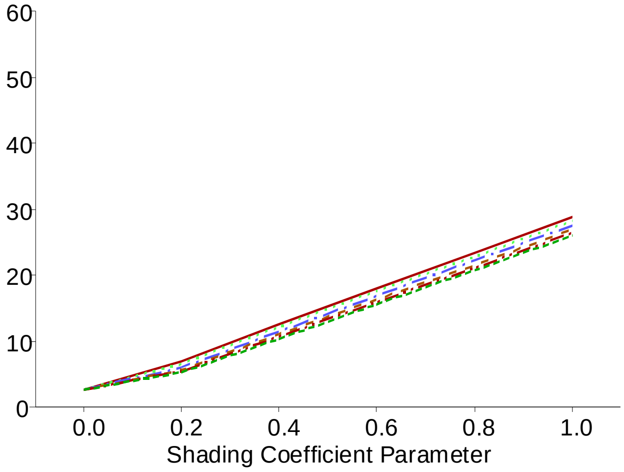

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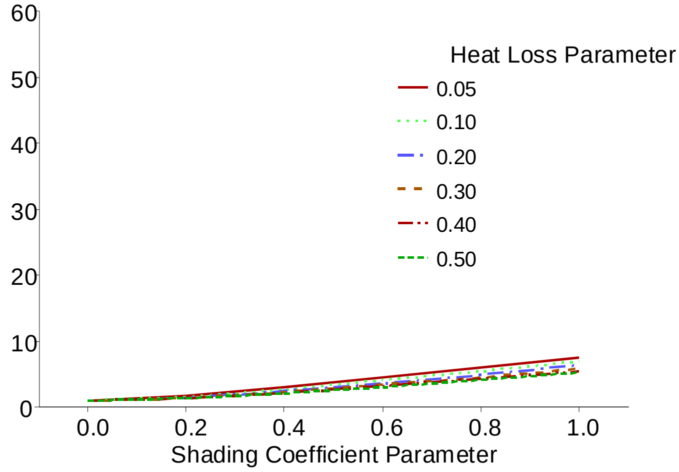

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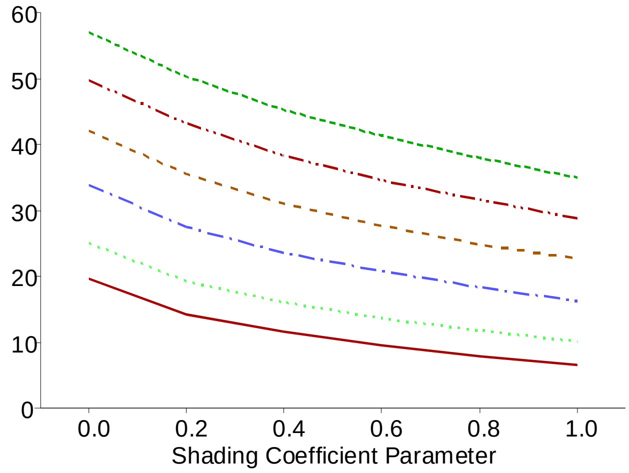
Figure A-5. East Orientation, 10.8 W/m^2 (1 W/ft^2) Internal Loads[6]

[6] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.



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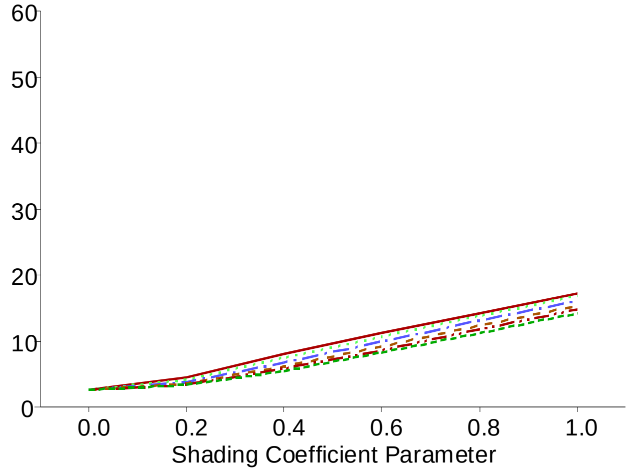

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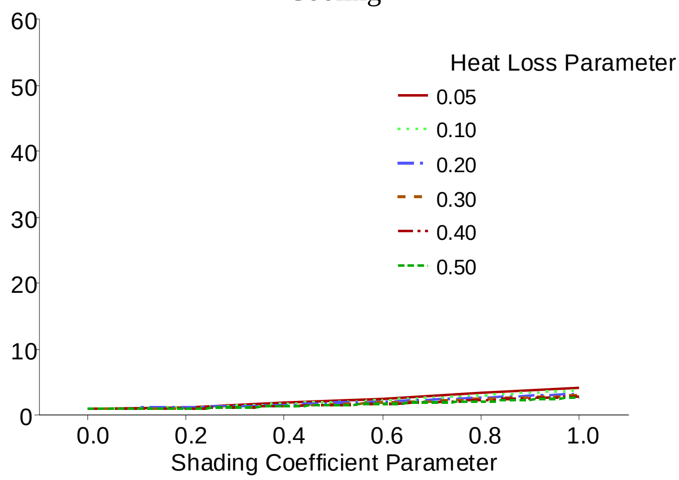

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Figure A-6. North Orientation, 10.8 W/m^2 (1 W/ft^2) Internal Loads[7]

[7] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.

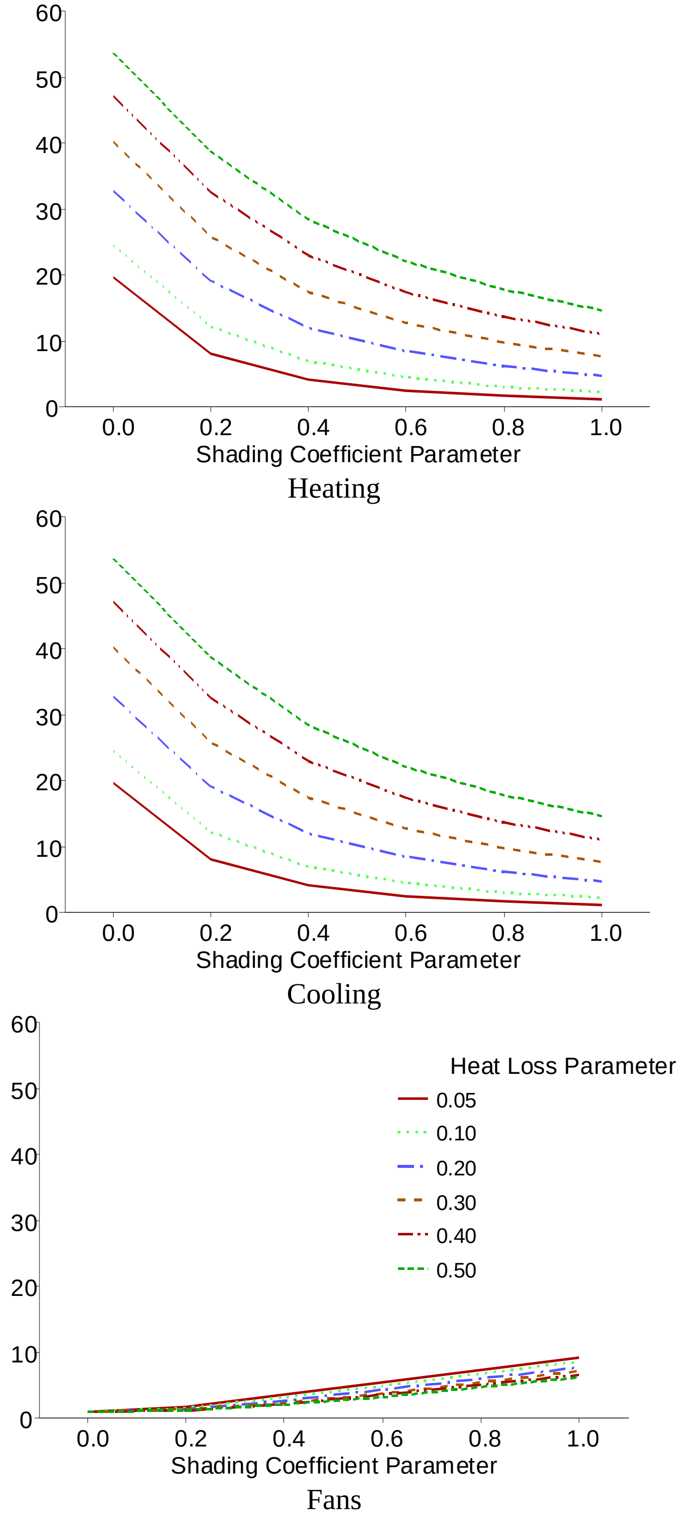

Figure A-7. South Orientation, 10.8 W/m^2 (1 W/ft^2) Internal Loads[8]

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[8] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.

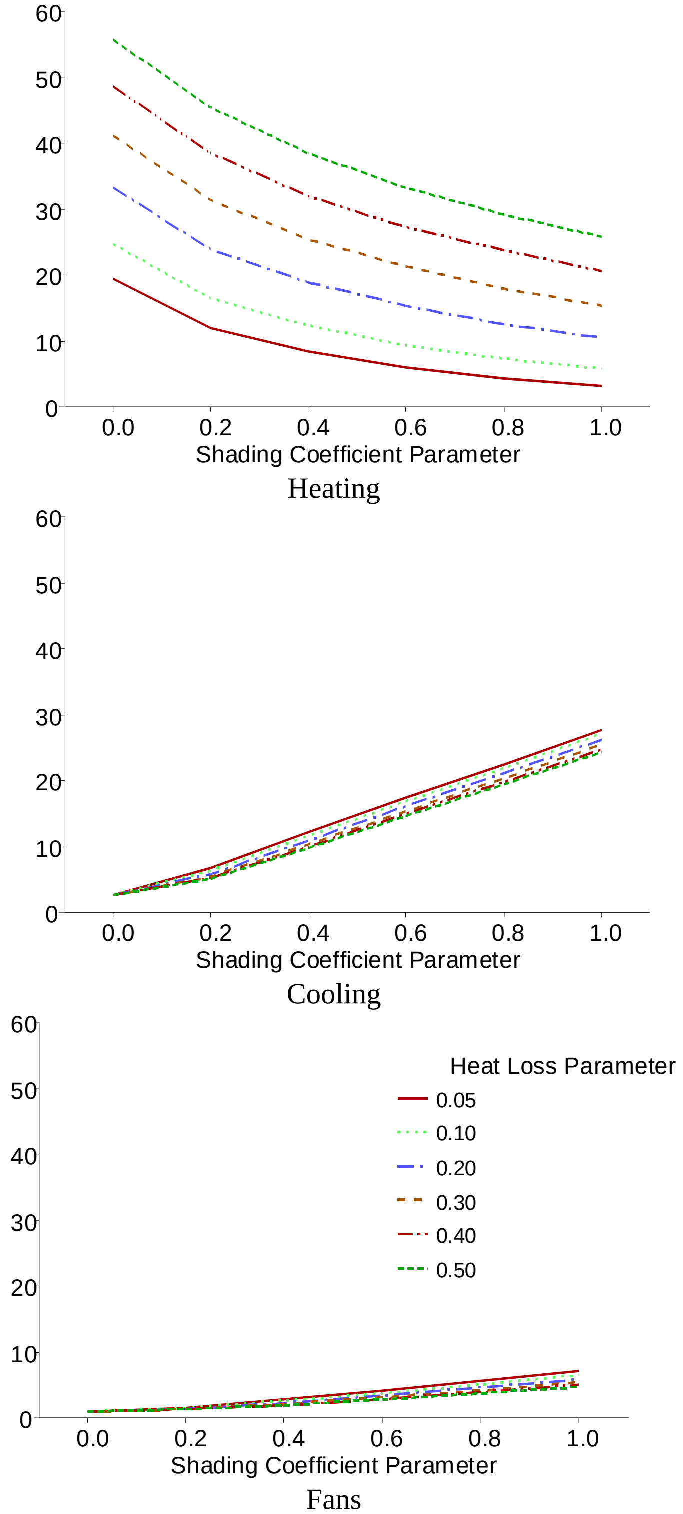


Figure A-8. West Orientation, 10.8 W/m² (1 W/ft²) Internal Loads[9]

[9] The units for the Y-axis are in kWh/ft². To convert to kWh/m², multiply by 10.76; to convert to MJ/m², multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft²•°F). To convert to W/m²•K, multiply by 5.678.

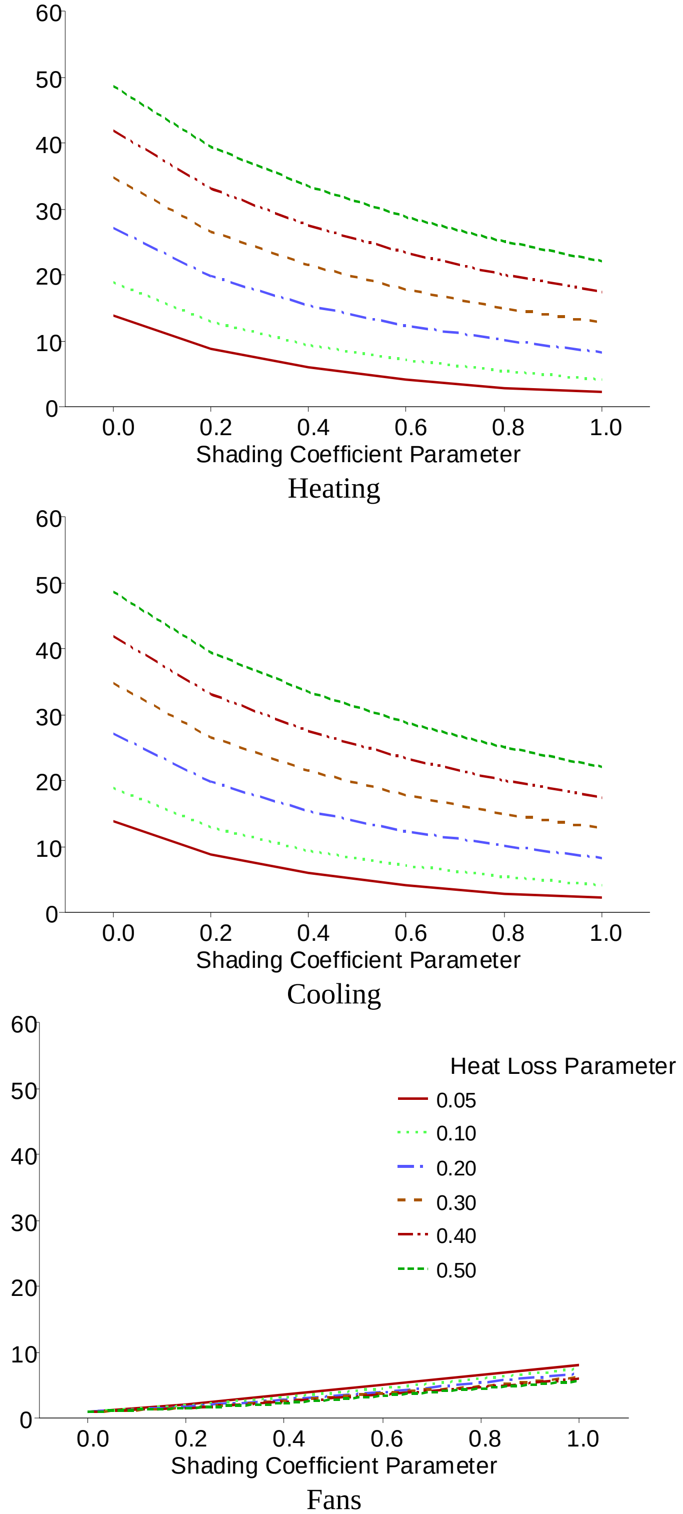


Figure A-9. East Orientation, 21.5 W/m^2 (2 W/ft^2) Internal Loads[10]

[10] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.

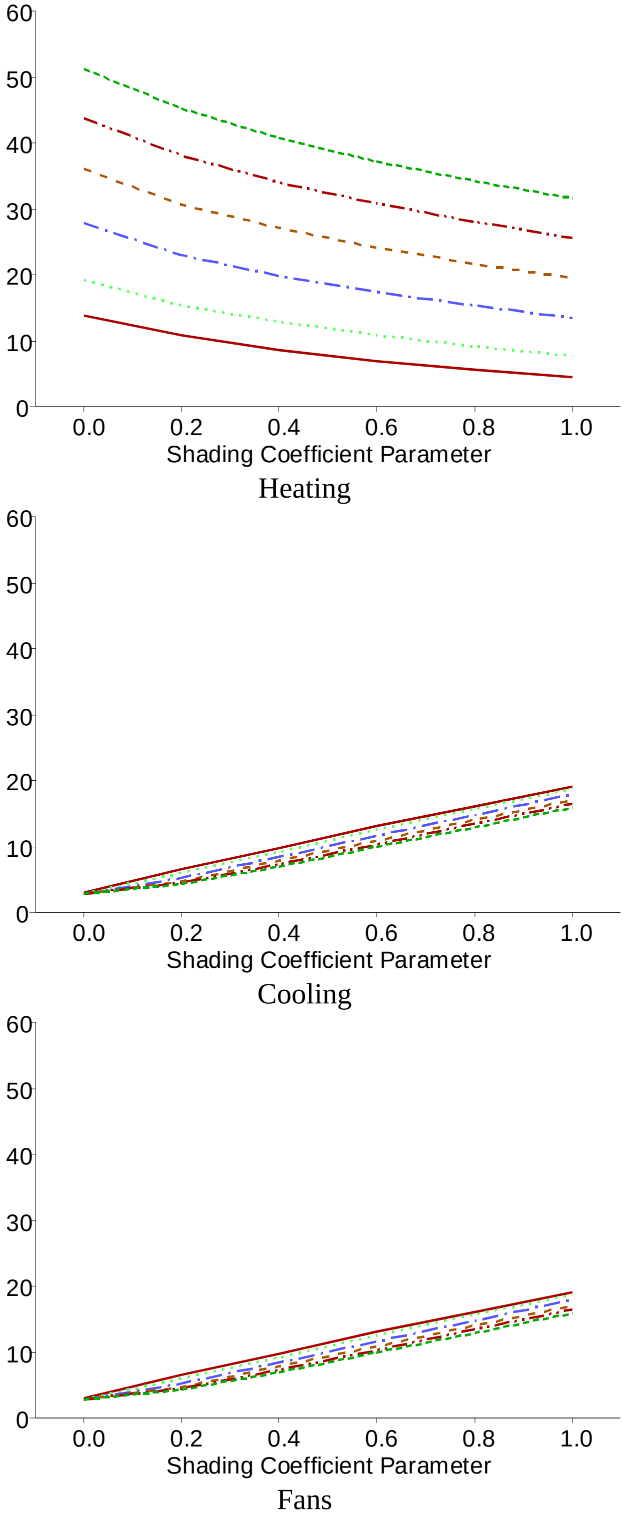
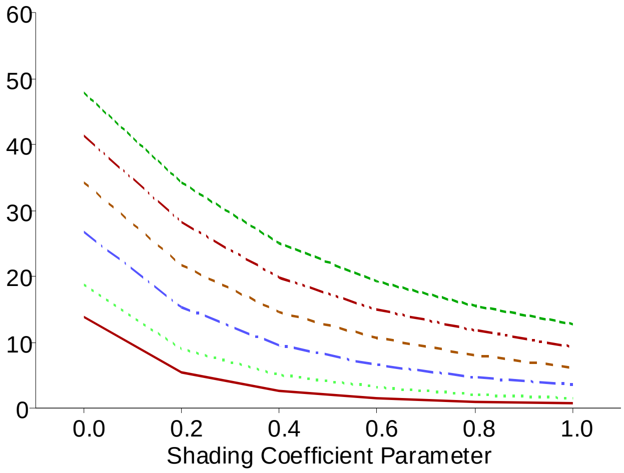
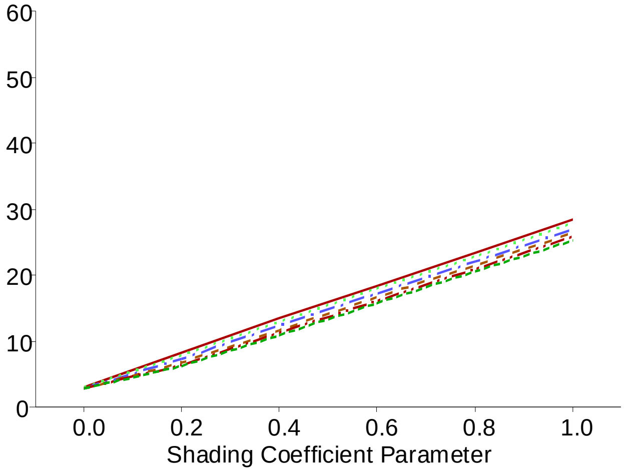


Figure A-10. North Orientation, 21.5 W/m^2 (2 W/ft^2) Internal Loads[11]

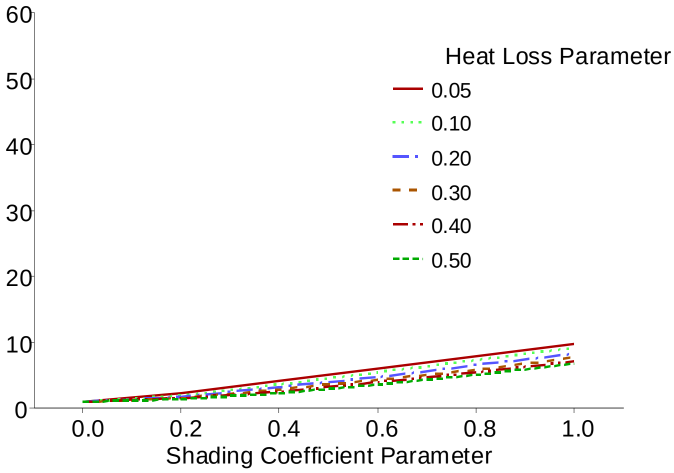
[11] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.



Heating



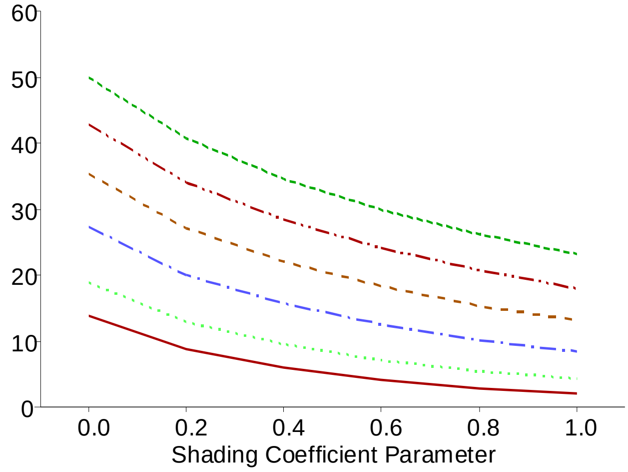
Cooling



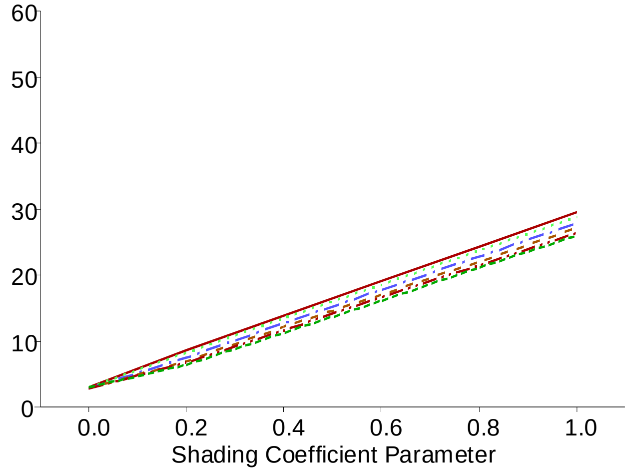
Fans

Figure A-11. South Orientation, 21.5 W/m^2 (2 W/ft^2) Internal Loads[12]

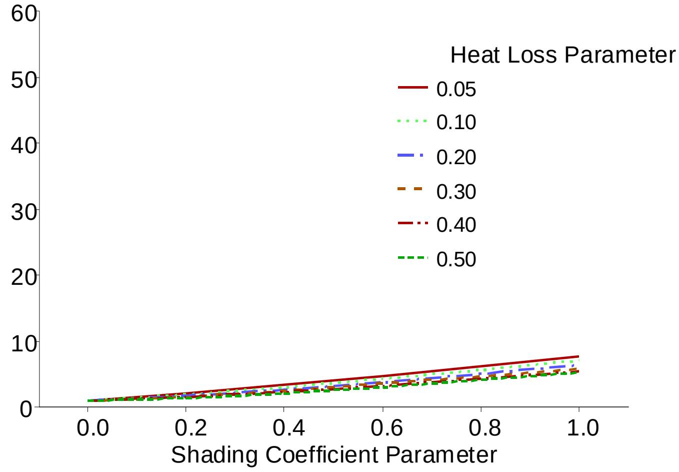
[12] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.



Heating



Cooling



Fans

Figure A-12. West Orientation, 21.5 W/m^2 (2 W/ft^2) Internal Loads[13]

[13] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.

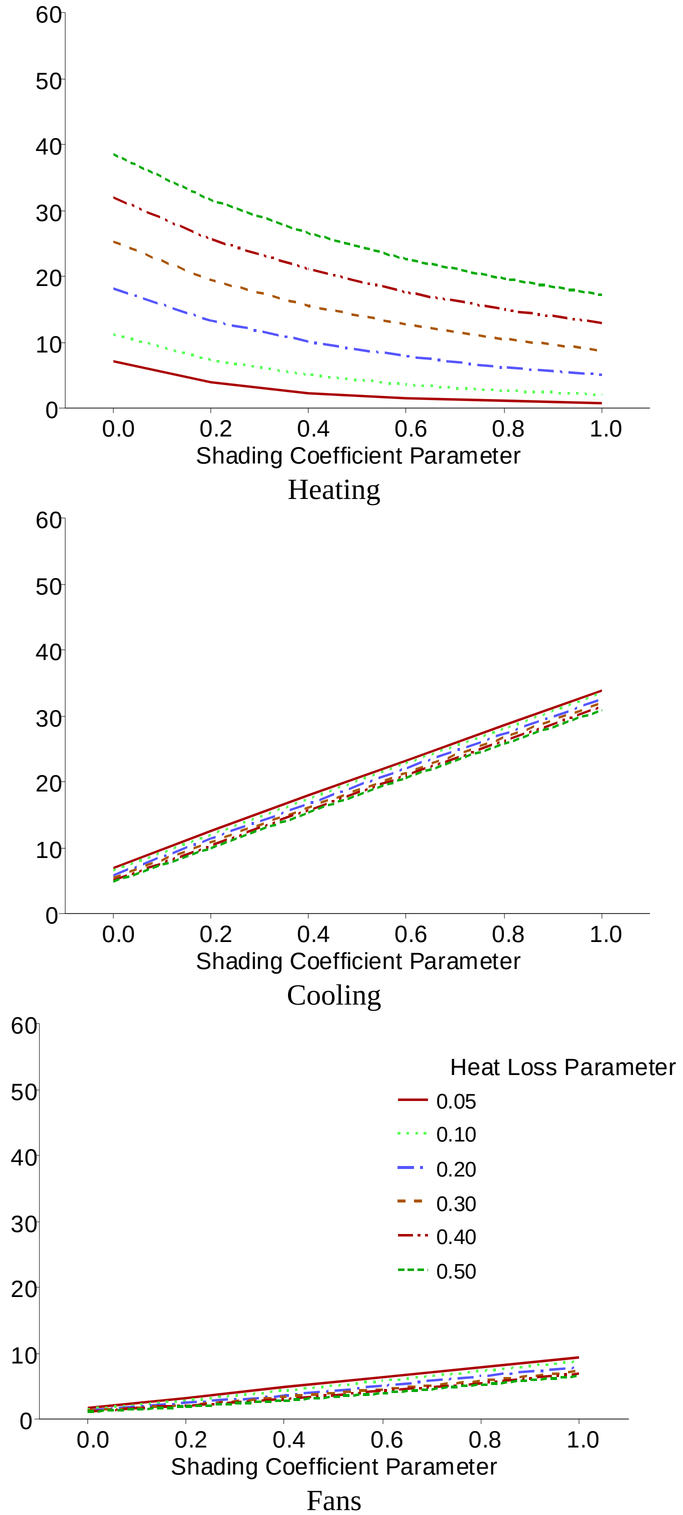
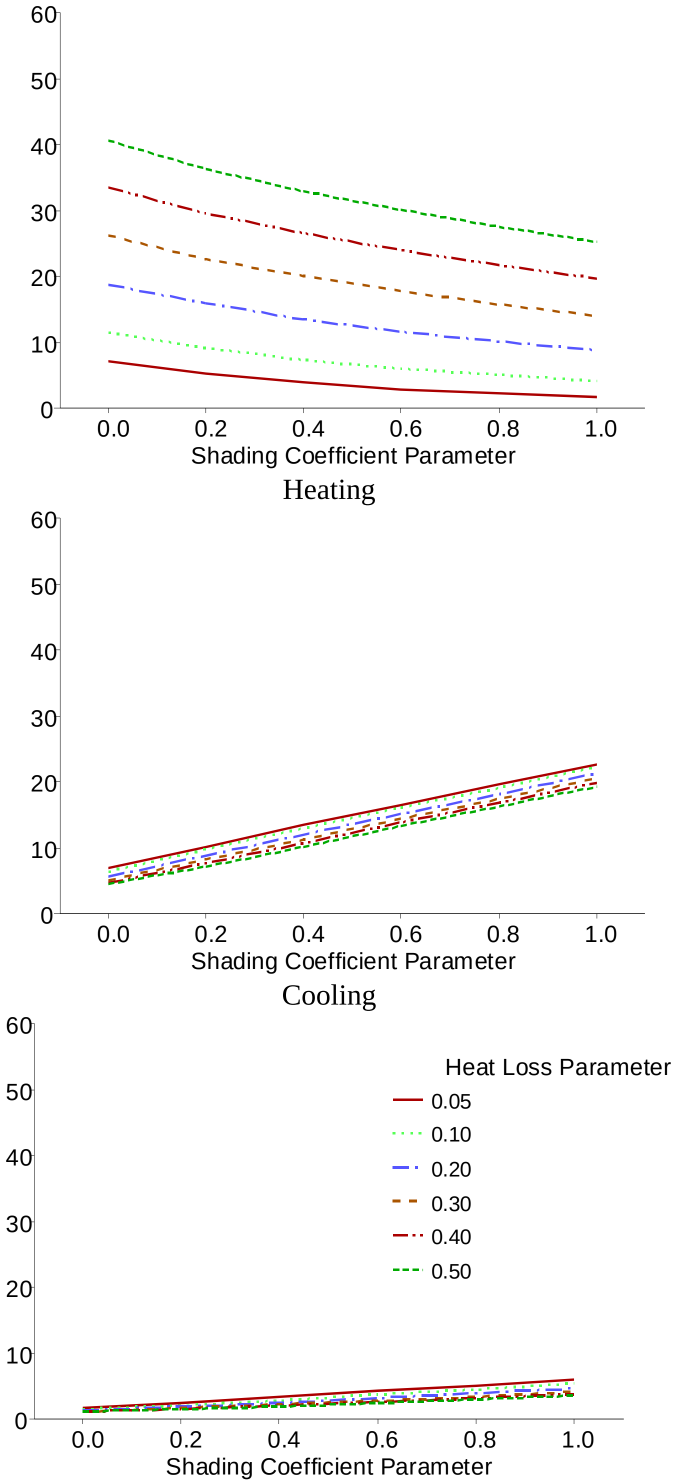


Figure A-13. East Orientation, 43 W/m^2 (4 Wft^2) Internal Loads[14]

[14] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.



Fans

Figure A-14. North Orientation, 43 W/m^2 (4 W/ft^2) Internal Loads[15]

[15] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.

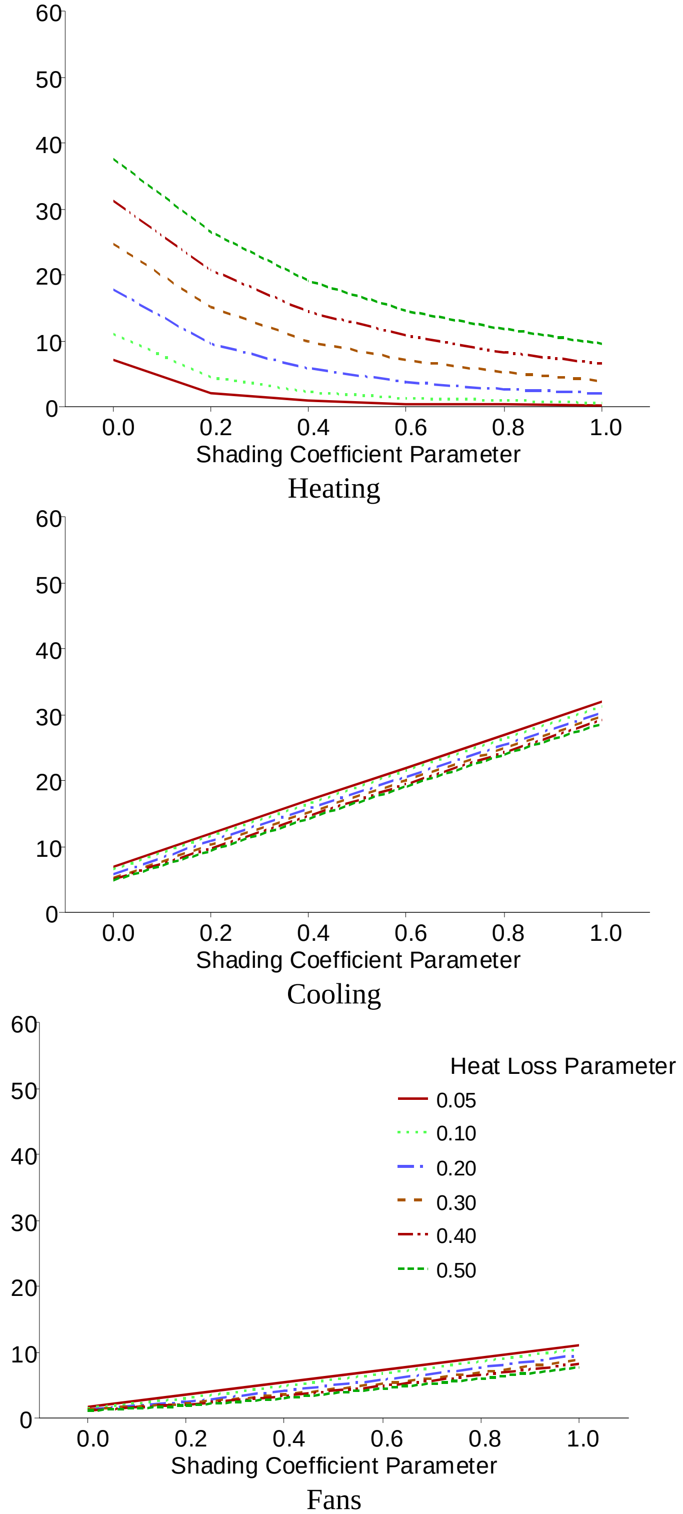


Figure A-15. South Orientation, 43 W/m^2 (4 W/ft^2) Internal Loads[16]

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[16] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.

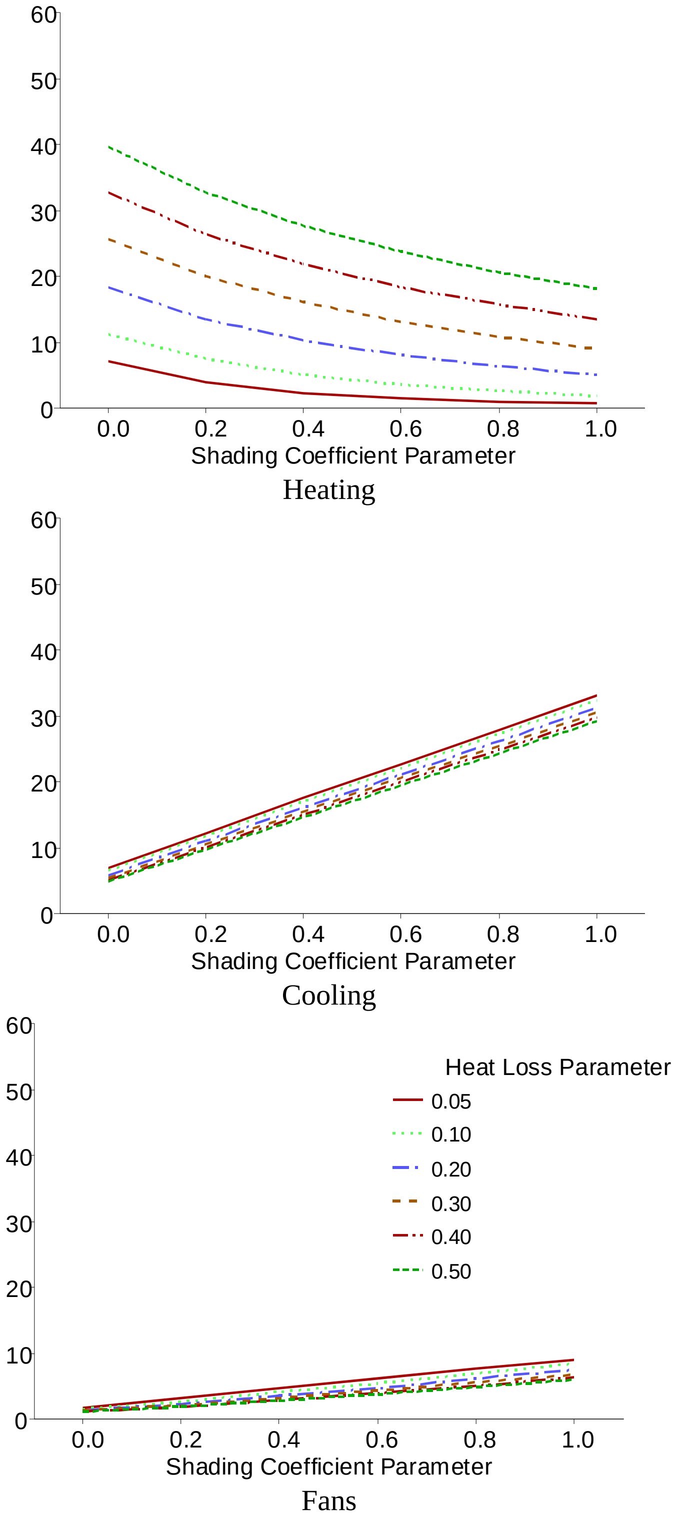

Figure A-16. West Orientation, 43 W/m² (4 W/ft²) Internal Loads[17]

[17] The units for the Y-axis are in kWh/ft². To convert to kWh/m², multiply by 10.76; to convert to MJ/m², multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft²•°F). To convert to W/m²•K, multiply by 5.678.

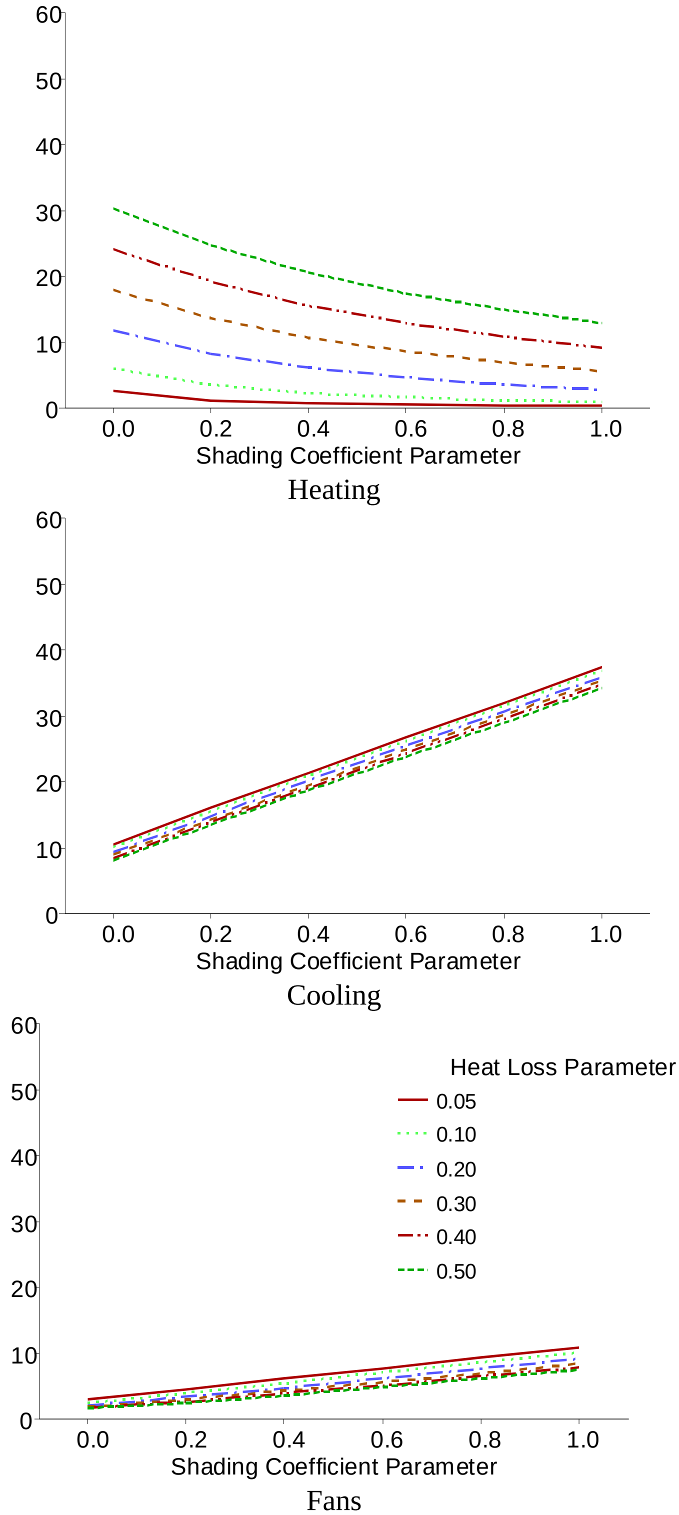

Figure A-17. East Orientation, 64.6 W/m^2 (6 W/ft^2) Internal Loads[18]

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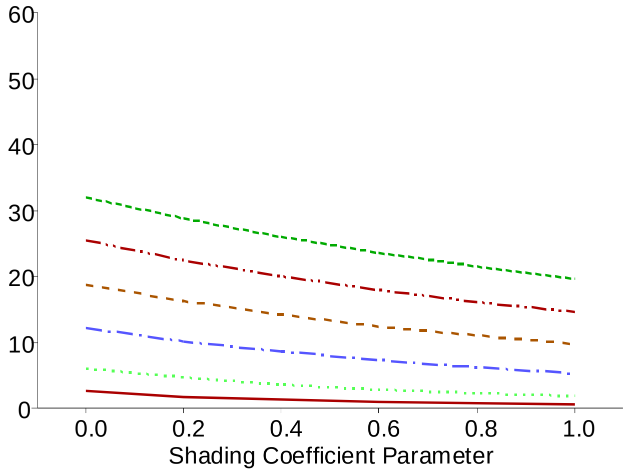
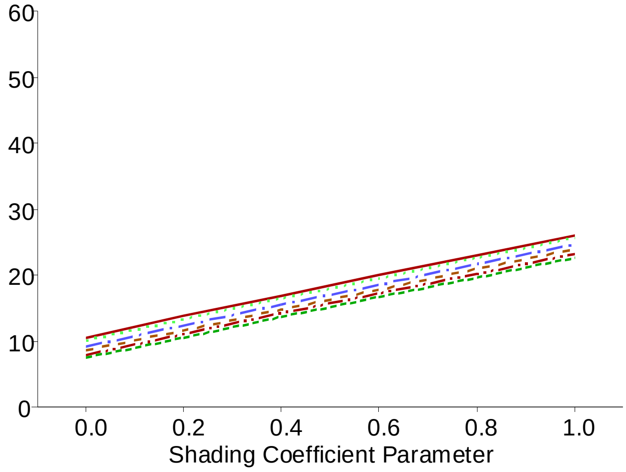
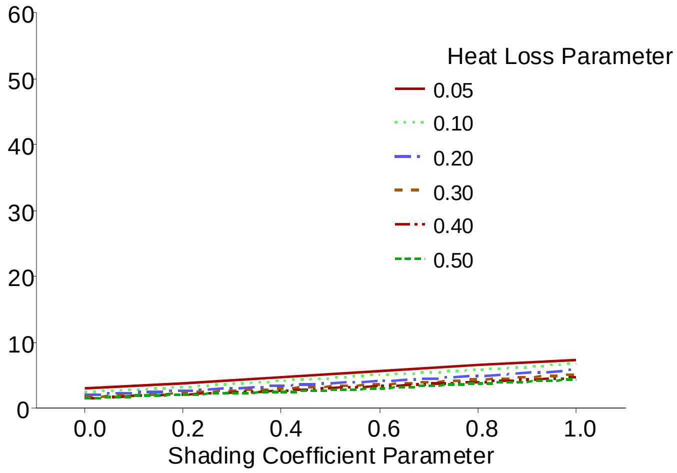
[18] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in $Btu/(h•ft^2•°F)$. To convert to $W/m^2•K$, multiply by 5.678.



Heating



Cooling



Fans

Figure A-18. North Orientation, 64.6 W/m^2 (6 W/ft^2) Internal Loads[19]

[19] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.

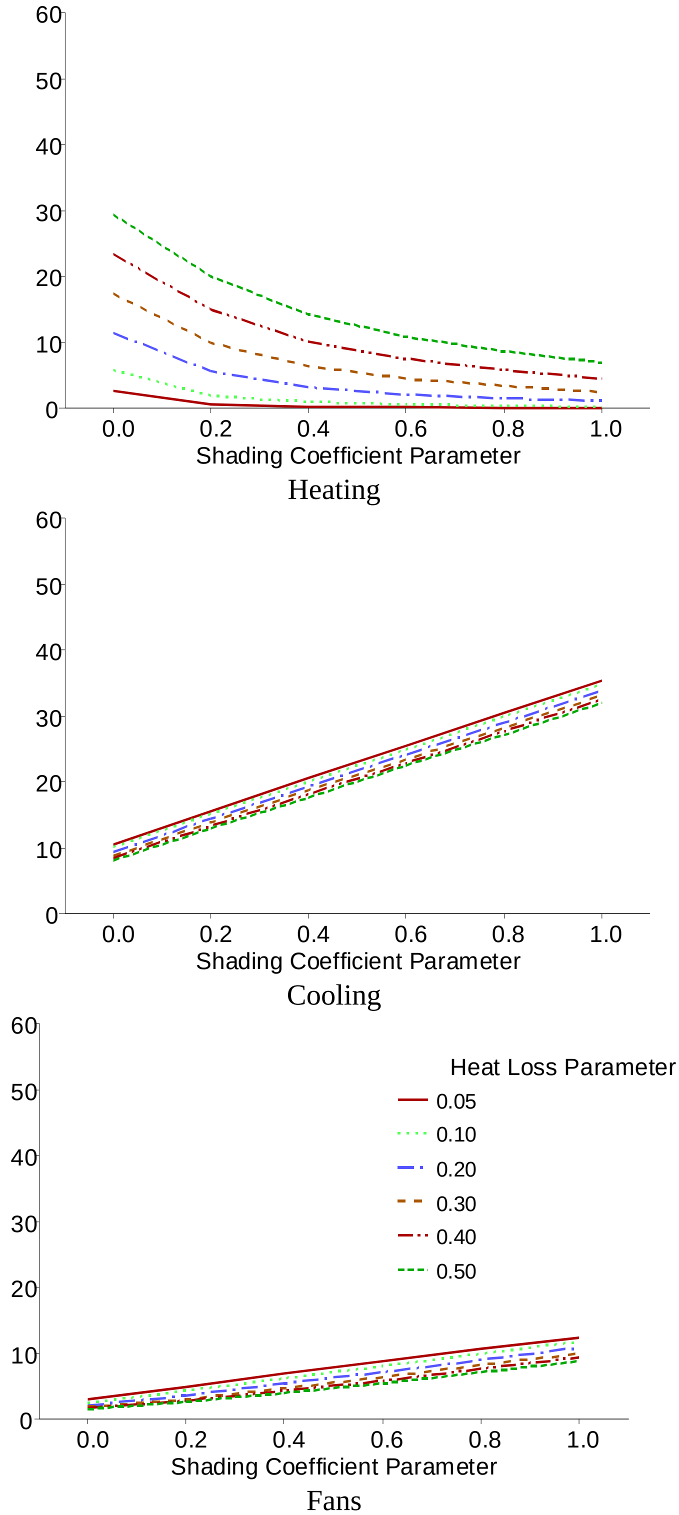


Figure A-19. South Orientation, 64.6 W/m² (6 W/ft²) Internal Loads[20]

[20] The units for the Y-axis are in kWh/ft². To convert to kWh/m², multiply by 10.76; to convert to MJ/m², multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft²•°F). To convert to W/m²•K, multiply by 5.678.

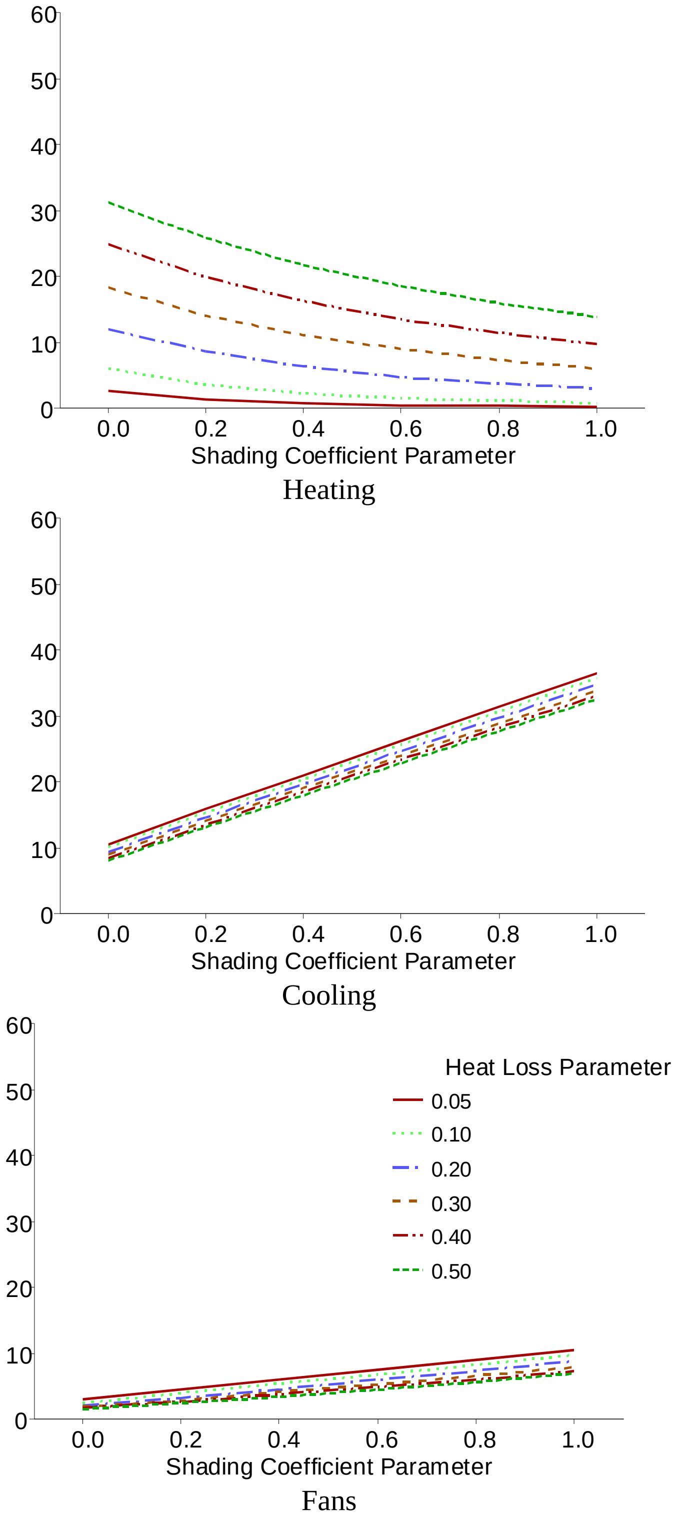


Figure A-20. West Orientation, 64.6 W/m² (6 W/ft²) Internal Loads[21]

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[21] The units for the Y-axis are in kWh/ft². To convert to kWh/m², multiply by 10.76; to convert to MJ/m², multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft²•°F). To convert to W/m²•K, multiply by 5.678.

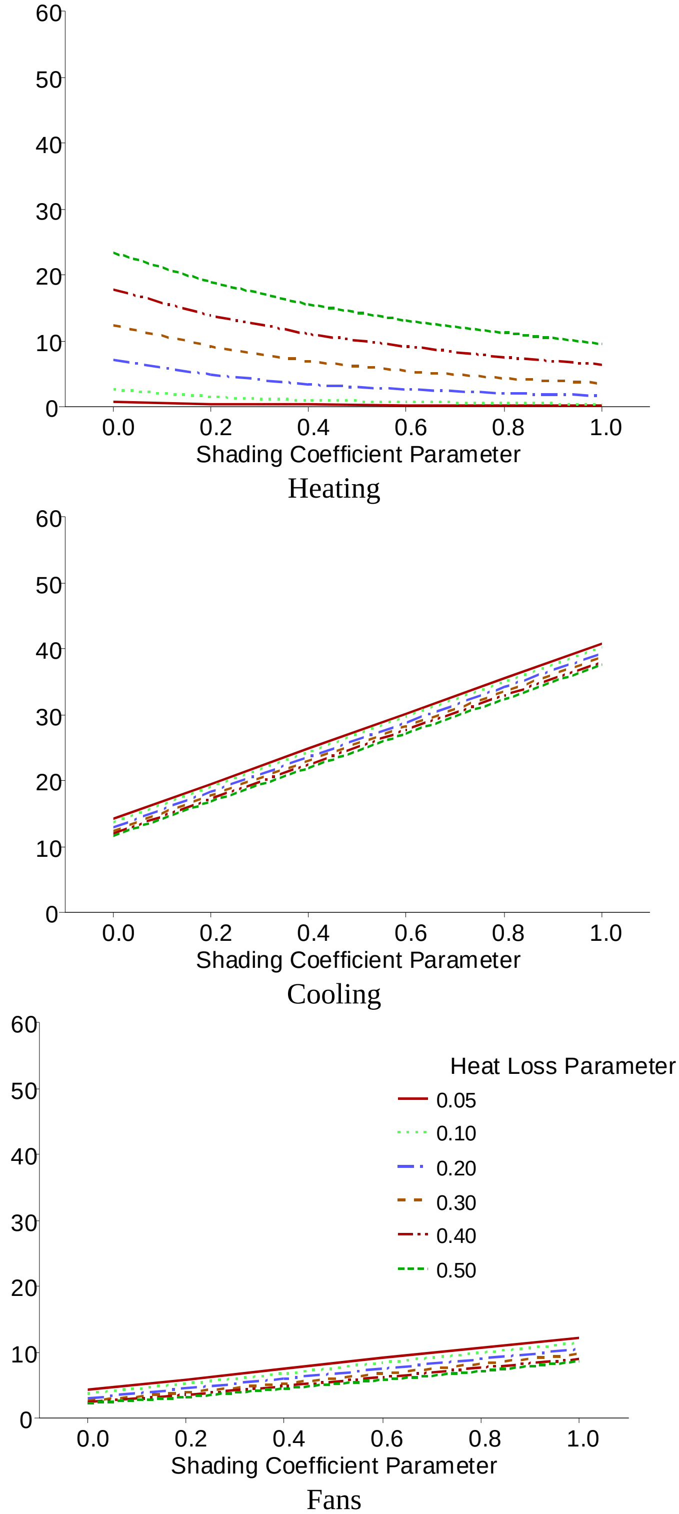

Figure A-21. East Orientation, 86.1 W/m^2 (8 W/ft^2) Internal Loads[22]

[22] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.

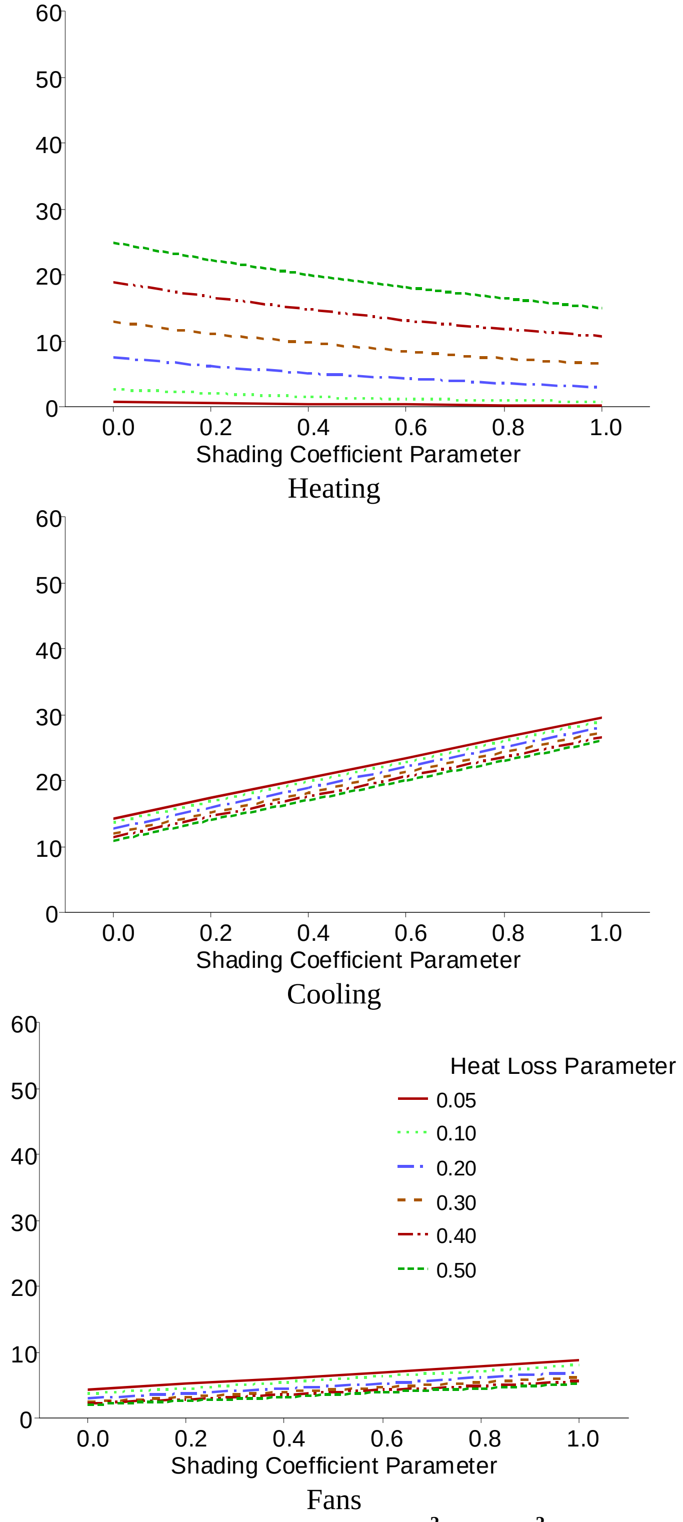

Figure A-22. North Orientation, 86.1 W/m^2 (8 W/ft^2) Internal Loads[23]

[23] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.

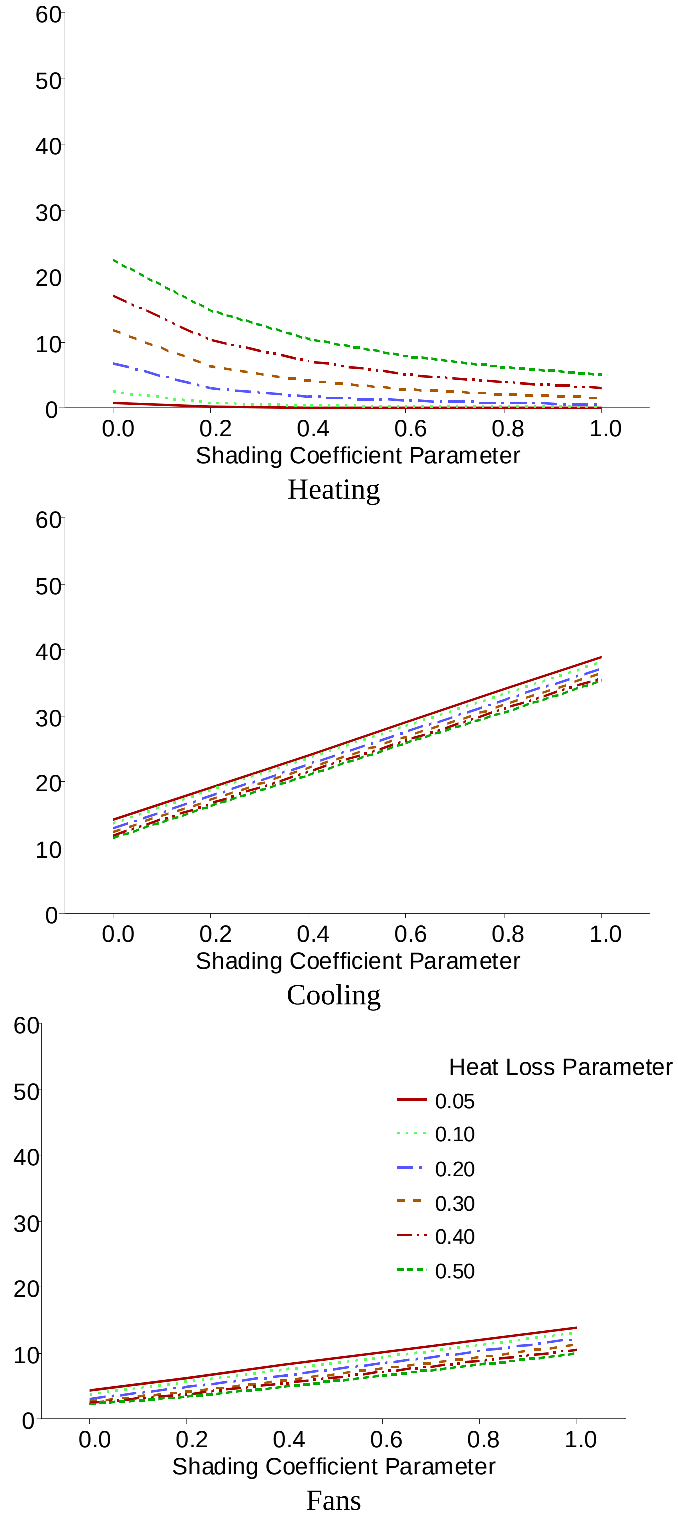

Figure A-23. South Orientation, 86.1 W/m^2 (8 W/ft^2) Internal Loads[24]

[24] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.

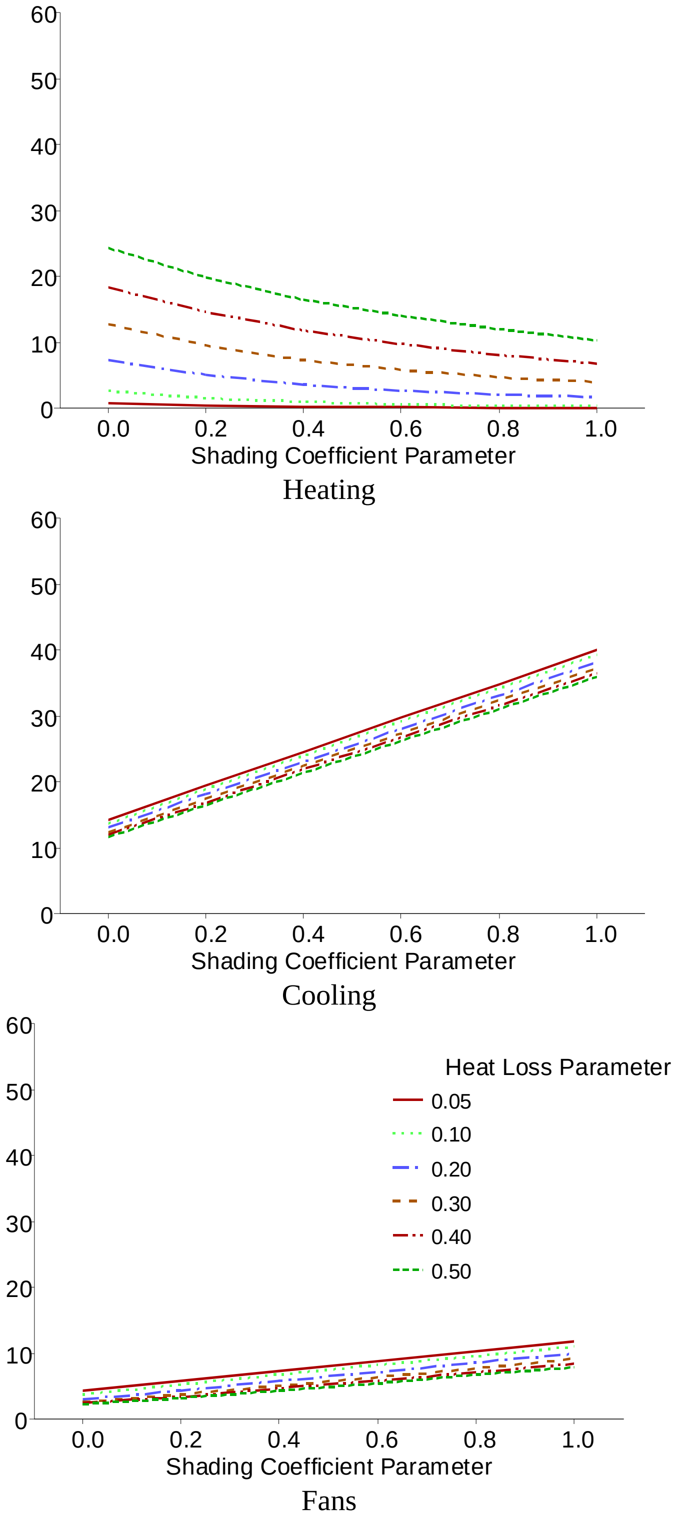

Figure A-24. West Orientation, 86.1 W/m^2 (8 W/ft^2) Internal Loads[25]

[25] The units for the Y-axis are in kWh/ft^2. To convert to kWh/m^2, multiply by 10.76; to convert to MJ/m^2, multiply by 38.75. The heat loss parameters are U-values in Btu/(h•ft^2•°F). To convert to W/m^2•K, multiply by 5.678.

Appendix B
Prescriptive Envelope Requirements and Results of Evaluation of Utility Incentives

B.1 Introduction

Appendix B contains the tables of building envelope requirements developed specifically for five Ontario locations (Ottawa, Sault Ste. Marie, Schefferville, Toronto, and Windsor) and the results of the DOE-2.1E simulations and cost-effectiveness calculations for the wall insulation, roof insulation, and fenestration options evaluated for utility incentives and described in Chapters 3 and 4.

B.2 Simplified Building Envelope Requirements for Ontario

Tables B-1 through B-5 were developed using the trade-off software in ASHRAE Standard 90.1-1989 for specific climate conditions in Ontario. Crawley (1994) provides more information about the method used to generate the specific values. These five tables of simplified building envelope requirements were the baseline used to define the DOE-2.1E building model described in Section 3.3. The table number in parentheses refers to the Standard 90.1 Alternate Compliance Method table.

B.3 Energy and Economic Performance Results for Wall, Roof and Fenestration Cases

Tables B-6 through B-10 present wall insulation simulation results for the five locations. Similarly, Tables B-11 through B-15 present roof insulation simulation results for the five locations. Finally, Tables B-16 through B-20 present fenestration simulation results for the five Ontario locations. All fenestration options in Tables B-16 through B-20 are double-pane glazing. Visionwall has two panes of glass, two low-e films, a krypton gas fill, and a well-constructed, thermally broken frame.

Table B-1. (Table 8A-31) Simplified Building Envelope Requirements

Fenestration-to-Wall Ratio	Shading Coefficient (SC)	Maximum overall U-Value (U_{of}) for Fenestration, W/(m^2-K)	
		Heated and Cooled Building	Heated-Only Building
≤ 0.2	≥ 0.80	4.2	4.03
	0.60-0.79	4.2	3.41
	0.40-0.59	4.2	2.73
	0.20-0.39	4.2	2.04
	0.00-0.19	4.2	1.25
0.21-0.40	≥ 0.80	NA	3.35
	0.60-0.79	NA	2.84
	0.40 -0.59	1.87	2.27
	0.20-0.39	2.84	1.65
	0.00-0.19	3.41	0.91
0.41-0.60	≥ 0.80	NA	2.95
	0.60-0.79	NA	2.56
	0.40-0.59	NA	2.10
	020-0.39	1.48	1.48
	0.00-0.19	2.27	0.74

Opaque Envelope Component		Maximum Overall U-Value, W/(m^2-K)
Opaque Wall	Heat Capacity, W/(m-K)	
	HC < 17	0.449
	17 ≤ HC < 26	0.483
	HC ≥ 26	0.511
Roof		0.278
Wall Adjacent to Unconditioned Space		0.68
Floor Over Unconditioned Space		0.25

Opaque Envelope Component			Minimum Overall R-Value, m^2-K/W
Wall Below Grade			1.76
Unheated Slab on Grade	Insulation Position	Depth or Width, m	
	Horizontal	0.6	3.17
		0.9	2.64
		1.2	1.94
	Vertical	0.6	1.41
		0.9	1.06
		1.2	0.70
Heated Slab on Grade	Insulation Position	Depth or Width, m	
	Horizontal	0.6	3.52
		0.9	2.99
		1.2	2.29
	Vertical	0.6	1.76
		0.9	1.41
		1.2	1.06

Table B-2. (Table 8A-32) Simplified Building Envelope Requirements

Fenestration-to-Wall Ratio	Shading Coefficient (SC)	Maximum Overall U-Value (U_{of}) for Fenestration, W/(m^2-K)	
		Heated and Cooled Building	Heated-Only Building
≤ 0.2	≥ 0.80	4.20	3.63
	0.60-0.79	4.20	3.01
	0.40-0.59	4.20	2.38
	0.20-0.39	4.20	1.76
	0.00-0.19	4.20	1.02
0.21-0.40	≥ 0.80	NA	3.01
	0.60 - 0.79	NA	2.56
	0.40-0.59	2.10	2.04
	0.20-0.39	2.61	1.42
	0.00-0.19	2.95	0.74
0.41-0.60	≥ 0.80	NA	2.67
	0.60-0.79	NA	2.33
	0.40-0.59	NA	1.87
	0.20-0.39	1.59	1.31
	0.00-0.19	2.04	0.62

Opaque Envelope Component		Maximum Overall U-Value, W/(m^2-K)
Opaque Wall	Heat Capacity, W/(m-K)	
	HC < 17	0.426
	17 ≤ HC < 26	0.466
	HC ≥ 26	0.494
Roof		0.278
Wall Adjacent to Unconditioned Space		0.62
Floor Over Unconditioned Space		0.227

Opaque Envelope Component			Minimum Overall R-Value, m^2-K/W
Wall Below Grade			1.94
Unheated Slab on Grade	Insulation Position	Depth or Width, m	
	Horizontal	0.6	3.17
		0.9	2.64
		1.2	1.94
	Vertical	0.6	1.41
		0.9	1.06
		1.2	0.70
Heated Slab on Grade	Insulation Position	Depth or Width, m	
	Horizontal	0.6	3.52
		0.9	2.99
		1.2	2.29
	Vertical	0.6	1.76
		0.9	1.41
		1.2	1.06

Table B-3. (Table 8A-33) Simplified Building Envelope Requirements

Fenestration-to-Wall Ratio	Shading Coefficient (SC)	Maximum Overall U-Value (U_{of}) for Fenestration, W/(m^2-K)	
		Heated and Cooled Building	Heated-Only Building
≤ 0.2	≥ 0.80	4.20	3.58
	0.60-0.79	4.20	3.01
	0.40-0.59	4.20	2.38
	0.20-0.39	4.20	1.76
	0.00-0.19	4.20	1.02
0.21-0.40	≥ 0.80	NA	2.95
	0.60-0.79	NA	2.50
	0.40-0.59	2.27	1.99
	0.20-0.39	2.56	1.42
	0.00-0.19	2.67	0.68
0.41-0.60	≥ 0.80	NA	2.56
	0.60-0.79	NA	2.21
	0.40-0.59	NA	1.82
	0.20-0.39	1.65	1.25
	0.00-0.19	1.87	0.62

Opaque Envelope Component		Maximum Overall U-Value, W/(m^2-K)
Opaque Wall	Heat Capacity, W/(m-K)	
	HC < 17	0.380
	17 ≤ HC < 26	0.409
	HC ≥ 26	0.432
Roof		0.256
Wall Adjacent to Unconditioned Space		0.62
Floor Over Unconditioned Space		0.221

Opaque Envelope Component			Minimum Overall R-Value, m^2-K/W
Wall Below Grade			2.11
Unheated Slab on Grade	Insulation Position	Depth or Width, m	
	Horizontal	0.6	3.17
		0.9	2.64
		1.2	1.94
	Vertical	0.6	1.41
		0.9	1.06
		1.2	0.70
Heated Slab on Grade	Insulation Position	Depth or Width, m	
	Horizontal	0.6	3.52
		0.9	2.99
		1.2	2.29
	Vertical	0.6	1.76
		0.9	1.41
		1.2	1.06

Table B-4. (Table 8A-36) Simplified Building Envelope Requirements

Fenestration-to-Wall Ratio	Shading Coefficient (SC)	Maximum Overall U-Value (U_{of}) for Fenestration, W/(m^2-K)	
		Heated and Cooled Building	Heated-Only Building
≤ 0.2	≥ 0.80	4.20	3.58
	0.60-0.79	4.20	3.01
	0.40-0.59	4.20	2.44
	0.20-0.39	4.20	1.87
	0.00-0.19	4.20	1.14
0.21-0.40	≥ 0.80	NA	2.90
	0.60-0.79	2.04	2.44
	0.40-0.59	2.33	1.99
	0.20-0.39	2.44	1.42
	0.00-0.19	2.44	0.74
0.41-0.60	≥ 0.80	NA	2.50
	0.60-0.79	NA	2.16
	0.40-0.59	1.31	1.76
	0.20-0.39	1.70	1.25
	0.00-0.19	1.76	0.62

Opaque Envelope Component		Maximum Overall U-Value, W/(m^2-K)
Opaque Wall	Heat Capacity, W/(m-K)	
	HC < 17	0.335
	17 ≤ HC < 26	0.352
	HC ≥ 26	0.363
Roof		0.227
Wall Adjacent to Unconditioned Space		0.57
Floor Over Unconditioned Space		0.221

Opaque Envelope Component			Minimum Overall R-Value, m^2-K/W
Wall Below Grade			2.29
Unheated Slab on Grade	Insulation Position	Depth or Width, m	
	Horizontal	0.6	3.17
		0.9	2.64
		1.2	1.94
	Vertical	0.6	1.41
		0.9	1.06
		1.2	0.70
Heated Slab on Grade	Insulation Position	Depth or Width, m	
	Horizontal	0.6	3.52
		0.9	2.99
		1.2	2.29
	Vertical	0.6	1.76
		0.9	1.41
		1.2	1.06

Table B-5. (Table 8A-38) Simplified Building Envelope Requirements

Fenestration-to-Wall Ratio	Shading Coefficient (SC)	Maximum Overall U-Value (U_{of}) for Fenestration, W/(m^2-K)	
		Heated and Cooled Building	Heated-Only Building
≤ 0.2	≥ 0.80	4.20	3.80
	0.60-0.79	4.20	3.29
	0.40-0.59	4.20	2.78
	0.20-0.39	4.20	2.21
	0.00-0.19	4.20	1.53
0.21-0.40	≥ 0.80	1.76	2.90
	0.60-0.79	2.21	2.50
	0.40-0.59	2.38	2.04
	0.20.0.39	2.44	1.53
	0.00-0.19	2.38	0.91
0.41-0.60	≥ 0.80	NA	2.38
	0,60-0.79	NA	2.16
	0.40-0.59	1.48	1.76
	0.20-0.39	1.70	1.31
	0.00-0.19	1.70	0.68

Opaque Envelope Component		Maximum Overall U-Value, W/(m^2-K)
Opaque Wall	Heat Capacity, W/(m-K)	
	HC < 17	0.261
	17 ≤ HC < 26	0.261
	HC ≥ 26	0.267
Roof		0.176
Wall Adjacent to Unconditioned Space		0.494
Floor Over Unconditioned Space		0.227

Opaque Envelope Component			Minimum Overall R-Value, m^2-K/W
Wall Below Grade			2.82
Unheated Slab on Grade	Insulation Position	Depth or Width, m	
	Horizontal	0.6	3.17
		0.9	2.64
		1.2	1.94
	Vertical	0.6	1.41
		0.9	1.06
		1.2	0.70
Heated Slab on Grade	Insulation Position	Depth or Width, m	
	Horizontal	0.6	3.52
		0.9	2.99
		1.2	2.29
	Vertical	0.6	1.76
		0.9	1.41
		1.2	1.06

Table B-6. Simulation Results for Wall Insulation Options in Ottawa

Internal Loads, W/m²	Fenestration-to-Wall Ratio	Add Wall Insulation, mm	Annual Energy Performance		Wall Area, m²
			kWh	kWh/m²	
21.5	0.2	Baseline	135,472	244.77	356.9
		19 mm (R 0.7)	132,142	238.80	
		38 mm (R 1.4)	129,996	234.96	
	0.4	Baseline	158,846	286.69	267.7
		19 mm (R 0.7)	156,411	282.32	
		38 mm (R 1.4)	154,820	279.47	
	0.6	Baseline	183,058	330.11	178.4
		19 mm (R 0.7)	181,449	327.22	
		38 mm (R 1.4)	180,407	325.36	
43.0	0.2	Baseline	171,996	310.28	356.9
		19 mm (R 0.7)	169,100	305.08	
		38 mm (R 1.4)	167,255	301.77	
	0.4	Baseline	195,601	352.61	267.7
		19 mm (R 0.7)	193,429	348.71	
		38 mm (R 1.4)	192,015	346.17	
	0.6	Baseline	220,175	396.67	178.4
		19 mm (R 0.7)	218,687	394.00	
		38 mm (R 1.4)	217,741	392.31	

Table B-7. Simulation Results for Wall Insulation Options in Sault Ste. Marie

Internal Loads, W/m²	Fenestration-to-Wall Ratio	Add Wall Insulation, mm	Annual Energy Performance		Wall Area, m²
			kWh	kWh/m²	
21.5	0.2	Baseline	130,415	235.87	356.9
		19 mm (R 0.7)	127,737	231.06	
		38 mm (R 1.4)	125,923	227.81	
	0.4	Baseline	154,053	278.25	267.7
		19 mm (R 0.7)	152,069	274.70	
		38 mm (R 1.4)	150,717	272.27	
	0.6	Baseline	178,704	322.47	178.4
		19 mm (R 0.7)	177,430	320.19	
		38 mm (R 1.4)	176,556	318.61	
43.0	0.2	Baseline	165,677	299.11	356.9
		19 mm (R 0.7)	163,382	294.99	
		38 mm (R 1.4)	161,826	292.20	
	0.4	Baseline	189,599	342.00	267.7
		19 mm (R 0.7)	187,829	338.82	
		38 mm (R 1.4)	186,640	336.69	
	0.6	Baseline	214,399	386.48	178.4
		19 mm (R 0.7)	213,240	384.40	
		38 mm (R 1.4)	212,448	382.98	

Table B-8. Simulation Results for Wall Insulation Options in Schefferville

Internal Loads, W/m^2	Fenestration-to-Wall Ratio	Add Wall Insulation, mm	Annual Energy Performance		Wall Area, m^2
			kWh	kWh/m^2	
21.5	0.2	Baseline	170,587	308.58	356.9
		19 mm (R 0.7)	167,952	303.85	
		38 mm (R 1.4)	166,020	300.39	
	0.4	Baseline	203,155	366.98	267.7
		19 mm (R 0.7)	201,204	363.48	
		38 mm (R 1.4)	199,789	360.94	
	0.6	Baseline	236,728	427.19	178.4
		19 mm (R 0.7)	235,448	424.90	
		38 mm (R 1.4)	234,516	423.22	
43.0	0.2	Baseline	193,027	348.82	356.9
		19 mm (R 0.7)	190,607	344.48	
		38 mm (R 1.4)	188,849	341.33	
	0.4	Baseline	226,266	408.43	267.7
		19 mm (R 0.7)	224,438	405.16	
		38 mm (R 1.4)	223,110	402.77	
	0.6	Baseline	260,330	469.51	178.4
		19 mm (R 0.7)	259,106	467.33	
		38 mm (R 1.4)	258,234	465.76	

Table B-9. Simulation Results for Wall Insulation Options in Toronto

Internal Loads, (W/m^2)	Fenestration-to-Wall Ratio	Add Wall Insulation, mm	Annual Energy Performance		Wall Area, m^2
			kWh	kWh/m^2	
21.5	0.2	Baseline	126,830	229.23	356.9
		19 mm (R 0.7)	123,263	222.84	
		38 mm (R 1.4)	121,072	218.91	
	0.4	Baseline	149,063	269.11	267.7
		19 mm (R 0.7)	146,477	264.47	
		38 mm (R 1.4)	144,875	261.60	
	0.6	Baseline	172,079	310.38	178.4
		19 mm (R 0.7)	170,374	307.32	
		38 mm (R 1.4)	169,313	305.42	
43.0	0.2	Baseline	164,952	297.60	356.9
		19 mm (R 0.7)	161,904	292.13	
		38 mm (R 1.4)	160,075	288.85	
	0.4	Baseline	187,233	337.55	267.7
		19 mm (R 0.7)	184,967	333.50	
		38 mm (R 1.4)	183,592	331.03	
	0.6	Baseline	210,149	378.64	178.4
		19 mm (R 0.7)	208,615	375.90	
		38 mm (R 1.4)	207,665	374.19	

Table B-10. Simulation Results for Wall Insulation Options in Windsor

Internal Loads, W/m²	Fenestration-to-Wall Ratio	Add Wall Insulation, mm	Annual Energy Performance		Wall Area, m²
			kWh	kWh/m²	
21.5	0.2	Baseline	121,756	219.92	356.9
		19 mm (R 0.7)	118,263	213.66	
		38 mm (R 1.4)	116,811	211.06	
	0.4	Baseline	144,959	261.53	267.7
		19 mm (R 0.7)	142,446	257.03	
		38 mm (R 1.4)	140,919	254.29	
	0.6	Baseline	168,179	303.17	178.4
		19 mm (R 0.7)	166,551	300.26	
		38 mm (R 1.4)	165,549	298.46	
43.0	0.2	Baseline	164,208	296.06	356.9
		19 mm (R 0.7)	161,302	290.84	
		38 mm (R 1.4)	160,184	288.84	
	0.4	Baseline	187,135	337.18	267.7
		19 mm (R 0.7)	184,998	333.34	
		38 mm (R 1.4)	183,712	331.03	
	0.6	Baseline	210,128	378.41	178.4
		19 mm (R 0.7)	208,661	375.77	
		38 mm (R 1.4)	207,780	374.19	

Table B-11. Simulation Results for Roof Insulation Options in Ottawa

Internal Loads, W/m²	Fenestration-to-Wall Ratio	Add Roof Insulation, mm	Annual Energy Performance	
			kWh	kWh/m²
21.5	0.2	Baseline	150,124	271.04
		50 mm (R 1.8)	147,388	266.14
		100 mm (R 3.5)	144,558	261.07
	0.4	Baseline	175,598	316.73
		50 mm (R 1.8)	170,345	307.31
		100 mm (R 3.5)	167,608	302.40
	0.6	Baseline	199,489	359.58
		50 mm (R 1.8)	194,359	350.38
		100 mm (R 3.5)	191,675	345.57
43.0	0.2	Baseline	185,198	333.95
		50 mm (R 1.8)	182,727	329.51
		100 mm (R 3.5)	180,211	325.01
	0.4	Baseline	211,119	380.43
		50 mm (R 1.8)	206,268	371.74
		100 mm (R 3.5)	203,769	367.25
	0.6	Baseline	235,463	424.08
		50 mm (R 1.8)	230,661	415.48
		100 mm (R 3.5)	228,174	411.01

Table B-12. Simulation Results for Roof Insulation Options in Sault Ste. Marie

Internal Loads, W/m²	Fenestration-to-Wall Ratio	Add Roof Insulation, mm	Annual Energy Performance	
			kWh	kWh/m²
21.5	0.2	Baseline	146,221	264.21
		50 mm (R 1.8)	141,659	256.03
		100 mm (R 3.5)	139,136	251.50
	0.4	Baseline	169,251	305.51
		50 mm (R 1.8)	164,881	297.68
		100 mm (R 3.5)	162,456	293.33
	0.6	Baseline	193,549	349.09
		50 mm (R 1.8)	189,274	341.43
		100 mm (R 3.5)	186,903	337.16
43.0	0.2	Baseline	179,611	324.09
		50 mm (R 1.8)	175,568	316.84
		100 mm (R 3.5)	173,305	312.78
	0.4	Baseline	203,391	366.73
		50 mm (R 1.8)	199,388	359.56
		100 mm (R 3.5)	197,189	355.61
	0.6	Baseline	228,094	411.03
		50 mm (R 1.8)	224,104	403.88
		100 mm (R 3.5)	221,919	399.96

Table B-13. Simulation Results for Roof Insulation Options in Schefferville

Internal Loads, W/m²	Fenestration-to-Wall Ratio	Add Roof Insulation, mm	Annual Energy Performance	
			kWh	kWh/m²
21.5	0.2	Baseline	188,928	341.47
		50 mm (R 1.8)	184,594	333.70
		100 mm (R 3.5)	181,891	328.85
	0.4	Baseline	221,128	399.22
		50 mm (R 1.8)	216,869	391.58
		100 mm (R 3.5)	214,242	386.87
	0.6	Baseline	254,438	458.95
		50 mm (R 1.8)	250,232	451.41
		100 mm (R 3.5)	247,653	446.79
43.0	0.2	Baseline	210,063	379.38
		50 mm (R 1.8)	206,011	372.10
		100 mm (R 3.5)	203,490	367.58
	0.4	Baseline	243,284	438.94
		50 mm (R 1.8)	239,252	431.71
		100 mm (R 3.5)	236,751	427.24
	0.6	Baseline	277,239	499.85
		50 mm (R 1.8)	273,178	492.56
		100 mm (R 3.5)	270,718	488.15

Table B-14. Simulation Results for Roof Insulation Options in Toronto

Internal Loads, W/m^2	Fenestration-to-Wall Ratio	Add Roof Insulation, mm	Annual Energy Performance	
			kWh	kWh/m^2
21.5	0.2	Baseline	143,508	259.14
		50 mm (R 1.8)	137,787	248.88
		100 mm (R 3.5)	134,596	243.15
	0.4	Baseline	165,513	298.60
		50 mm (R 1.8)	159,961	288.65
		100 mm (R 3.5)	157,210	283.71
	0.6	Baseline	188,026	338.97
		50 mm (R 1.8)	182,741	329.50
		100 mm (R 3.5)	180,105	324.77
43.0	0.2	Baseline	179,554	323.78
		50 mm (R 1.8)	174,196	314.17
		100 mm (R 3.5)	171,664	309.63
	0.4	Baseline	202,024	364.08
		50 mm (R 1.8)	197,033	355.13
		100 mm (R 3.5)	194,563	350.70
	0.6	Baseline	224,805	404.93
		50 mm (R 1.8)	219,902	396.14
		100 mm (R 3.5)	217,488	391.81

Table B-15. Simulation Results for Roof Insulation Options in Windsor

Internal Loads, W/m^2	Fenestration-to-Wall Ratio	Add Roof Insulation, mm	Annual Energy Performance	
			kWh	kWh/m^2
21.5	0.2	Baseline	136,655	246.65
		50 mm (R 1.8)	131,625	237.62
		100 mm (R 3.5)	129,151	233.19
	0.4	Baseline	158,368	285.58
		50 mm (R 1.8)	153,651	277.12
		100 mm (R 3.5)	151,302	272.92
	0.6	Baseline	181,319	326.75
		50 mm (R 1.8)	177,406	319.72
		100 mm (R 3.5)	175,089	315.57
43.0	0.2	Baseline	177,074	319.13
		50 mm (R 1.8)	172,659	311.21
		100 mm (R 3.5)	170,504	307.35
	0.4	Baseline	199,014	358.48
		50 mm (R 1.8)	194,788	350.89
		100 mm (R 3.5)	192,698	347.15
	0.6	Baseline	221,988	399.68
		50 mm (R 1.8)	218,430	393.29
		100 mm (R 3.5)	216,343	389.56

Table B-16. Simulation Results for Fenestration Options in Ottawa

Internal Loads, W/m²	Fenestration -to-Wall Ratio	Fenestration Option	Annual Energy Performance		Fenestration Area, m²
			kWh	kWh/m²	
21.5	0.2	Aluminum Frame	135,472	244.77	89.2
		Thermal Break Frame	134,918	243.78	
		Vinyl Frame	134,480	242.99	
		Low-E (e=0.4)	131,828	238.24	
		Low-E (e=0.2)	121,744	220.15	
		Low-E (e=0.1)	119,467	216.07	
		Visionwall	114,216	206.66	
	0.4	Aluminum Frame	158,846	286.69	178.4
		Thermal Break Frame	158,311	285.73	
		Vinyl Frame	157,887	284.97	
		Low-E (e=0.4)	152,581	275.46	
		Low-E (e=0.2)	133,595	241.41	
		Low-E (e=0.1)	128,080	231.51	
		Visionwall	116,936	211.53	
	0.6	Aluminum Frame	183,058	330.11	267.7
		Thermal Break Frame	182,526	329.16	
		Vinyl Frame	182,096	328.38	
		Low-E (e=0.4)	174,213	314.25	
		Low-E (e-0.2)	147,283	265.95	
		Low-E (e=0.1)	138,247	249.75	
		Visionwall	121,466	219.65	
43.0	0.2	Aluminum Frame	171,996	310.28	89.2
		Thermal Break Frame	171,549	309.47	
		Vinyl Frame	171,190	308.82	
		Low-E (e=0.4)	168,789	304.52	
		Low-E (e=0.2)	160,572	289.79	
		Low-E (e=0.1)	157,934	285.05	
		Visionwall	152,638	275.55	
	0.4	Aluminum Frame	195,601	352.61	178.4
		Thermal Break Frame	195,141	351.78	
		Vinyl Frame	194,771	351.11	
		Low-E (e=0.4)	190,112	342.76	
		Low-E (e=0.2)	174,202	314.22	
		Low-E (e=0.1)	168,325	303.69	
		Visionwall	157,836	284.88	
	0.6	Aluminum Frame	220,175	396.67	267.7
		Thermal Break Frame	219,700	395.82	
		Vinyl Frame	219,313	395.13	
		Low-E (e=0.4)	211,894	381.82	
		Low-E (e=0.2)	189,068	340.89	
		Low-E (e=0.1)	179,429	323.60	
		Visionwall	163,912	295.77	

Table B-17. Simulation Results for Fenestration Options in Sault Ste. Marie

Internal Loads, W/m²	Fenestration-to-Wall Ratio	Fenestration Option	Annual Energy Performance		Fenestration Area, m²
			kWh	kWh/m²	
21.5	0.2	Aluminum Frame	130,415	235.87	89.2
		Thermal Break Frame	129,827	234.82	
		Vinyl Frame	129,343	233.94	
		Low-E (e-0.4)	126,697	229.20	
		Low-E (e=0.2)	116,513	210.93	
		Low-E (e=0.1)	114,501	207.32	
		Visionwall	109,126	197.68	
	0.4	Aluminum Frame	154,053	278.25	178.4
		Thermal Break Frame	153,470	277.21	
		Vinyl Frame	153,006	276.38	
		Low-E (e=0.4)	147,677	266.83	
		Low-E (e=0.2)	128,923	233.19	
		Low-E (e=0.1)	123,602	223.65	
		Visionwall	112,250	203.29	
	0.6	Aluminum Frame	178,704	322.47	267.7
		Thermal Break Frame	178,134	321.44	
		Vinyl Frame	177,685	320.64	
		Low-E (e=0.4)	169,854	306.60	
		Low-E (e=0.2)	142,047	256.72	
		Low-E (e=0.1)	134,236	242.71	
		Visionwall	116,391	210.71	
43.0	0.2	Aluminum Frame	165,677	299.11	89.2
		Thermal Break Frame	165,191	298.23	
		Vinyl Frame	164,808	297.55	
		Low-E (e=0.4)	162,430	293.27	
		Low-E (e=0.2)	154,352	278.79	
		Low-E (e=0.1)	151,663	273.97	
		Visionwall	146,413	264.56	
	0.4	Aluminum Frame	189,599	342.00	178.4
		Thermal Break Frame	189,108	341.12	
		Vinyl Frame	188,700	340.39	
		Low-E (e=0.4)	183,906	331.80	
		Low-E (e=0.2)	168,559	304.27	
		Low-E (e=0.1)	162,530	293.46	
		Visionwall	151,871	274.34	
	0.6	Aluminum Frame	214,399	386.48	267.7
		Thermal Break Frame	213,905	385.58	
		Vinyl Frame	213,489	384.84	
		Low-E (e=0.4)	206,153	371.69	
		Low-E (e=0.2)	182,668	329.57	
		Low-E (e=0.1)	174,218	314.42	
		Visionwall	157,637	284.69	

Table B-18. Simulation Results for Fenestration Options in Schefferville

Internal Loads, W/m^2	Fenestration-to-Wall Ratio	Fenestration Option	Annual Energy Performance		Fenestration Area, m^2
			kWh	kWh/m^2	
21.5	0.2	Aluminum Frame	170,587	308.58	89.2
		Thermal Break Frame	169,611	306.83	
		Vinyl Frame	168,814	305.40	
		Low-E (e=0.4)	164,638	297.91	
		Low-E (e=0.2)	147,449	267.08	
		Low-E (e=0.1)	145,851	264.22	
		Visionwall	137,913	249.99	
	0.4	Aluminum Frame	203,155	366.98	178.4
		Thermal Break Frame	202,195	365.26	
		Vinyl Frame	201,401	363.84	
		Low-E (e=0.4)	193,051	348.87	
		Low-E (e=0.2)	160,206	289.96	
		Low-E (e=0.1)	155,558	281.62	
		Visionwall	139,191	252.28	
	0.6	Aluminum Frame	236,728	427.19	267.7
		Thermal Break Frame	235,772	425.48	
		Vinyl Frame	234,998	424.09	
		Low-E (e=0.4)	222,550	401.77	
		Low-E (e=0.2)	175,134	316.73	
		Low-E (e=0.1)	167,020	302.18	
		Visionwall	142,312	257.87	
43.0	0.2	Aluminum Frame	193,027	348.82	89.2
		Thermal Break Frame	192,161	347.27	
		Vinyl Frame	191,449	345.99	
		Low-E (e=0.4)	187,549	338.99	
		Low-E (e=0.2)	172,636	312.26	
		Low-E (e=0.1)	170,289	308.05	
		Visionwall	162,464	294.02	
	0.4	Aluminum Frame	226,266	408.43	178.4
		Thermal Break Frame	225,391	406.86	
		Vinyl Frame	224,658	405.54	
		Low-E (e=0.4)	216,785	391.43	
		Low -E (e=0.2)	187,783	339.41	
		Low-E (e=0.1)	182,115	329.26	
		Visionwall	166,384	301.04	
	0.6	Aluminum Frame	260,330	469.51	267.7
		Thermal Break Frame	259,435	467.91	
		Vinyl Frame	258,703	466.60	
		Low-E (e=0.4)	246,949	445.52	
		Low-E (e=0.2)	204,111	368.70	
		Low-E (e=0.1)	195,000	352.36	
		Visionwall	171,640	310.47	

Table B-19. Simulation Results for Fenestration Options in Toronto

Internal Loads, W/m²	Fenestration-to-Wall Ratio	Fenestration Option	Annual Energy Performance kWh	Annual Energy Performance kWh/m²	Fenestration Area, m²
21.5	0.2	Aluminum Frame	126,830	229.23	89.2
		Thermal Break Frame	126,355	228.38	
		Vinyl Frame	125,966	227.68	
		Low-E (e=0.4)	123,510	223.28	
		Low-E (e=0.2)	114,774	207.61	
		Low-E (e=0.1)	112,489	203.51	
		Visionwall	106,655	193.06	
	0.4	Aluminum Frame	149,063	269.11	178.4
		Thermal Break Frame	148,588	268.26	
		Vinyl Frame	148,209	267.57	
		Low-E (".4)	143,332	258.83	
		Low-E (e=0.2)	127,182	229.87	
		Low-E (e=0.1)	121,409	219.51	
		Visionwall	110,791	200.47	
	0.6	Aluminum Frame	172,079	310.38	267.7
		Thermal Break Frame	171,609	309.53	
		Vinyl Frame	171,233	308.87	
		Low-E (e=0.4)	164,022	295.93	
		Low-E (e=0.2)	140,749	254.19	
		Low-E (e=0.1)	131,599	237.79	
		Visionwall	115,698	209.27	
43.0	0.2	Aluminum Frame	164,952	297.60	89.2
		Thermal Break Frame	164,570	296.91	
		Vinyl Frame	164,256	296.35	
		Low-E (e=0.4)	162,047	292.38	
		Low-E (e=0.2)	155,194	280.09	
		Low-E (e=0.1)	152,424	275.13	
		Visionwall	146,860	265.15	
	0.4	Aluminum Frame	187,233	337.55	178.4
		Thermal Break Frame	186,839	336.84	
		Vinyl Frame	186,533	336.29	
		Low-E (e=0.4)	182,106	328.36	
		Low-E (e=0.2)	169,117	305.07	
		Low-E (e=0.1)	162,831	293.79	
		Visionwall	153,037	276.23	
	0.6	Aluminum Frame	210,149	378.64	267.7
		Thermal Break Frame	209,749	377.93	
		Vinyl Frame	209,415	377.33	
		Low-E (e=0.4)	202,810	365.48	
		Low-E (e=0.2)	183,574	330.99	
		Low-E (e-0.1)	173,907	313.65	
		Visionwall	159,497	287.81	

Table B-20. Simulation Results for Fenestration Options in Windsor

Internal Loads, W/m²	Fenestration-to-Wall Ratio	Fenestration Option	Annual Energy Performance		Fenestration Area, m²
			kWh	kWh/m²	
21.5	0.2	Aluminum Frame	121,756	219.92	89.2
		Thermal Break Frame	121,344	219.19	
		Vinyl Frame	121,027	218.62	
		Low-E (e=0.4)	118,774	214.58	
		Low-E (e-0.2)	111,329	201.23	
		Low-E (e=0.1)	108,572	196.28	
		Visionwall	103,556	187.29	
	0.4	Aluminum Frame	144,959	261.53	178.4
		Thermal Break Frame	144,554	260.81	
		Vinyl Frame	144,234	260.24	
		Low-E (e=0.4)	139,688	252.09	
		Low-E (e=0.2)	125,846	227.26	
		Low-E (e=0.1)	119,472	215.83	
		Visionwall	109,253	197.51	
	0.6	Aluminum Frame	168,179	303.17	267.7
		Thermal Break Frame	167,788	302.47	
		Vinyl Frame	167,480	301.93	
		Low-E (e=0.4)	160,677	289.72	
		Low-E (e=0.2)	141,067	254.56	
		Low-E (e=0.1)	130,884	236.30	
		Visionwall	115,255	208.27	
43.0	0.2	Aluminum Frame	164,208	296.06	89.2
		Thermal Break Frame	163,899	295.50	
		Vinyl Frame	163,659	295.07	
		Low-E (e=0.4)	161,664	291.50	
		Low-E (e=0.2)	155,962	281.27	
		Low-E (e=0.1)	152,856	275.69	
		Visionwall	148,050	267.07	
	0.4	Aluminum Frame	187,135	337.18	178.4
		Thermal Break Frame	186,810	336.58	
		Vinyl Frame	186,555	336.13	
		Low-E (e=0.4)	182,459	328.78	
		Low-E (e=0.2)	171,728	309.54	
		Low-E (e=0.1)	164,908	297.31	
		Visionwall	155,424	280.31	
	0.6	Aluminum Frame	210,128	378.41	267.7
		Thermal Break Frame	209,789	377.79	
		Vinyl Frame	209,511	377.30	
		Low-E (e=0.4)	203,306	366.17	
		Low-E (e=0.2)	187,702	338.19	
		Low-E (e=0.1)	177,118	319.21	
		Visionwall	162,986	293.87	

Appendix C
Simulation Results for the Energy Star Buildings Analyses

C.1 Introduction

This appendix contains summaries of the simulation results of the analyses performed in support of the Energy Star Buildings program. As noted in Chapter 4, more than 25,000 DOE-2.1E simulations were performed for a variety of tests.

Tables C-1 through C-6 summarize the energy performance simulation results for the base case existing office buildings in each of the 18 locations. Two cases—all-electric and gas heating systems—are shown for the low-rise, mid-rise, and high-rise office buildings.

Table C-1. DOE-2.1E Simulation Results for All-Electric Existing Low-Rise Office Building (4,461 m^2 (48,000 ft^2), 3 floors)

Location	Annual Energy, kWh/m^2	Annual Energy Cost, \$/m^2	Peak Demand, kW	Peak Chiller Load, kW	Fan Supply Air, l/s	Fan Motor Size, kW
Anchorage	300	25.07	765	197	20,071	50
Atlanta	282	21.74	824	608	32,054	77
Boston	294	30.67	844	513	25,969	65
Chicago	309	34.43	905	542	26,996	66
Cleveland	305	33.68	1,017	499	27,100	66
Fort Worth/Dallas	277	22.49	733	672	30,006	73
Honolulu	278	45.84	445	556	27,525	69
Los Angeles	241	33.36	433	478	28,974	72
Memphis	277	30.45	735	665	28,205	69
Miami	285	25.50	489	707	31,046	77
Minneapolis	338	24.10	1,023	542	27,131	66
New York	289	54.45	780	563	26,625	66
Omaha	304	25.29	929	615	27,540	66
Phoenix	285	28.30	489	703	36,089	87
San Antonio	290	18.94	810	710	35,826	87
San Francisco	233	37.44	470	341	25,892	64
Seattle	257	10.65	672	387	27,333	67
Washington, D.C.	278	25.72	732	661	27,395	67

Table C-2. DOE-2.1E Simulation Results for Gas-Heated Existing Low-Rise Office Building (4,461 m^2 (48,000 ft^2), 3 floors)

Location	Annual Energy, kWh/m^2	Annual Energy Cost, \$/m^2	Peak Demand, kW	Peak Chiller Load, kW	Fan Supply Air, l/s	Fan Motor Size, kW
Anchorage	376	17.75	289	197	20,071	50
Atlanta	314	18.40	422	608	32,054	77
Boston	353	21.95	390	513	25,969	65
Chicago	375	23.03	399	542	26,996	66
Cleveland	369	24.32	385	499	27,100	66
Fort Worth/Dallas	299	17.86	444	672	30,006	73
Honolulu	285	43.90	405	556	27,525	69
Los Angeles	257	30.02	384	478	28,974	72
Memphis	304	23.24	437	665	28,205	69
Miami	294	23.89	450	707	31,046	77
Minneapolis	423	17.43	395	542	27,131	66
New York	341	41.53	405	563	26,625	66
Omaha	363	20.44	427	615	27,540	66
Phoenix	298	26.47	452	703	36,089	87
San Antonio	314	17.00	458	710	35,826	87
San Francisco	249	32.39	338	341	25,902	64
Seattle	295	9.36	352	387	27,333	67
Washington, D.C.	317	23.13	443	661	27,395	67

Table C-3. DOE-2.1E Simulation Results for All-Electric Existing Mid-Rise Office Building (118,216 m^2 (96,000 ft^2), 7 floors)

Location	Annual Energy, kWh/m^2	Annual Energy Cost, \$/m^2	Peak Demand, kW	Peak Chiller Load, kW	Fan Supply Air, l/s	Fan Motor Size, kW
Anchorage	222	18.40	2,576	865	75,470	188
Atlanta	216	15.60	2,602	2226	113,367	271
Boston	219	22.38	2,625	1924	93,301	232
Chicago	232	25.61	3,083	2015	97,109	236
Cleveland	228	23.78	3,424	1885	97,866	236
Fort Worth/Dallas	214	17.00	2,247	2500	105,852	258
Honolulu	223	36.80	1,400	2068	97,663	243
Los Angeles	185	24.32	1,337	1783	103,327	257
Memphis	214	22.81	2,156	2117	100,163	247
Miami	228	20.23	1,545	2557	109,246	271
Minneapolis	254	18.51	3,499	2040	98,469	238
New York	217	40.89	2,577	2093	95,589	236
Omaha	230	19.15	3,118	2311	99,983	239
Phoenix	223	19.91	1,531	2511	126,134	301
San Antonio	225	14.63	2,503	2567	125,385	303
San Francisco	179	27.65	1,190	1336	93,677	233
Seattle	190	7.75	2,071	1456	98,821	243
Washington, D.C.	211	19.26	2,276	2434	98,043	242

Table C-4. DOE-2.1E Simulation Results for Gas-Heated Existing Mid-Rise Office Building (118,216 m^2 (96,000 ft^2), 7 floors)

Location	Annual Energy, kWh/m^2	Annual Energy Cost, \$/m^2	Peak Demand, kW	Peak Chiller Load, kW	Fan Supply Air, l/s	Fan Motor Size, kW
Anchorage	278	13.88	930	865	75,470	188
Atlanta	237	13.67	1,368	2226	113,367	271
Boston	260	16.79	1,267	1924	93,301	232
Chicago	278	17.65	1,297	2015	97,109	236
Cleveland	273	17.22	1,253	1885	97,866	236
Fort Worth/Dallas	227	14.31	1,466	2500	105,852	258
Honolulu	227	35.83	1,322	2068	97,663	243
Los Angeles	194	22.70	1,241	1783	103,105	257
Memphis	230	18.29	1,425	2434	100,163	247
Miami	232	19.37	1,468	2557	109,246	271
Minneapolis	316	13.23	1,303	2040	98,469	238
New York	252	32.28	1,321	2093	95,589	236
Omaha	272	15.82	1,406	2311	99,983	239
Phoenix	230	19.05	1,457	2511	135,582	301
San Antonio	241	13.45	1,488	2567	125,385	303
San Francisco	187	25.29	1,089	1336	93,677	233
Seattle	214	6.99	1,129	1456	98,816	243
Washington, D.C.	236	17.75	1,452	2434	98,043	242

Table C-5. DOE-2.1E Simulation Results for All-Electric Existing High-Rise Office Building (78,067 m^2 (840,000 ft^2), 20 floors)

Location	Annual Energy, kWh/m^2	Annual Energy Cost, \$/m^2	Peak Demand, kW	Peak Chiller Load, kW	Fan Supply Air, l/s	Fan Motor Size, kW
Anchorage	204	16.79	9,559	3,942	303,311	754
Atlanta	202	14.20	9,410	8,838	432,958	1035
Boston	201	20.12	9,693	7,786	361,151	898
Chicago	212	23.13	11,775	8,050	375,975	916
Cleveland	208	20.55	12,488	7,744	379,866	916
Fort Worth/Dallas	202	15.28	7,423	10,058	403,739	984
Honolulu	213	34.86	5,590	8,254	375,738	934
Los Angeles	177	22.92	5,344	7,125	396,116	985
Memphis	201	20.34	8,016	9,640	384,110	946
Miami	216	19.05	6,128	10,016	415,614	1034
Minneapolis	230	16.36	13,065	8,338	383,043	925
New York	199	36.91	9,161	8,455	369,673	910
Omaha	211	17.22	11,404	9,246	389,088	930
Phoenix	209	17.86	6,009	9,699	475,580	1136
San Antonio	210	13.56	9,029	10,005	473,347	1142
San Francisco	172	26.15	4,827	5,521	364,338	906
Seattle	178	6.99	7,285	5,919	383,351	943
Washington, D.C.	196	17.75	8,027	9,664	378,010	931

Table C-6. DOE-2.1E Simulation Results for Gas-Heated Existing High-Rise Office Building (78,067 m^2 (840,000 ft^2), 20 floors)

Location	Annual Energy, kWh/m^2	Annual Energy Cost, $\$/m^2$	Peak Demand, kW	Peak Chiller Load, kW	Fan Supply Air, l/s	Fan Motor Size, kW
Anchorage	251	13.02	3,854	3,942	303,311	754
Atlanta	219	12.59	5,423	8,838	432,958	1035
Boston	233	15.60	5,074	7,786	361,151	898
Chicago	251	16.46	5,162	8,050	375,975	916
Cleveland	245	15.39	5,051	7,744	379,866	916
Fort Worth/Dallas	213	13.45	5,863	10,058	403,739	984
Honolulu	217	33.89	5,255	8,254	375,738	934
Los Angeles	184	21.30	4,933	7,125	396,116	985
Memphis	214	17.11	5,651	9,640	384,110	946
Miami	220	18.29	5,797	10,016	415,614	1019
Minneapolis	282	12.16	5,250	8,338	383,043	925
New York	228	29.91	5,290	8,455	369,673	910
Omaha	247	14.63	5,593	9,246	389,088	930
Phoenix	215	17.00	5,704	9,699	475,580	1136
San Antonio	223	12.48	5,827	10,005	473,347	1142
San Francisco	179	24.10	4,394	5,521	364,329	906
Seattle	196	6.56	4,520	5,919	383,351	943
Washington, D.C.	217	16.57	5,759	9,664	378,010	931

C.2 Cost Curves

Figures C-1 through C-6 show cost curves as a function of capacity, size, or other attributes for variable speed drive fans (Figure C-1), high-efficiency fan motors (Figure C-2), retrofit of existing chiller (Figure C-3), new high-efficiency centrifugal chiller (Figure C-4), variable speed pump drives (Figure C-5), and new high-efficiency gas-fired boilers (Figure C-6). These costs were used in the ESB economic evaluation described in Chapter 4. As noted in Chapter 4, the analyses for the ESB economic evaluation was prepared in Imperial units commonly used in the United States: horsepower, ton (chiller capacity), and million Btu (mmBtu). Conversion factors to Metric units are provided in footnotes for each figure.

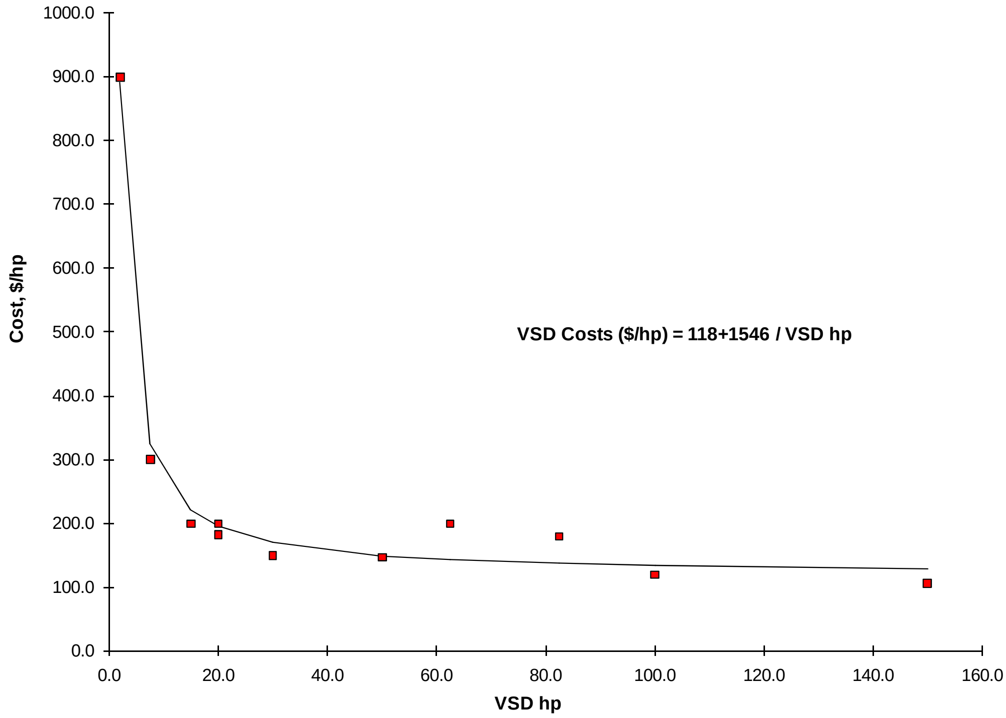

Figure C-1. Variable Speed Drive Fans[1,2]

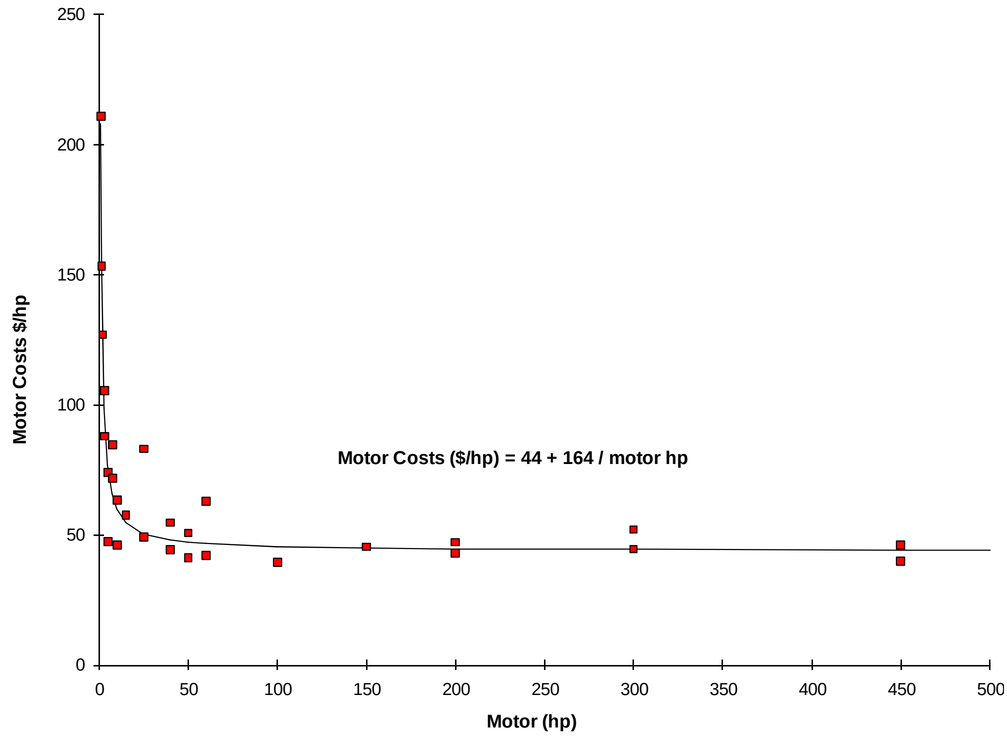

Figure C-2. High-Efficiency Fan Motors[3]

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[1] Multiply hp (horsepower) by 0.7457 to obtain kW.
[2] Enviro-Management and Research (1993).
[3] McCoy, Litman, and Douglass (1993) and WSEO (1994).

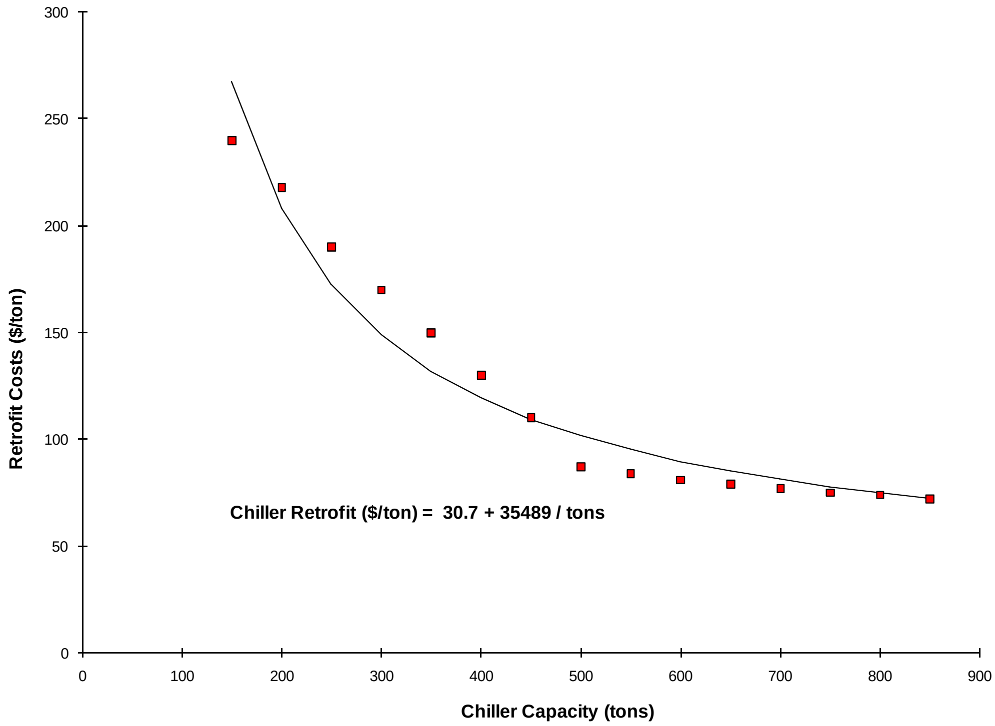

Figure C-3. Non-CFC Retrofit of Existing Chiller[4,5]

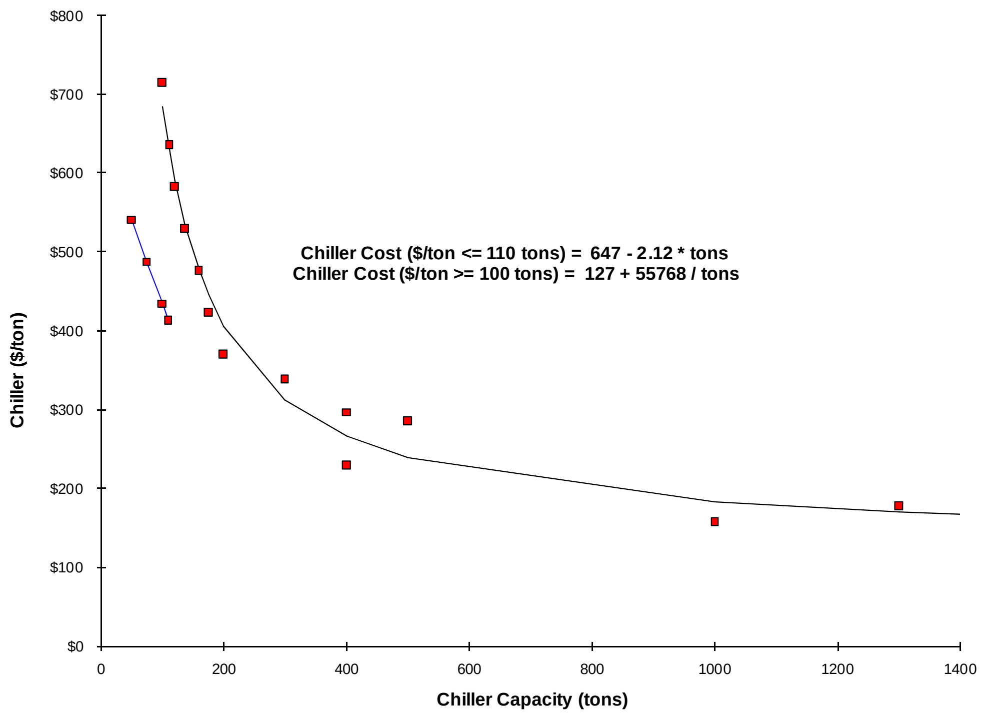

Figure C-4. New High-Efficiency Non-CFC Centrifugal Chiller[6]

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[4] Multiply tons (chiller capacity) by 3.517 to obtain kW.
[5] Trane Company (1993) and York Corporation (1993).
[6] Konkel (1987).

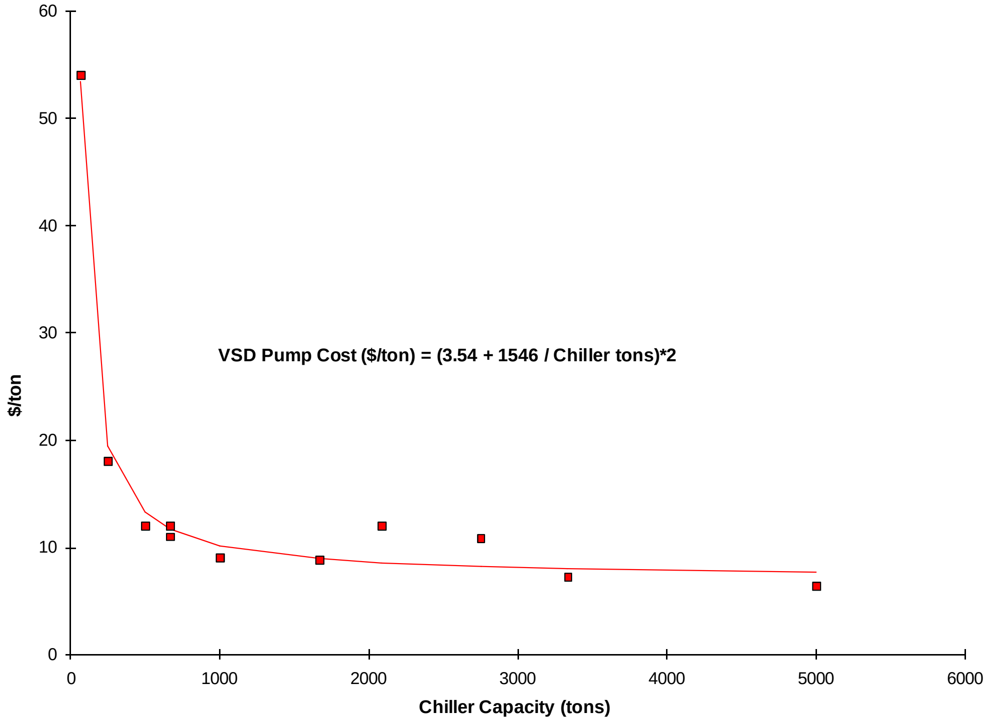

Figure C-5. Variable Speed Pump Drives[7,8]

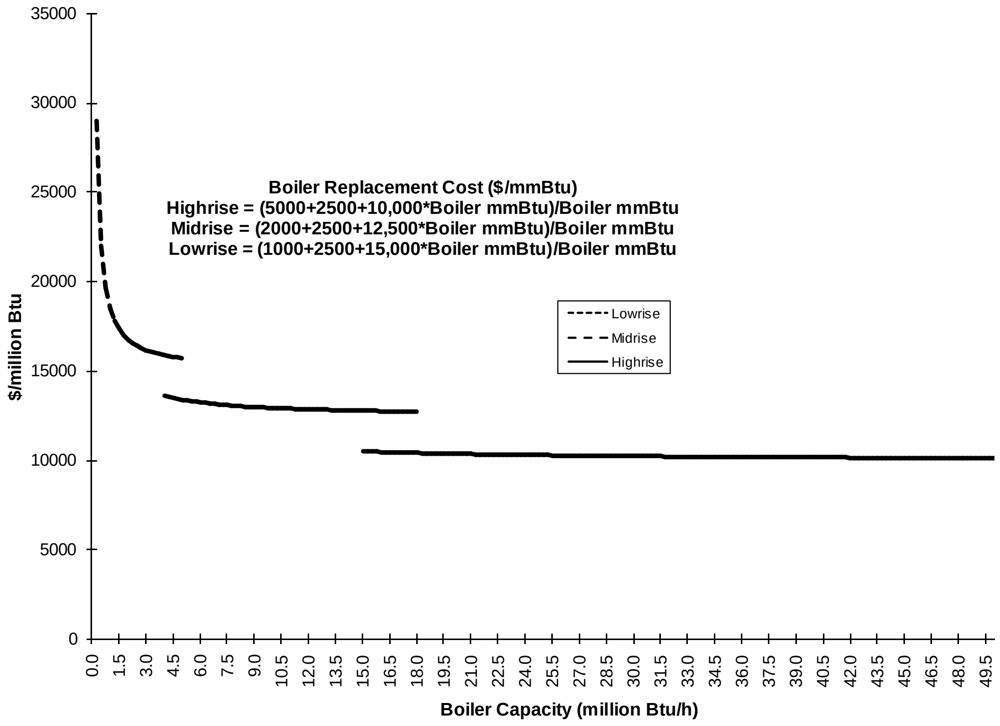

Figure C-6. New High-Efficiency Gas-Fired Boiler[9][10]

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[7] Multiply tons (chiller capacity) by 3.517 to obtain kW.
[8] Enviro-Management and Research (1993).
[9] Multiply million Btu/h (boiler capacity) by 293.1 to obtain kW.
[10] ICF Consulting (1993).

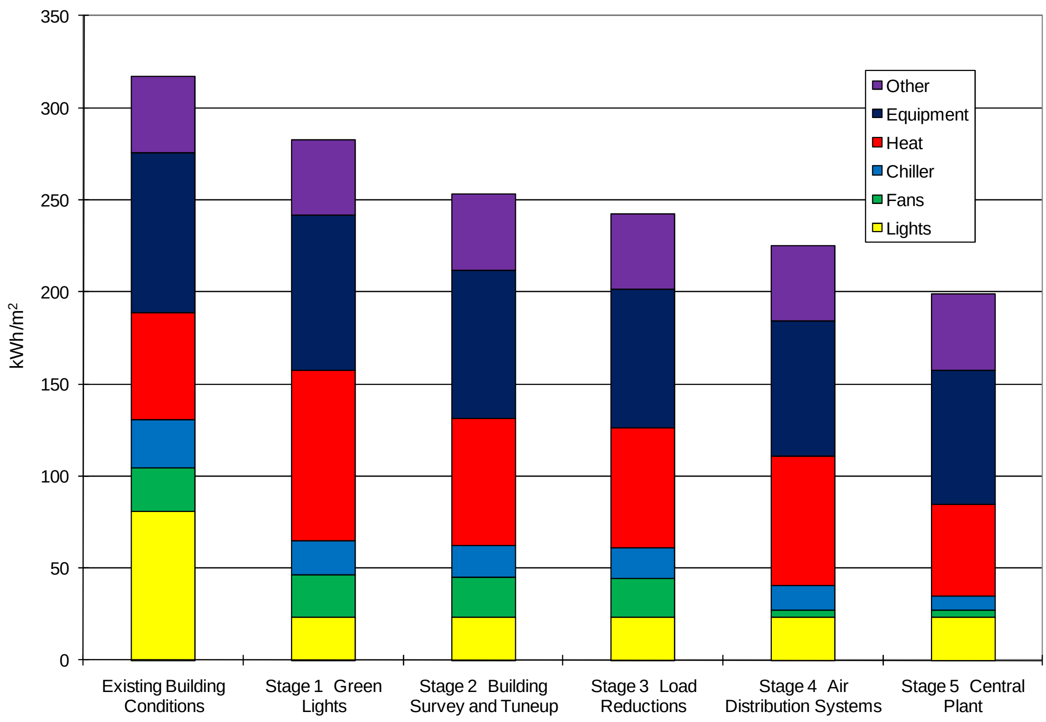

Figure C-7. Energy End-Use by Stage for Low-Rise Office Building with Gas Heat in Washington, D.C.

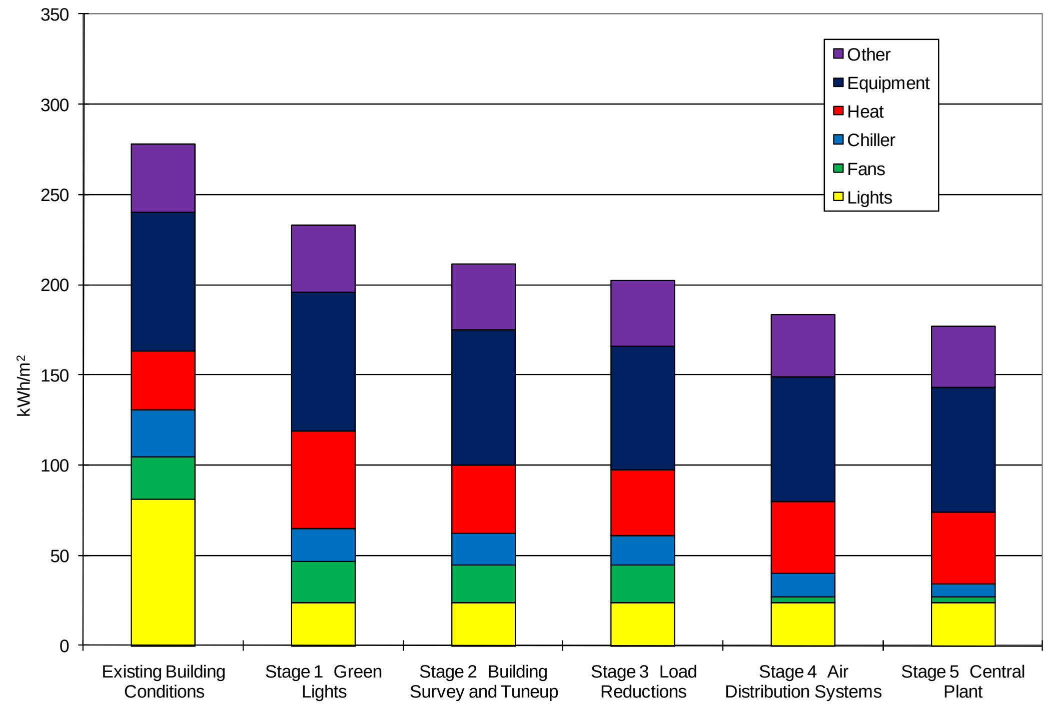

Figure C-8. Energy End-Use by Stage for Low-Rise Office Building with Electric Heat in Washington, D.C.

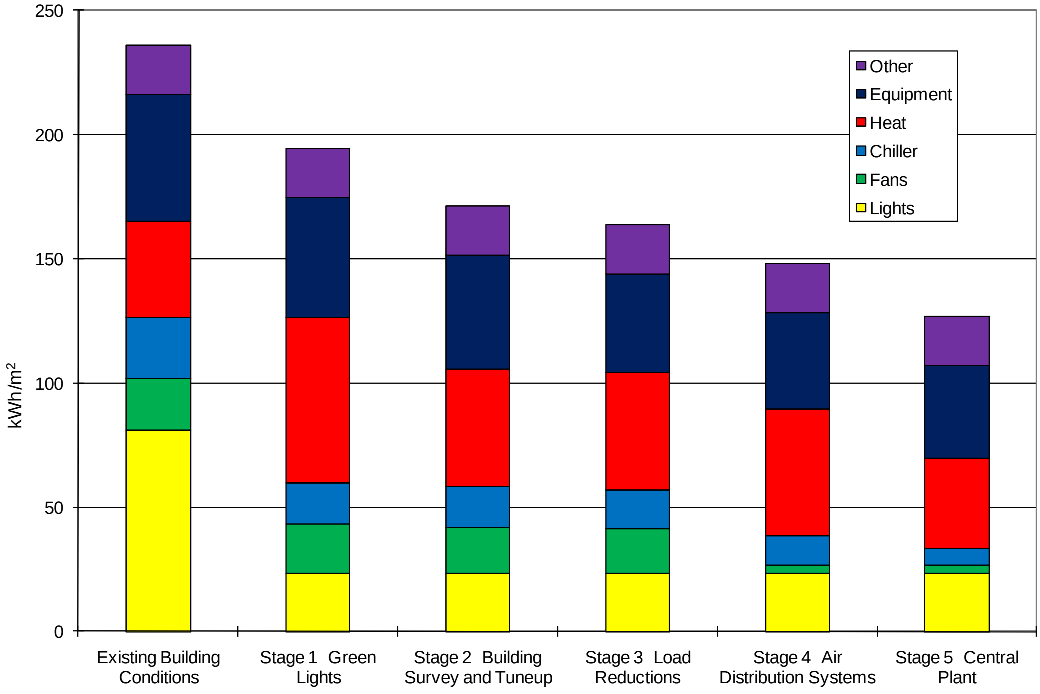

Figure C-9. Energy End-Use by Stage for Mid-Rise Office Building with Gas Heat in Washington, D.C.

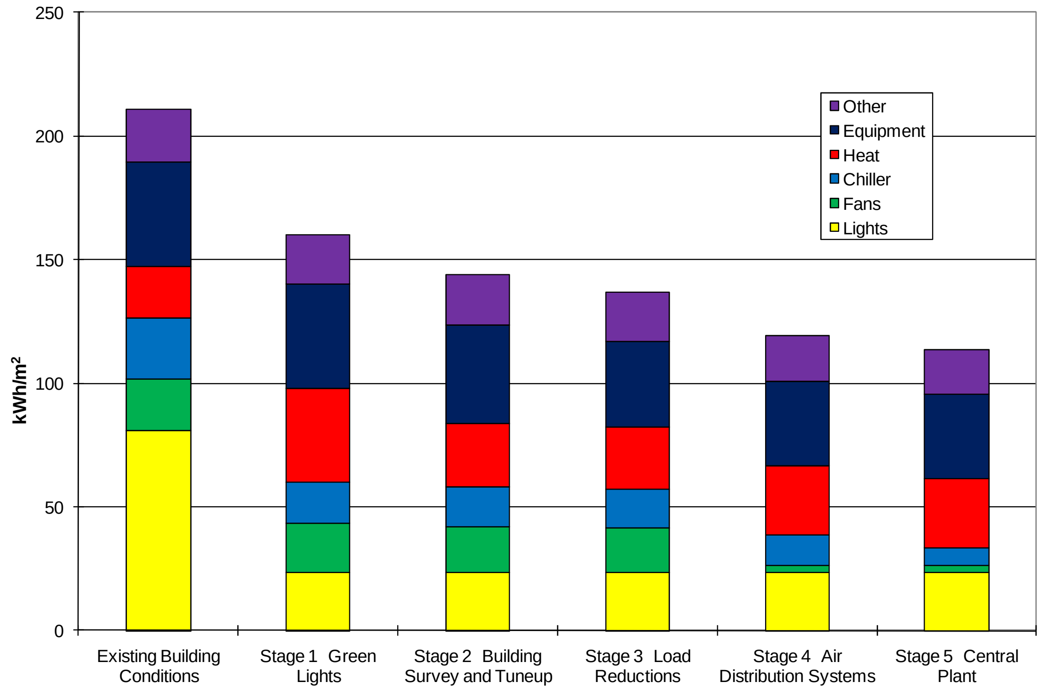

Figure C-10. Energy End-Use by Stage for Mid-Rise Office Building with Electric Heat in Washington, D.C.

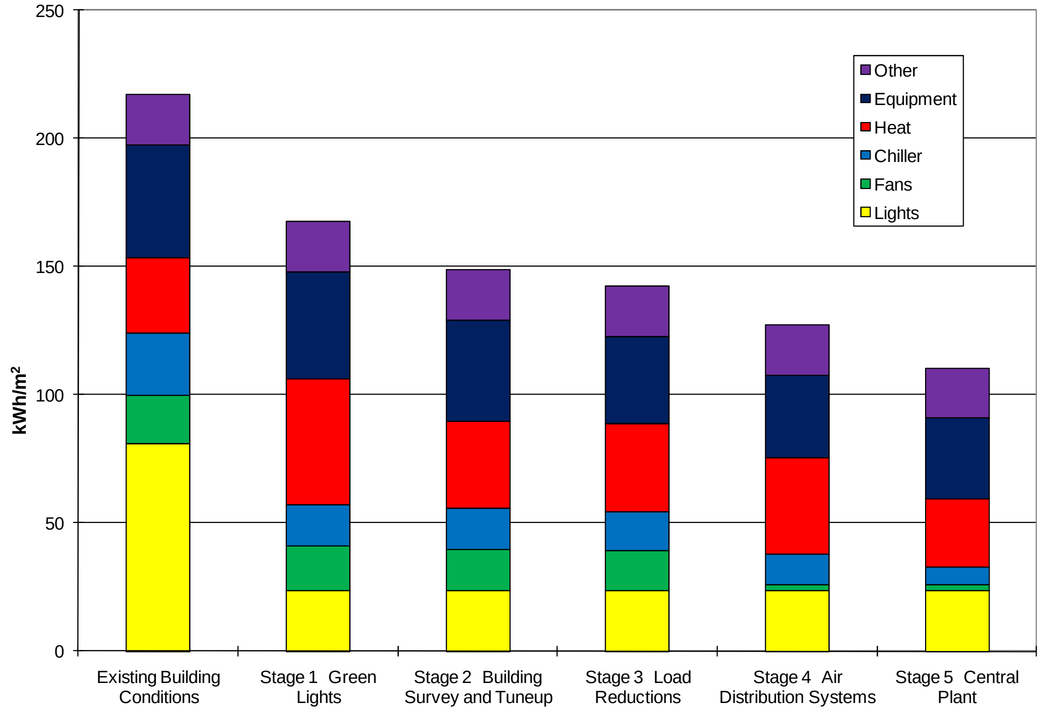

Figure C-11. Energy End-Use by Stage for High-Rise Office Building with Gas Heat in Washington, D.C.

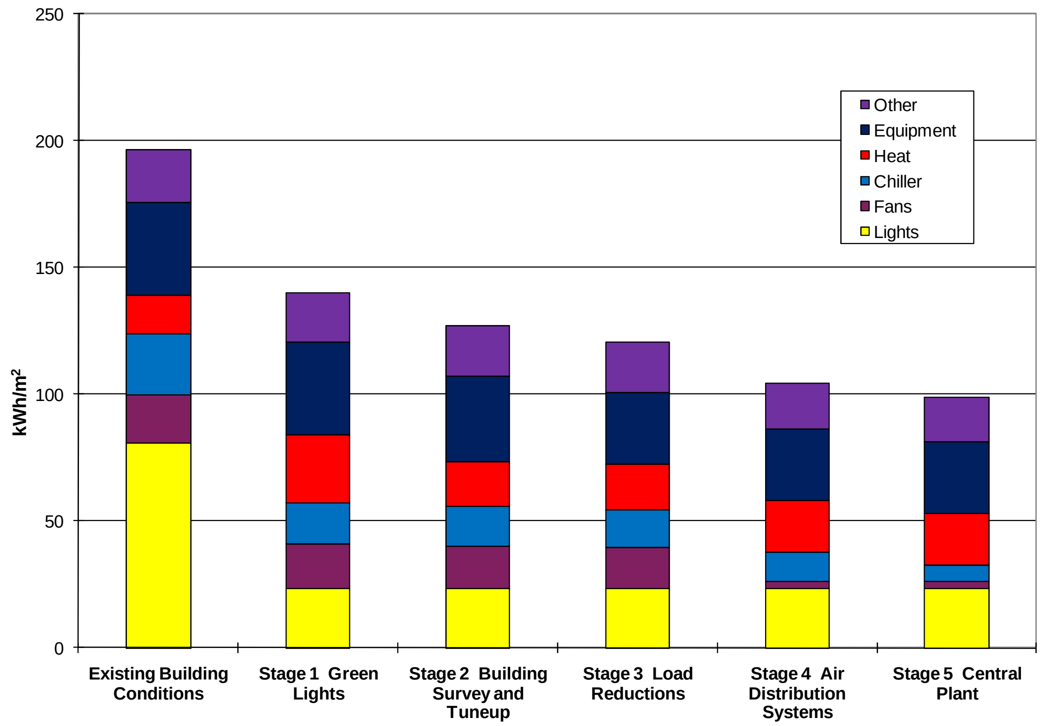

Figure C-12. Energy End-Use by Stage for High-Rise Office Building with Electric Heat in Washington, D.C.

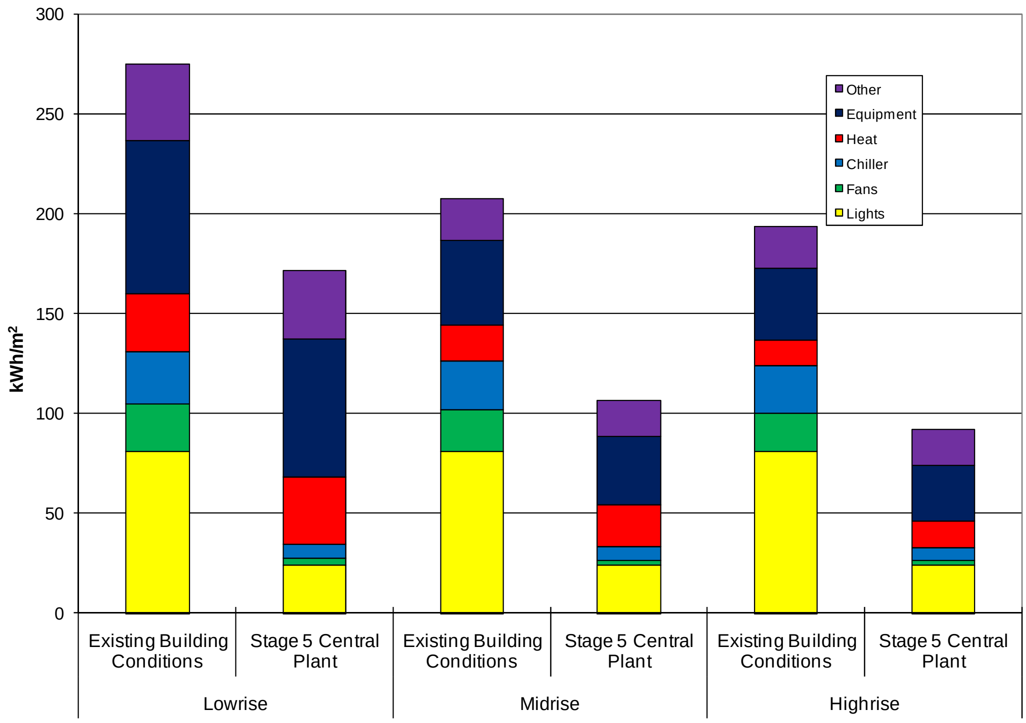

Figure C-13. Comparison of Energy End-Uses for Existing Buildings and ENERGY STAR Buildings Upgrade for the Three Office Building Sizes in Washington, D.C.

Table C-7. Average Energy Savings, Economic Returns, and Load Reductions by Office Building Size for All Locations

Size/Energy Source		Percent Reduction[11] **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
Low-Rise	All Fuels	**37%** (23/*48*)	**40%** (24/*51*)	**53%** (26/*127*)	**40%** (14/*51*)	**46%** (35/*55*)	**31%** (29/*33*)	**63%** (61/*64*)
	All-Electric	**37%** (25/*48*)	**35%** (24/*48*)	**61%** (26/*127*)	**29%** (14/*44*)	**45%** (35/*51*)	**31%** (29/*33*)	**62%** (61/*64*)
	Gas Heat	**37%** (23/*47*)	**44%** (29/*51*)	**47%** (27/*127*)	**48%** (39/*51*)	**46%** (35/*55*)	**32%** (29/*33*)	**63%** (61/*64*)
Mid-Rise	All Fuels	**46%** (26/*57*)	**50%** (33/*59*)	**58%** (16/*135*)	**47%** (4/*60*)	**47%** (35/*61*)	**35%** (31/*37*)	**64%** (62/*65*)
	All-Electric	**47%** (35/*57*)	**44%** (33/*58*)	**61%** (16/*135*)	**32%** (4/*54*)	**46%** (35/*61*)	**34%** (31/*37*)	**64%** (62/*65*)
	Gas Heat	**46%** (26/*56*)	**54%** (43/*59*)	**56%** (21/*135*)	**57%** (49/*60*)	**47%** (42/*61*)	**35%** (32/*37*)	**64%** (63/*65*)
High-Rise	All Fuels	**50%** (38/*59*)	**53%** (36/*61*)	**67%** (21/*157*)	**48%** (17/*61*)	**48%** (43/*64*)	**37%** (34/*43*)	**66%** (64/*69*)
	All-Electric	**51%** (40/*59*)	**47%** (36/*59*)	**71%** (21/*157*)	**33%** (17/*56*)	**48%** (43/*64*)	**38%** (34/*43*)	**66%** (64/*69*)
	Gas-Heat	**50%** (38/*58*)	**57%** (48/*61*)	**64%** (24/*157*)	**59%** (51/*61*)	**48%** (43/*64*)	**37%** (34/*40*)	**66%** (64/*67*)

Table C-8. Average Energy Savings, Economic Returns, and Load Reductions for All Three Office Buildings and All Locations

Energy Source	Percent Reduction **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**44%** (23/*59*)	**47%** (24/*61*)	**58%** (16/*157*)	**45%** (4/*61*)	**47%** (35/*64*)	**34%** (29/*43*)	**64%** (61/*69*)
All-Electric	**44%** (25/*59*)	**41%** (24/*59*)	**63%** (16/*157*)	**31%** (4/*56*)	**46%** (35/*64*)	**34%** (29/*43*)	**64%** (61/*69*)
Gas Heat	**44%** (23/*58*)	**51%** (29/*61*)	**54%** (21/*157*)	**54%** (39/*61*)	**47%** (35/*64*)	**34%** (29/*40*)	**64%** (61/*67*)

[11] The averages of building size are weighted based on the existing office building stock. The averages across locations are unweighted.

Table C-9. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for Anchorage

Energy Source	Percent Reduction **Average** (Min/*Max*)						
	Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**32%** (25/*42*)	**41%** (24/*56*)	**50%** (39/*64*)	**41%** (21/*61*)	**58%** (45/*64*)	**35%** (29/*40*)	**64%** (61/*67*)
All-Electric	**32%** (25/*40*)	**32%** (24/*39*)	**55%** (47/*64*)	**24%** (21/*27*)	**56%** (45/*64*)	**34%** (29/*40*)	**64%** (61/*67*)
Gas Heat	**32%** (25/*42*)	**48%** (42/*56*)	**46%** (39/*53*)	**52%** (43/*61*)	**59%** (55/*64*)	**35%** (30/*40*)	**64%** (62/*67*)

Table C-10. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for Atlanta

Energy Source	Percent Reduction **Average** (Min/*Max*)						
	Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**43%** (31/*52*)	**48%** (36/*60*)	**45%** (42/*54*)	**45%** (34/*60*)	**46%** (46/*46*)	**35%** (33/*38*)	**64%** (63/*66*)
All-Electric	**46%** (40/*52*)	**45%** (36/*52*)	**46%** (42/*54*)	**34%** (34/*34*)	**46%** (46/*46*)	**35%** (33/*38*)	**64%** (63/*66*)
Gas Heat	**40%** (31/*51*)	**51%** (40/*60*)	**45%** (42/*47*)	**53%** (42/*60*)	**46%** (46/*46*)	**35%** (33/*38*)	**64%** (63/*66*)

Table C-11. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for Boston

Energy Source	Percent Reduction **Average** (Min/*Max*)						
	Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**39%** (29/*45*)	**44%** (29/*57*)	**54%** (39/*89*)	**44%** (29/*59*)	**44%** (40/*45*)	**34%** (30/*37*)	**64%** (62/*66*)
All-Electric	**38%** (29/*45*)	**34%** (29/*39*)	**66%** (50/*89*)	**30%** (29/*32*)	**43%** (40/*45*)	**34%** (30/*37*)	**64%** (62/*66*)
Gas Heat	**41%** (35/*45*)	**51%** (44/*57*)	**45%** (39/*54*)	**54%** (48/*59*)	**44%** (44/*45*)	**34%** (31/*37*)	**64%** (62/*66*)

Table C-12. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for Chicago

Energy Source	Percent Reduction **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**41%** (34/*47*)	**46%** (32/*58*)	**57%** (42/*70*)	**45%** (30/*58*)	**43%** (43/*43*)	**35%** (32/*38*)	**64%** (63/*66*)
All-Electric	**40%** (34/*46*)	**37%** (32/*41*)	**63%** (60/*70*)	**32%** (30/*34*)	**43%** (43/*43*)	**35%** (32/*38*)	**64%** (63/*66*)
Gas Heat	**42%** (37/*47*)	**52%** (45/*58*)	**54%** (42/*62*)	**54%** (48/*58*)	**43%** (43/*43*)	**35%** (32/*38*)	**64%** (63/*66*)

Table C-13. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for Cleveland

Energy Source	Percent Reduction **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**40%** (33/*46*)	**42%** (29/*55*)	**48%** (40/*59*)	**45%** (30/*60*)	**45%** (45/*46*)	**36%** (33/*39*)	**65%** (63/*67*)
All-Electric	**39%** (33/*45*)	**34%** (29/*39*)	**54%** (52/*59*)	**31%** (30/*33*)	**45%** (45/*46*)	**36%** (33/*39*)	**65%** (63/*67*)
Gas Heat	**41%** (37/*46*)	**48%** (40/*55*)	**44%** (40/*52*)	**55%** (48/*60*)	**45%** (45/*46*)	**36%** (33/*39*)	**65%** (63/*67*)

Table C-14. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for Fort Worth

Energy Source	Percent Reduction **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**47%** (37/*55*)	**50%** (37/*61*)	**41%** (33/*51*)	**44%** (19/*61*)	**46%** (44/*48*)	**35%** (33/*37*)	**64%** (63/*65*)
All-Electric	**49%** (42/*55*)	**43%** (37/*47*)	**42%** (33/*51*)	**26%** (19/*29*)	**46%** (44/*47*)	**35%** (33/*37*)	**64%** (63/*65*)
Gas Heat	**46%** (37/*53*)	**55%** (49/*61*)	**41%** (36/*49*)	**56%** (50/*61*)	**47%** (46/*48*)	**35%** (33/*37*)	**64%** (63/*65*)

Table C-15. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for Honolulu

Energy Source	Percent Reduction **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**53%** (46/*59*)	**56%** (48/*61*)	**137%** (127/*157*)	**53%** (44/*59*)	**45%** (45/*46*)	**33%** (31/*36*)	**63%** (62/*65*)
All-Electric	**54%** (48/*59*)	**55%** (48/*59*)	**137%** (127/*157*)	**51%** (44/*56*)	**45%** (45/*46*)	**33%** (31/*36*)	**63%** (62/*65*)
Gas Heat	**53%** (46/*58*)	**57%** (51/*61*)	**137%** (127/*157*)	**54%** (48/*59*)	**45%** (45/*46*)	**33%** (31/*36*)	**63%** (62/*65*)

Table C-16. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for Los Angeles

Energy Source	Percent Reduction **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**47%** (37/*55*)	**50%** (37/*59*)	**73%** (59/*98*)	**44%** (19/*60*)	**49%** (48/*53*)	**33%** (30/*43*)	**63%** (62/*69*)
All-Electric	**48%** (40/*55*)	**46%** (37/*54*)	**80%** (71/*98*)	**29%** (19/*41*)	**49%** (48/*53*)	**34%** (30/*43*)	**64%** (62/*69*)
Gas Heat	**45%** (37/*52*)	**52%** (43/*59*)	**67%** (59/*82*)	**55%** (48/*60*)	**48%** (48/*49*)	**32%** (30/*35*)	**63%** (62/*64*)

Table C-17. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for Memphis

Energy Source	Percent Reduction **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**47%** (40/*54*)	**48%** (37/*59*)	**53%** (35/*67*)	**45%** (28/*60*)	**47%** (47/*48*)	**34%** (32/*37*)	**64%** (63/*65*)
All-Electric	**48%** (41/*54*)	**42%** (37/*46*)	**62%** (60/*67*)	**29%** (28/*30*)	**47%** (47/*48*)	**34%** (32/*37*)	**64%** (63/*65*)
Gas Heat	**46%** (40/*52*)	**53%** (46/*59*)	**47%** (35/*61*)	**56%** (50/*60*)	**47%** (47/*48*)	**34%** (32/*37*)	**64%** (63/*65*)

Table C-18. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for Miami

Energy Source	Percent Reduction **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**54%** (47/*59*)	**55%** (46/*60*)	**58%** (41/*80*)	**50%** (33/*60*)	**47%** (47/*48*)	**32%** (30/*34*)	**63%** (62/*64*)
All-Electric	**54%** (48/*59*)	**53%** (46/*58*)	**64%** (49/*80*)	**42%** (33/*53*)	**47%** (47/*48*)	**32%** (30/*34*)	**63%** (62/*64*)
Gas Heat	**53%** (47/*58*)	**56%** (51/*60*)	**54%** (41/*80*)	**56%** (50/*60*)	**47%** (47/*48*)	**32%** (30/*34*)	**63%** (62/*64*)

Table C-19. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for Minneapolis

Energy Source	Percent Reduction **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**40%** (31/*47*)	**42%** (30/*54*)	**41%** (28/*67*)	**46%** (31/*60*)	**44%** (40/*46*)	**35%** (31/*39*)	**64%** (62/*66*)
All-Electric	**35%** (31/*42*)	**33%** (30/*36*)	**53%** (44/*67*)	**34%** (31/*35*)	**41%** (40/*46*)	**34%** (31/*39*)	**63%** (62/*66*)
Gas Heat	**43%** (39/*47*)	**48%** (42/*54*)	**32%** (28/*38*)	**55%** (48/*60*)	**45%** (45/*46*)	**36%** (31/*39*)	**64%** (62/*66*)

Table C-20. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for New York

Energy Source	Percent Reduction **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**41%** (33/*46*)	**46%** (33/*56*)	**96%** (78/*118*)	**44%** (26/*60*)	**46%** (45/*46*)	**35%** (32/*38*)	**64%** (63/*66*)
All-Electric	**40%** (33/*46*)	**38%** (33/*43*)	**105%** (100/*118*)	**30%** (26/*33*)	**46%** (45/*46*)	**35%** (32/*38*)	**64%** (63/*66*)
Gas Heat	**41%** (36/*46*)	**52%** (45/*56*)	**89%** (78/*107*)	**54%** (48/*60*)	**46%** (45/*46*)	**35%** (32/*38*)	**64%** (63/*66*)

Table C-21. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for Omaha

Energy Source	Percent Reduction **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**42%** (35/*47*)	**45%** (34/*55*)	**43%** (35/*53*)	**45%** (28/*61*)	**51%** (51/*52*)	**36%** (33/*39*)	**65%** (64/*67*)
All-Electric	**41%** (35/*47*)	**38%** (34/*43*)	**47%** (45/*53*)	**30%** (28/*33*)	**51%** (51/*52*)	**36%** (33/*39*)	**65%** (64/*67*)
Gas Heat	**43%** (38/*47*)	**49%** (43/*55*)	**40%** (35/*48*)	**56%** (50/*61*)	**51%** (51/*52*)	**36%** (33/*39*)	**65%** (64/*67*)

Table C-22. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for Phoenix

Energy Source	Percent Reduction **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**52%** (44/*58*)	**51%** (41/*59*)	**53%** (42/*71*)	**48%** (29/*60*)	**46%** (46/*47*)	**34%** (32/*36*)	**64%** (63/*65*)
All-Electric	**53%** (46/*58*)	**48%** (41/*55*)	**58%** (48/*71*)	**37%** (29/*47*)	**46%** (46/*47*)	**34%** (32/*36*)	**64%** (63/*65*)
Gas Heat	**51%** (44/*56*)	**53%** (47/*59*)	**50%** (42/*61*)	**56%** (50/*60*)	**46%** (46/*47*)	**34%** (32/*36*)	**64%** (63/*65*)

Table C-23. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for San Antonio

Energy Source	Percent Reduction **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**47%** (38/*55*)	**51%** (42/*59*)	**40%** (31/*52*)	**45%** (30/*60*)	**48%** (47/*48*)	**33%** (31/*35*)	**63%** (62/*64*)
All-Electric	**49%** (43/*55*)	**48%** (42/*54*)	**41%** (31/*52*)	**30%** (30/*31*)	**48%** (47/*48*)	**33%** (31/*35*)	**63%** (62/*64*)
Gas Heat	**45%** (38/*53*)	**53%** (47/*59*)	**40%** (32/*45*)	**56%** (51/*60*)	**48%** (47/*48*)	**33%** (31/*35*)	**63%** (62/*64*)

Table C-24. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for San Francisco

Energy Source	Percent Reduction **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**47%** (37/*55*)	**49%** (36/*60*)	**84%** (70/*110*)	**35%** (4/*59*)	**43%** (41/*46*)	**34%** (31/*37*)	**63%** (62/*65*)
All-Electric	**48%** (39/*55*)	**45%** (36/*53*)	**91%** (79/*110*)	**11%** (4/*17*)	**43%** (41/*46*)	**34%** (31/*37*)	**63%** (62/*65*)
Gas Heat	**46%** (37/*53*)	**53%** (44/*60*)	**79%** (70/*97*)	**53%** (45/*59*)	**43%** (41/*46*)	**34%** (31/*37*)	**63%** (62/*65*)

Table C-25. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for Seattle

Energy Source	Percent Reduction **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**32%** (23/*46*)	**36%** (26/*48*)	**23%** (16/*27*)	**38%** (25/*51*)	**38%** (35/*43*)	**32%** (29/*37*)	**63%** (61/*65*)
All-Electric	**35%** (28/*46*)	**32%** (26/*41*)	**21%** (16/*26*)	**28%** (25/*30*)	**37%** (35/*43*)	**32%** (29/*37*)	**62%** (61/*65*)
Gas Heat	**30%** (23/*38*)	**39%** (29/*48*)	**24%** (21/*27*)	**46%** (39/*51*)	**40%** (35/*43*)	**33%** (29/*37*)	**63%** (61/*65*)

Table C-26. Average Energy Savings, Economic Returns, and Load Reductions for all Office Building Sizes for Washington

Energy Source	Percent Reduction **Average** (Min/*Max*) Annual Energy	Annual Energy Cost	Internal Rate of Return	Peak Demand	Peak Chiller Load	Fan Supply Air	Fan Motor Size
All Fuels	**43%** (36/*50*)	**47%** (36/*56*)	**48%** (32/*62*)	**45%** (24/*61*)	**50%** (50/*51*)	**35%** (32/*37*)	**64%** (63/*66*)
All-Electric	**43%** (36/*50*)	**42%** (36/*48*)	**54%** (50/*62*)	**27%** (24/*29*)	**50%** (50/*51*)	**34%** (32/*37*)	**64%** (63/*66*)
Gas Heat	**43%** (37/*49*)	**50%** (43/*56*)	**44%** (32/*56*)	**57%** (51/*61*)	**50%** (50/*51*)	**35%** (32/*37*)	**64%** (63/*66*)

C.3 References

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Appendix D
Summary Simulation Results for the Evaluation of Potential Climate Change and Heat Islands Impacts

This appendix contains summary simulation results of the analyses performed in research on the potential impacts of the IPCC climate change scenarios and heat islands. The research is discussed in Chapters 3 and 5. As noted in Chapter 5, more than 1,200 EnergyPlus simulations were performed for a variety of tests. The figures and tables in this appendix are for the three locations discussed in detailed in Chapter 5: San Juan, Puerto Rico; Washington, D.C., USA; and Resolute, Nunavut, Canada[1]. The data are Megajoules/m^2. The energy end uses are heating, reheat, cooling, fans, lights, plug loads, and service water heating (SHW). Heating, reheat, and SHW are natural gas; cooling, fans, lights, and plug loads are electricity. At the beginning of each location, six tables of simulation results are presented:

- Annual Source Energy End-Use Consumption for Typical Year Weather Data (IWEC, CWEC or TMY2).
- Annual Source Energy End-Use Consumption for Low Year Weather Data.
- Annual Source Energy End-Use Consumption for High Year Weather Data.
- Monthly Source Energy End-Use Consumption for Standard Building, Climate Change Scenarios, and Heat Island Cases.
- Monthly Source Energy End-Use Consumption for Developing Building, Climate Change Scenarios, and Heat Island Cases.
- Monthly Source Energy End-Use Consumption for Low-Energy Building, Climate Change Scenarios, and Heat Island Cases.

Each of the first three tables contains annual energy end-use data for the standard, developing, and low-energy buildings by climate change scenario and heat island case. Each of the second three tables contains the monthly energy end-use data for the standard, developing, and low-energy buildings by climate change scenario and heat island case. Where no data are shown in the table, that value either is not calculated (as in the case of reheat energy for the low-energy building) or is zero.

[1] Similar figures and tables for the other 22 locations are available from the author upon request—organized by location and Köppen climate zone (see Table 3-13 for a list of locations).

For each location, the six tables are followed by 13 figures:

1. Annual Source Energy End-Use Consumption for Standard, Developing, and Low-Energy Buildings using Typical Year, Climate Change Scenarios, and Heat Island Cases.
2. Annual Source Energy End-Use Consumption for Standard Building and Climate Change Scenarios.
3. Annual Source Energy End-Use Consumption for Developing Building and Climate Change Scenarios.
4. Annual Source Energy End-Use Consumption for Low-Energy Building and Climate Change Scenarios.
5. Annual Source Energy End-Use Consumption for Standard Building and Heat Island Cases.
6. Annual Source Energy End-Use Consumption for Developing Building and Heat Island Cases.
7. Annual Source Energy End-Use Consumption for Low-Energy Building and Heat Island Cases.
8. Monthly Source Energy End-Use Consumption for Standard Building and Climate Change Scenarios.
9. Monthly Source Energy End-Use Consumption for Developing Building and Climate Change Scenarios.
10. Monthly Source Energy End-Use Consumption for Low-Energy Building and Climate Change Scenarios.
11. Monthly Source Energy End-Use Consumption for Standard Building and Heat Island Cases.
12. Monthly Source Energy End-Use Consumption for Developing Building and Heat Island Cases.
13. Monthly Source Energy End-Use Consumption for Low-Energy Building and Heat Island Cases.

The first figure for each location shows the annual source energy end-use consumption of standard, developing, and low-energy buildings using typical, high, and low weather data in comparison with the climate change scenario and heat island cases. These figures also contrast the substantial differences in annual energy performance possible between the standard building (based on the requirements of ASHRAE Standard 90.1-2004), the developing building (based on data from locations without building energy standards), and the low-energy building (designed to minimize energy loads). The energy consumption of the developing building is usually 10-20 percent higher than that of the standard building. The energy consumption of the low-energy building is usually 50-60 percent lower than that of the standard building.

The second through fourth figures for each location compare the annual source energy end-use consumption of the standard, developing, and low-energy buildings, respectively, and the climate change scenarios.

The fifth through seventh figures for each location compare the annual source energy end-use consumption of the standard, developing, and low-energy buildings, respectively, and the heat island cases.

The eighth through tenth figures for each location compare the monthly source energy end-use consumption for the standard, developing, and low-energy buildings, respectively, with the climate change scenarios. The monthly data demonstrate where end-use swapping occurs in each location. Usually, this extends the cooling season and reduces the months in which heating is required. For the eighth through the thirteenth figures, the results presented here are typical weather data (TMY2, CWEC, or IWEC) only.

The eleventh through thirteenth figures for each location compare the monthly source energy end-use consumption for the standard, developing, and low-energy buildings, respectively, with the heat island cases.

Each table or figure has a numbering suffix of D.x-y, where x is the location number (1 for San Juan, 2 for Washington, and 3 for Resolute) and y is the figure number (1 to 13), listed in the order above.

D.1 San Juan, Puerto Rico (Climate Am)

Table D.1-1. Annual Source Energy End-Use Consumption in San Juan, Puerto Rico, for Typical Year Weather Data

Scenario	Standard	Annual Energy End-Use, MJ/m^2							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	Standard	2.3	0.6	447.4	204.2	249.3	115.8	152.6	1172.1
	Developing	0.5	0.2	561.8	269.6	249.3	115.8	152.6	1349.8
	Low-Energy	0.0		189.4	148.7	37.9	81.1	97.8	554.9
A1FI	Standard	0.6	0.5	671.8	204.2	249.3	115.8	152.6	1394.8
	Developing	0.1	0.0	844.1	269.6	249.3	115.8	152.6	1631.4
	Low-Energy	0.0		202.0	150.2	37.6	81.1	97.8	568.6
A2	Standard	1.0	0.5	597.1	204.2	249.3	115.8	152.6	1320.5
	Developing	0.1	0.0	760.3	269.6	249.3	115.8	152.6	1547.6
	Low-Energy	0.0		194.2	149.9	37.7	81.1	97.8	560.6
B1	Standard	1.1	0.4	572.5	204.2	249.3	115.8	152.6	1295.8
	Developing	0.1	0.0	732.5	269.6	249.3	115.8	152.6	1519.8
	Low-Energy	0.0		193.0	149.9	37.6	81.1	97.8	559.4
B2	Standard	1.0	0.5	581.7	204.2	249.3	115.8	152.6	1305.0
	Developing	0.1	0.0	743.1	269.6	249.3	115.8	152.6	1530.5
	Low-Energy	0.0		193.5	149.9	37.6	81.1	97.8	559.8
HtIsLo	Standard	2.3	0.8	457.6	204.2	249.3	115.8	152.6	1182.5
	Developing	0.5	0.2	574.1	269.6	249.3	115.8	152.6	1362.0
	Low-Energy	0.0		190.1	148.9	37.9	81.1	97.8	555.8
HtIsHi	Standard	1.7	1.3	502.8	204.2	249.3	115.8	152.6	1227.5
	Developing	0.5	0.0	625.4	269.6	249.3	115.8	152.6	1413.1
	Low-Energy	0.0		192.3	149.5	37.9	81.1	97.8	558.6

Table D.1-2. Annual Source Energy End-Use Consumption in San Juan, Puerto Rico, for Low Year Weather Data

Scenario	Standard	Annual Energy End-Use, MJ/m^2							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	Standard	0.8	0.1	439.4	204.2	249.3	115.8	152.6	1162.2
	Developing	0.3	0.0	552.2	269.6	249.3	115.8	152.6	1339.7
	Low-Energy	0.0		190.3	149.0	37.7	81.1	97.8	555.9
A1FI	Standard	0.4	0.2	662.7	204.2	249.3	115.8	152.6	1385.0
	Developing	0.0		833.0	269.6	249.3	115.8	152.6	1620.2
	Low-Energy	0.0		200.6	150.3	37.5	81.1	97.8	567.3
A2	Standard	0.4	0.1	593.1	204.2	249.3	115.8	152.6	1315.5
	Developing	0.0		754.0	269.6	249.3	115.8	152.6	1541.3
	Low-Energy	0.0		195.1	150.1	37.6	81.1	97.8	561.6
B1	Standard	0.4	0.1	570.4	204.2	249.3	115.8	152.6	1292.7
	Developing	0.0	0.0	729.2	269.6	249.3	115.8	152.6	1516.5
	Low-Energy	0.0		194.2	150.1	37.5	81.1	97.8	560.6
B2	Standard	0.4	0.1	579.4	204.2	249.3	115.8	152.6	1301.6
	Developing	0.0	0.0	738.9	269.6	249.3	115.8	152.6	1526.2
	Low-Energy	0.0		194.6	150.1	37.5	81.1	97.8	561.1
HtIsLo	Standard	1.0	0.2	449.2	204.2	249.3	115.8	152.6	1172.1
	Developing	0.2	0.0	562.4	269.6	249.3	115.8	152.6	1349.8
	Low-Energy	0.0		190.8	149.2	37.8	81.1	97.8	556.6
HtIsHi	Standard	1.2	0.5	491.6	204.2	249.3	115.8	152.6	1215.2
	Developing	0.3	0.0	609.6	269.6	249.3	115.8	152.6	1397.2
	Low-Energy	0.0		192.1	149.6	37.8	81.1	97.8	558.3

Table D.1-3. Annual Source Energy End-Use Consumption in San Juan, Puerto Rico, for High Year Weather Data

Scenario	Standard	Annual Energy End-Use, MJ/m²							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	Standard	1.9	1.2	507.1	204.2	249.3	115.8	152.6	1232.1
	Developing	0.4	0.3	623.8	269.6	249.3	115.8	152.6	1411.7
	Low-Energy	0.0		192.2	149.1	38.0	81.1	97.8	558.2
A1FI	Standard	0.3	0.4	739.9	204.2	249.3	115.8	152.6	1462.4
	Developing	0.0	0.0	922.0	269.6	249.3	115.8	152.6	1709.3
	Low-Energy	0.0		215.0	150.3	37.7	81.1	97.8	581.9
A2	Standard	0.6	0.6	664.5	204.2	249.3	115.8	152.6	1387.6
	Developing	0.1	0.0	834.2	269.6	249.3	115.8	152.6	1621.5
	Low-Energy	0.0		201.8	150.2	37.8	81.1	97.8	568.5
B1	Standard	0.7	0.6	639.4	204.2	249.3	115.8	152.6	1362.5
	Developing	0.1	0.0	805.9	269.6	249.3	115.8	152.6	1593.2
	Low-Energy	0.0		198.7	150.1	37.8	81.1	97.8	565.4
B2	Standard	0.7	0.6	648.8	204.2	249.3	115.8	152.6	1371.9
	Developing	0.1	0.0	816.8	269.6	249.3	115.8	152.6	1604.1
	Low-Energy	0.0		199.8	150.1	37.8	81.1	97.8	566.5
HtIsLo	Standard	1.9	1.3	517.6	204.2	249.3	115.8	152.6	1242.5
	Developing	0.4	0.2	635.9	269.6	249.3	115.8	152.6	1423.7
	Low-Energy	0.0		192.5	149.3	38.0	81.1	97.8	558.6
HtIsHi	Standard	1.2	1.5	563.1	204.2	249.3	115.8	152.6	1287.6
	Developing	0.4	0.1	688.0	269.6	249.3	115.8	152.6	1475.7
	Low-Energy	0.0		194.3	149.7	38.0	81.1	97.8	560.9

Table D.1-4. Monthly Source Energy End-Use Consumption in San Juan, Puerto Rico, for Standard Building, Climate Change Scenarios, and Heat Island Cases

Scenario	Month	Monthly Energy End-Use, MJ/m²							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	January	0.350	0.080	32.416	16.896	20.856	9.688	12.770	93.1
	February	0.300	0.041	28.691	15.488	18.918	8.788	11.605	83.8
	March	0.148	0.021	33.482	17.424	20.996	9.753	12.912	94.7
	April	0.154	0.023	35.979	17.600	21.564	10.017	13.045	98.4
	May	0.088	0.029	36.300	17.424	20.996	9.753	12.909	97.5
	June	0.090	0.034	40.511	16.896	20.752	9.640	12.653	100.6
	July	0.103	0.090	42.045	17.600	21.668	10.066	13.172	104.7
	August	0.171	0.048	41.563	17.424	20.996	9.753	12.918	102.9
	September	0.149	0.040	43.236	16.896	20.752	9.640	12.644	103.4
	October	0.126	0.030	42.526	17.600	21.668	10.066	13.173	105.2
	November	0.159	0.048	33.882	15.312	18.456	8.573	11.603	88.0
	December	0.447	0.153	36.762	17.600	21.668	10.066	13.166	99.9
A1FI	January	0.095	0.091	57.070	16.896	20.856	9.688	12.774	117.5
	February	0.118	0.088	48.085	15.488	18.918	8.788	11.605	103.1
	March	0.063	0.032	53.821	17.424	20.996	9.753	12.912	115.0
	April	0.047	0.038	55.944	17.600	21.564	10.017	13.045	118.3
	May	0.041	0.033	51.405	17.424	20.996	9.753	12.909	112.6
	June	0.027	0.031	52.786	16.896	20.752	9.640	12.653	112.8
	July	0.035	0.035	55.864	17.600	21.668	10.066	13.172	118.4
	August	0.025	0.021	58.394	17.424	20.996	9.753	12.918	119.5
	September	0.010	0.016	60.592	16.896	20.752	9.640	12.644	120.5
	October	0.019	0.018	63.505	17.600	21.668	10.066	13.173	126.0
	November	0.022	0.024	54.048	15.312	18.456	8.573	11.603	108.0
	December	0.099	0.099	60.320	17.600	21.668	10.066	13.166	123.0
A2	January	0.167	0.045	47.248	16.896	20.856	9.688	12.774	107.7
	February	0.161	0.051	41.896	15.488	18.918	8.788	11.605	96.9
	March	0.064	0.009	47.993	17.424	20.996	9.753	12.912	109.2

Scenario	Month	Monthly Energy End-Use, MJ/m^2							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	April	0.082	0.036	49.570	17.600	21.564	10.017	13.045	111.9
	May	0.071	0.031	47.392	17.424	20.996	9.753	12.909	108.6
	June	0.043	0.041	50.758	16.896	20.752	9.640	12.653	110.8
	July	0.050	0.047	53.136	17.600	21.668	10.066	13.172	115.7
	August	0.068	0.049	52.301	17.424	20.996	9.753	12.918	113.5
	September	0.041	0.032	54.301	16.896	20.752	9.640	12.644	114.3
	October	0.048	0.026	54.727	17.600	21.668	10.066	13.173	117.3
	November	0.060	0.031	45.664	15.312	18.456	8.573	11.603	99.7
	December	0.170	0.097	52.144	17.600	21.668	10.066	13.166	114.9
B1	January	0.156	0.036	45.178	16.896	20.856	9.688	12.774	105.6
	February	0.148	0.024	39.700	15.488	18.918	8.788	11.605	94.7
	March	0.047	0.008	45.391	17.424	20.996	9.753	12.912	106.5
	April	0.090	0.027	47.201	17.600	21.564	10.017	13.045	109.5
	May	0.077	0.025	45.221	17.424	20.996	9.753	12.909	106.4
	June	0.051	0.038	48.790	16.896	20.752	9.640	12.653	108.8
	July	0.059	0.048	51.254	17.600	21.668	10.066	13.172	113.9
	August	0.082	0.050	50.492	17.424	20.996	9.753	12.918	111.7
	September	0.047	0.031	53.024	16.896	20.752	9.640	12.644	113.0
	October	0.058	0.023	52.800	17.600	21.668	10.066	13.173	115.4
	November	0.071	0.029	44.045	15.312	18.456	8.573	11.603	98.1
	December	0.182	0.086	49.427	17.600	21.668	10.066	13.166	112.2
B2	January	0.160	0.040	45.922	16.896	20.856	9.688	12.774	106.3
	February	0.148	0.030	40.378	15.488	18.918	8.788	11.605	95.4
	March	0.048	0.007	46.344	17.424	20.996	9.753	12.912	107.5
	April	0.089	0.030	48.055	17.600	21.564	10.017	13.045	110.4
	May	0.075	0.028	45.984	17.424	20.996	9.753	12.909	107.2
	June	0.047	0.039	49.538	16.896	20.752	9.640	12.653	109.6
	July	0.057	0.047	51.671	17.600	21.668	10.066	13.172	114.3
	August	0.077	0.049	51.095	17.424	20.996	9.753	12.918	112.3
	September	0.045	0.032	53.290	16.896	20.752	9.640	12.644	113.3
	October	0.054	0.026	53.625	17.600	21.668	10.066	13.173	116.2
	November	0.064	0.031	45.175	15.312	18.456	8.573	11.603	99.2
	December	0.180	0.094	50.624	17.600	21.668	10.066	13.166	113.4
Heat Island Low	January	0.347	0.090	33.264	16.896	20.856	9.688	12.770	93.9
	February	0.307	0.048	29.516	15.488	18.918	8.788	11.605	84.7
	March	0.179	0.030	34.337	17.424	20.996	9.753	12.912	95.6
	April	0.176	0.036	36.808	17.600	21.564	10.017	13.045	99.2
	May	0.101	0.034	37.141	17.424	20.996	9.753	12.909	98.4
	June	0.089	0.045	41.258	16.896	20.752	9.640	12.653	101.3
	July	0.103	0.102	42.786	17.600	21.668	10.066	13.172	105.5
	August	0.150	0.070	42.415	17.424	20.996	9.753	12.918	103.7
	September	0.130	0.069	44.090	16.896	20.752	9.640	12.644	104.2
	October	0.139	0.050	43.443	17.600	21.668	10.066	13.173	106.1
	November	0.157	0.066	34.764	15.312	18.456	8.573	11.603	88.9
	December	0.401	0.173	37.765	17.600	21.668	10.066	13.166	100.8
Heat Island High	January	0.289	0.203	37.550	16.896	20.856	9.688	12.770	98.3
	February	0.270	0.157	33.140	15.488	18.918	8.788	11.605	88.4
	March	0.188	0.097	38.300	17.424	20.996	9.753	12.912	99.7
	April	0.159	0.079	40.084	17.600	21.564	10.017	13.045	102.5
	May	0.085	0.064	40.366	17.424	20.996	9.753	12.909	101.6
	June	0.039	0.044	44.666	16.896	20.752	9.640	12.653	104.7
	July	0.047	0.081	46.143	17.600	21.668	10.066	13.172	108.8
	August	0.072	0.070	45.841	17.424	20.996	9.753	12.918	107.1
	September	0.061	0.068	48.233	16.896	20.752	9.640	12.644	108.3
	October	0.080	0.080	47.585	17.600	21.668	10.066	13.173	110.3
	November	0.098	0.111	38.763	15.312	18.456	8.573	11.603	92.9
	December	0.271	0.250	42.081	17.600	21.668	10.066	13.166	105.1

Table D.1-5. Monthly Source Energy End-Use Consumption in San Juan, Puerto Rico, for Developing Building, Climate Change Scenarios, and Heat Island Cases

Scenario	Month	Monthly Energy End-Use, MJ/m^2							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	January	0.145	0.045	41.422	22.310	20.856	9.688	12.770	107.2
	February	0.103	0.017	37.084	20.451	18.918	8.788	11.605	97.0
	March	0.067	0.010	43.257	23.007	20.996	9.753	12.912	110.0
	April	0.015	0.006	45.502	23.240	21.564	10.017	13.045	113.4
	May	0.001		45.446	23.007	20.996	9.753	12.909	112.1
	June			50.229	22.310	20.752	9.640	12.653	115.6
	July	0.000		52.059	23.240	21.668	10.066	13.172	120.2
	August	0.010	0.003	51.376	23.007	20.996	9.753	12.918	118.1
	September	0.001	0.000	53.266	22.310	20.752	9.640	12.644	118.6
	October		0.000	53.100	23.240	21.668	10.066	13.173	121.2
	November	0.014	0.003	42.605	20.219	18.456	8.573	11.603	101.5
	December	0.175	0.126	46.491	23.240	21.668	10.066	13.166	114.9
A1FI	January	0.027	0.003	73.089	22.310	20.856	9.688	12.774	138.7
	February	0.020	0.003	62.098	20.451	18.918	8.788	11.605	121.9
	March	0.002		68.790	23.007	20.996	9.753	12.912	135.5
	April	0.003		70.025	23.240	21.564	10.017	13.045	137.9
	May			63.609	23.007	20.996	9.753	12.909	130.3
	June			65.234	22.310	20.752	9.640	12.653	130.6
	July			69.297	23.240	21.668	10.066	13.172	137.4
	August	0.006		71.816	23.007	20.996	9.753	12.918	138.5
	September			75.016	22.310	20.752	9.640	12.644	140.4
	October			79.788	23.240	21.668	10.066	13.173	147.9
	November	0.003		68.310	20.219	18.456	8.573	11.603	127.2
	December	0.018		77.013	23.240	21.668	10.066	13.166	145.2
A2	January	0.020	0.003	61.954	22.310	20.856	9.688	12.774	127.6
	February	0.019	0.004	54.968	20.451	18.918	8.788	11.605	114.8
	March	0.002	0.000	62.188	23.007	20.996	9.753	12.912	128.9
	April	0.004		62.958	23.240	21.564	10.017	13.045	130.8
	May	0.001		59.349	23.007	20.996	9.753	12.909	126.0
	June			62.998	22.310	20.752	9.640	12.653	128.4
	July			66.271	23.240	21.668	10.066	13.172	134.4
	August	0.007		64.960	23.007	20.996	9.753	12.918	131.6
	September			68.056	22.310	20.752	9.640	12.644	133.4
	October			69.897	23.240	21.668	10.066	13.173	138.0
	November	0.003		58.886	20.219	18.456	8.573	11.603	117.7
	December	0.023	0.005	67.780	23.240	21.668	10.066	13.166	135.9
B1	January	0.026	0.005	59.517	22.310	20.856	9.688	12.774	125.2
	February	0.016	0.001	52.343	20.451	18.918	8.788	11.605	112.1
	March	0.001	0.001	59.195	23.007	20.996	9.753	12.912	125.9
	April	0.006		60.233	23.240	21.564	10.017	13.045	128.1
	May	0.001		56.815	23.007	20.996	9.753	12.909	123.5
	June			60.716	22.310	20.752	9.640	12.653	126.1
	July			64.241	23.240	21.668	10.066	13.172	132.4
	August	0.006		63.146	23.007	20.996	9.753	12.918	129.8
	September			66.767	22.310	20.752	9.640	12.644	132.1
	October			67.547	23.240	21.668	10.066	13.173	135.7
	November	0.002		57.121	20.219	18.456	8.573	11.603	116.0
	December	0.030	0.017	64.823	23.240	21.668	10.066	13.166	133.0
B2	January	0.025	0.005	60.426	22.310	20.856	9.688	12.774	126.1
	February	0.017	0.001	53.119	20.451	18.918	8.788	11.605	112.9
	March	0.001	0.001	60.379	23.007	20.996	9.753	12.912	127.0
	April	0.005		61.234	23.240	21.564	10.017	13.045	129.1
	May	0.000		57.714	23.007	20.996	9.753	12.909	124.4
	June			61.616	22.310	20.752	9.640	12.653	127.0
	July			64.698	23.240	21.668	10.066	13.172	132.8
	August	0.006		63.776	23.007	20.996	9.753	12.918	130.5
	September			67.030	22.310	20.752	9.640	12.644	132.4
	October			68.607	23.240	21.668	10.066	13.173	136.8
	November	0.004		58.317	20.219	18.456	8.573	11.603	117.2
	December	0.027	0.011	66.228	23.240	21.668	10.066	13.166	134.4

Scenario	Month	Monthly Energy End-Use, MJ/m² Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
Heat Island Low	January	0.138	0.047	42.553	22.310	20.856	9.688	12.774	108.4
	February	0.102	0.019	37.996	20.451	18.918	8.788	11.605	97.9
	March	0.037	0.019	44.214	23.007	20.996	9.753	12.912	110.9
	April	0.015	0.004	46.442	23.240	21.564	10.017	13.045	114.3
	May	0.003		46.344	23.007	20.996	9.753	12.909	113.0
	June	0.001		51.072	22.310	20.752	9.640	12.653	116.4
	July			53.002	23.240	21.668	10.066	13.172	121.1
	August	0.009	0.001	52.462	23.007	20.996	9.753	12.918	119.1
	September	0.002		54.432	22.310	20.752	9.640	12.644	119.8
	October	0.000		54.309	23.240	21.668	10.066	13.173	122.5
	November	0.019	0.000	43.689	20.219	18.456	8.573	11.603	102.6
	December	0.153	0.117	47.571	23.240	21.668	10.066	13.166	116.0
Heat Island High	January	0.154	0.012	47.356	22.310	20.856	9.688	12.774	113.2
	February	0.113	0.006	42.329	20.451	18.918	8.788	11.605	102.2
	March	0.027	0.001	48.787	23.007	20.996	9.753	12.912	115.5
	April	0.010		50.208	23.240	21.564	10.017	13.045	118.1
	May	0.006		50.015	23.007	20.996	9.753	12.909	116.7
	June	0.001		55.122	22.310	20.752	9.640	12.653	120.5
	July			57.013	23.240	21.668	10.066	13.172	125.2
	August	0.014		56.327	23.007	20.996	9.753	12.918	123.0
	September	0.001		58.669	22.310	20.752	9.640	12.644	124.0
	October	0.005		58.965	23.240	21.668	10.066	13.173	127.1
	November	0.021		48.036	20.219	18.456	8.573	11.603	106.9
	December	0.135	0.016	52.527	23.240	21.668	10.066	13.166	120.8

Table D.1-6. Monthly Source Energy End-Use Consumption in San Juan, Puerto Rico, for Low-Energy Building, Climate Change Scenarios, and Heat Island Cases

Scenario	Month	Monthly Energy End-Use, MJ/m² Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	January	0.007		15.017	12.181	3.449	6.782	8.187	45.6
	February	0.007		13.445	11.112	2.899	6.152	7.435	41.0
	March	0.000		16.134	12.553	3.112	6.827	8.276	46.9
	April			16.680	12.849	3.081	7.012	8.365	48.0
	May			16.290	12.693	2.982	6.827	8.262	47.1
	June			15.978	12.438	2.899	6.748	8.120	46.2
	July			16.683	12.968	2.983	7.046	8.441	48.1
	August			16.290	12.744	3.032	6.827	8.266	47.2
	September			15.979	12.426	3.055	6.748	8.116	46.3
	October			16.680	12.924	3.487	7.046	8.441	48.6
	November			14.185	11.080	3.218	6.001	7.416	41.9
	December	0.002		16.056	12.759	3.699	7.046	8.452	48.0
A1FI	January			17.103	12.454	3.358	6.782	8.185	47.9
	February			14.724	11.368	2.861	6.152	7.435	42.5
	March			16.490	12.759	3.090	6.827	8.276	47.4
	April			17.224	12.977	3.071	7.012	8.365	48.6
	May			16.459	12.774	3.005	6.827	8.262	47.3
	June			16.241	12.452	2.937	6.748	8.120	46.5
	July			17.035	12.983	3.042	7.046	8.441	48.5
	August			17.363	12.773	3.035	6.827	8.266	48.3
	September			17.528	12.452	3.047	6.748	8.116	47.9
	October			18.090	12.982	3.437	7.046	8.441	50.0
	November			15.594	11.190	3.154	6.001	7.416	43.4
	December			18.135	12.998	3.603	7.046	8.452	50.2
A2	January			16.075	12.390	3.359	6.782	8.185	46.8
	February			14.576	11.320	2.862	6.152	7.435	42.3
	March			16.275	12.740	3.090	6.827	8.276	47.2
	April			16.734	12.969	3.072	7.012	8.365	48.2
	May			16.317	12.766	3.009	6.827	8.262	47.2
	June			16.101	12.452	2.938	6.748	8.120	46.4

Scenario	Month	Monthly Energy End-Use, MJ/m^2							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	July			16.838	12.983	3.042	7.046	8.441	48.4
	August			16.515	12.770	3.038	6.827	8.266	47.4
	September			16.383	12.451	3.049	6.748	8.116	46.7
	October			16.888	12.971	3.437	7.046	8.441	48.8
	November			14.401	11.172	3.156	6.001	7.416	42.1
	December			17.091	12.949	3.604	7.046	8.452	49.1
B1	January			16.014	12.378	3.359	6.782	8.185	46.7
	February			14.458	11.309	2.861	6.152	7.435	42.2
	March			16.238	12.730	3.090	6.827	8.276	47.2
	April			16.685	12.959	3.072	7.012	8.365	48.1
	May			16.294	12.759	3.006	6.827	8.262	47.1
	June			16.019	12.452	2.936	6.748	8.120	46.3
	July			16.755	12.983	3.041	7.046	8.441	48.3
	August			16.398	12.769	3.038	6.827	8.266	47.3
	September			16.246	12.450	3.049	6.748	8.116	46.6
	October			16.770	12.969	3.437	7.046	8.441	48.7
	November			14.309	11.169	3.156	6.001	7.416	42.1
	December			16.855	12.936	3.604	7.046	8.452	48.9
B2	January			16.028	12.382	3.359	6.782	8.185	46.7
	February			14.549	11.314	2.861	6.152	7.435	42.3
	March			16.253	12.733	3.089	6.827	8.276	47.2
	April			16.697	12.963	3.072	7.012	8.365	48.1
	May			16.298	12.761	3.006	6.827	8.262	47.2
	June			16.042	12.452	2.936	6.748	8.120	46.3
	July			16.769	12.983	3.041	7.046	8.441	48.3
	August			16.429	12.770	3.038	6.827	8.266	47.3
	September			16.268	12.450	3.049	6.748	8.116	46.6
	October			16.811	12.969	3.437	7.046	8.441	48.7
	November			14.366	11.171	3.155	6.001	7.416	42.1
	December			16.959	12.942	3.604	7.046	8.452	49.0
Heat Island Low	January	0.003		15.303	12.202	3.451	6.782	8.187	45.9
	February	0.002		13.705	11.135	2.913	6.152	7.435	41.3
	March			16.186	12.574	3.129	6.827	8.276	47.0
	April			16.680	12.876	3.081	7.012	8.365	48.0
	May			16.290	12.714	2.982	6.827	8.262	47.1
	June			15.980	12.445	2.900	6.748	8.120	46.2
	July			16.690	12.975	2.983	7.046	8.441	48.1
	August			16.294	12.755	3.031	6.827	8.266	47.2
	September			15.983	12.435	3.066	6.748	8.116	46.3
	October			16.680	12.936	3.488	7.046	8.441	48.6
	November			14.185	11.097	3.223	6.001	7.416	41.9
	December	0.001		16.147	12.776	3.700	7.046	8.452	48.1
Heat Island High	January			15.809	12.282	3.450	6.782	8.187	46.5
	February			14.302	11.224	2.912	6.152	7.435	42.0
	March			16.136	12.677	3.128	6.827	8.276	47.0
	April			16.696	12.949	3.080	7.012	8.365	48.1
	May			16.324	12.761	2.982	6.827	8.262	47.2
	June			16.112	12.452	2.899	6.748	8.120	46.3
	July			16.841	12.983	2.982	7.046	8.441	48.3
	August			16.451	12.770	3.030	6.827	8.266	47.3
	September			16.142	12.451	3.065	6.748	8.116	46.5
	October			16.751	12.972	3.487	7.046	8.441	48.7
	November			14.231	11.158	3.222	6.001	7.416	42.0
	December			16.515	12.845	3.699	7.046	8.452	48.6

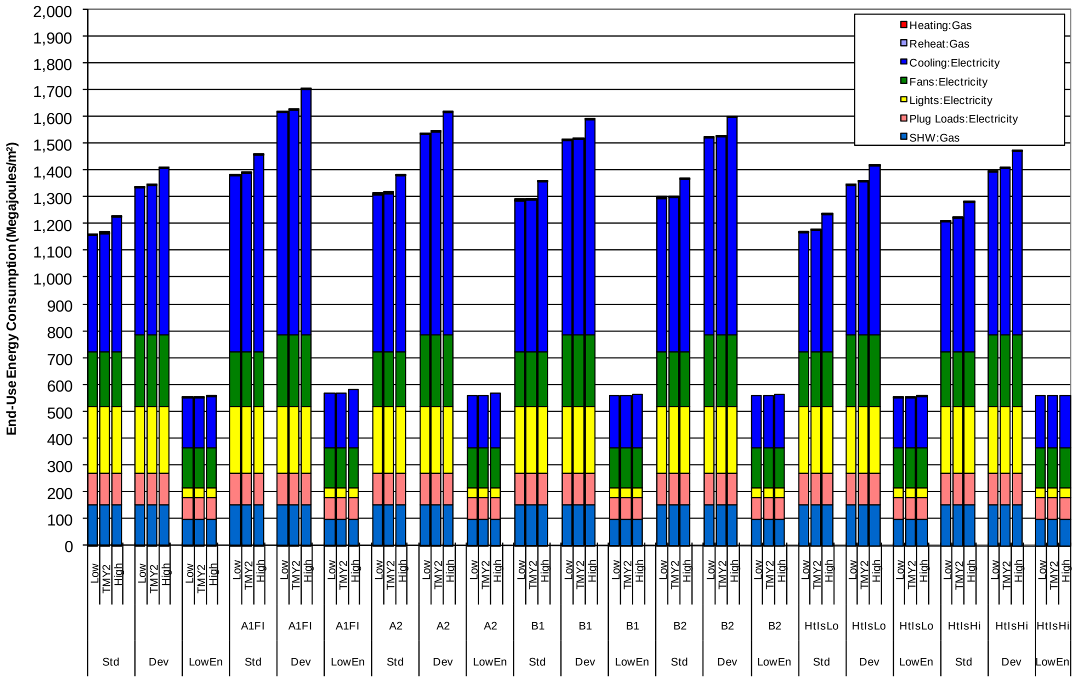

Figure D.1-1. Annual Source Energy End-Use Consumption in San Juan, Puerto Rico, for Standard, Developing, and Low-Energy Buildings Using Typical Year, Climate Change Scenarios, and Heat Island Cases

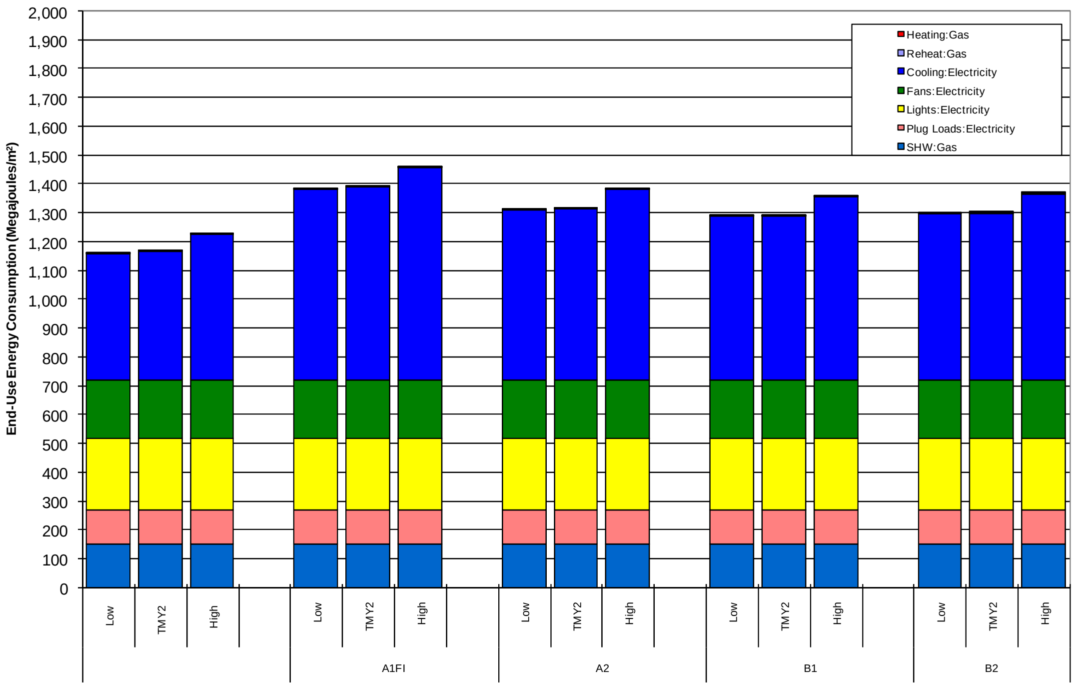

Figure D.1-2. Annual Source Energy End-Use Consumption in San Juan, Puerto Rico, for Standard Building and Climate Change Scenarios

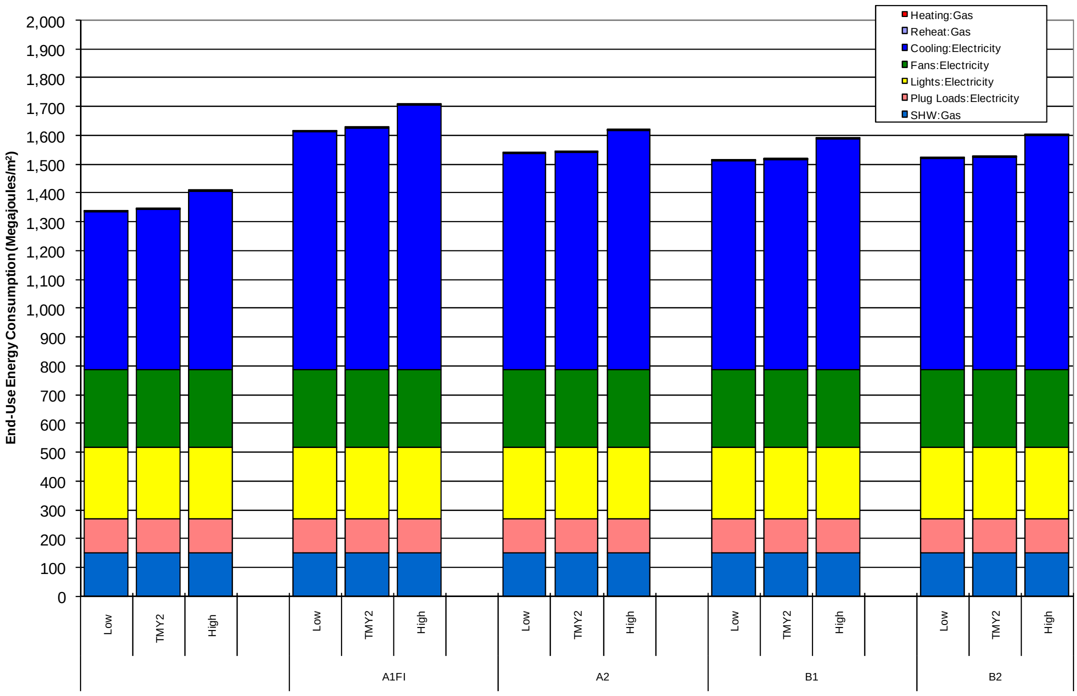

Figure D.1-3. Annual Source Energy End-Use Consumption in San Juan, Puerto Rico, for Developing Building and Climate Change Scenarios

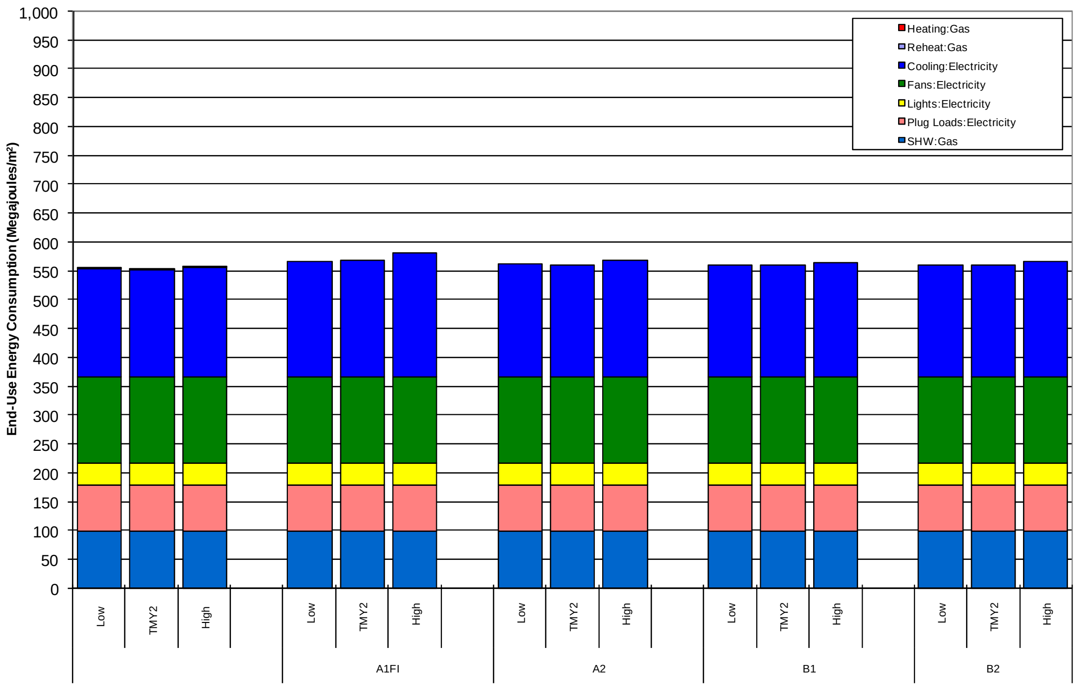

Figure D.1-4. Annual Source Energy End-Use Consumption in San Juan, Puerto Rico, for Low-Energy Building and Climate Change Scenarios

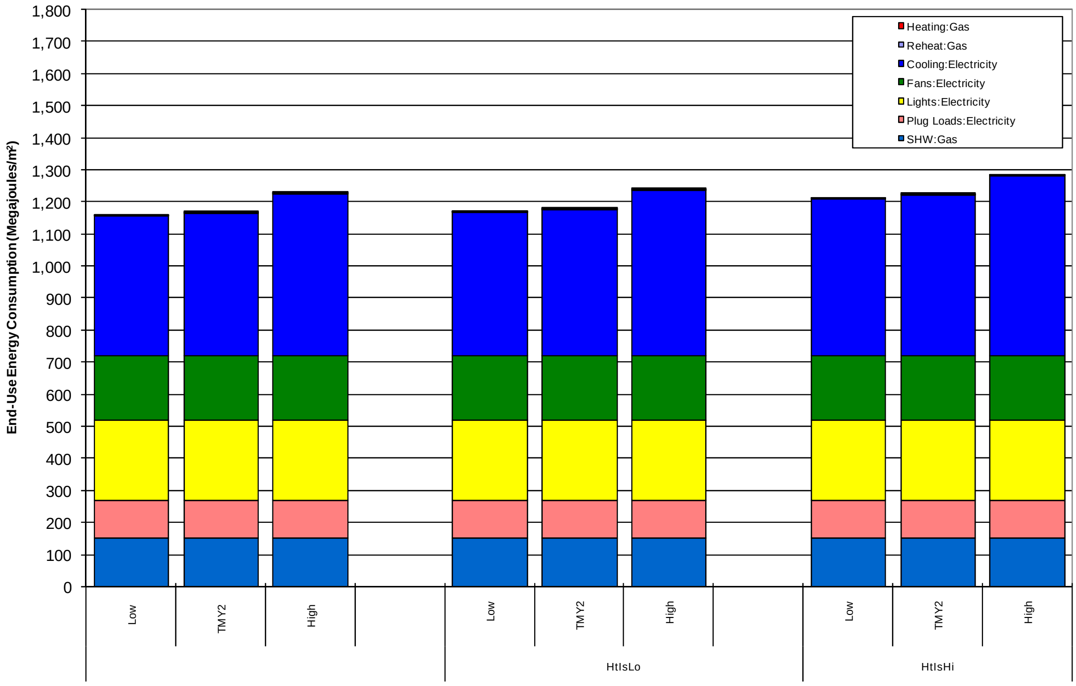

Figure D.1-5. Annual Source Energy End-Use Consumption in San Juan, Puerto Rico for Standard Building and Heat Island Cases

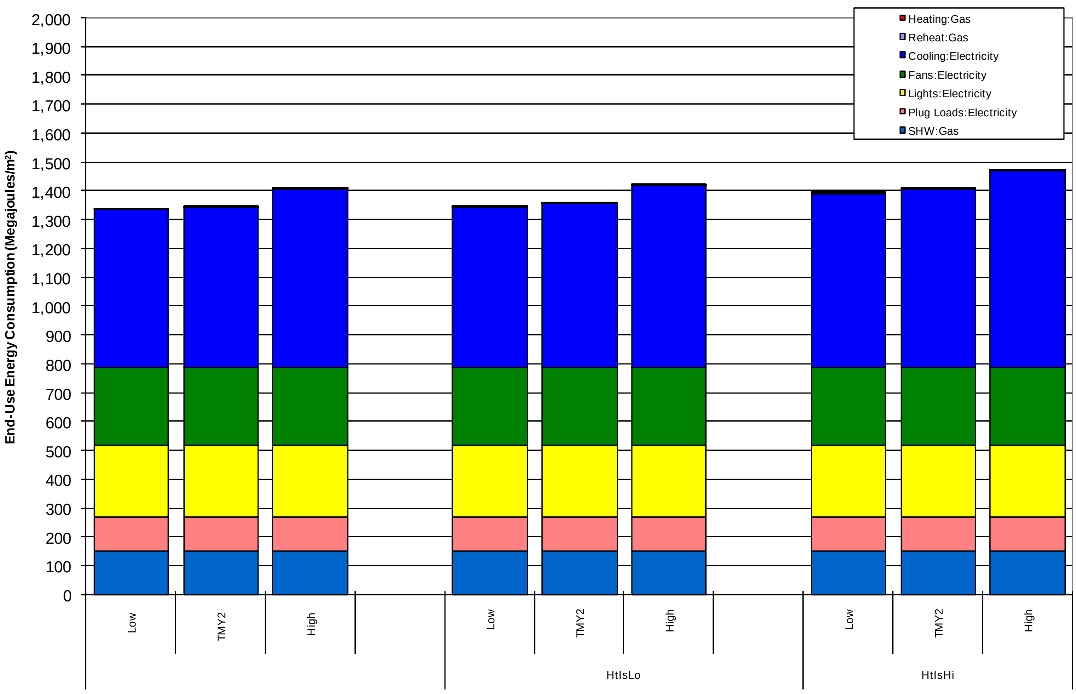

Figure D.1-6. Annual Source Energy End-Use Consumption in San Juan, Puerto Rico, for Developing Building and Heat Island Cases

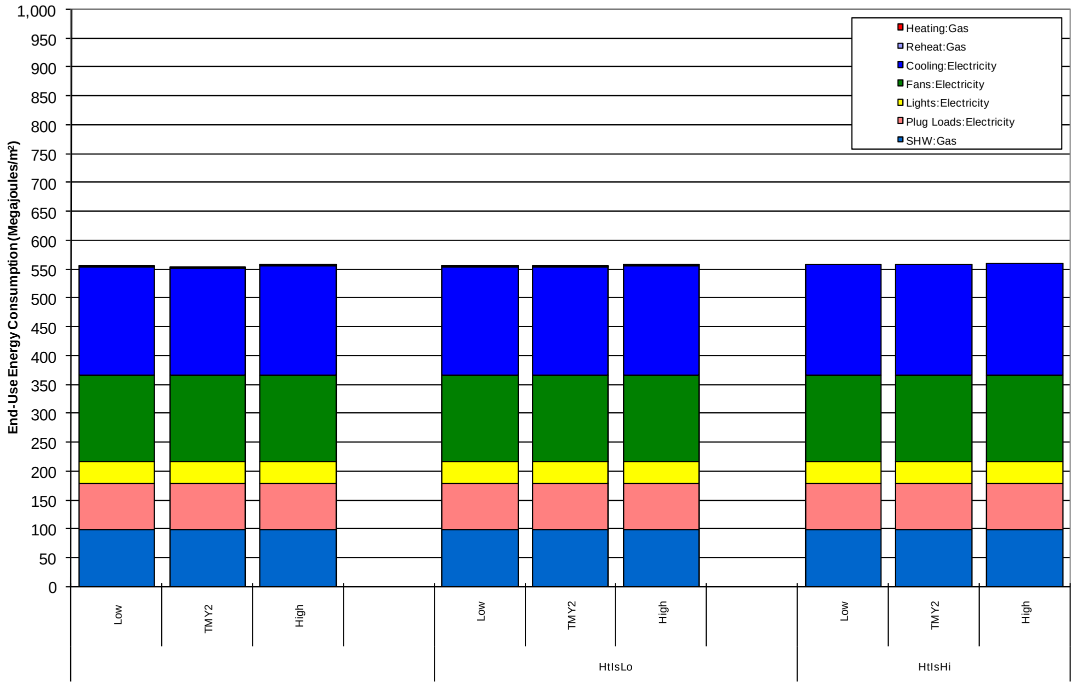

Figure D.1-7. Annual Source Energy End-Use Consumption in San Juan, Puerto Rico, for Low-Energy Building and Heat Island Cases

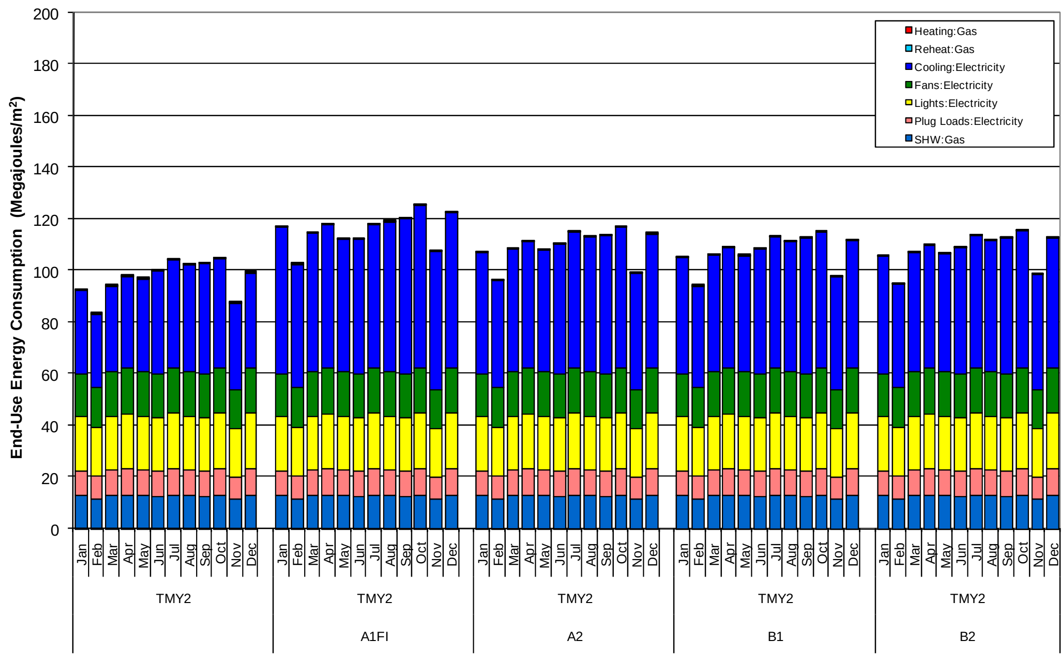

Figure D.1-8. Monthly Source Energy End-Use Consumption in San Juan, Puerto Rico, for Standard Building and Climate Change Scenarios

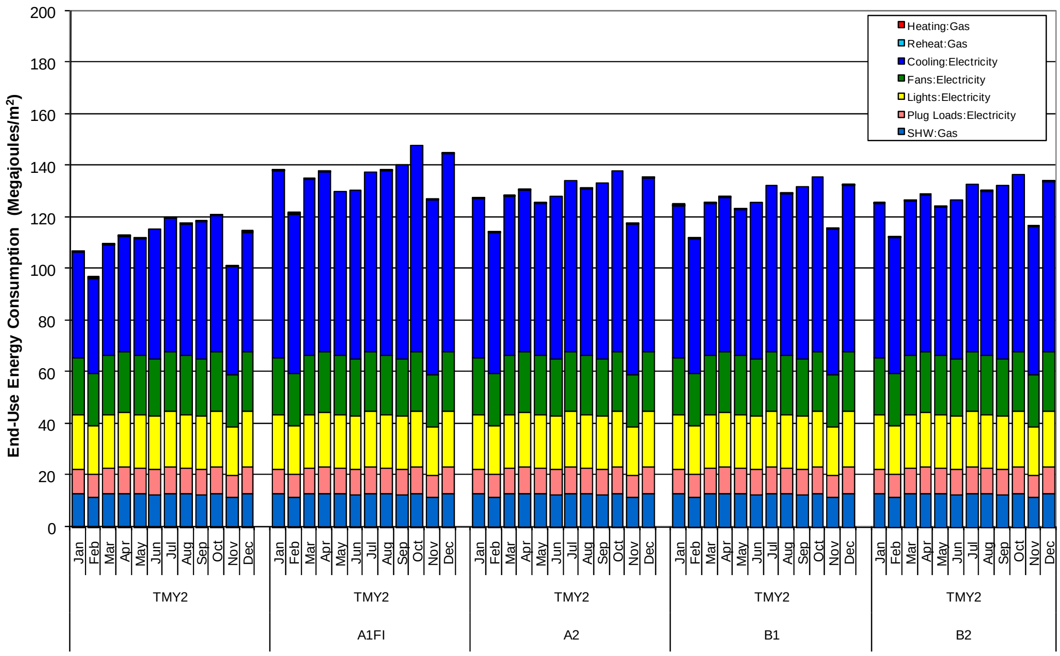

Figure D.1-9. Monthly Source Energy End-Use Consumption in San Juan, Puerto Rico, for Developing Building and Climate Change Scenarios

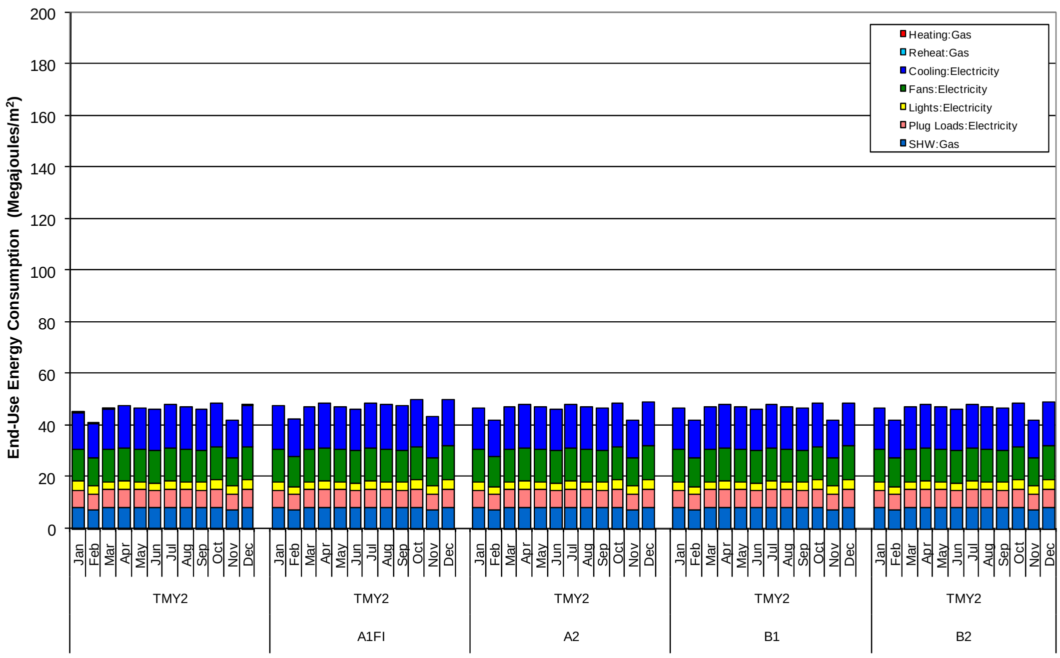

Figure D.1-10. Monthly Source Energy End-Use Consumption in San Juan, Puerto, Rico for Low-Energy Building and Climate Change Scenarios

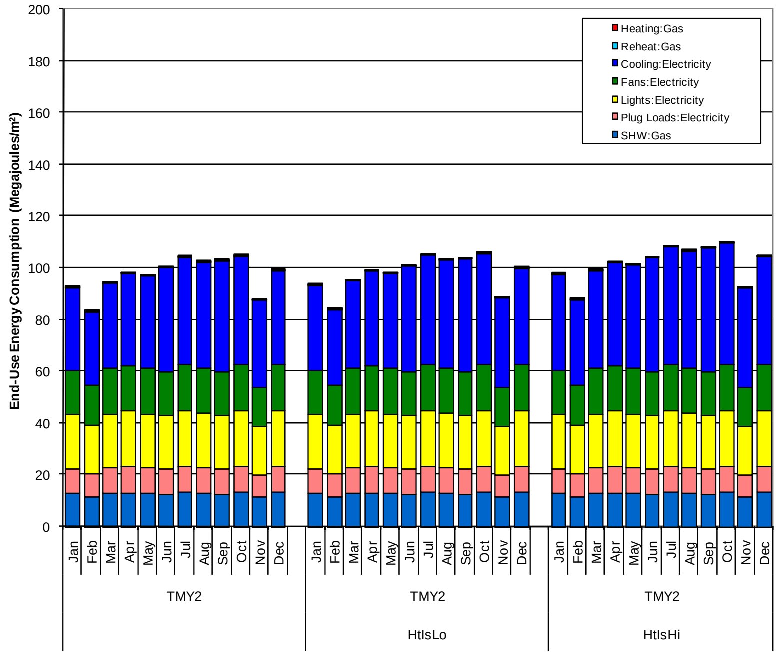

Figure D.1-11. Monthly Source Energy End-Use Consumption in San Juan, Puerto, Rico for Standard Building and Heat Island Cases

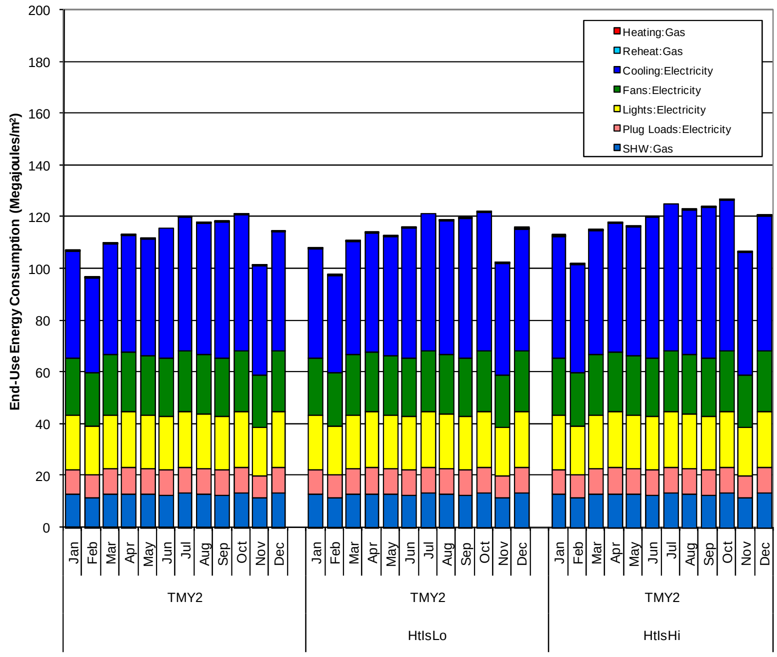

Figure D.1-12. Monthly Source Energy End-Use Consumption in San Juan, Puerto Rico, for Developing Building and Heat Island Cases

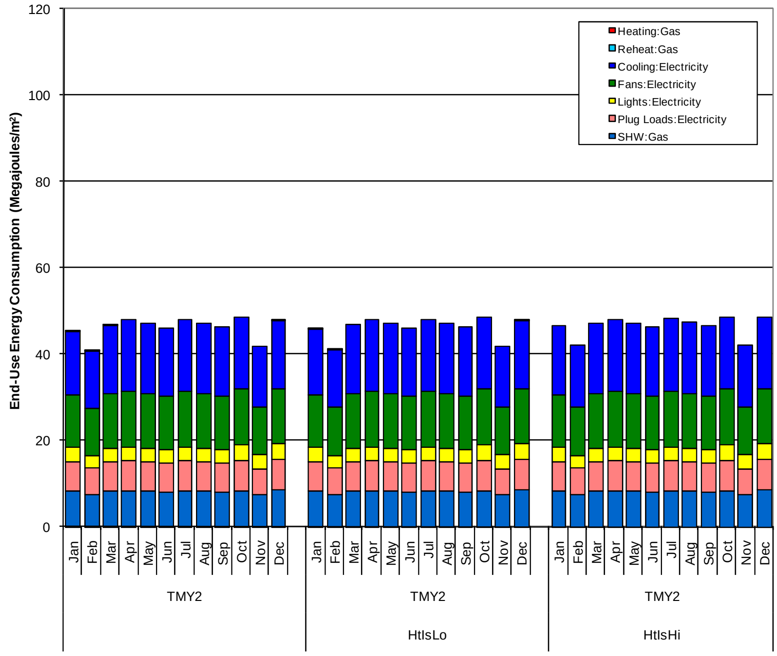

Figure D.1-13. Monthly Source Energy End-Use Consumption in San Juan, Puerto, Rico for Low-Energy Building and Heat Island Cases

D.2 Washington, D.C., USA (Climate Dfa)

Table D.2-1. Annual Source Energy End-Use Consumption in Washington, D.C., USA, for Typical Year Weather Data

		Annual Energy End-Use, MJ/m²							
Scenario	Standard	Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	Standard	234.9	13.2	173.6	273.8	249.3	115.8	152.6	1213.2
	Developing	234.0	18.9	232.8	352.2	249.3	115.8	152.6	1355.6
	Low-Energy	73.4		57.7	140.9	40.9	81.1	97.8	491.8
A1FI	Standard	183.9	6.2	205.4	273.8	249.3	115.8	152.6	1186.9
	Developing	174.7	8.8	323.7	352.2	249.3	115.8	152.6	1377.0
	Low-Energy	45.5		57.0	155.0	40.0	81.1	97.8	476.4
A2	Standard	184.9	6.4	207.7	273.8	249.3	115.8	152.6	1190.4
	Developing	175.8	8.8	324.2	352.2	249.3	115.8	152.6	1378.6
	Low-Energy	45.9		57.1	154.7	40.0	81.1	97.8	476.5
B1	Standard	140.9	10.0	286.1	273.8	249.3	115.8	152.6	1228.4
	Developing	133.7	14.4	414.0	352.2	249.3	115.8	152.6	1431.9
	Low-Energy	31.1		79.1	159.5	40.2	81.1	97.8	488.8
B2	Standard	144.5	9.1	297.0	273.8	249.3	115.8	152.6	1242.0
	Developing	137.2	12.7	425.0	352.2	249.3	115.8	152.6	1444.8
	Low-Energy	33.1		82.2	159.6	40.2	81.1	97.8	493.9
HtIsLo	Standard	227.6	13.5	175.4	273.8	249.3	115.8	152.6	1208.0
	Developing	226.3	19.4	234.3	352.2	249.3	115.8	152.6	1349.9
	Low-Energy	70.1		57.1	141.7	41.0	81.1	97.8	488.7
HtIsHi	Standard	202.9	16.1	193.0	273.8	249.3	115.8	152.6	1203.4
	Developing	199.0	22.3	252.9	352.2	249.3	115.8	152.6	1344.1
	Low-Energy	56.9		55.9	144.9	41.0	81.1	97.8	477.5

Table D.2-2. Annual Source Energy End-Use Consumption in Washington, D.C., USA, for Low Year Weather Data

		Annual Energy End-Use, MJ/m²							
Scenario	Standard	Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	Standard	182.5	13.0	183.8	273.8	249.3	115.8	152.6	1170.8
	Developing	180.1	21.4	246.5	352.2	249.3	115.8	152.6	1317.8
	Low-Energy	52.2		57.6	144.1	40.5	81.1	97.8	473.3
A1FI	Standard	130.5	7.6	231.5	273.8	249.3	115.8	152.6	1160.9
	Developing	119.3	11.6	361.0	352.2	249.3	115.8	152.6	1361.7
	Low-Energy	26.9		57.6	161.7	39.4	81.1	97.8	464.5
A2	Standard	131.6	9.3	235.1	273.8	249.3	115.8	152.6	1167.4
	Developing	120.6	13.7	364.6	352.2	249.3	115.8	152.6	1368.7
	Low-Energy	27.1		57.6	161.3	39.5	81.1	97.8	464.3
B1	Standard	100.2	8.6	317.4	273.8	249.3	115.8	152.6	1217.5
	Developing	93.5	13.1	456.9	352.2	249.3	115.8	152.6	1433.3
	Low-Energy	17.7		82.7	166.1	39.6	81.1	97.8	485.0
B2	Standard	102.5	8.4	327.1	273.8	249.3	115.8	152.6	1229.4
	Developing	95.3	12.4	467.9	352.2	249.3	115.8	152.6	1445.4
	Low-Energy	19.0		85.8	166.1	39.6	81.1	97.8	489.3
HtIsLo	Standard	177.1	14.3	187.6	273.8	249.3	115.8	152.6	1170.4
	Developing	174.5	21.7	250.2	352.2	249.3	115.8	152.6	1316.2
	Low-Energy	49.4		57.5	144.9	40.6	81.1	97.8	471.2
HtIsHi	Standard	156.8	17.2	206.0	273.8	249.3	115.8	152.6	1171.4
	Developing	152.9	25.7	268.7	352.2	249.3	115.8	152.6	1317.2
	Low-Energy	38.5		57.1	148.2	40.6	81.1	97.8	463.2

Table D.2-3. Annual Source Energy End-Use Consumption in Washington, D.C., USA, for High Year Weather Data

Scenario	Standard	Annual Energy End-Use, MJ/m²							
		Heatin g	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	Standard	231.5	22.3	203.2	273.8	249.3	115.8	152.6	1248.4
	Developing	235.6	33.5	265.0	352.2	249.3	115.8	152.6	1403.8
	Low-Energy	73.3		48.6	139.7	42.1	81.1	97.8	482.5
A1FI	Standard	187.7	12.7	228.0	273.8	249.3	115.8	152.6	1219.8
	Developing	183.4	17.8	338.1	352.2	249.3	115.8	152.6	1409.2
	Low-Energy	50.1		48.4	154.0	40.9	81.1	97.8	472.2
A2	Standard	188.9	13.7	231.7	273.8	249.3	115.8	152.6	1225.8
	Developing	185.0	20.0	341.4	352.2	249.3	115.8	152.6	1416.2
	Low-Energy	50.5		48.4	153.6	40.9	81.1	97.8	472.2
B1	Standard	145.3	19.3	312.9	273.8	249.3	115.8	152.6	1268.9
	Developing	142.6	27.2	434.4	352.2	249.3	115.8	152.6	1474.1
	Low-Energy	35.8		76.1	158.3	41.1	81.1	97.8	490.1
B2	Standard	148.2	16.7	321.1	273.8	249.3	115.8	152.6	1277.4
	Developing	146.1	25.1	443.7	352.2	249.3	115.8	152.6	1484.7
	Low-Energy	37.9		79.3	158.4	41.1	81.1	97.8	495.5
HtIsLo	Standard	225.1	22.3	205.3	273.8	249.3	115.8	152.6	1244.1
	Developing	228.6	34.3	267.4	352.2	249.3	115.8	152.6	1400.1
	Low-Energy	69.9		48.2	140.4	42.1	81.1	97.8	479.5
HtIsHi	Standard	202.6	25.5	221.1	273.8	249.3	115.8	152.6	1240.7
	Developing	204.1	37.6	283.8	352.2	249.3	115.8	152.6	1395.3
	Low-Energy	57.3		47.4	143.4	42.1	81.1	97.8	469.1

Table D.2-4. Monthly Source Energy End-Use Consumption in Washington, D.C., USA, for Standard Building, Climate Change Scenarios, and Heat Island Cases

Scenario	Month	Monthly Energy End-Use, MJ/m²							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	January	50.459	0.074	0.080	22.657	20.856	9.688	12.774	116.6
	February	35.159	0.107	0.606	20.769	18.918	8.788	11.605	96.0
	March	22.801	0.551	2.712	23.365	20.996	9.753	12.912	93.1
	April	20.467	1.800	7.416	23.601	21.564	10.017	13.033	97.9
	May	8.091	3.417	21.523	23.365	20.996	9.753	12.922	100.1
	June	2.672	0.987	30.517	22.657	20.752	9.640	12.636	99.9
	July	0.690	0.149	37.612	23.601	21.668	10.066	13.170	107.0
	August	3.160	1.113	30.969	23.365	20.996	9.753	12.916	102.3
	September	7.038	3.250	27.488	22.657	20.752	9.640	12.641	103.5
	October	12.083	1.241	13.582	23.601	21.668	10.066	13.179	95.4
	November	27.410	0.294	0.843	20.533	18.456	8.573	11.603	87.7
	December	44.868	0.259	0.263	23.601	21.668	10.066	13.166	113.9
A1FI	January	38.668	0.073	3.277	22.657	20.856	9.688	12.774	108.0
	February	26.663	0.140	1.662	20.769	18.918	8.788	11.605	88.5
	March	18.338	0.421	4.172	23.365	20.996	9.753	12.912	90.0
	April	16.754	0.425	7.357	23.601	21.564	10.017	13.033	92.7
	May	6.922	1.865	22.547	23.365	20.996	9.753	12.922	98.4
	June	1.724	0.708	31.843	22.657	20.752	9.640	12.636	100.0
	July	0.132	0.018	38.545	23.601	21.668	10.066	13.170	107.2
	August	2.115	0.317	33.400	23.365	20.996	9.753	12.916	102.9
	September	5.575	1.400	31.483	22.657	20.752	9.640	12.641	104.1
	October	8.216	0.482	20.509	23.601	21.668	10.066	13.179	97.7
	November	22.110	0.130	4.750	20.533	18.456	8.573	11.603	86.2
	December	36.722	0.186	5.810	23.601	21.668	10.066	13.166	111.2
A2	January	38.730	0.073	3.348	22.657	20.856	9.688	12.774	108.1
	February	26.404	0.119	1.868	20.769	18.918	8.788	11.605	88.5
	March	18.366	0.451	4.098	23.365	20.996	9.753	12.912	89.9

Scenario	Month	Monthly Energy End-Use, MJ/m²							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	April	17.156	0.876	8.330	23.601	21.564	10.017	13.033	94.6
	May	6.955	1.780	22.698	23.365	20.996	9.753	12.922	98.5
	June	1.963	0.663	32.330	22.657	20.752	9.640	12.636	100.6
	July	0.284	0.032	40.066	23.601	21.668	10.066	13.170	108.9
	August	2.240	0.390	33.920	23.365	20.996	9.753	12.916	103.6
	September	5.414	1.102	30.511	22.657	20.752	9.640	12.641	102.7
	October	8.115	0.445	20.566	23.601	21.668	10.066	13.179	97.6
	November	22.358	0.187	4.294	20.533	18.456	8.573	11.603	86.0
	December	36.923	0.276	5.622	23.601	21.668	10.066	13.166	111.3
B1	January	30.701	0.151	4.266	22.657	20.856	9.688	12.770	101.1
	February	21.486	0.512	2.752	20.769	18.918	8.788	11.605	84.8
	March	14.458	0.946	7.587	23.365	20.996	9.753	12.912	90.0
	April	13.997	2.087	13.642	23.601	21.564	10.017	13.033	97.9
	May	4.204	2.389	32.295	23.365	20.996	9.753	12.922	105.9
	June	0.660	0.038	42.217	22.657	20.752	9.640	12.636	108.6
	July		0.019	56.387	23.601	21.668	10.066	13.170	124.9
	August	0.759	0.201	44.439	23.365	20.996	9.753	12.916	112.4
	September	3.252	1.424	38.284	22.657	20.752	9.640	12.641	108.6
	October	6.168	0.600	29.256	23.601	21.668	10.066	13.179	104.5
	November	17.340	0.996	7.459	20.533	18.456	8.573	11.603	85.0
	December	27.829	0.597	7.554	23.601	21.668	10.066	13.166	104.5
B2	January	33.249	0.144	3.969	22.657	20.856	9.688	12.770	103.3
	February	22.120	0.424	2.490	20.769	18.918	8.788	11.605	85.1
	March	14.704	0.893	7.300	23.365	20.996	9.753	12.912	89.9
	April	13.501	2.077	13.944	23.601	21.564	10.017	13.033	97.7
	May	3.823	1.920	33.509	23.365	20.996	9.753	12.922	106.3
	June	0.427	0.032	45.329	22.657	20.752	9.640	12.636	111.5
	July		0.019	56.747	23.601	21.668	10.066	13.170	125.3
	August	0.638	0.256	49.092	23.365	20.996	9.753	12.916	117.0
	September	2.721	1.158	39.751	22.657	20.752	9.640	12.641	109.3
	October	5.824	0.601	30.346	23.601	21.668	10.066	13.179	105.3
	November	17.090	1.186	7.831	20.533	18.456	8.573	11.603	85.3
	December	30.383	0.365	6.718	23.601	21.668	10.066	13.166	106.0
Heat Island Low	January	49.166	0.098	0.102	22.657	20.856	9.688	12.774	115.3
	February	34.168	0.172	0.624	20.769	18.918	8.788	11.605	95.0
	March	22.133	0.614	2.831	23.365	20.996	9.753	12.912	92.6
	April	20.103	1.622	7.679	23.601	21.564	10.017	13.033	97.6
	May	7.945	3.426	21.703	23.365	20.996	9.753	12.922	100.1
	June	2.395	1.014	30.913	22.657	20.752	9.640	12.636	100.0
	July		0.108	37.685	23.601	21.668	10.066	13.170	106.3
	August	2.871	1.011	30.731	23.365	20.996	9.753	12.916	101.6
	September	6.467	3.443	27.377	22.657	20.752	9.640	12.641	103.0
	October	11.591	1.408	14.282	23.601	21.668	10.066	13.179	95.8
	November	26.688	0.329	1.206	20.533	18.456	8.573	11.603	87.4
	December	43.680	0.284	0.311	23.601	21.668	10.066	13.166	112.8
Heat Island High	January	43.966	0.218	0.321	22.657	20.856	9.688	12.770	110.5
	February	30.802	0.440	1.068	20.769	18.918	8.788	11.605	92.4
	March	19.913	0.812	3.765	23.365	20.996	9.753	12.912	91.5
	April	18.766	1.961	9.203	23.601	21.564	10.017	13.033	98.1
	May	7.056	3.641	23.355	23.365	20.996	9.753	12.922	101.1
	June	1.443	1.155	32.475	22.657	20.752	9.640	12.636	100.8
	July		0.094	39.815	23.601	21.668	10.066	13.170	108.4
	August	1.804	0.898	32.819	23.365	20.996	9.753	12.916	102.6
	September	5.090	3.985	28.649	22.657	20.752	9.640	12.641	103.4
	October	10.369	1.483	16.840	23.601	21.668	10.066	13.179	97.2
	November	24.243	0.761	3.492	20.533	18.456	8.573	11.603	87.7
	December	39.346	0.681	1.173	23.601	21.668	10.066	13.166	109.7

Table D.2-5. Monthly Source Energy End-Use Consumption in Washington, D.C., USA, for Developing Building, Climate Change Scenarios, and Heat Island Cases

Scenario	Month	Monthly Energy End-Use, MJ/m^2							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	January	50.580	0.092	0.090	29.146	20.856	9.688	12.774	123.2
	February	34.076	0.250	0.695	26.717	18.918	8.788	11.605	101.0
	March	22.091	0.711	3.742	30.057	20.996	9.753	12.912	100.3
	April	20.142	2.488	10.239	30.361	21.564	10.017	13.033	107.8
	May	7.629	4.804	29.367	30.057	20.996	9.753	12.922	115.5
	June	2.460	1.261	41.013	29.146	20.752	9.640	12.636	116.9
	July	0.671	0.073	48.575	30.361	21.668	10.066	13.170	124.6
	August	3.081	1.287	40.816	30.057	20.996	9.753	12.916	118.9
	September	7.047	5.385	37.479	29.146	20.752	9.640	12.641	122.1
	October	12.366	1.759	19.490	30.361	21.668	10.066	13.179	108.9
	November	27.959	0.312	0.840	26.414	18.456	8.573	11.603	94.2
	December	45.896	0.517	0.468	30.361	21.668	10.066	13.166	122.1
A1FI	January	36.629	0.089	10.271	29.146	20.856	9.688	12.770	119.4
	February	24.957	0.279	7.826	26.717	18.918	8.788	11.605	99.1
	March	16.652	0.470	9.970	30.057	20.996	9.753	12.912	100.8
	April	15.329	0.619	13.807	30.361	21.564	10.017	13.033	104.7
	May	6.373	2.029	32.305	30.057	20.996	9.753	12.922	114.4
	June	1.615	0.743	44.906	29.146	20.752	9.640	12.636	119.4
	July	0.066	0.036	55.010	30.361	21.668	10.066	13.170	130.4
	August	1.946	0.831	48.443	30.057	20.996	9.753	12.916	124.9
	September	5.415	2.437	45.267	29.146	20.752	9.640	12.641	125.3
	October	7.541	0.867	33.401	30.361	21.668	10.066	13.179	117.1
	November	22.040	0.161	10.380	26.414	18.456	8.573	11.603	97.6
	December	36.168	0.246	12.068	30.361	21.668	10.066	13.166	123.7
A2	January	36.697	0.089	10.293	29.146	20.856	9.688	12.770	119.5
	February	24.645	0.247	8.218	26.717	18.918	8.788	11.605	99.1
	March	16.734	0.491	9.933	30.057	20.996	9.753	12.912	100.9
	April	15.824	1.281	14.426	30.361	21.564	10.017	13.033	106.5
	May	6.336	1.990	32.498	30.057	20.996	9.753	12.922	114.6
	June	1.765	0.880	45.150	29.146	20.752	9.640	12.636	120.0
	July	0.160	0.033	56.096	30.361	21.668	10.066	13.170	131.6
	August	2.144	0.686	48.453	30.057	20.996	9.753	12.916	125.0
	September	5.266	1.796	44.332	29.146	20.752	9.640	12.641	123.6
	October	7.377	0.705	33.415	30.361	21.668	10.066	13.179	116.8
	November	22.401	0.246	9.557	26.414	18.456	8.573	11.603	97.2
	December	36.436	0.376	11.784	30.361	21.668	10.066	13.166	123.9
B1	January	28.725	0.149	11.440	29.146	20.856	9.688	12.770	112.8
	February	20.054	0.792	9.483	26.717	18.918	8.788	11.605	96.4
	March	13.125	1.211	14.632	30.057	20.996	9.753	12.912	102.7
	April	12.874	3.175	21.268	30.361	21.564	10.017	13.033	112.3
	May	3.792	3.373	44.959	30.057	20.996	9.753	12.922	125.9
	June	0.663	0.131	56.099	29.146	20.752	9.640	12.636	129.1
	July			73.115	30.361	21.668	10.066	13.170	148.4
	August	0.732	0.160	59.546	30.057	20.996	9.753	12.916	134.2
	September	3.273	2.168	53.104	29.146	20.752	9.640	12.641	130.7
	October	5.627	0.997	42.823	30.361	21.668	10.066	13.179	124.7
	November	17.234	1.514	13.367	26.414	18.456	8.573	11.603	97.2
	December	27.561	0.726	14.198	30.361	21.668	10.066	13.166	117.7
B2	January	31.224	0.131	11.123	29.146	20.856	9.688	12.770	114.9
	February	20.575	0.582	9.107	26.717	18.918	8.788	11.605	96.3
	March	13.439	1.099	14.340	30.057	20.996	9.753	12.912	102.6
	April	12.457	2.983	21.573	30.361	21.564	10.017	13.033	112.0
	May	3.327	2.832	46.370	30.057	20.996	9.753	12.922	126.3
	June	0.371	0.071	59.202	29.146	20.752	9.640	12.636	131.8
	July			73.503	30.361	21.668	10.066	13.170	148.8
	August	0.606	0.289	64.725	30.057	20.996	9.753	12.916	139.3
	September	2.599	1.451	54.348	29.146	20.752	9.640	12.641	130.6
	October	5.396	0.942	43.897	30.361	21.668	10.066	13.179	125.5
	November	17.024	1.756	13.704	26.414	18.456	8.573	11.603	97.5
	December	30.141	0.594	13.154	30.361	21.668	10.066	13.166	119.2

Scenario	Month	Monthly Energy End-Use, MJ/m^2 Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
Heat Island Low	January	49.228	0.108	0.106	29.146	20.856	9.688	12.774	121.9
	February	32.956	0.243	0.691	26.717	18.918	8.788	11.605	99.9
	March	21.472	0.712	3.839	30.057	20.996	9.753	12.912	99.7
	April	19.710	2.505	10.609	30.361	21.564	10.017	13.033	107.8
	May	7.436	4.958	29.483	30.057	20.996	9.753	12.922	115.6
	June	2.270	1.320	41.220	29.146	20.752	9.640	12.636	117.0
	July	0.369	0.045	48.827	30.361	21.668	10.066	13.170	124.5
	August	2.824	1.231	40.376	30.057	20.996	9.753	12.916	118.2
	September	6.459	5.388	37.189	29.146	20.752	9.640	12.641	121.2
	October	11.882	1.915	20.224	30.361	21.668	10.066	13.179	109.3
	November	27.170	0.377	1.251	26.414	18.456	8.573	11.603	93.8
	December	44.540	0.579	0.531	30.361	21.668	10.066	13.166	120.9
Heat Island High	January	43.589	0.262	0.364	29.146	20.856	9.688	12.774	116.7
	February	29.116	0.637	1.163	26.717	18.918	8.788	11.605	96.9
	March	19.188	1.005	4.787	30.057	20.996	9.753	12.912	98.7
	April	18.136	2.769	12.233	30.361	21.564	10.017	13.033	108.1
	May	6.560	5.058	31.136	30.057	20.996	9.753	12.922	116.5
	June	1.342	1.510	43.004	29.146	20.752	9.640	12.636	118.0
	July	0.050	0.001	51.037	30.361	21.668	10.066	13.170	126.4
	August	1.713	1.228	42.707	30.057	20.996	9.753	12.916	119.4
	September	5.073	5.674	38.090	29.146	20.752	9.640	12.641	121.0
	October	10.236	2.180	23.089	30.361	21.668	10.066	13.179	110.8
	November	24.371	1.053	3.802	26.414	18.456	8.573	11.603	94.3
	December	39.608	0.955	1.508	30.361	21.668	10.066	13.166	117.3

Table D.2-6. Monthly Source Energy End-Use Consumption in Washington, D.C., USA, for Low-Energy Building, Climate Change Scenarios, and Heat Island Cases

Scenario	Month	Monthly Energy End-Use, MJ/m^2 Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	January	19.253			9.216	4.426	6.782	8.187	47.9
	February	12.711		0.014	8.432	3.469	6.152	7.435	38.2
	March	7.076		0.396	10.015	3.301	6.827	8.276	35.9
	April	5.141		0.693	10.578	2.958	7.012	8.357	34.7
	May	0.760		5.659	13.158	2.613	6.827	8.271	37.3
	June	0.005		11.869	14.759	2.391	6.748	8.105	43.9
	July	0.001		16.594	15.709	2.566	7.046	8.439	50.4
	August	0.117		12.053	14.674	2.711	6.827	8.267	44.6
	September	0.569		6.734	13.402	3.014	6.748	8.109	38.6
	October	2.166		3.675	12.797	3.636	7.046	8.440	37.8
	November	9.017			8.452	4.270	6.001	7.416	35.2
	December	16.616			9.749	5.541	7.046	8.452	47.4
A1FI	January	11.840			10.203	4.275	6.782	8.189	41.3
	February	7.780		0.078	9.564	3.378	6.152	7.435	34.4
	March	4.536		0.396	11.851	3.272	6.827	8.276	35.2
	April	3.108		0.693	12.461	2.914	7.012	8.357	34.5
	May	0.497		5.645	14.254	2.661	6.827	8.271	38.2
	June	0.003		11.700	15.202	2.423	6.748	8.105	44.2
	July			16.215	16.113	2.536	7.046	8.439	50.3
	August	0.056		12.053	15.216	2.637	6.827	8.267	45.1
	September	0.255		6.734	14.422	2.946	6.748	8.109	39.2
	October	0.819		3.494	14.655	3.532	7.046	8.440	38.0
	November	5.366			9.932	4.061	6.001	7.416	32.8
	December	11.236			11.165	5.374	7.046	8.452	43.3
A2	January	11.873			10.208	4.277	6.782	8.189	41.3
	February	7.615		0.085	9.640	3.371	6.152	7.435	34.3
	March	4.549		0.410	11.842	3.272	6.827	8.276	35.2
	April	3.298		0.693	12.246	2.932	7.012	8.357	34.5
	May	0.491		5.645	14.273	2.617	6.827	8.271	38.1
	June	0.004		11.799	15.148	2.428	6.748	8.105	44.2
	July			16.213	16.058	2.541	7.046	8.439	50.3
	August	0.058		12.014	15.173	2.645	6.827	8.267	45.0

	September	0.250		6.734	14.447	2.939	6.748	8.109	39.2
	October	0.794		3.495	14.706	3.524	7.046	8.440	38.0
	November	5.603			9.815	4.095	6.001	7.416	32.9
	December	11.385			11.106	5.393	7.046	8.452	43.4
B1	January	8.620			10.534	4.270	6.782	8.187	38.4
	February	5.468		0.095	9.999	3.376	6.152	7.435	32.5
	March	3.007		0.948	12.586	3.273	6.827	8.276	34.9
	April	2.168		2.433	12.787	2.949	7.012	8.357	35.7
	May	0.189		9.005	14.698	2.633	6.827	8.271	41.6
	June			15.612	15.417	2.439	6.748	8.105	48.3
	July			18.247	16.278	2.561	7.046	8.439	52.6
	August	0.007		16.103	15.676	2.658	6.827	8.267	49.5
	September	0.073		10.133	14.737	2.964	6.748	8.109	42.8
	October	0.398		6.200	14.997	3.543	7.046	8.440	40.6
	November	3.258			10.240	4.117	6.001	7.416	31.0
	December	7.873		0.368	11.597	5.413	7.046	8.452	40.7
B2	January	9.605			10.387	4.269	6.782	8.187	39.2
	February	5.797		0.092	9.948	3.377	6.152	7.435	32.8
	March	3.100		0.920	12.533	3.273	6.827	8.276	34.9
	April	2.050		2.589	12.844	2.949	7.012	8.357	35.8
	May	0.151		9.608	14.800	2.633	6.827	8.271	42.3
	June			16.436	15.470	2.438	6.748	8.105	49.2
	July			18.254	16.283	2.561	7.046	8.439	52.6
	August	0.002		16.593	15.805	2.658	6.827	8.267	50.2
	September	0.048		11.228	14.822	2.964	6.748	8.109	43.9
	October	0.346		6.458	15.039	3.544	7.046	8.440	40.9
	November	3.130			10.279	4.117	6.001	7.416	30.9
	December	8.858			11.426	5.411	7.046	8.452	41.2
Heat Island Low	January	18.670			9.224	4.450	6.782	8.187	47.3
	February	12.202		0.014	8.443	3.474	6.152	7.435	37.7
	March	6.684		0.382	10.066	3.308	6.827	8.276	35.5
	April	4.816		0.679	10.691	2.963	7.012	8.357	34.5
	May	0.664		5.588	13.245	2.617	6.827	8.271	37.2
	June	0.003		11.784	14.834	2.395	6.748	8.105	43.9
	July			16.255	15.777	2.571	7.046	8.439	50.1
	August	0.096		12.067	14.747	2.715	6.827	8.267	44.7
	September	0.471		6.734	13.555	3.019	6.748	8.109	38.6
	October	1.946		3.565	12.941	3.648	7.046	8.440	37.6
	November	8.523			8.463	4.271	6.001	7.416	34.7
	December	16.008			9.757	5.546	7.046	8.452	46.8
Heat Island High	January	16.094			9.269	4.450	6.782	8.187	44.8
	February	10.170			8.487	3.474	6.152	7.435	35.7
	March	5.152		0.368	10.285	3.308	6.827	8.276	34.2
	April	3.568		0.481	11.035	2.963	7.012	8.357	33.4
	May	0.355		5.291	13.762	2.617	6.827	8.271	37.1
	June			11.502	15.134	2.395	6.748	8.105	43.9
	July			16.386	16.042	2.570	7.046	8.439	50.5
	August	0.031		11.728	15.086	2.715	6.827	8.267	44.7
	September	0.188		6.791	13.978	3.019	6.748	8.109	38.8
	October	1.146		3.353	13.426	3.648	7.046	8.440	37.1
	November	6.585			8.606	4.271	6.001	7.416	32.9
	December	13.571			9.802	5.546	7.046	8.452	44.4

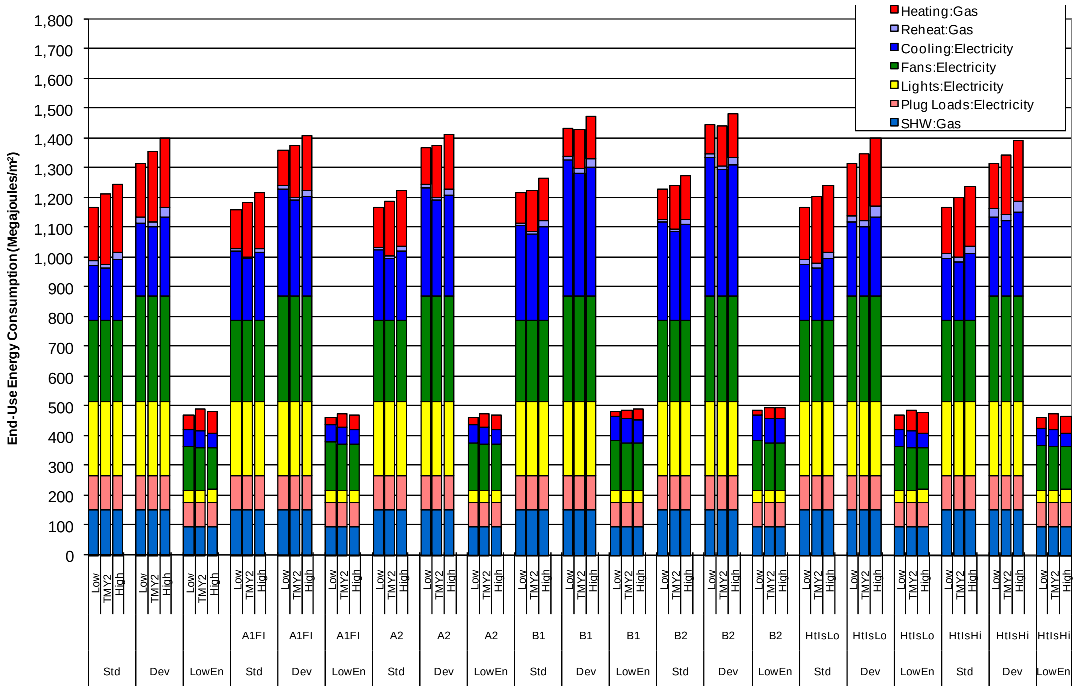

Figure D.2-1. Annual Source Energy End-Use Consumption in Washington, D.C., USA, for Standard, Developing, and Low-Energy Buildings Using Typical Year, Climate Change Scenarios, and Heat Island Cases

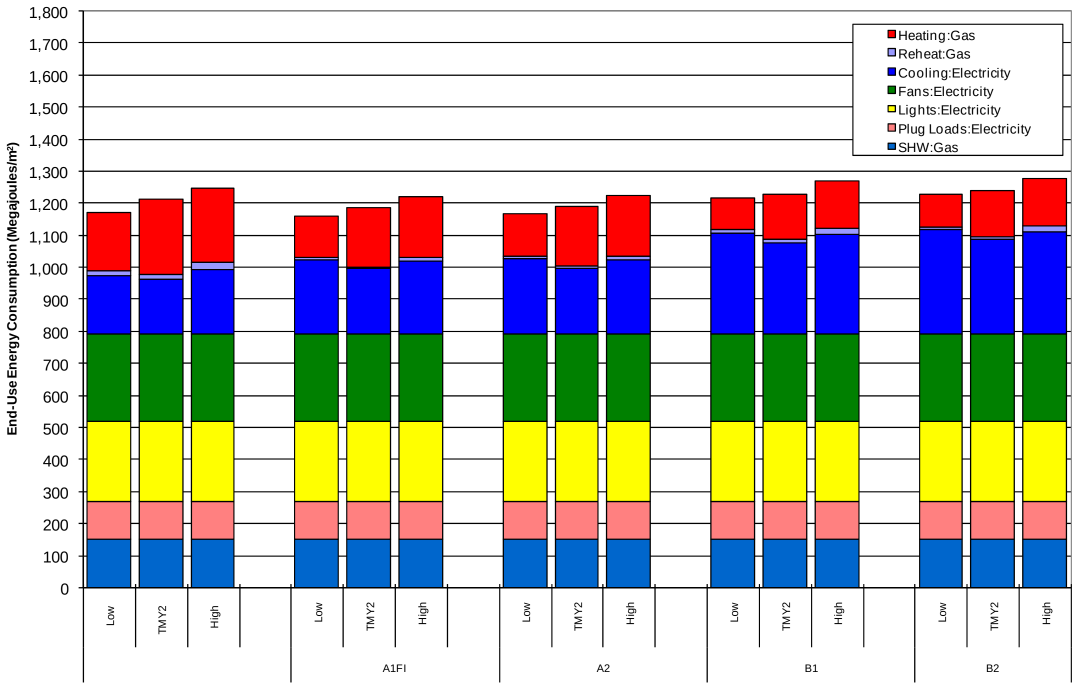

Figure D.2-2. Annual Source Energy End-Use Consumption in Washington, D.C., USA, for Standard Building and Climate Change Scenarios

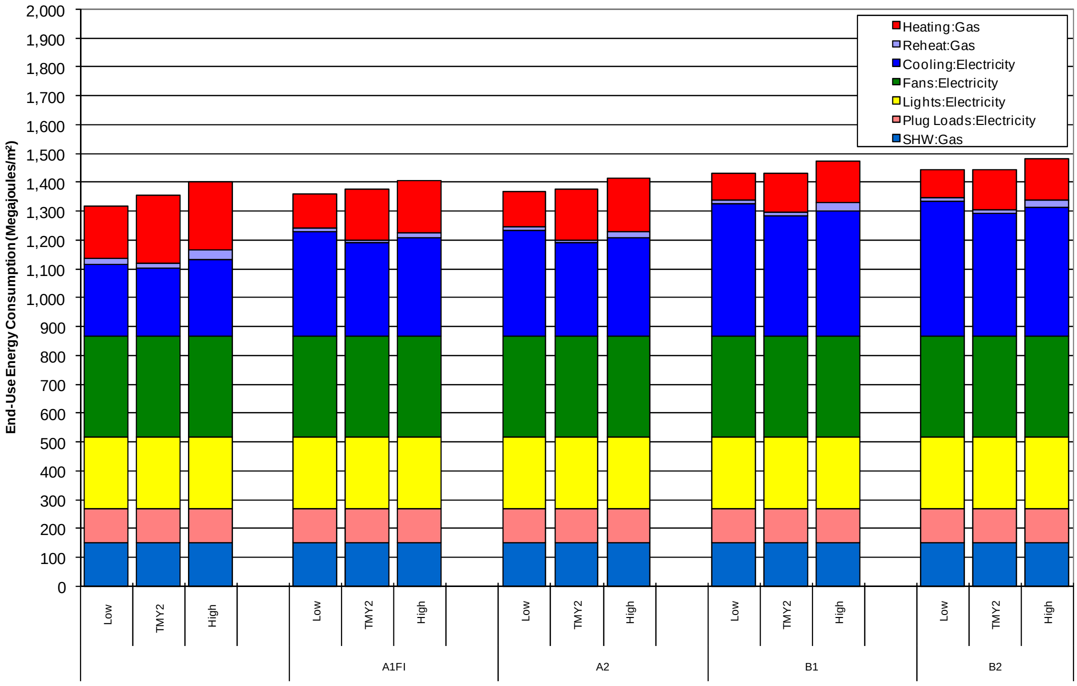

Figure D.2-3. Annual Source Energy End-Use Consumption in Washington, D.C., USA, for Developing Building and Climate Change Scenarios

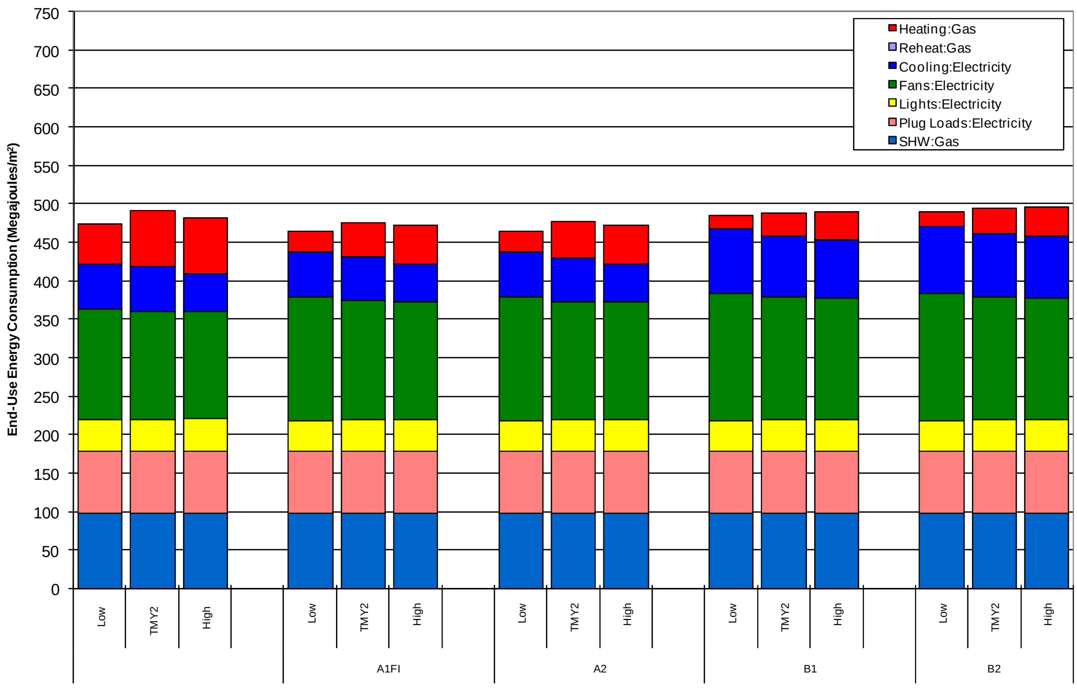

Figure D.2-4. Annual Source Energy End-Use Consumption in Washington, D.C., USA, for Low-Energy Building and Climate Change Scenarios

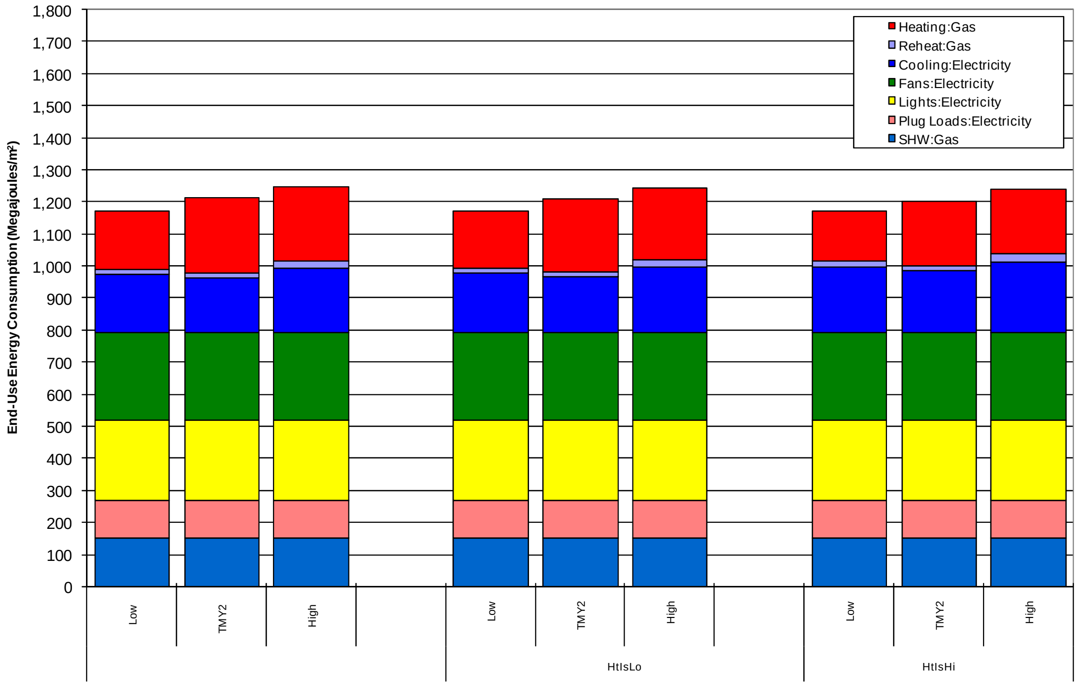

Figure D.2-5. Annual Source Energy End-Use Consumption in Washington, D.C., USA, for Standard Building and Heat Island Cases

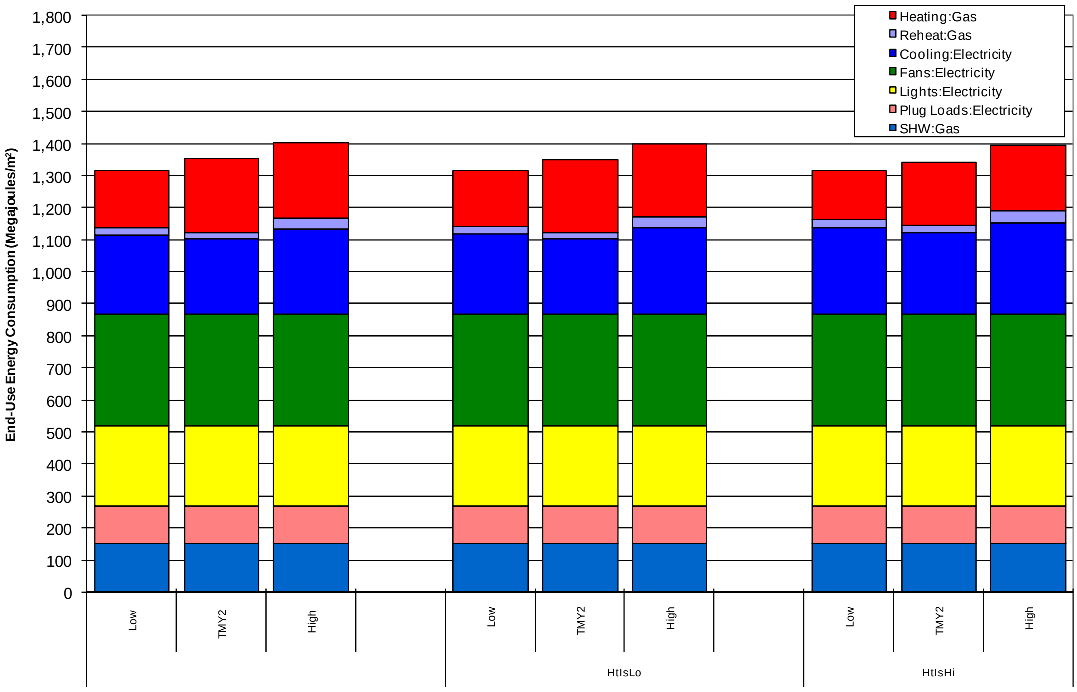

Figure D.2-6. Annual Source Energy End-Use Consumption in Washington, D.C., USA, for Developing Building and Heat Island Cases

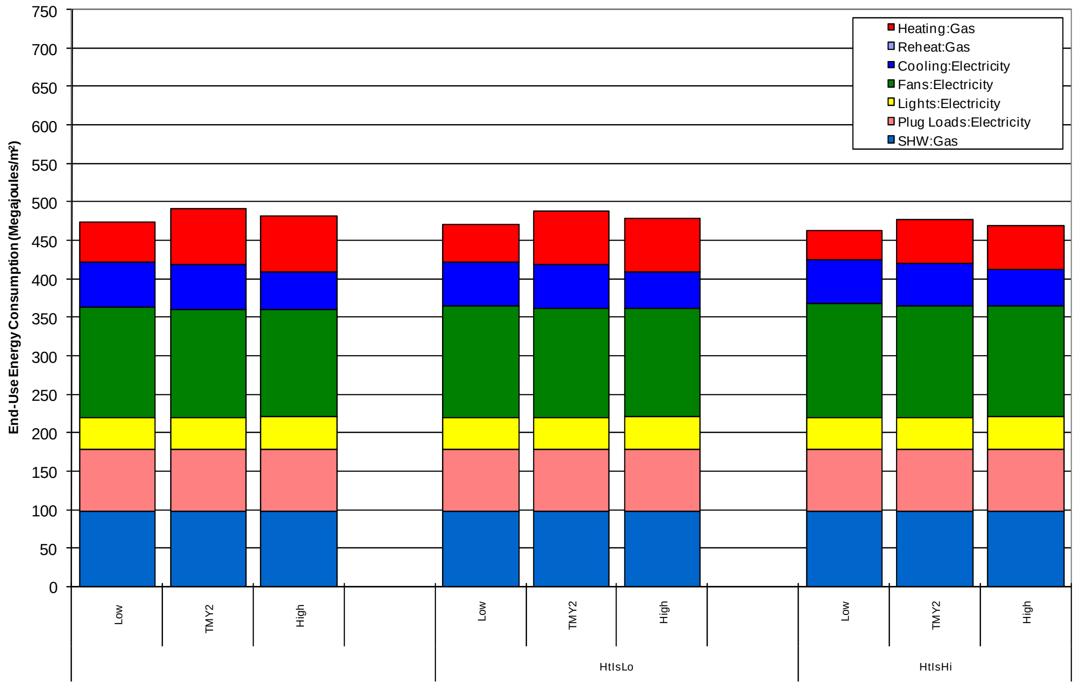

Figure D.2-7. Annual Source Energy End-Use Consumption in Washington, D.C., USA, for Low-Energy Building and Heat Island Cases

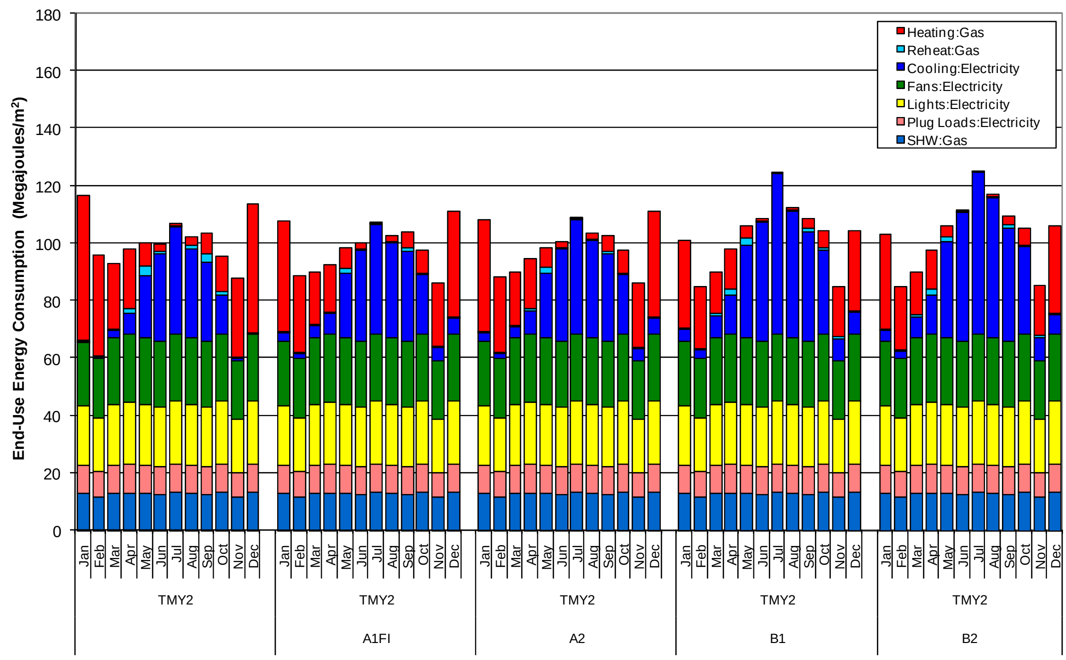

Figure D.2-8. Monthly Source Energy End-Use Consumption in Washington, D.C., USA, for Standard Building and Climate Change Scenarios

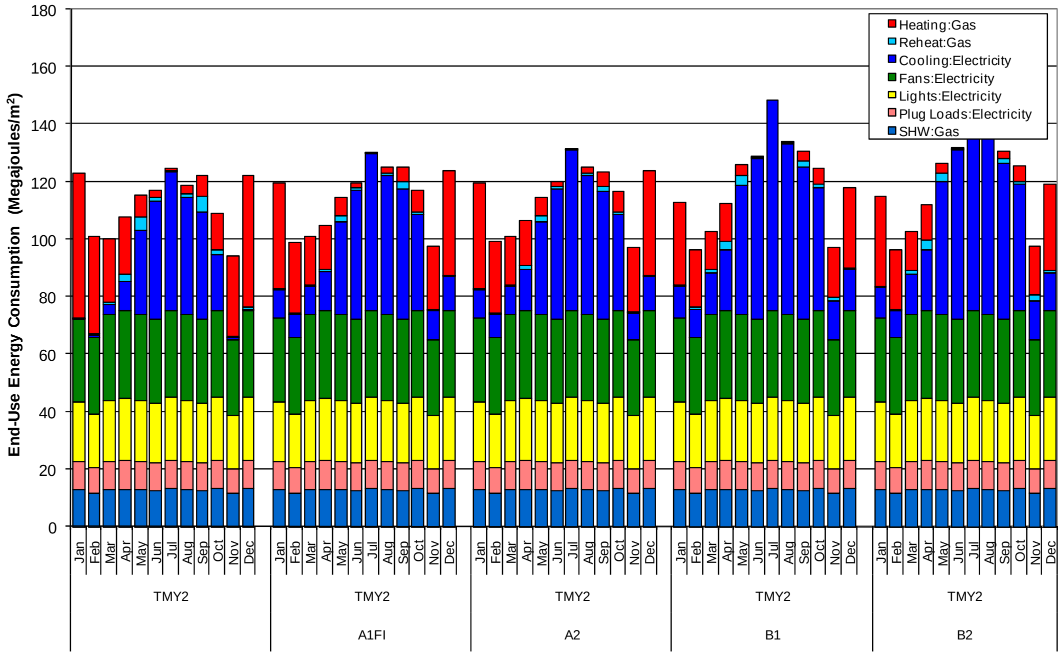

Figure D.2-9. Monthly Source Energy End-Use Consumption in Washington, D.C., USA, for Developing Building and Climate Change Scenarios

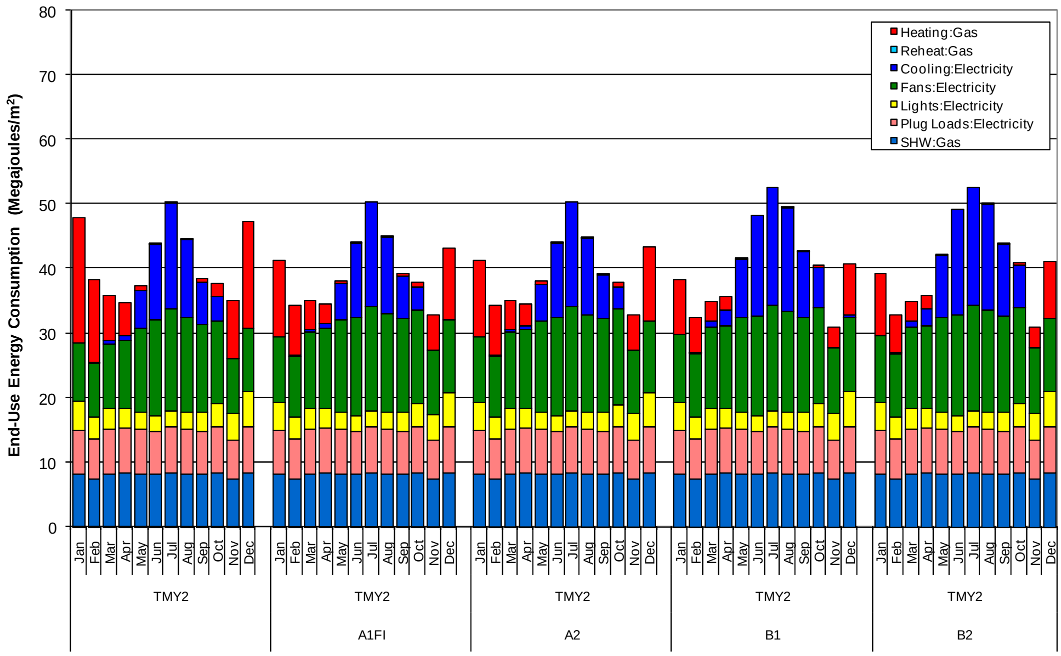

Figure D.2-10. Monthly Source Energy End-Use Consumption in Washington, D.C., USA, for Low-Energy Building and Climate Change Scenarios

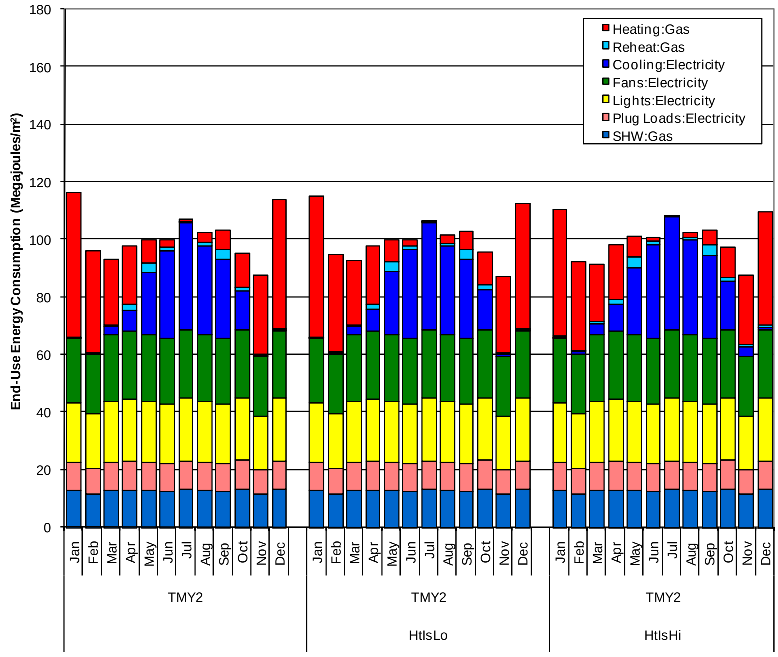

Figure D.2-11. Monthly Source Energy End-Use Consumption in Washington, D.C., USA, for Standard Building and Heat Island Cases

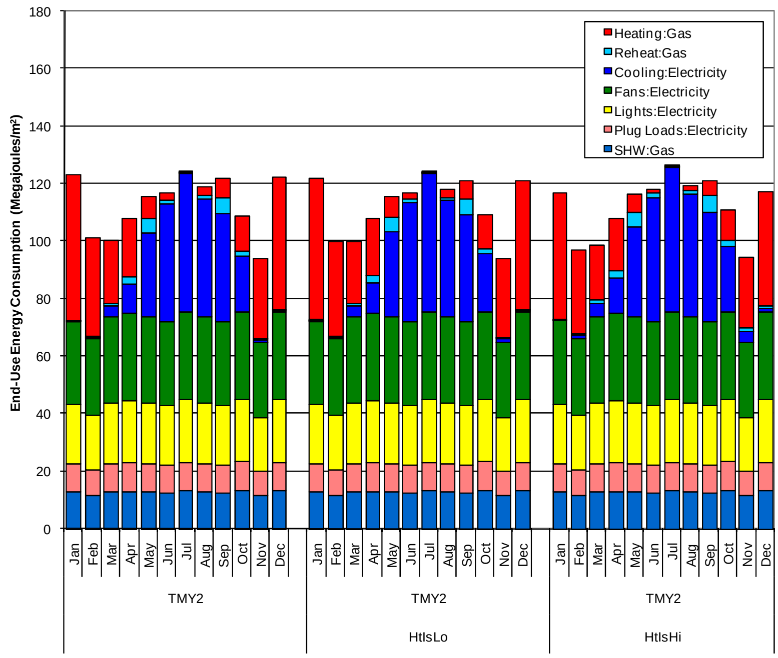

Figure D.2-12. Monthly Source Energy End-Use Consumption in Washington, D.C., USA, for Developing Building and Heat Island Cases

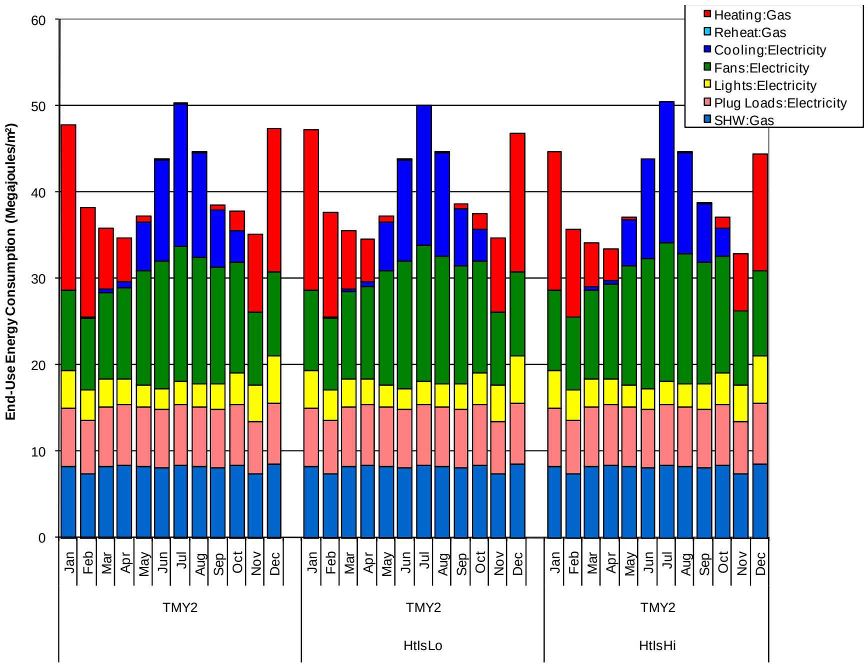

Figure D.2-13. Monthly Source Energy End-Use Consumption in Washington, D.C., USA, for Low-Energy Building and Heat Island Cases

D.3 Resolute, Nunavut, Canada (Climate ET)

Table D.3-1. Annual Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Typical Year Weather Data

Scenario	Standard	Annual Energy End-Use, MJ/m^2							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	Standard	668.5		3.9	371.3	249.3	115.8	152.6	1561.4
	Developing	918.9	0.0	5.4	351.4	249.3	115.8	152.6	1793.5
	Low-Energy	371.6			120.6	74.2	81.1	97.8	745.2
A1FI	Standard	450.6	0.1	18.3	371.3	249.3	115.8	152.6	1357.9
	Developing	627.7	0.1	23.9	351.4	249.3	115.8	152.6	1520.9
	Low-Energy	254.6		0.1	124.4	73.5	81.1	97.8	631.5
A2	Standard	470.2	0.0	18.3	371.3	249.3	115.8	152.6	1377.5
	Developing	655.7	0.1	23.6	351.4	249.3	115.8	152.6	1548.5
	Low-Energy	266.3		0.2	124.4	73.5	81.1	97.8	643.2
B1	Standard	523.4		18.1	371.3	249.3	115.8	152.6	1430.5
	Developing	727.5	0.1	23.2	351.4	249.3	115.8	152.6	1619.9
	Low-Energy	295.1		0.2	123.7	73.5	81.1	97.8	671.2
B2	Standard	506.9		18.5	371.3	249.3	115.8	152.6	1414.3
	Developing	705.8	0.0	23.6	351.4	249.3	115.8	152.6	1598.6
	Low-Energy	286.6		0.2	123.9	73.5	81.1	97.8	663.0
HtIsLo	Standard	652.2		4.1	371.3	249.3	115.8	152.6	1545.2
	Developing	898.0	0.0	5.7	351.4	249.3	115.8	152.6	1772.9
	Low-Energy	362.9			121.1	74.2	81.1	97.8	737.0
HtIsHi	Standard	638.6		4.2	371.3	249.3	115.8	152.6	1531.8
	Developing	880.3	0.0	5.9	351.4	249.3	115.8	152.6	1755.3
	Low-Energy	355.4			121.4	74.2	81.1	97.8	729.9

Table D.3-2. Annual Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Low Year Weather Data

Scenario	Standard	Annual Energy End-Use, MJ/m^2							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	Standard	615.1		6.1	371.3	249.3	115.8	152.6	1510.1
	Developing	848.6	0.0	8.9	351.4	249.3	115.8	152.6	1726.6
	Low-Energy	347.3		0.0	123.3	74.0	81.1	97.8	723.5
A1FI	Standard	412.9	0.1	20.3	371.3	249.3	115.8	152.6	1322.3
	Developing	571.6	0.3	27.0	351.4	249.3	115.8	152.6	1467.9
	Low-Energy	231.2		0.1	126.4	73.5	81.1	97.8	610.1
A2	Standard	432.3	0.1	20.3	371.3	249.3	115.8	152.6	1341.6
	Developing	599.6	0.2	25.6	351.4	249.3	115.8	152.6	1494.5
	Low-Energy	243.4		0.1	126.2	73.6	81.1	97.8	622.0
B1	Standard	481.2	0.0	20.0	371.3	249.3	115.8	152.6	1390.1
	Developing	667.0	0.1	25.0	351.4	249.3	115.8	152.6	1561.2
	Low-Energy	271.3		0.0	125.6	73.5	81.1	97.8	649.3
B2	Standard	466.2	0.0	20.3	371.3	249.3	115.8	152.6	1375.5
	Developing	646.5	0.1	25.4	351.4	249.3	115.8	152.6	1541.1
	Low-Energy	263.2		0.1	125.8	73.5	81.1	97.8	641.4
HtIsLo	Standard	600.1		6.2	371.3	249.3	115.8	152.6	1495.2
	Developing	829.0	0.0	9.1	351.4	249.3	115.8	152.6	1707.2
	Low-Energy	339.0		0.0	123.8	74.1	81.1	97.8	715.7
HtIsHi	Standard	587.3		6.3	371.3	249.3	115.8	152.6	1482.6
	Developing	812.1	0.0	9.3	351.4	249.3	115.8	152.6	1690.5
	Low-Energy	331.8		0.0	124.1	74.1	81.1	97.8	708.8

Table D.3-3. Annual Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for High Year Weather Data

Scenario	Standard	Annual Energy End-Use, MJ/m^2							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	Standard	743.2		5.0	371.3	249.3	115.8	152.6	1637.2
	Developing	1010.1		5.0	351.4	249.3	115.8	152.6	1884.2
	Low-Energy	405.2		0.0	119.3	73.9	81.1	97.8	777.3
A1FI	Standard	515.6	0.0	16.7	371.3	249.3	115.8	152.6	1421.2
	Developing	712.4	0.1	20.8	351.4	249.3	115.8	152.6	1602.3
	Low-Energy	286.5		0.3	122.4	73.3	81.1	97.8	661.3
A2	Standard	537.2	0.0	16.6	371.3	249.3	115.8	152.6	1442.7
	Developing	741.9	0.0	20.3	351.4	249.3	115.8	152.6	1631.3
	Low-Energy	298.6		0.2	122.3	73.3	81.1	97.8	673.2
B1	Standard	592.3		18.1	371.3	249.3	115.8	152.6	1499.4
	Developing	815.5	0.0	21.1	351.4	249.3	115.8	152.6	1705.7
	Low-Energy	327.4		0.2	121.8	73.3	81.1	97.8	701.4
B2	Standard	575.3		17.9	371.3	249.3	115.8	152.6	1482.2
	Developing	793.1	0.0	21.1	351.4	249.3	115.8	152.6	1683.3
	Low-Energy	318.7		0.3	121.9	73.3	81.1	97.8	693.0
HtIsLo	Standard	725.7		5.3	371.3	249.3	115.8	152.6	1619.9
	Developing	988.1		5.5	351.4	249.3	115.8	152.6	1862.6
	Low-Energy	396.2		0.0	119.7	73.9	81.1	97.8	768.6
HtIsHi	Standard	711.1		5.5	371.3	249.3	115.8	152.6	1605.6
	Developing	969.7		5.6	351.4	249.3	115.8	152.6	1844.4
	Low-Energy	388.5		0.0	119.9	73.9	81.1	97.8	761.1

Table D.3-4. Monthly Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Standard Building, Climate Change Scenarios, and Heat Island Cases

Scenario	Month	Monthly Energy End-Use, MJ/m^2							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	January	114.238			30.727	20.856	9.688	12.767	188.3
	February	97.866			28.167	18.918	8.788	11.605	165.3
	March	74.741		0.523	31.687	20.996	9.753	12.912	150.6
	April	41.441		1.615	32.008	21.564	10.017	13.033	119.7
	May	15.774		0.455	31.687	20.996	9.753	12.922	91.6
	June	8.396		0.999	30.727	20.752	9.640	12.636	83.1
	July	13.345		0.062	32.008	21.668	10.066	13.170	90.3
	August	17.386		0.198	31.687	20.996	9.753	12.916	92.9
	September	27.118			30.727	20.752	9.640	12.641	100.9
	October	58.834		0.067	32.008	21.668	10.066	13.179	135.8
	November	83.582			27.847	18.456	8.573	11.603	150.1
	December	115.802			32.008	21.668	10.066	13.166	192.7
A1FI	January	82.096			30.727	20.856	9.688	12.778	156.1
	February	70.942		0.390	28.167	18.918	8.788	11.605	138.8
	March	48.066		3.411	31.687	20.996	9.753	12.912	126.8
	April	26.881		4.214	32.008	21.564	10.017	13.033	107.7
	May	11.114		2.908	31.687	20.996	9.753	12.922	89.4
	June	7.628		3.102	30.727	20.752	9.640	12.636	84.5
	July	12.357		1.490	32.008	21.668	10.066	13.170	90.8
	August	15.281	0.093	1.948	31.687	20.996	9.753	12.916	92.7
	September	23.018		0.399	30.727	20.752	9.640	12.641	97.2
	October	44.185		0.391	32.008	21.668	10.066	13.179	121.5
	November	46.759			27.847	18.456	8.573	11.603	113.2
	December	62.259			32.008	21.668	10.066	13.166	139.2
A2	January	86.279			30.727	20.856	9.688	12.778	160.3
	February	72.895		0.470	28.167	18.918	8.788	11.605	140.8
	March	48.356		3.306	31.687	20.996	9.753	12.912	127.0

Scenario	Month	Monthly Energy End-Use, MJ/m²							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	April	28.236		4.092	32.008	21.564	10.017	13.033	108.9
	May	11.232		2.945	31.687	20.996	9.753	12.922	89.5
	June	7.331		3.298	30.727	20.752	9.640	12.636	84.4
	July	12.325		1.593	32.008	21.668	10.066	13.170	90.8
	August	15.323	0.036	1.785	31.687	20.996	9.753	12.916	92.5
	September	23.416		0.394	30.727	20.752	9.640	12.641	97.6
	October	45.719		0.379	32.008	21.668	10.066	13.179	123.0
	November	47.725			27.847	18.456	8.573	11.603	114.2
	December	71.390			32.008	21.668	10.066	13.166	148.3
B1	January	91.436			30.727	20.856	9.688	12.767	165.5
	February	82.028		0.361	28.167	18.918	8.788	11.605	149.9
	March	54.311		3.494	31.687	20.996	9.753	12.912	133.2
	April	31.066		4.198	32.008	21.564	10.017	13.033	111.9
	May	11.946		2.737	31.687	20.996	9.753	12.922	90.0
	June	7.649		3.172	30.727	20.752	9.640	12.636	84.6
	July	12.349		1.732	32.008	21.668	10.066	13.170	91.0
	August	15.456		1.653	31.687	20.996	9.753	12.916	92.5
	September	24.051		0.363	30.727	20.752	9.640	12.641	98.2
	October	47.268		0.401	32.008	21.668	10.066	13.179	124.6
	November	54.838			27.847	18.456	8.573	11.603	121.3
	December	91.040			32.008	21.668	10.066	13.166	167.9
B2	January	93.954			30.727	20.856	9.688	12.767	168.0
	February	77.191		0.419	28.167	18.918	8.788	11.605	145.1
	March	52.211		3.642	31.687	20.996	9.753	12.912	131.2
	April	30.174		4.202	32.008	21.564	10.017	13.033	111.0
	May	11.424		2.856	31.687	20.996	9.753	12.922	89.6
	June	7.538		3.186	30.727	20.752	9.640	12.636	84.5
	July	12.353		1.735	32.008	21.668	10.066	13.170	91.0
	August	15.435		1.637	31.687	20.996	9.753	12.916	92.4
	September	23.957		0.373	30.727	20.752	9.640	12.641	98.1
	October	47.170		0.401	32.008	21.668	10.066	13.179	124.5
	November	52.373			27.847	18.456	8.573	11.603	118.9
	December	83.102			32.008	21.668	10.066	13.166	160.0
Heat Island Low	January	111.162			30.727	20.856	9.688	12.767	185.2
	February	95.541			28.167	18.918	8.788	11.605	163.0
	March	73.267		0.535	31.687	20.996	9.753	12.912	149.2
	April	40.851		1.670	32.008	21.564	10.017	13.033	119.1
	May	15.003		0.546	31.687	20.996	9.753	12.922	90.9
	June	8.066		1.017	30.727	20.752	9.640	12.636	82.8
	July	13.249		0.054	32.008	21.668	10.066	13.170	90.2
	August	17.207		0.194	31.687	20.996	9.753	12.916	92.8
	September	26.548			30.727	20.752	9.640	12.641	100.3
	October	57.425		0.068	32.008	21.668	10.066	13.179	134.4
	November	81.157			27.847	18.456	8.573	11.603	147.6
	December	112.679			32.008	21.668	10.066	13.166	189.6
Heat Island High	January	109.645			30.727	20.856	9.688	12.767	183.7
	February	93.735			28.167	18.918	8.788	11.605	161.2
	March	70.439		0.559	31.687	20.996	9.753	12.912	146.3
	April	39.740		1.726	32.008	21.564	10.017	13.033	118.1
	May	14.586		0.583	31.687	20.996	9.753	12.922	90.5
	June	7.952		1.008	30.727	20.752	9.640	12.636	82.7
	July	13.240		0.053	32.008	21.668	10.066	13.170	90.2
	August	17.131		0.204	31.687	20.996	9.753	12.916	92.7
	September	25.489			30.727	20.752	9.640	12.641	99.2
	October	55.671		0.077	32.008	21.668	10.066	13.179	132.7
	November	79.896			27.847	18.456	8.573	11.603	146.4
	December	111.101			32.008	21.668	10.066	13.166	188.0

Table D.3-5. Monthly Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Developing Building, Climate Change Scenarios, and Heat Island Cases

Scenario	Month	Monthly Energy End-Use, MJ/m²							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	January	154.103			29.085	20.856	9.688	12.767	226.5
	February	133.556			26.661	18.918	8.788	11.605	199.5
	March	104.605		0.187	29.994	20.996	9.753	12.912	178.4
	April	60.156		0.956	30.297	21.564	10.017	13.033	136.0
	May	20.140		0.871	29.994	20.996	9.753	12.922	94.7
	June	10.082		1.959	29.085	20.752	9.640	12.636	84.2
	July	16.780		0.647	30.297	21.668	10.066	13.170	92.6
	August	21.004	0.003	0.770	29.994	20.996	9.753	12.916	95.4
	September	40.564			29.085	20.752	9.640	12.641	112.7
	October	84.584		0.039	30.297	21.668	10.066	13.179	159.8
	November	116.405			26.358	18.456	8.573	11.603	181.4
	December	156.950			30.297	21.668	10.066	13.166	232.1
A1FI	January	114.286			29.085	20.856	9.688	12.778	186.7
	February	100.094		0.282	26.661	18.918	8.788	11.605	166.3
	March	69.290		3.047	29.994	20.996	9.753	12.912	146.0
	April	38.896		4.404	30.297	21.564	10.017	13.033	118.2
	May	14.889		3.615	29.994	20.996	9.753	12.922	92.2
	June	9.024		3.942	29.085	20.752	9.640	12.636	85.1
	July	13.249		3.625	30.297	21.668	10.066	13.170	92.1
	August	17.318	0.144	3.886	29.994	20.996	9.753	12.916	95.0
	September	31.334		0.712	29.085	20.752	9.640	12.641	104.2
	October	64.001	0.004	0.408	30.297	21.668	10.066	13.179	139.6
	November	67.435			26.358	18.456	8.573	11.603	132.4
	December	87.900			30.297	21.668	10.066	13.166	163.1
A2	January	119.725			29.085	20.856	9.688	12.778	192.1
	February	102.541		0.358	26.661	18.918	8.788	11.605	168.9
	March	69.551		2.842	29.994	20.996	9.753	12.912	146.0
	April	40.914		4.165	30.297	21.564	10.017	13.033	120.0
	May	15.104		3.667	29.994	20.996	9.753	12.922	92.4
	June	8.736		4.131	29.085	20.752	9.640	12.636	85.0
	July	13.629		3.676	30.297	21.668	10.066	13.170	92.5
	August	17.654	0.081	3.636	29.994	20.996	9.753	12.916	95.0
	September	32.357		0.699	29.085	20.752	9.640	12.641	105.2
	October	66.336		0.402	30.297	21.668	10.066	13.179	141.9
	November	68.774			26.358	18.456	8.573	11.603	133.8
	December	100.381			30.297	21.668	10.066	13.166	175.6
B1	January	126.230			29.085	20.856	9.688	12.778	198.6
	February	114.016		0.241	26.661	18.918	8.788	11.605	180.2
	March	77.605		2.968	29.994	20.996	9.753	12.912	154.2
	April	44.946		4.073	30.297	21.564	10.017	13.033	123.9
	May	15.999		3.469	29.994	20.996	9.753	12.922	93.1
	June	9.140		3.987	29.085	20.752	9.640	12.636	85.2
	July	14.098		3.928	30.297	21.668	10.066	13.170	93.2
	August	17.877	0.053	3.484	29.994	20.996	9.753	12.916	95.1
	September	33.818		0.677	29.085	20.752	9.640	12.641	106.6
	October	68.673		0.416	30.297	21.668	10.066	13.179	144.3
	November	78.451			26.358	18.456	8.573	11.603	143.4
	December	126.617			30.297	21.668	10.066	13.166	201.8
B2	January	129.402			29.085	20.856	9.688	12.778	201.8
	February	107.986		0.294	26.661	18.918	8.788	11.605	174.3
	March	74.928		3.134	29.994	20.996	9.753	12.912	151.7
	April	43.547		4.136	30.297	21.564	10.017	13.033	122.6
	May	15.336		3.589	29.994	20.996	9.753	12.922	92.6
	June	8.943		4.012	29.085	20.752	9.640	12.636	85.1
	July	14.093		3.929	30.297	21.668	10.066	13.170	93.2
	August	17.988	0.046	3.454	29.994	20.996	9.753	12.916	95.1
	September	33.652		0.680	29.085	20.752	9.640	12.641	106.4
	October	68.537		0.416	30.297	21.668	10.066	13.179	144.2
	November	75.128			26.358	18.456	8.573	11.603	140.1
	December	116.255			30.297	21.668	10.066	13.166	191.5

Scenario	Month	Monthly Energy End-Use, MJ/m^2							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
Heat Island Low	January	150.471			29.085	20.856	9.688	12.767	222.9
	February	130.778			26.661	18.918	8.788	11.605	196.8
	March	102.862		0.193	29.994	20.996	9.753	12.912	176.7
	April	59.516		0.984	30.297	21.564	10.017	13.033	135.4
	May	19.376		1.020	29.994	20.996	9.753	12.922	94.1
	June	9.566		2.055	29.085	20.752	9.640	12.636	83.7
	July	15.879		0.659	30.297	21.668	10.066	13.170	91.7
	August	20.559	0.004	0.798	29.994	20.996	9.753	12.916	95.0
	September	39.757			29.085	20.752	9.640	12.641	111.9
	October	82.684		0.040	30.297	21.668	10.066	13.179	157.9
	November	113.348			26.358	18.456	8.573	11.603	178.3
	December	153.221			30.297	21.668	10.066	13.166	228.4
Heat Island High	January	148.659			29.085	20.856	9.688	12.767	221.1
	February	128.637			26.661	18.918	8.788	11.605	194.6
	March	99.416		0.204	29.994	20.996	9.753	12.912	173.3
	April	58.262		1.017	30.297	21.564	10.017	13.033	134.2
	May	18.917		1.083	29.994	20.996	9.753	12.922	93.7
	June	9.254		2.095	29.085	20.752	9.640	12.636	83.5
	July	15.436		0.663	30.297	21.668	10.066	13.170	91.3
	August	20.162	0.004	0.837	29.994	20.996	9.753	12.916	94.7
	September	38.194			29.085	20.752	9.640	12.641	110.3
	October	80.282		0.049	30.297	21.668	10.066	13.179	155.5
	November	111.743			26.358	18.456	8.573	11.603	176.7
	December	151.339			30.297	21.668	10.066	13.166	226.5

Table D.3-6. Monthly Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Low-Energy Building, Climate Change Scenarios, and Heat Island Cases

Scenario	Month	Monthly Energy End-Use, MJ/m^2							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	January	60.772			9.642	12.595	6.782	8.188	98.0
	February	52.685			8.838	9.637	6.152	7.435	84.7
	March	42.449			9.956	4.447	6.827	8.276	72.0
	April	28.170			10.139	2.187	7.012	8.357	55.9
	May	8.091			10.229	1.450	6.827	8.271	34.9
	June	2.038			11.291	1.354	6.748	8.105	29.5
	July	5.385			11.334	2.082	7.046	8.439	34.3
	August	7.523			10.571	2.541	6.827	8.267	35.7
	September	19.274			9.755	4.246	6.748	8.109	48.1
	October	36.237			10.053	9.427	7.046	8.440	71.2
	November	46.796			8.738	11.131	6.001	7.416	80.1
	December	62.198			10.044	13.085	7.046	8.452	100.8
A1FI	January	47.091			9.642	12.595	6.782	8.188	84.3
	February	40.754		0.007	8.874	9.427	6.152	7.435	72.6
	March	28.392		0.108	10.410	4.027	6.827	8.276	58.0
	April	17.133		0.019	10.603	2.210	7.012	8.357	45.3
	May	4.284			10.733	1.568	6.827	8.271	31.7
	June	1.739		0.003	11.756	1.585	6.748	8.105	29.9
	July	3.585			12.379	2.141	7.046	8.439	33.6
	August	3.991			11.262	2.524	6.827	8.267	32.9
	September	14.490			9.802	4.138	6.748	8.109	43.3
	October	27.434			10.174	9.114	7.046	8.440	62.2
	November	28.385			8.738	11.131	6.001	7.416	61.7
	December	37.344			10.044	13.085	7.046	8.452	76.0
A2	January	49.070			9.642	12.595	6.782	8.188	86.3
	February	41.595		0.007	8.890	9.420	6.152	7.435	73.5
	March	28.490		0.113	10.401	4.033	6.827	8.276	58.1
	April	18.236		0.016	10.573	2.213	7.012	8.357	46.4
	May	4.488			10.737	1.568	6.827	8.271	31.9
	June	1.605			11.937	1.592	6.748	8.105	30.0
	July	3.859			12.295	2.138	7.046	8.439	33.8
	August	4.344			11.197	2.526	6.827	8.267	33.2

Scenario	Month	Monthly Energy End-Use, MJ/m²							
		Heating	Reheat	Cooling	Fans	Lights	Plug Loads	SHW	Total Energy
	September	15.038			9.799	4.132	6.748	8.109	43.8
	October	28.420		0.026	10.166	9.112	7.046	8.440	63.2
	November	28.945			8.738	11.131	6.001	7.416	62.2
	December	42.175			10.044	13.085	7.046	8.452	80.8
B1	January	51.371			9.642	12.595	6.782	8.188	88.6
	February	45.604		0.008	8.868	9.404	6.152	7.435	77.5
	March	31.815		0.078	10.306	4.027	6.827	8.276	61.3
	April	20.486		0.013	10.512	2.213	7.012	8.357	48.6
	May	5.107			10.611	1.568	6.827	8.271	32.4
	June	1.816			11.740	1.592	6.748	8.105	30.0
	July	4.209			12.167	2.130	7.046	8.439	34.0
	August	4.886			11.091	2.521	6.827	8.267	33.6
	September	15.786			9.795	4.126	6.748	8.109	44.6
	October	29.414		0.060	10.158	9.111	7.046	8.440	64.2
	November	32.865			8.738	11.131	6.001	7.416	66.2
	December	51.728			10.044	13.085	7.046	8.452	90.4
B2	January	52.489			9.642	12.595	6.782	8.188	89.7
	February	43.502		0.008	8.877	9.404	6.152	7.435	75.4
	March	30.742		0.102	10.336	4.027	6.827	8.276	60.3
	April	19.741		0.019	10.530	2.213	7.012	8.357	47.9
	May	4.658			10.703	1.568	6.827	8.271	32.0
	June	1.708			11.824	1.592	6.748	8.105	30.0
	July	4.207			12.169	2.130	7.046	8.439	34.0
	August	4.976			11.064	2.521	6.827	8.267	33.7
	September	15.702			9.795	4.129	6.748	8.109	44.5
	October	29.357		0.057	10.158	9.111	7.046	8.440	64.2
	November	31.539			8.738	11.131	6.001	7.416	64.8
	December	48.018			10.044	13.085	7.046	8.452	86.6
Heat Island Low	January	59.613			9.642	12.595	6.782	8.188	96.8
	February	51.746			8.838	9.660	6.152	7.435	83.8
	March	41.772			9.957	4.456	6.827	8.276	71.3
	April	27.878			10.140	2.191	7.012	8.357	55.6
	May	7.302			10.273	1.450	6.827	8.271	34.1
	June	1.674			11.539	1.354	6.748	8.105	29.4
	July	4.769			11.495	2.083	7.046	8.439	33.8
	August	7.102			10.627	2.542	6.827	8.267	35.4
	September	18.853			9.756	4.250	6.748	8.109	47.7
	October	35.450			10.054	9.439	7.046	8.440	70.4
	November	45.748			8.738	11.133	6.001	7.416	79.0
	December	60.966			10.044	13.085	7.046	8.452	99.6
Heat Island High	January	59.019			9.642	12.595	6.782	8.188	96.2
	February	51.041			8.838	9.660	6.152	7.435	83.1
	March	40.473			9.958	4.456	6.827	8.276	70.0
	April	27.275			10.143	2.191	7.012	8.357	55.0
	May	6.901			10.293	1.450	6.827	8.271	33.7
	June	1.502			11.688	1.354	6.748	8.105	29.4
	July	4.471			11.597	2.083	7.046	8.439	33.6
	August	6.757			10.663	2.542	6.827	8.267	35.1
	September	18.013			9.758	4.250	6.748	8.109	46.9
	October	34.419			10.056	9.439	7.046	8.440	69.4
	November	45.188			8.738	11.133	6.001	7.416	78.5
	December	60.332			10.044	13.085	7.046	8.452	99.0

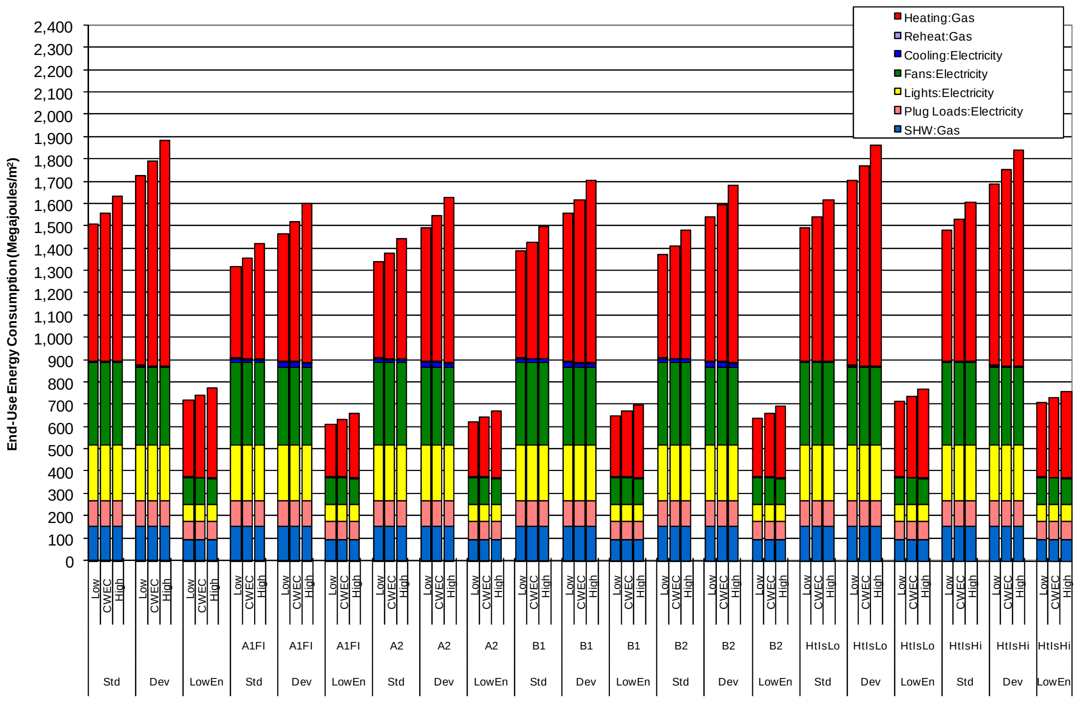

Figure D.3-1. Annual Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Standard, Developing, and Low-Energy Buildings Using Typical Year, Climate Change Scenarios, and Heat Island Cases

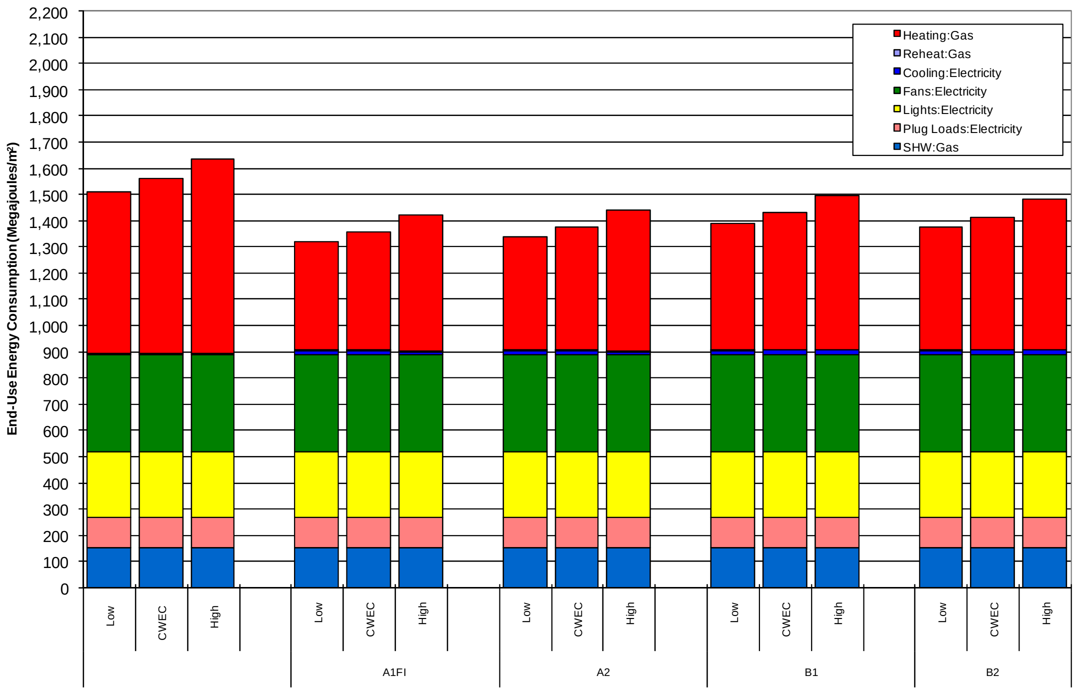

Figure D.3-2. Annual Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Standard Building and Climate Change Scenarios

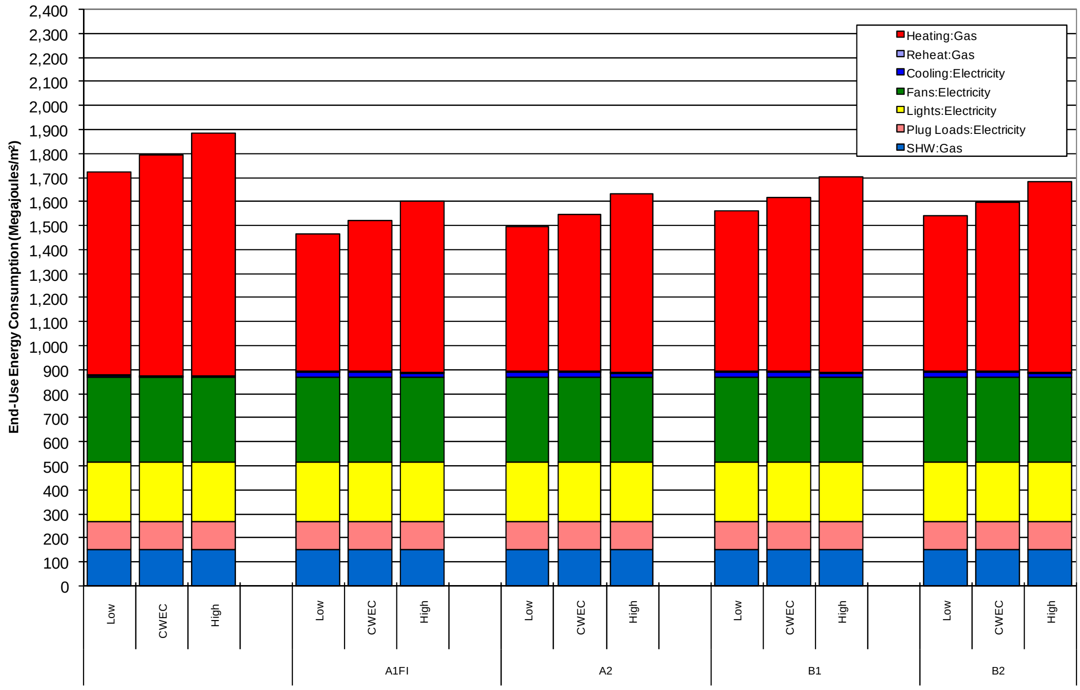

Figure D.3-3. Annual Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Developing Building and Climate Change Scenarios

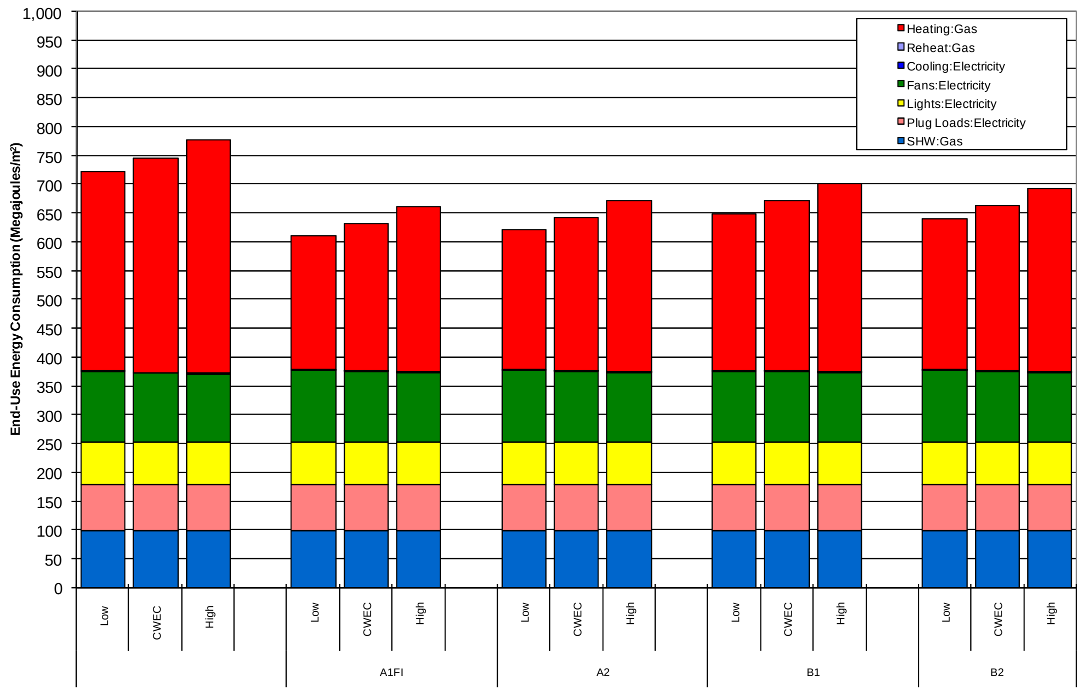

Figure D.3-4. Annual Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Low-Energy Building and Climate Change Scenarios

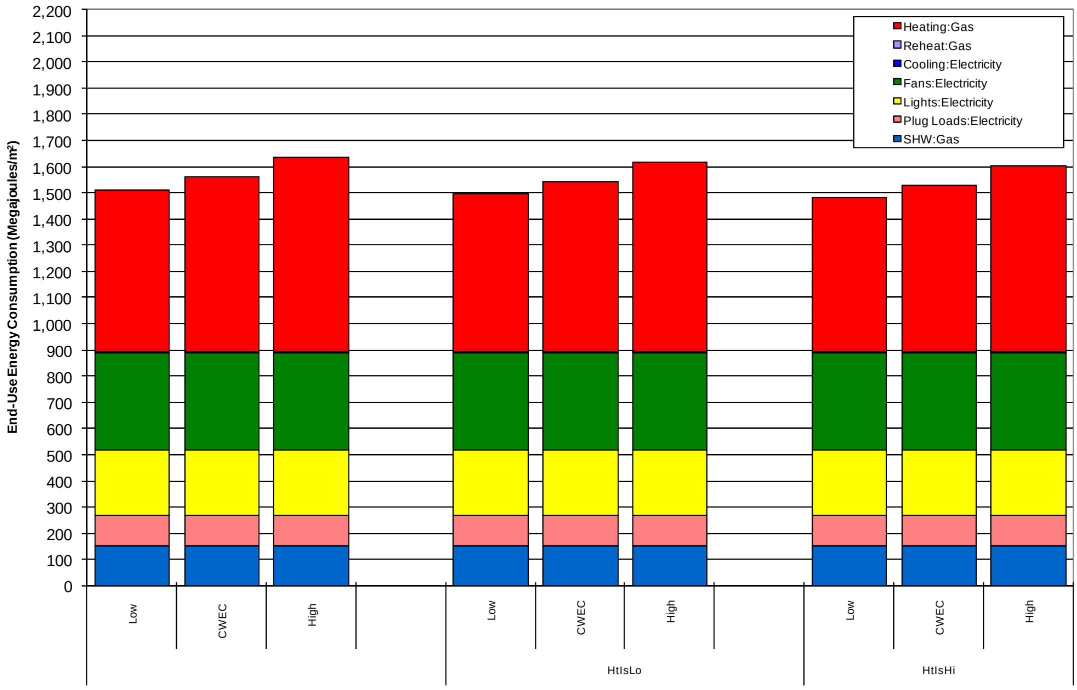

Figure D.3-5. Annual Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Standard Building and Heat Island Cases

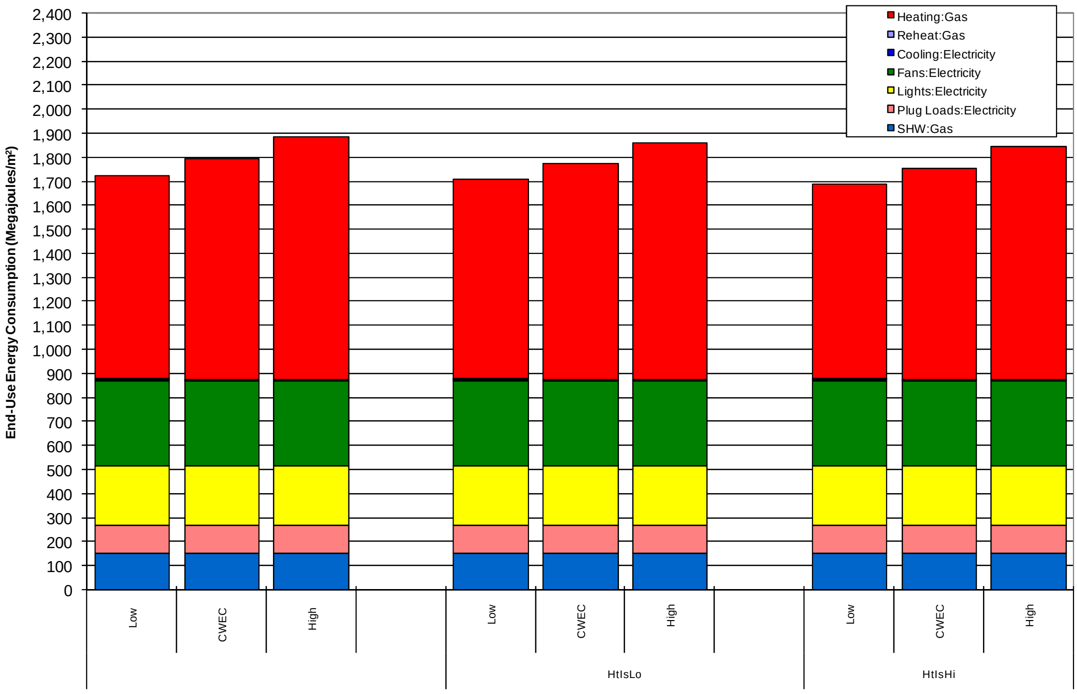

Figure D.3-6. Annual Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Developing Building and Heat Island Cases

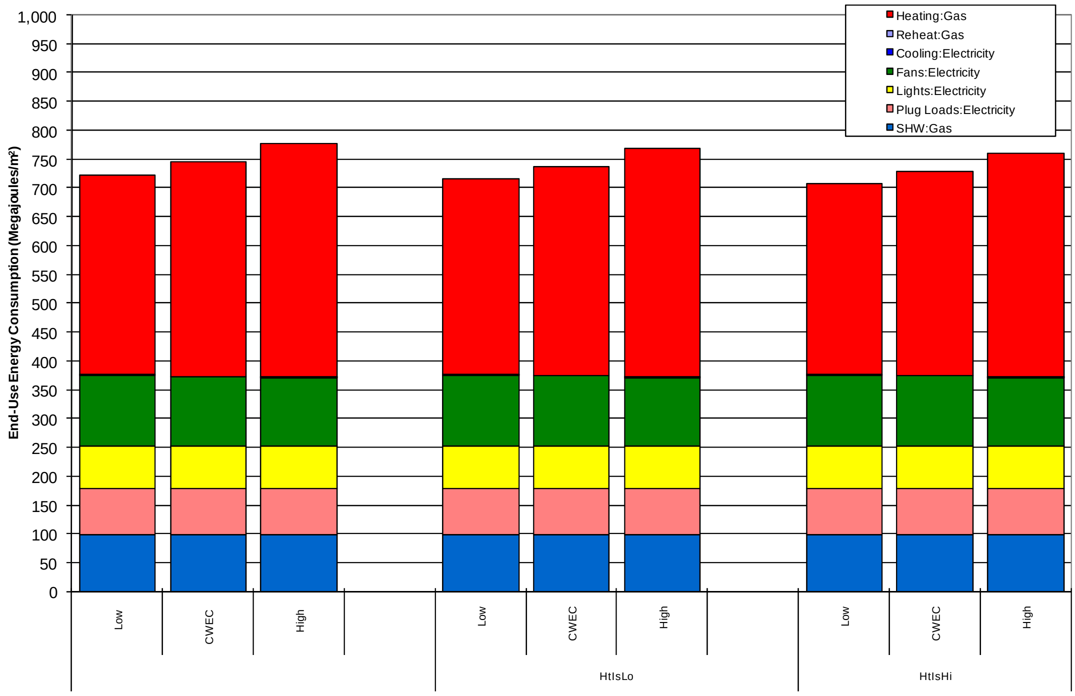

Figure D.3-7. Annual Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Low-Energy Building and Heat Island Cases

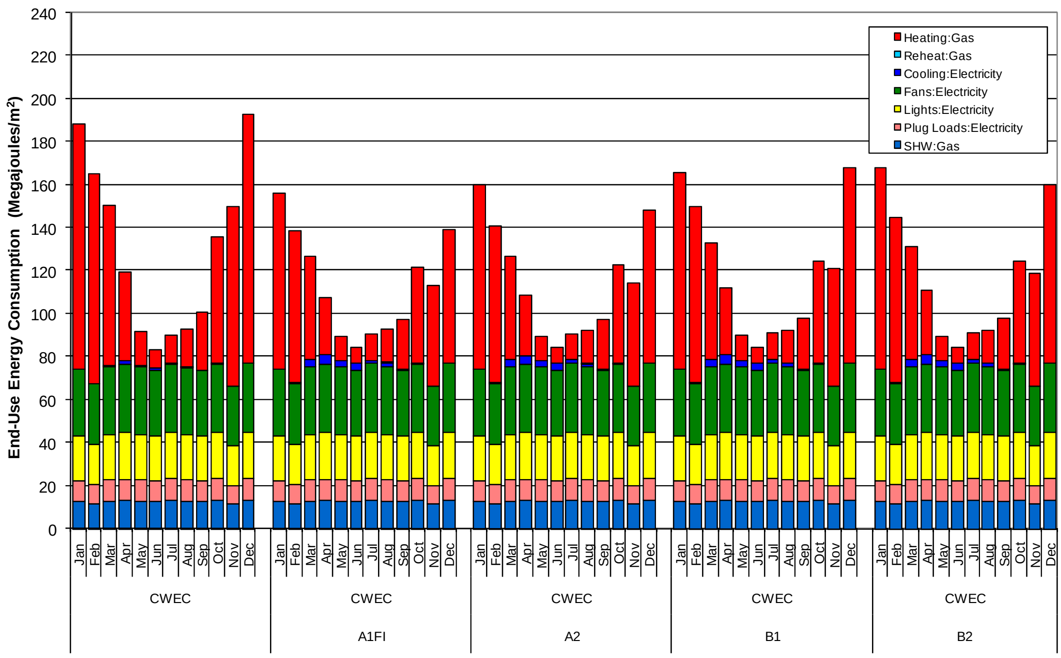

Figure D.3-8. Monthly Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Standard Building and Climate Change Scenarios

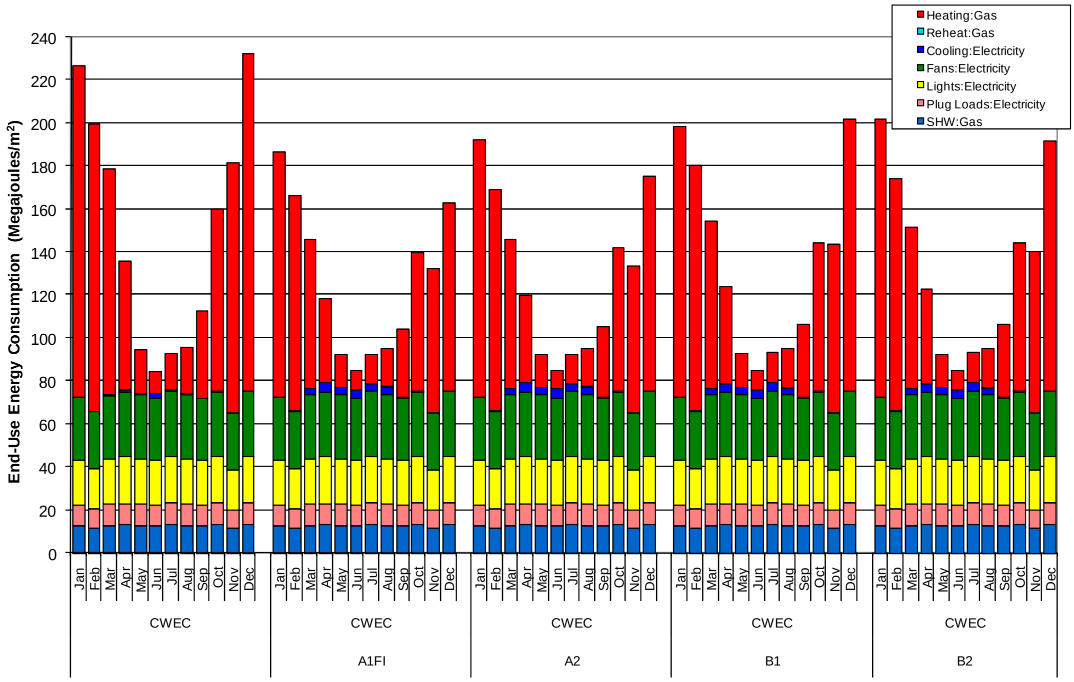

Figure D.3-9. Monthly Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Developing Building and Climate Change Scenarios

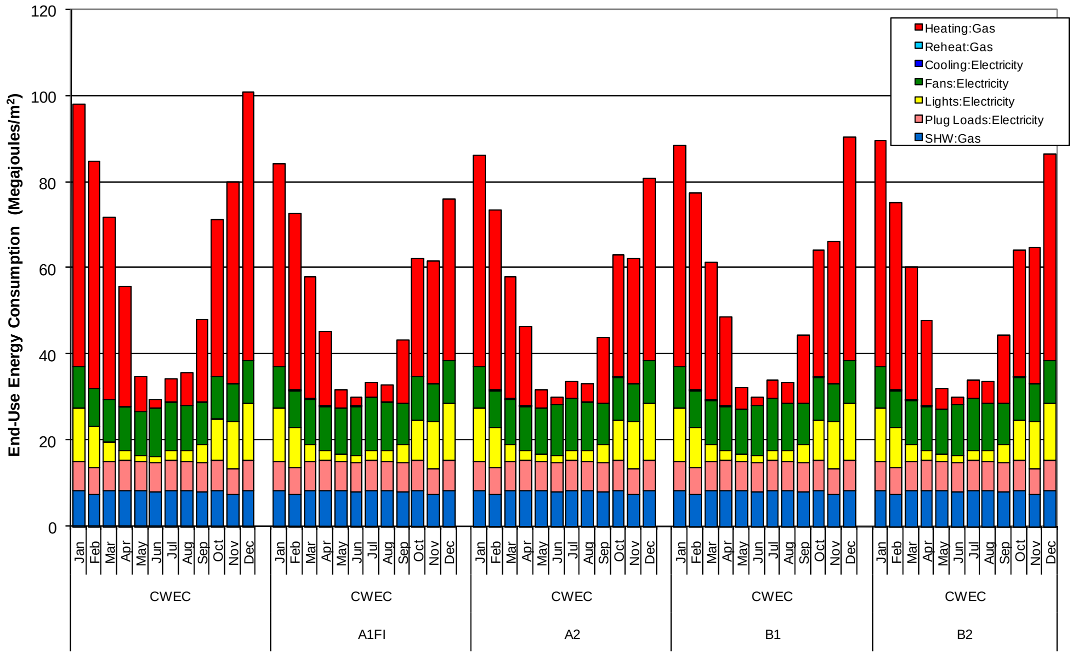

Figure D.3-10. Monthly Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Low-Energy Building and Climate Change Scenarios

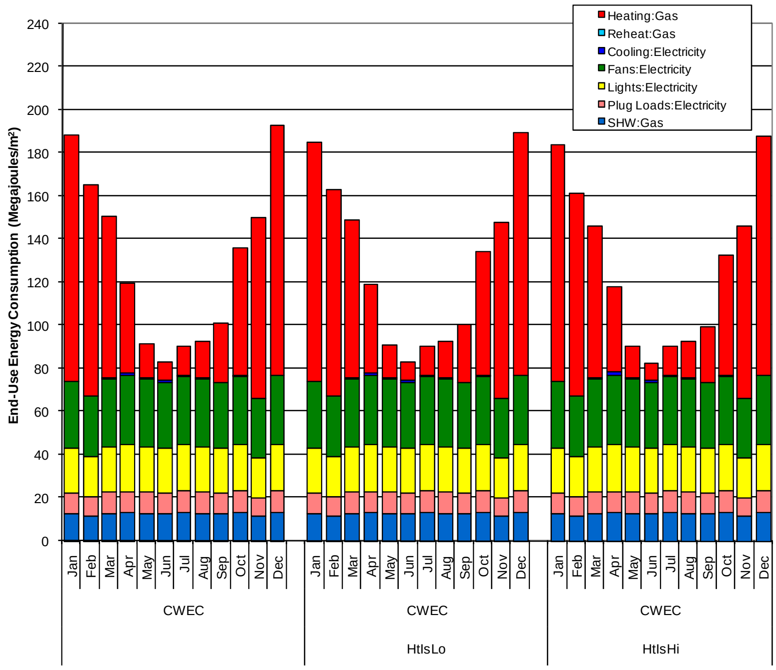

Figure D.3-11. Monthly Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Standard Building and Heat Island Cases

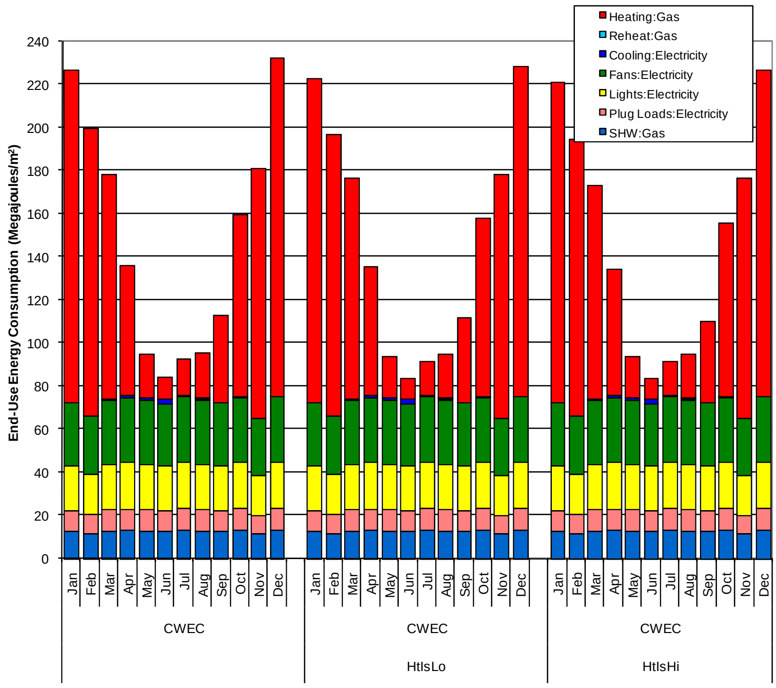

Figure D.3-12. Monthly Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Developing Building and Heat Island Cases

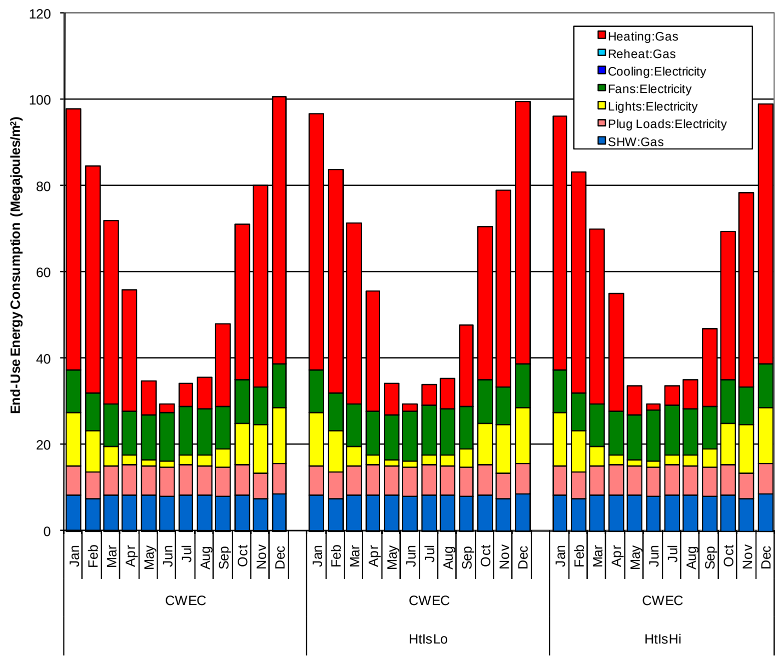

Figure D.3-13. Monthly Source Energy End-Use Consumption in Resolute, Nunavut, Canada, for Low-Energy Building and Heat Island Cases