AN ANALYSIS OF MAXIMUM RESIDENTIAL ENERGY-EFFICIENCY IN HOT AND HUMID CLIMATES

A Thesis

by

MINI MALHOTRA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2005

Major Subject: Architecture

AN ANALYSIS OF MAXIMUM RESIDENTIAL ENERGY-EFFICIENCY

IN HOT AND HUMID CLIMATES

A Thesis

by

MINI MALHOTRA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee,	Jeff S. Haberl
Committee Members,	Anat Geva
	David E. Claridge
Head of Department,	Mardelle M. Shepley

December 2005

Major Subject: Architecture

ABSTRACT

An Analysis of Maximum Residential Energy-Efficiency in Hot and Humid Climates.

(December 2005)

Mini Malhotra, B.Arch., Birla Institute of Technology

Chair of Advisory Committee: Dr. Jeff S. Haberl

Energy-efficient building design involves minimizing the energy use and optimizing the performance of individual systems and components of the building. The benefits of energy-efficient design, in the residential sector, are direct and tangible, provided that design strategies with a substantial combined energy and cost-saving potential are adopted.

Many studies have been performed to evaluate the energy-saving potential and the cost-effectiveness of various design options, and to identify conditions for optimizing the performance of building systems and components. The results of these studies, published in various resources, were analyzed discretely using different techniques, and were reported using different bases for comparison. Considering the complex interaction of, and energy flows through various building components, it is difficult to directly compare/combine the results from various studies to determine the energy-saving potential of combination of strategies, and to select an appropriate set of strategies for making design decisions.

Therefore, this thesis develops a comprehensive survey and analysis of energy-efficient design strategies and their energy-saving potential, in isolation as well as in combination, using a DOE-2 simulation model of a prototype house in the hot and humid climate of Houston, Texas. Optimized strategies that included building configuration, materials/ assembly for building envelop components, and efficient mechanical and electrical systems, equipment and appliances, were applied in combination that could minimize the annual energy use. Application of these

strategies is expected to allow downsizing systems and equipment and to confirm their operation at their rated performance, resulting in additional installation and operation cost savings.

The study is concluded by outlining the procedures for selecting optimized set of strategies, and by developing guidelines for achieving maximum energy-efficiency in single-family detached houses in hot and humid climates. Thus, this study will facilitate the selection of energy-saving measures for their individual or combined application for developing energy-efficient residences in hot and humid climates.

DEDICATION

To my parents

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to the chair of my advisory committee, Dr. Jeff Haberl, for guiding my work with his dedicated attention, expertise and knowledge. I would like to thank Dr. David Claridge and Dr. Anat Geva for being on the committee and giving valuable input to the thesis. I would also like to extend my appreciation to Dr. Warren Heffington for giving his valuable time to review my thesis and attend my defense.

I am grateful to the staff of the Energy Systems Laboratory, especially, Don Gilman and his team, for developing the program that has helped speed up my analysis with the DOE-2; Shirley Muns for her assistance in understanding the building codes and construction practices; Juan Carlos Baltazar for providing me with the valuable information on the solar thermal and PV systems; and Bahman Yazdani for his expert advice on the economic aspects of this study.

I would like to thank my colleagues Jaya, Mushtaq, Chayapa, Seongchan, Piljae and Soolyeon for sharing their views and knowledge, which helped me solve various issues related to this study. Special thanks to Victor and Sakkara whose research were two valuable resources throughout my study.

My special thanks to my Uncle Rajiv for his support and encouragement throughout and for providing an exceptional model for me to follow as a researcher that continues to inspire me.

I appreciate the timely help from Shivani, Suchismita and Rituparna for their willingness to edit and proof-read this thesis, and the constant support, kindness and concern from Anshul, Raghavendra and Purna. Many thanks to Shruti, Vidhya, Bharati, Pavana, Vakula and Anupriya for being supportive friends at various stages of my study. I thank all of them for helping me get through all the good and not-so-good times during my study.

Finally and most importantly, I am deeply grateful to my family for their love, support, patience, and encouragement which helped me overcome obstacles and accomplish my goals.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

Page

LIST OF TABLES (Continued)

Page

1. INTRODUCTION

1.1. Background

Energy-efficient building design involves minimizing the energy use and optimizing the performance of individual components of the building's energy consuming systems. The benefits of energy-efficient design, in the residential sector, are direct and tangible, provided that the strategies with the most combined energy and cost-saving potential are adopted. Many studies have been performed to evaluate the energy-saving potential and cost-effectiveness of various strategies for residential energy-efficiency, which are examined in the literature review. These studies have used many different analytical techniques, and therefore, it requires different criteria for comparing the results between studies. In addition, due to the complex interaction of and energy flows through the various building components, it can be inappropriate to combine results from individual components, directly, to determine the total energy-saving potential of a group of strategies, for making design decisions. Therefore, this thesis investigated the individual and combined energy-saving potential of various strategies to determine an optimum combination that could minimize energy use of a residence in a hot and humid climate.

1.2. Purpose and Objectives

The purpose of this thesis is to achieve maximum energy-efficiency in the single-family residences in hot and humid climates, using available technology that is simulatable with the DOE-2. The objectives of this thesis are to analyze the energy-saving potential of different strategies, applied individually as well as in combination, and to demonstrate a methodology for selecting a set of strategies based on their combined energy-saving potential. To accomplish the objectives of this study, the following tasks were performed:

This thesis follows the style and format of the *ASHRAE Transactions.*

1) Investigate residential energy-saving strategies and their energy-saving potential from the previous research,
2) Use a 2000 International Energy Conservation Code (IECC) compliant DOE-2 simulation model of a single-family detached house for the analysis,
3) Apply all simulatable energy-saving strategies to the simulation model of the house, individually as well as in combination,
4) Determine an optimized set of strategies from the analysis of the simulation results and annualized life-cycle cost analysis, and,
5) Develop guidelines for maximizing energy savings in the single-family detached residences in hot and humid climates.

1.3. Organization of the Thesis

The thesis is divided into eight sections. Section 1 provides the introduction to this study by providing a relevant background, establishing the need, and stating the purpose and objectives of this study.

Section 2 reviews and discusses the previous studies related to this thesis, in order to provide a basis for conducting this research. The literature review covers information on building systems and components that affect energy use, including an optimized set of design strategies for energy-efficient residences, case studies of high performance homes and a review of the simulation software for energy-efficient building design.

Section 3 discusses the significance of the work and its contribution to the energy-efficient building design and research. The scope and limitations of the work are also discussed in this section.

Section 4 describes the methodology used in the study. This includes a survey of the previous studies as discussed in the literature review, the development of the 2000 IECC compliant simulation model of the basecase house, simulation of the basecase house and of the house with energy-efficient measures, and a description of the economic analysis of those measures.

Section 5 describes the characteristics of the basecase house and includes architectural and construction details, drawings, occupancy, and characteristics of lights, equipment, HVAC and DHW systems.

Section 6 discusses the results of the simulations of the basecase house and the house with energy-efficient measures, summarizes the results and provides an analysis. The findings of the analyses are used to evaluate the energy-saving potential of individual measures as well as combination of those measures.

Section 7 discusses the results of the economic analysis of all the energy-efficient measures. This includes estimating the annualized cost of applying those measures that were proven to be effective in reducing building energy use in this study. The analysis is this section is performed for the individual application as well as for the combined application of those measures to the basecase house.

Section 8 provides conclusion and proposes recommendations for future research in this area. The conclusions are presented to form guidelines to achieve maximum energy-efficiency in single-family residences in hot and humid climates.

2. LITERATURE REVIEW

The main sources of literature that were reviewed include: the ASHRAE Handbook, ASHRAE Transactions, the 2004 Building Energy Databook, Energy and Buildings, Home Energy magazine, the Symposium on Improving Building Systems in Hot and Humid Climates; publications by the American Council for an Energy Efficient Economy, the Florida Solar Energy Center, the International Building Performance Simulation Association; and reports from the Lawrence Berkeley National Laboratory, the National Renewable Energy Laboratory, the Oak Ridge National Laboratory, the Rocky Mountain Institute and the U.S. Department of Energy.

The categories of the literature review that are most relevant to this thesis are: 1) building systems and components that affect residential energy use, 2) optimized combination of strategies for energy-efficient residences, 3) case-studies of high-performance homes, and 4) simulation software for energy-efficient residential building design. Under these categories, previous research and new technologies that reduce residential energy use were reviewed. The findings are discussed in this section with the primary focus on strategies for hot and humid climates.

2.1. Building Systems and Components Affecting Residential Energy Use

Research related to building systems and components that includes: 1) the building envelope, 2) space heating and cooling systems, 3) domestic hot water systems, 4) lighting, and 5) appliances, which contribute to the energy use of a residence, were reviewed to investigate energy-efficient design options, their energy-saving potential, and conditions for their optimal performance.

2.1.1. Building Envelope

Residential buildings are usually skin-dominated, having smaller internal heat generation as compared to the heat gain/loss through the envelope (Givoni 1998). The building envelope can contribute up to 73% of the total heat gain/loss in a residence (DOE 2004). Building envelope characteristics such as building geometry and orientation, properties of materials, type and quality of construction, and its interaction with the outdoor conditions, impact the heat gain and loss through the envelope. These characteristics affect the energy required for space heating and cooling. Therefore, decisions about envelope characteristics are governed by the objective of promoting or restricting the heat gain or loss, which depends on the climatic characteristics of the building site, and heating/cooling season.

2.1.1.1. Building Configuration

Many researchers have explored the relationship between architectural form and energy use to better understand the energy consequences of basic design decisions. The studies that are most relevant to this thesis include: Brown and DeKay (2001), Watson and Labs (1983), Givoni (1998), Lechner (2001), ASHRAE (2001a), Friedman (2000) and Olgyay (1963). In these studies, recommendations were made for the design development stage, to create a form that could guide and shape energy flows in a desired way.

Brown and DeKay (2001) listed strategies for the organization, shape, orientation and location of building groups and building spaces, and the building envelope components, to obtain space heating, cooling and daylighing benefits from the sun and wind. Watson and Labs (1983) discussed control strategies for promoting/restricting heat gain and loss through the envelope by means of wind breaks, plants and water, indoor/outdoor rooms, earth sheltering, solar walls and windows, thermal envelope, shading and natural ventilation. Givoni (1998) discussed effects of building design features such as the layout, window orientation, shading and ventilation, on the indoor environment and energy use. Based on these effects, he provided design guidelines for improving comfort and energy conservation in different climates. Lechner (2001) prioritized design strategies for buildings in different climatic regions in the U.S. For hot and humid climates, he recommended natural ventilation as the highest priority measure for summer cooling and moisture removal, followed by that for protection from the summer sun and exposure to the winter sun.

These studies suggest that a compact plan with smaller exposed wall area and a reduced roof size reduces the energy demand of a mechanically conditioned building, whereas a spread-out plan has the potential for natural ventilation and natural illumination. Compact designs, attached or clustered buildings and earth sheltering can protect from extreme temperatures as well as from undesired winds. Orienting the building along the east-west axis, maximizing wintertime exposure to the south, southeast and southwest sides, providing a clear solar access, sunspaces on the south, buffer spaces along the north, and temperature zoning inside the building can maximize solar gain and minimize heat loss in the winter. Building envelope shading should be added to these measures, to minimize heat gain in the summer. On the other hand, for natural ventilation, orienting and planning the building for maximum contact to outdoors to capture the prevailing winds, open indoor plan, high ceiling, two story spaces, open stairwells and elevated living spaces are recommended for maximizing air-flow indoors.

Therefore, for residences in hot and humid climates, a trade off is required for building shapes that could minimize exposure to the summer sun while encouraging air movement, if natural ventilation is one of the design strategies. Aiming for this objective, Givoni (1998) suggested a changeable configuration for a residential building plan, in which the inward recessed porches of the building were equipped with operable insulated shutters. The open configuration of the building, with windows in the rooms overlooking shaded porches, allows natural ventilation and restricts direct solar gain in hot and humid summers; whereas a closed configuration, with insulated panels closed, creates a compact building and reduces heat loss in the winter.

However, in contrast with the recommendations for natural ventilation, ASHRAE (2001a) stated that this measure is not considered practical in hot and humid climates or in cold climates, since intentional openings cannot always guarantee adequate temperature and humidity control or indoor air quality. It also recommends having a reasonably tight building envelope and a properly designed and operated mechanically ventilated system for residences, to avoid possible difficulties of lack of control of ventilation rates, poor humidity control, air moisture infiltration and lack of opportunity to recover the energy used to condition the ventilation air.

Due to the limitation of the DOE-2 program in accurately modeling natural ventilation and air movement, this study focuses and analyzes the latter approach.

Other studies have also quantified the effect of building shape and exposure on the energy use. For example, Friedman (2000) recommended rectangular shapes for buildings to minimize heat gain and loss through the envelope. He showed up to 15% savings by simplifying an L-shape floor plan to a rectangle, and up to 21% and 43% savings by redesigning a one-story detached unit as a duplex and as a row house, respectively. Olgyay (1963) found that for the hot and humid climate of Miami, Florida, a length-to-width ratio of 1:1.7 was the optimum that resulted in minimum heat loss in the winter and minimum heat gain in the summer.

These studies suggest that for a mechanically heated and cooled single-family, detached house in a hot and humid climate, a two storied compact rectangular design along the east-west axis with an optimum length-to-width ratio has the potential to reduce heating and cooling load, and minimize energy use, significantly.

2.1.1.2. Thermal Properties of Opaque Elements

The properties of opaque building envelope elements that determine the thermal performance of a building include: insulating value, thermal mass of the construction material, the location/sequence of different layers of the assembly, and the absorptance and emissivity of the exterior surface of the finish materials. Many studies have examined these properties and their effect on building energy use. The studies that are most relevant to this thesis include: ASHRAE (2001a), ORNL (2002), ICC(1999), DOE (2000), SIPA (2004), ICFA (2004), Ternes et al. (1994), Chulsukon (2002), Rasisuttha and Haberl (2004), Kootin-Sanwu (2004), Kosny et al. (1998) Kossecka and Kosney (1998), Kosny et al. (2001), Miller et al. (2002), Berdahl and Bretz (1997), Parker et al. (2000), Akbari and Konopacki (1998), Simpson and McPherson (1997), Parker and Barkaszi (1997) and Parker et al. (2002).

Insulating Value

Thermal insulation retards conductive, convective and/or radiative heat transfer (ASHRAE 2001a). Providing adequate insulation in the building envelope is critical for energy-efficiency. ORNL (2002) provided guidelines for selecting the type and level of insulation for different envelope components in residences in different U.S. climates. For a gas-heated wood-frame house with a slab-on-grade floor in a hot and humid climate, it recommended that an insulation level of R-11 to R-15 be provided for wall cavities, R-38 for attics and cathedral ceilings, and R-4 for slab perimeters. These values exceed the minimum levels required by the ICC (1999), including the 2001 Supplement, which are based on the glazing area and the location of the house.

Besides insulation, all the materials used for the wall and roof assemblies have some insulating value, and thus, also contribute to the thermal performance of the building envelope. Therefore, the choice of construction type and materials can also have a significant effect on building energy use.

Although, light-weight wood frame construction with 2x4 studs spaced 16 inches on center. is the most common construction for residences in U.S., other construction techniques such as optimum value engineering (OVE), structural insulated panels (SIPs) and insulated concrete forms (ICFs) have been developed that provide improved insulation and airtight construction. By using 2x4 or 2x6 studs spaced at 24 inches on center, OVE walls have reduced thermal bridging through the framing and provide more space for insulation. This results in a higher whole-wall R-value that can save up to 5% annual heating and cooling cost (DOE 2000). SIPs are high-performance panels for walls, floor and roof that are typically made using expanded polystyrene (EPS) or polyisocyanurate rigid foam insulation sandwiched between two structural skins of oriented strand board (OSB). Having no thermal breaks or penetrations in the panels, SIPs have higher R-values (R-15 to R-50, depending of the EPS core thickness) and are 95% more airtight than wood-frame construction. These allow for smaller HVAC systems and can result in up to 50% energy savings (SIPA 2004). ICFs are foam insulation forms for poured concrete walls that remain in place as a permanent part of the wall assembly. These forms provide a continuous insulation, sound barrier and provide a backing for interior and exterior wall finishes. ICF walls have higher R-values (R-17 to R-26, compared to R-9 to R-15 for wood-frame walls), high thermal mass, and are 50% more airtight than wood-frame walls. ICF walls can reduce heating and cooling energy by 30-40%, with higher savings associated with large houses (ICFA 2004).

Many studies have also quantified the energy savings from improved insulation. Ternes et al. (1994) showed 9% energy use reduction and 15% average peak demand reduction in Arizona, by retrofitting exterior masonary wall insulation from R-3 to R-13. They showed the highest annual cooling energy savings in hot and dry climates, with the least energy savings in southern climates, which suggested much lower heating and cooling loads through walls in southern climates than in hot and dry climates. A study of a typical uninsulated masonry house (partially air-conditioned at night) in the hot and humid climate of Bangkok, Thailand by Chulsukon (2002) showed 3-4% annual energy savings from light-weight walls with R-11 batt insulation and from cement tile roof with R-11 batt insulation. Another study of a similar house in Bangkok, Thailand, by Rasisutta and Haberl (2004), showed 8% of total energy reduction from light-weight concrete block walls with R-10 exterior insulation, and 9% reduction from similar wall construction with R-10 interior insulation. A similar study of a Habitat for Humanity house in the hot-humid climate of Central Texas by Kootin-Sanwu (2004) showed a small annual electricity savings, but a high cooling energy savings in the summer from improved insulation in light-weight walls.

These studies suggest that high R-values and low air infiltration loss could be achieved with advanced construction techniques, which can result in significant energy savings. However, high cooling energy savings are expected in residences in hot and humid climates.

Thermal Mass

Thermal mass provides significant benefit in shifting peak load conditions and reducing overall heat gain or loss, provided that average outside temperature is moderate. This allows reduced HVAC system size that could result in energy and cost savings. However, these benefits depend on the configuration of the wall assembly (i.e., insulation inside or outside thermal mass relative to the building interior) and the climatic conditions.

Kosny et al. (1998) and Kossecka and Kosney (1998) showed that the most effective configurations were mass walls with thermal mass being in good contact with the interior of the building. They found that Phoenix, Arizona was the most favorable location, and Minneapolis, Minnesota was the worst location for the application of the mass walls systems. Mass walls with an R-value less than 4 were ineffective in all locations considered, except in Phoenix. Kossecka and Kosney (1998) demonstrated up to 11% of heating and cooling energy savings from mass walls by optimizing mass and insulation distribution on the wall. A similar study by Kosny et al. (2001) showed whole-building energy savings of up to 8% in Minneapolis, Minnesota and 18% in Bakersfield, California, for high R-value walls. Studies by Chulsukon (2002) and Rasisuttha and Haberl (2004) analyzed different combinations of insulation and thermal mass in houses in the hot and humid climate of Bangkok, Thailand, which were partially air-conditioned at night, as opposed to the studies discussed above. Chulsukon (2002) demonstrated 4% savings from lightweight construction with R-11 insulation, and 3% savings from 4-inch brick wall with 2-inch polystyrene insulation, as compared to uninsulated 4-inch brick wall. Rasisuttha and Haberl (2004) demonstrated more savings from light weight concrete block walls, especially with insulation on the inside wall than from high thermal mass walls (8-inch and 12-inch brick walls). These studies showed that for a house with HVAC system not operating continuously, interior insulation provides more energy savings than thermal mass only, in order to achieve the desired temperature in a short time. Higher savings from thermal mass are expected in a house with HVAC system operating continuously.

These studies demonstrate the benefits of thermal mass for climates with moderate average outside temperatures, and suggest considering this strategy also, in addition to the previously discussed advanced construction techniques, in order to reduce building energy use in hot and humid climates. They also suggest that thermal mass is more effective with exterior insulation, when HVAC system operates continuously; and with interior insulation, when HVAC operates for short periods.

Reflectance and Emissivity

For skin-dominated buildings such as residences, reflectance and thermal emissivity of the exterior surfaces of the building can provide significant opportunity for energy savings. A high solar reflectance reduces summertime solar heating, and a high infrared (IR) emittance increases radiative cooling of the surface. The resulting reduced building surface temperature reduces the heat transfer into the building as well as the surrounding urban air temperatures that would have increased due to convective cooling of the hot building surfaces. However, the increased reflectance can cause higher reflective solar gain on surrounding surfaces. In general, this combined effect can produce direct and indirect cooling energy savings in moderate to predominantly hot climates. In cold climates, surfaces with moderate reflectance and low IR emittance will save on heating (Miller et al. 2002).

A strong correlation between roof temperature in sunlight and solar absorptance was demonstrated by Berdahl and Bretz (1997). They recommended high heat reflectance, high thermal emissivity and high convection coefficients for keeping roof surfaces cool. On the other hand, high total solar reflectance with a low ratio of visible to heat reflectance would reduce potential glare problems for a reflective roof system. Conversely, spectral data for the reflectance properties of 37 roofing material samples, by Parker et al. (2000), showed a higher visible to heat reflectance ratio for most of the tested options. However, all the samples were found to have the desirable property of high long-wave emissivity. These studies point to the eventual promise of highly reflective roofs in reducing heating energy use.

Several studies have documented the effects of roof reflectance and emissivity on building energy use. Akbari and Konopacki (1998) showed a 10-15% cooling energy use reduction from coating roofs white, with greater opportunity of energy savings in warm climates. In their study, decreasing the roof emissivity showed a 10% net increase in the annual utility bill in hot climates, and a 3% heating energy savings in very cold climates. No savings resulted in cold climates, due to the heating energy savings being equal to the cooling energy use penalties.

Besides the climate, insulation is another factor that impacts the energy savings from changing reflectance and emissivity. An analysis of a scale model with a white colored roof in Arizona, by Simpson and McPherson (1997) showed daily total and hourly peak cooling load reductions of approximately 5% with insulation, and 18-28% without insulation. They found ceiling insulation more effective in reducing the daytime heat gain than increased roof reflectance. The significantly lower temperature of white roofs on hot, sunny days indicated high emissivity as a desired property for high reflective coatings to realize the expected savings. Another study based on field tests in Florida by Parker and Barkaszi (1997) showed 2-43% cooling energy savings, averaging 19%, and 12-38% peak electrical demand reduction, averaging 22%. The data suggested a cooling energy-saving potential of up to 40%, with larger savings associated with poorly insulated roof assemblies, duct system in attic space and excessive attic air-infiltration. These results were confirmed by another study in Florida by Parker et al. (2002), where white reflective roofs in six side-by-side identical Habitat houses, with R-19 ceiling insulation and different roofing systems, showed 18-26% cooling energy use reduction and 28-35% peak demand reductions.

These studies suggest considering exterior surfaces with high emissivity and high reflectance to minimize envelope loads in hot and humid climates. They also show diminishing returns on roof reflectance and emissivity for high insulation levels in attics without ductwork. These studies were used to determine appropriate values for reflectance and emissivity for light-colored exterior walls and roof, and to find combinations of surface reflectance and insulation that could result in minimum energy use.

2.1.1.3. Fenestration

Windows are typically the weakest link in a building’s thermal barrier. They are responsible for 10-25% of a home’s winter heat loss in cold climates and approximately same amount of solar gain in warmer climates (RMI 1994). In 2002, windows accounted for 26% of the aggregate U.S. residential building heating load and 33% of the cooling loads (DOE 2004). Therefore, considering energy-efficient options for the fenestration system is an important energy-savings strategy. Many studies provide information about energy-efficient fenestration systems. The following references were found to be the most relevant: ASHRAE (2001a), LBNL (1997), Givoni (1998), Mayfield (2000), Pletzer et al. (1987), Farrar-Nagy et al. (2000), Nayarat (2003), RMI (1994), Fine and McElroy (1989) and Reilly et al. (1995).

Besides daylighting, minimizing the unwanted heat transfer through the windows is the prime objective of efficient fenestration design in a mechanically-cooled building. For a naturally ventilated building, size and placement of windows relative to wind movement is also critical; however, this should not compromise unwanted heat gain/loss. The energy impacts of fenestration can be optimized by using: (1) daylighting, (2) passive solar heat gain, (3) glazing with special transmission properties, and (4) insulated glazing with low air leakage. Heat flow through fenestration can be controlled by various single or multiple (insulating) glazings, interior and exterior shading, and spectrally-selective coatings and tinted glass (ASHRAE 2001a). In cold climates, multiple pane, low-e and gas-filled window configurations, or super windows that combine all the above advanced features are recommended. In hot climates, less expensive glazing with low-e coatings, gas fills, and shading are the most cost-effective energy-saving options (DOE 1997).

Besides glazing characteristics, insulated frames and spacers, good edge seals and airtight construction are equally important for energy-efficiency. Among the available window frame and spacer options, wood, fiberglass, and vinyl frames are better insulators over metal frames without a thermal break. Aluminum frames with a thermal break perform better than those without a thermal break. The thermal break or spacer thermal performance depends on its geometry and material composition (DOE 1997).

A mixed climate requires consideration of both heat loss control and solar heat gain protection. Carefully designed shading devices have significant energy-saving potential by reducing direct solar gain in the summer. However, for hot and humid climates, where the diffuse radiation from the sky comprises a significant portion of the total solar heat gain due to partly cloudy skies, shading from diffuse radiation is also important (Givoni 1998).

Mayfield (2000) discussed different shading options for residences such as overhangs, decks and porches, awnings, low-e films and coatings, shade screens, solar screens and rolling shutters, and gave guidelines for choosing a shading option for different contexts. Pletzer et al. (1987) estimated that up to 32% annual cooling energy savings and 5-15% annual energy cost savings from window shading devices. He also showed higher savings for interior than from exterior shading. Farrar-Nagy et al. (2000) showed a 14% reduction in afternoon peak electricity demand and a 30% reduction in daily total cooling electricity from a spectrally-selective glazing, overhang and site-shading combination, in a hot-dry climate. They demonstrated 22% daily cooling energy savings from overhangs and site shading, as compared to 11% savings from using spectrally selective glazing, only. Another study by Nayarat (2003), showed an 18-inch combined lightshelf as the most effective for a combined lighting and energy savings (7% annual energy savings and 28% lighting energy savings), and 6-foot horizontal overhangs with vertical fins the best for cooling energy savings. RMI (1994) reported heat gain/loss reductions from different shading options for cold and warm weathers. For cold-weather, it reported heat loss reductions of 25-40% from installing plastic barriers on single-pane windows, up to 50% by storm windows and up to 40% increase in solar gain by providing clear solar access on south windows. For warm-weather, it reported solar heat gain reduction of 40-50% from window shades and blinds, and 60-80% from insect screens or bamboo shades (RMI 1994).

Other options for energy-efficient fenestration design include switchable window transmittance coatings (DOE 1997) and dynamic window controls (ASHRAE 2001a), which can react to varying climatological and occupant demands. Fine and McElroy (1989) analyzed fixed and variable options for thermal insulation, roof and wall absorptance and window transmittance in Phoenix, Lexington and Minneapolis. Their results showed that the combination of switchable window transmittance and variable surface absorptance performed better than the best fixed options, with slightly more savings from switchable transmittance. However, variable thermal insulation resulted in smaller savings over the fixed super-insulation. Among all the locations analyzed, the highest savings were achieved in Minneapolis and the least savings were achieved in Phoenix.

For determining energy savings from the application of the selected optimum combination of fenestration properties, the Window-5 computer program was used that gives the DOE-2 the capability to account for the temperature effects on the U-value, to update the incident angle corrections for the solar heat gain properties and visible transmittance, and to account for the influence of framing elements on the heat transfer and solar heat gain through windows (Reilly et al. 1995). Mukhopadhyay (2005) analyzed improved fenestration using the WINDOW 5 method, and demonstrated 5% variation in overall energy consumption for the performance of the improved glazing options on each orientation.

These studies suggested to consider low-e, gas-filled windows with exterior shading, vinyl frames and air-tight construction for energy savings in hot and humid climates. Windows with switchable transmittance were found effective only for very cold climates; therefore they were not included in the analysis. For this thesis, effect of different combinations of glazing properties, window distribution on different orientations, and shading with horizontal overhangs were analyzed to determine the optimum combination for the improved house that could confirm a better thermal performance in a hot and humid climate.

2.1.2. Space Heating and Cooling Systems

Space heating and cooling in residences consumed 32% and 12% of the U.S. residential energy use in the year 2002, respectively (DOE 2004). For residences that are skin-dominated, the climate dictates whether heating or cooling is a major concern. Many studies have investigated space heating and cooling energy use and energy-efficient options to reduce the energy use. The studies that are most significant to this thesis include: Proctor et al. (1995), Proctor and Albright (1996), Hayden (1996), Marsh (1998) and Hedrick (2003a and 2003b).

The annual heating or cooling requirements of a house depend on the climate, size and type of the house, insulation level, air-tightness, solar gains, internal heat generation, thermostat setting, and other operational factors. Using energy-efficient strategies for these factors reduces a building's thermal load and allows reduced HVAC system size. Furthermore, properly sized and energy-efficient systems and equipment, achieve the longest run time cycle possible that optimizes the system performance and reduces energy use for space heating and cooling. Properly sized air-conditioners also perform better in terms of moisture removal ability, noise and comfort (Proctor et al. 1995 and Proctor and Albright 1996), which is an important comfort issue in hot and humid climates.

The efficiency of HVAC systems depends on the efficiency of the equipment used. The efficiency of a furnace or boiler ranges from 60% for a conventional natural gas furnace (with a standing pilot) to 96% for a high efficiency condensing gas furnace. Furnaces with electric or electronic ignition have fuel savings in the 3-9% range. Electric space heating equipment that uses resistance heating is typically 100% efficient. However, considerable distribution losses are associated with such devices and are responsible for much higher source energy consumption. Heat pumps can have efficiencies higher than 100%, since they transfer and upgrade heat from the outside air or ground, provided ambient conditions are suitable. For cooling, the Seasonal

Energy Efficiency Ratio (SEER) of an air source heat pump ranges from a minimum of 9 to a maximum of 16. The Heating Seasonal Performance Factor (HSPF) for heat pumps ranges from a minimum of 5.9 to a maximum of 8.8. For a ground source heat pump, the SEER ranges from 11 to17 due to a warmer source for heat rejection, and the HSPF ranges from 8.3 to 11.6 (Hayden 1996).

Other energy-saving measures include thermostat setbacks, efficient motor and fan systems, and moving the ducts into the conditioned space. Marsh (1998) specified up to 3% savings for every °F setback for a season, depending on the weather conditions, thermal efficiency of the building envelope and the thermal mass of the structure. Hedrick (2003a and 2003b) showed 9-18% average annual cooling electricity savings from moving ducts into the conditioned space in single-family houses.

These studies suggest using properly sized, energy-efficient systems, equipment with no pilot light, thermostat setback and installing ducts inside the conditioned space to minimize energy use.

2.1.3. Domestic Hot Water Systems

Domestic water heating is an important end-use in residences that includes heating water primarily for clothes washing, dishwashing and personal hygiene. Energy required for water heating accounted for 13% of the U.S. residential energy use in 2002, making it the second largest end-use after space heating and cooling in an average home (DOE 2004). Therefore, energy-efficiency in a domestic hot water (DHW) system is an important energy-saving strategy. A number of resources have analyzed DHW consumption in residences and have investigated ways to reduce energy for domestic water heating. The studies that are most significant to this research include: Stein and Reynolds (1992), Vieria and Sheinkopf (1992), Nadel et al. (1998), Thorne (1998), RMI (1994), Houseneeds (2005), Johnson and Wyatt (1997), DOE (2001b), Weingarten and Weingarten (1996).

The first step towards energy-efficiency in a DHW system begins with a reasonable estimation of hot water demand and proper sizing of the storage tank. Stein and Reynolds (1992) gave hot water consumption by use and the supply water temperatures at the point of use for different domestic purposes. Based on these values, they estimated that a family of four would require 70 gallons of hot water daily. However, actual hot water demand depends on the characteristics and operation of the appliances that use hot water, and on the schedule and preferences of the occupants.

The second step is to select an energy-efficient DHW system and distribution system, which affects the energy use for water heating, significantly. The main types of DHW systems discussed here include: electric resistance water heaters, gas water heaters, heat pump water heaters (HPWHs), integrated space conditioning/water heating systems, solar water heaters, demand water heaters and heat recovery units (HRUs).

Although the electric resistance water heater is the most common and least expensive, it has the highest operating cost. Gas water heaters have a higher first costs but lower operating costs, if natural gas is available for a residence. The energy factor (EF) for an electric resistance water heater ranges from 0.74 to 0.97, and for a gas water heater – from 0.40 to 0.63. HPWHs attain much higher efficiencies by using electricity to "pump heat" from the surrounding space. Units that draw air from and return it back to the house in the summer, and from and to the outdoors in the winter can provide additional savings (Vieira and Sheinkopf 1992). Nadel et al. (1998) reported an increase in water heater efficiency from 0.9 EF to 2.0 EF and a 50% energy savings from an add-on 600 Btu/hr capacity heat pump on a 50-gallon electric storage water heater.

Integrated systems provide both space conditioning and hot water heating with one appliance or energy source. In these systems, rejected heat from space cooling provides free water heating in the summer. This can result in 2-27 % savings in annual energy costs for space conditioning and water heating (Thorne 1998). Nadel et al. (1998) reported a 21% energy savings from a 3-ton 12 SEER integrated electric space conditioning/water heating system as compared to a 10 SEER 3-ton heat pump and a 0.86 EF, 40 gallon electric resistance water heater. They also reported a 17% energy savings from an integrated gas/ oil-fired space conditioning/water heating system with a combined annual efficiency of 90 AFUE, as compared to an 80 AFUE furnace and a 0.55 EF water heater.

Solar water heaters are good substitutes for electricity or gas water heaters for areas with adequate solar exposure year-round. They are usually classified by the means of fluid circulation. Passive systems rely on gravity for water circulation and require no external energy for operation. These systems, if unable to meet all of the hot water demand, can act as a pre-heater for conventional water heating systems, which can reduce energy consumption considerably. Active systems use pumps, sensors and heat exchangers to control and move the water/anti-freeze. They have high initial and maintenance cost but are the most energy-effective solar heating systems (RMI 1994). Solar water heaters usually require a backup heater to heat the water during periods of insufficient sunshine or high hot water demand (Vieira and Sheinkopf 1992).

Demand water heaters do not use a storage tank. This avoids heat loss through the tank walls and pipes, and reduces energy use by 15-20%. Unfortunately, due to the low flow-rate and high power consumption, they are suited only for small hot water requirements, and usually require special wiring arrangements. Combining a demand water heater with a solar water heating system can be the most energy-efficient system (RMI 1994). However, tankless gas water heaters without pilot lights are available for residential applications that can deliver over 5.3 gallons of hot water continuously, meeting two major hot water end uses, simultaneously (Houseneeds 2005).

A heat recovery unit (HRU) typically operates only in conjunction with a central air conditioner or heat pump and uses heat discharged by these systems to heat domestic water. These systems are usually applicable only to the new construction. Insulation is an important consideration for such a unit (Vieira and Sheinkopf 1992). Gravity-film heat exchanger (GFX), which is a drain-water heat recovery device, increases the EF of the water heating system by about 34%, thus, tripling the first-hour ratings (Johnson and Wyatt 1997). DOE (2001b) showed a saving of 40% of the total energy needed for the shower from GFX.

Vieira and Sheinkopf (1992) compared the annual energy savings from different water heating systems. They reported that, compared to an electric resistance water heater, annual water heating energy cost savings of 50-85% can be achieved from a solar water heater, 59-65% from a gas water heater, 40-50% from an HPWH, and 20-50% from an HRU. However, actual savings depend on the system size and efficiency and hot water consumption.

Besides installation of a properly sized and energy-efficient water heater, switching to water-efficient fixtures, energy-efficient appliances and following water conserving practices are also important for minimizing DHW consumption (RMI 1994). Other recommended energy and water saving measures include regular inspection, proper maintenance and upgrading various components of the water heater; providing adequate tank and piping insulation; installing heat traps to prevent convective heat loss, flue dampers for natural gas systems and timers for turning off DHW systems during off periods; and installing tempering tanks in warm or sunny areas, recirculation systems with controls and/or supplemental heating for instant hot water (Weingarten and Weingarten 1996).

These studies suggest that proper sizing and selection of DHW heating systems, optimizing operation and minimizing waste has a significant energy-saving potential. They also provide useful information for estimating the water heating demand for the basecase house, characteristics of an efficient DHW system for the simulation of the improved house and resultant savings. Among the DWH systems discussed, integrated systems and solar water heaters can not be simulated using the DOE-2, only. Instantaneous gas-fired DWH systems were found the most energy-saving options, and therefore were included in the analysis.

2.1.4. Lighting

Lighting affects building energy use in two ways: the energy required for lighting and the energy associated with removing or replacing the internal heat gain from lighting. Lighting accounted for 12% of the U.S. residential energy use in 2002 (DOE 2004). By integrating daylighting with energy-efficient electric lighting and controls, and following energy conserving practices, lighting energy use as well as the internal heat gain from electric lighting can be reduced significantly. A number of sources provide information about energy-efficient residential lighting options. The most relevant studies to this thesis include: DOE (1996), IESNA (2000), Stein and Reynolds (1992), Geltz (1993), Vieira and Sheinkopf (1992), RMI (1994), Conway (1994), Parker and Schrum (1997) and Tribwell (1997).

Based on EIAs Residential Energy Consumption Survey (RECS), the DOE (1996) provides residential lighting profiles in terms of lighting type, location, usage, costs and estimated potential savings. This study showed that in 1993, most of the single-family homes consumed between 750 and 999 kWh per year for lighting, with an average of 940.5 kWh. It also showed that in most of the rooms in a household, except for the kitchen and utility areas, incandescent lights are the most common, and account for at least 90% of the hours used. The average daily use per light in kitchens is about 3.8 hours, followed by living rooms (3.4 hours), and family rooms (3.3 hours). Rooms where lights are used less intensively are bedrooms (1.6 hours) and bathrooms (1.8 hours). The IESNA (2000) gives recommended illuminance values for different activities in residences. They recommended a lighting level of 30 lux (3 fc) for general lighting, 50 lux (5 fc) for dining, 300 lux (30 fc) for non-critical kitchen activities, normal reading and grooming and 500 lux (50 fc) for activities with critical seeing. Stein and Reynolds (1992) provided a relation between lighting levels and lighting loads for different light sources. For example, a lighting level of 75 lux (7.5 fc) causes a lighting load of 1 W/ft2 for an incandescent lamp and 0.3 W/ft2 for a fluorescent lamp. These studies were helpful in determining the lighting level, type and schedule for different areas of the basecase house, in order to estimate the lighting load for the basecase house, and energy-efficient lamp replacements.

Lighting energy-saving measures include: using efficient lamps and fixtures, task-oriented lighting, small-scale fixtures, multiple switching schemes, occupancy sensors, daylight with glare control, dimmers and timers, and the proper installation of lighting and equipment (i.e., adequate 120 VAC branch circuit capacity, good power quality and National Electric Code (NEC) compliance) (Geltz 1993).

Vieira and Sheinkopf (1992) gave light source characteristics for different lamp types which showed that fluorescents require one-fourth the electricity needed to power an incandescent lamp. A compact fluorescent lamp (CFL) offers the energy economy of a fluorescent lamp yet lasts 10-12 times longer than an incandescent lamp. Electronic ballasts eliminate 60 Hertz flicker and reduce power consumption by 25-40% compared to electromagnetic ballasts. Halogen lamps are less efficient than the CFL, but are still about 20% more efficient than incandescent lamps, and they last longer. Halogen Infrared Reflecting (HIR) lamps are 50% more efficient than standard incandescent lamps and also, last longer than incandescent lamps. Improved incandescent lamps, which are preferred for applications with limited use and/or frequent on/off cycles, consume about 10% less electricity than standard incandescent lamps (RMI 1994). The replacement of incandescent lamps with CFLs has one of the highest (35%) energy savings potential for lighting (DOE 1996).

Dimming incandescent lights by 10% to 75% saves 5% to 50% of lighting electricity (RMI 1994), motion detectors save lighting electricity by 40% in bathrooms, 30% in bedrooms and kitchens, and 20% in living rooms and kitchen/dining areas. An average of 26% annual operating cost savings were found with replacement with more efficient lamps, 45% with typical manual on/off controls with dimmers, timers, or sensors, 57% with an integrated system of efficient lamps, efficient luminaries and appropriate controls (Conway 1994). These measures, integrated with daylighting, can save up to 90% of lighting electricity (RMI 1994).

Studies by Parker and Schrum (1997) and Tribwell (1997) identified the best opportunities for lighting retrofits. Both these studies identified living, kitchen, porches and outdoors as high-energy use areas, and thus, were good candidates for CFL replacement. Parker and Schrum (1997) estimated 4,050 kWh annual lighting energy use with 24% variation in lighting load between June and November, and a 56% reduction in lighting loads from CFL replacement. They recommended replacement of all lamps that are used for more than 3 hours per day. Tribwell (1997) estimated 1,800 kWh/yr per household average lighting energy use, and 50% more energy use in winter months than in summer months. He found no correlation between energy use and the heated floor area, the number-of-occupants or the hour-of-occupancy. However, conservation habits, behavior and other occupancy factors were found to affect energy use.

These studies helped in estimating lighting load for the basecase house, determining the reduced lighting load from energy-efficient lighting for the simulation of the improved house and compare resultant savings with the expected savings. For the analysis, only CFLs were considered as energy-efficient lighting improvement over the basecase.

2.1.5. Appliances

Major appliances in residences include refrigerators, clothes washers, clothes dryers, dishwashers, cooking equipment and home electronics. Together, they accounted for 29% of the U.S. residential energy use in 2002 (DOE 2004). Therefore, using energy-efficient products and following energy conserving practices have a great energy-saving potential.. This section discusses appliance energy use and energy-saving options in four categories: refrigerators, wet cleaning equipment, cooking options and home electronics. The studies providing information about appliance energy use and energy-saving options that are relevant to this study include: DOE (2004), Nadel et al. (1998), Sullivan (1995), DOE (2001a), RMI (1994), Mitchell-Jackson and Meier (2001), Rosen and Meier (2000), Ross and Meier (2000), Wilson et al. (2003) and ACEEE (2004).

2.1.5.1. Refrigerators

Refrigerators and freezers are the most consumptive home appliances, since they operate continuously year-round. They accounted for 9% of the U.S. residential energy use in 2002 (DOE 2004). A typical 20 cu. ft. refrigerator unit with a top-mounted freezer and no ice maker, meeting the 2001 federal minimum efficiency standards, consumes approximately 496 kWh/year, which is equivalent to a constant load of 56 W (Nadel et al. 1998).

Energy-saving considerations in selecting refrigerators include size (larger units consume more energy and are more expensive), configuration (side-by-side refrigerator/ freezer units consume 10 to 25% more energy than units with freezer on top or bottom) and defrost type (automatic defrost consumes 40 to 50% more energy than manual defrost, provided the freezer is defrosted regularly). Optional features such as automatic ice makers, through-the-door dispensers and anti-sweat heaters add about 10%, 14-20% and 5-10% to the energy use, respectively. Other energy-saving strategies are proper refrigerator placement to avoid direct sunlight and close contact with hot appliances, adequate clearance to allow sufficient airflow, lower room temperature, and adequate temperature setting (i.e. 37°F to 40°F inside the refrigerator, 10°F to 15°F inside the freezer and 0°F to 5°F, for long term storage). Regular maintenance such as cleaning of condenser coils and checking door seals, and replacement of old refrigerators also reduced energy cost (Sullivan 1995 and DOE 2001a).

2.1.5.2. Wet Cleaning Equipment

Wet cleaning equipment includes clothes washers, clothes dryers and dishwashers. They accounted for 5% of the U.S. residential energy use in the year 2002 (DOE 2004). Ninety percent of the energy used in operating a washing machine goes toward heating the water. Water saving versions can cut water and energy usage by more than 40% (DOE 2001a). Horizontal-axis clothes washers use 30-60% less water and 50-70% less energy than a typical vertical-axis machine that consumes approximately 924 kWh/year (RMI 1994). High efficiency vertical-axis clothes washers by Whirlpool addressed consumer preference for front loading machines, and provided

42% energy savings as well as water and sewer savings, from reduced hot water use and reduced drying requirements (Nadel et al. 1998). Low temperature washing produces a 13% energy cost savings for each 10% reduction in water temperature. Also, using the small capacity setting for less than full loads can cut water use by 50%. Other energy-saving measures for clothes washers include locating them near the hot water tank, insulating hot water pipes to minimize the heat loss, and using models with faster spin speeds and advanced sensors and controls (RMI 1994).

Energy use of clothes dryers depend on the fuel type the dryer uses. Gas dryers will cost 15-25 cents/load, compared to 31-40 cents/load for electric dryers. Energy-saving measures for clothes dryers include using cool down cycles, locating them in a heated space, regular cleaning and proper maintenance. Simple timers, advanced temperature and moisture sensors in clothes dryers can reduce dryer energy use by 10-15% (RMI 1994 and DOE 2001a).

Dishwashers typically use 700-850 kWh of electricity annually, the majority of which is used to heat the water. Therefore, water-efficient dishwashers that require less water can save up to 50% of the energy to heat the water (RMI 1994). High-efficiency dishwashers by Frigidaire with low water use provide 26% electricity savings and 32% gas savings, as compared to a standard 22-24 inch NAECA (National Appliance Energy Conservation Act) compliant dishwasher (Nadel et al. 1998). Other energy-saving features for dishwashers are a built-in water-heating booster that allows lower temperature settings on the main DHW heater, variable wash cycles that reduce water use, and an air-dry option that avoids using the electric heater during the drying cycle (Sullivan 1995).

Microprocessor controls in new clothes washers detect wash water turbidity, load size, fabric type, and adjust water usage, temperature, wash speed and agitation accordingly. Similarly, advanced dishwasher controls detect wash water turbidity, and control water level and water temperature, with resultant energy savings of approximately 23%. In combination, they have the potential of 20% energy savings (Nadel et al. 1998).

2.1.5.3. Cooking Options

Cooking contributed to 5% of the U.S. residential energy use in 2002 (DOE 2004). Efficiencies of different cooking options vary with the type of food to be cooked/heated. For example, for boiling water, efficiencies for different cooking options are: 55% for a microwave oven, 70% for an electric stove, and 40% for a gas stove. On the other hand, for cooking potatoes, efficiencies of the same options are: 55%, 14% and 6%, respectively. Microwave ovens are the most convenient and the most energy-saving cooking option. They use one-third as much energy as conventional ovens (about 110 kWh/yr of electricity, including approximately 24 kWh/yr in standby mode), and are recommended especially for heating smaller portions (no preheating required, time savings, and less heat loss). Although electric stoves consume 25% less electricity they have more heat loss for heating smaller portions. Gas stoves require more energy than a microwave; however, they usually cost less to use due to the lower price of natural gas. The recommended practices for using microwaves include heating single portions, defrosting in the refrigerator rather than in the microwave, and unplugging the oven when not in use for long periods (Mitchell-Jackson and Meier 2001).

Other features can make cooking appliances more efficient. Self-cleaning ovens are usually better insulated and therefore are up to 20% more energy-efficient when used appropriately (RMI 1994). Electric ranges with ceramic, halogen, or induction range elements are more efficient than those with electric coils or solid disk elements (DOE 2001a). Gas ranges with electronic or thermal igniters instead of standing pilot lights save energy. Electric convection ovens are expensive but cost about 30% less to operate than conventional electric ovens because they circulate air inside the oven to improve efficiency and reduce cooking time (Sullivan 1995). Energy cost comparisons of different cooking methods by RMI (1994) show the highest energy cost (16 cents) for electric ovens and the lowest energy cost (3 cents) using for microwave ovens for cooking an equivalent amount of food.

2.1.5.4. Home Electronics

According to Rosen and Meier (2000) major consumer electronics in the U.S. homes include video and audio products, set-top boxes, and telephones and related devices, which accounted for over 10% of the U.S. residential electricity consumption in 1999. They estimated that 60% of the energy used by consumer electronics was consumed in the standby mode. Another study by Ross and Meier (2000) showed that the total standby power in California homes ranged 5-26% of their annual electricity use. The large variation in the standby power of similar appliances demonstrated that some manufacturers were able to reduce standby losses without degrading performance. Their study estimated a 68% reduction in standby losses by replacing existing units with appliances with 1Watt or less of standby power.

All these studies suggest a significant energy-saving potential through the use of energy-efficient appliances and following good practices for energy-efficiency. Information about the top-rated energy-efficient products on the market is available in Wilson et al. (2003) and ACEEE (2004) that were helpful in estimating the reduction in appliance energy use for the improved house. These options were analyzed with the DOE-2 in a simplified manner, by using an equivalent constant load from the total annual energy use for the selected energy-efficient appliances.

2.2. Optimized Combinations of Strategies for Energy-Efficient Residences

Several studies have investigated the energy-saving potential of multiple energy-efficient measures applied in combination. This section discusses some of these studies, including: Rasisuttha and Haberl (2004), Gamble et al. (2004), Chulsukon (2002) and Kootin-Sanwu (2004).

Rasisuttha and Haberl (2004) analyzed individual and combined effect of various energy-efficient strategies for building components, building systems and renewable energy systems, in order to reduce energy consumption in residential buildings (partially air-conditioned at night), in a hot and humid climate region (Thailand). They showed maximum total energy savings (9.08%) resulting from light-weight concrete block walls with insulation on the inside wall, when compared to the basecase house with 4-inch brick walls. They also showed that this strategy combined with improved ceiling insulation, replacement of single pane clear glass with double-pane low-e glazing, exterior shading, efficient systems, lighting and refrigerator resulted in 20% savings. Further addition of solar thermal and photovoltaic (PV) systems to the above combination reduced the annual energy use by 72.58%.

Chulsukon (2002) examined the lifetime building energy consumption of a similar house (partially air-conditioned at night) in Bangkok, Thailand. In order to reduce the energy required for the building operation, he analyzed several strategies that included: insulated walls and roof, improved glass type, light-colored exterior surfaces, increased ground reflectance and variation in thermostat setting. He showed maximum annual energy savings of up to 13% from improved glass type and from variation in thermostat setting, followed by 3-4% savings from wall insulation, roof insulation, and light-colored exterior wall surfaces and 1-2% savings from increased ground reflectance and a light-colored roof. He demonstrated up to 30% annual energy savings by combining all the above mentioned strategies.

Gamble et al. (2004) demonstrated up to 75% energy savings in hot climates, from energy-efficiency packages that include: advanced framing, decreased window area, increased insulation, windows with lower U-values and SHGC, addition of overhangs and porches, lower absorptivity roofs, decreased infiltration, programmable thermostats, installation of Energy Star products for lighting and appliances, efficient heating, cooling and water heating equipment, and ductwork with reduced leakage. They also showed a net-zero energy use by coupling such upgrade packages with PV systems, with net overall costs close to that of standard code built homes.

Kootin-Sanwu (2004) investigated the energy-saving potential of envelope, systems and landscape improvements for low-income housing in the hot-humid climates of the U.S. He found CFL replacement, use of equipment without pilot lights, and air-conditioner with a longer-lasting stainless steel heat exchanger as the most economically favorable measures. Improved insulation had a small effect on the annual electricity use. However, it produced significant cooling energy savings in the summer.

These studies helped in determining the most effective combination of energy-efficient strategies that could minimize the energy use in residences. Besides, these studies provided advice on how the energy-efficient measures were simulated, since the analyses were performed using DOE-2 simulation program.

2.3. Case Studies of High-Performance Houses

Case studies of energy-efficient houses provide an extensive opportunity for a comparative analysis, with an emphasis on the following parameters: 1) building characteristics, 2) mechanical and electrical systems, 3) energy-efficient measures, 4) added cost of incorporating these measures, 5) energy performance, and 6) cost savings. The case studies that were reviewed include: Building America homes in the United States (Building America 2004), the IBACOS demonstration home in Pittsburg, Pennsyslvania (Kent 2003), Oak Ridge National Laboratory's net-zero energy home in Tennessee (Christian 2005 and Christian et al. 2003), Hammond's off-grid house in Arizona (Casebolt 1993), and the high efficiency houses in Colorado (Smith 2001).

Energy-efficient features in Building America's high performance production homes in six different climate regions of U.S. included advanced framing, detailed air sealing and insulation, double-pane, low-e, vinyl-framed windows, an un-vented attic, efficient systems, fan cycling and an outside air damper cycling controls as common features. These features allowed downsizing of the air conditioner and a simplified duct layout, which helped offset the added cost of incorporating these features (Building America 2004).

The IBACOS demonstration home, in Pittsburg, Pennsylvania, has an improved building envelope, improved floor framing and duct design, efficient lighting, systems and appliances, and energy recovery ventilators (ERVs). These features increased the construction cost by approximately 5% and reduced annual cooling and heating (space and water) energy use by more than 55% beyond the 1993 MEC benchmark (Kent 2003).

Christian (2005) provided the general features of the four ORNL near net-zero energy homes built in Tennessee, and focused on the first of these four houses for reporting measured energy performance. The common features of these houses are: an airtight envelope with structural insulated panels (SIPs); efficient windows (0.34 U-factor, 0.33 SHGC); ducts inside the conditioned space; solar PV; mechanical ventilation; efficient lighting, systems and appliances; reflective, standing-seam, metal roof; and an integrated heat pump water heater (HPWH). The metering results of the first ORNL net-zero energy home showed 35% heating and cooling energy savings from the ducts inside the conditioned space, 10% less energy use from SIPs, 60% DHW savings from the HPWH and 5% DHW savings from the heat recovery shower. These features increased the construction cost of the first zero energy home by 57%; while, combined with the grid-connected 2 kW solar PV, they resulted in 65% energy cost savings (Christian et al. 2003).

Hammond’s off-grid solar home in Arizona, which is equipped with a PV system with a back-up generator, has a cathedral ceiling, open plan, thermal mass, an earth-sheltered basement, overhangs and decks on the large south-facing windows, high insulation levels, passive ventilation, efficient lighting, systems and appliances, roof rain-water collection, a low-flush toilet, low-flow shower heads, a closed-loop water circulating system, and insulated hot water lines. These features accompanied with energy and water conserving practices allowed the installation of a smaller, less expensive PV system. These measures reduced the energy use to 855 kWh/year as compared to 9,300 kWh in nearby homes (Casebolt 1993).

A passive solar house in West Pueblo, Colorado had air-tight concrete construction, natural ventilation with thermal mass, shading, solar heating, and efficient windows that resulted in 56% energy savings as compared to the MEC base-case house. The analysis indicated a potential energy savings of 70.4% with increased insulation (Smith 2001).

From these studies, it is found that improved an building envelope, efficient windows, and efficient lighting, systems and appliances are the most common measures that provided significant energy savings.

2.4. Simulation Software for Energy-Efficient Building Design

Software tools that are used for energy-efficient building designs were reviewed to better understand their capabilities, and to identify the simulation options. The software tools that were found to have significant importance include HEED (EERE 2005 and UCLA 2005), Home Energy Saver (EERE 2005 and LBNL 2005), EnergyGauge USA (EERE 2005, Parker et al. 1999), and BEopt (Christensen et al. 2005) for simulating various energy-efficient options.

HEED (Home Energy Efficient Design), developed by UCLA (2005) is an energy design tool that compares a user defined building against two basecase buildings, one that meets the energy code and another that incorporates more energy-efficiency features. It lets the user make various remodeling changes and see their effect on building energy use. The options that can be analyzed include building shape and orientation, envelope, windows, shading (fixed and operable), thermal mass, ventilation, daylighting, appliances, internal loads, and HVAC systems (EERE 2005). It estimated the energy cost of $1821.75 for the building similar to the basecase located in California that meets the California Energy Code, $1442 (22% savings) for the basecase house compliant with IECC (2000), and $923 (49% savings) for the most energy-efficient building (UCLA 2005).

Home Energy Saver is an internet-based, decision-support tool for calculating energy use for all end uses in residential buildings. The computation is based on the methods developed at Lawrence Berkeley National Laboratory (including DOE-2 for the HVAC calculations). Separate modules are provided for heating/cooling, envelope, domestic hot water, appliances and miscellaneous uses, and lighting. By simply changing one or more features, users can estimate how much energy can be saved by implementing energy-efficiency improvements (EERE 2005). The energy bill for an average house in Houston was estimated as $1706 and $962 for an efficient house. Based on the input for the basecase house, the annual energy bill was estimated to be $1785 (LBNL 2005).

EnergyGauge USA allows calculation and rating of energy use of residential buildings, and analysis of Manual-J system sizing (ACCA 2004) and cost-effectiveness of energy upgrades. It uses the DOE-2.1e with a number of enhancements, which allow simulation of duct air leakage and heat transfer, air infiltration, mechanical ventilation systems and improved modeling of slab, crawlspace, basement foundation types and thermal bridging in stud assemblies and improved calculation of HVAC systems (EERE 2005 and Parker et al. 1999).

Christensen et al. (2005) described the BEopt – a software for identifying optimal building designs on the path to net zero energy, where the user selects from predefined options to be considered in the optimization. Energy savings are calculated relative to a reference: either a user-defined basecase building or a climate-specific Building America benchmark building automatically generated by the BEopt. At each step along the path, the BEopt runs individual simulations using DOE-2 and TRNSYS for all user selected options and searches for the most cost-effective combination of options.

These reports provided a well-structured methodology for identifying optimal building designs. However, certain issues were not fully explained or considered. For example, there was no description about how the building geometry was input using the BEopt software. Also, the report did not explain the basecase cost by component, against which the additional cost could be compared. Finally, the strategies that could be included as predefined options were different construction types and the layering of exterior surfaces, frame types, shading options.

2.5. Summary of Literature Review

This thesis focuses on residential energy-efficiency in hot and humid climates. Therefore, residential building systems and components were investigated in terms of their cost-effective ability to reduce energy use. The combined energy-saving potential of different measures was investigated from the studies focused on the whole-building energy use and case-studies of high-performance homes. Simulation software for energy-efficient building design were reviewed to identify simulatable design options and their ability to provide a cross-check of the simulation results, as needed. These studies helped in developing the basecase house, determining the measures to be analyzed with the DOE-2 simulation program, determining the combinations of measures that minimize energy use, and compare the simulated savings from this study.

The energy-efficient strategies that were analyzed in this study include those that could be simulated with DOE-2, which are associated with the building geometry; construction type with different materials, insulation levels and thermal mass; finish materials; fenestration system that includes glass and frame type, exterior shading, window area and window distribution in different orientations; energy-efficient space heating and cooling systems, domestic hot water heating systems; and energy-efficient lighting and appliances. Among the strategies studied, natural ventilation and daylighting were not analyzed, considering the limitations of the DOE-2 simulation program in accurately modeling their effect on building energy use. Therefore, further investigation is suggested utilizing supplementary simulation programs to test the effect of airflow and daylighting.

3. SIGNIFICANCE OF THE STUDY

3.1. Significance of the Work

This thesis is significant to the development of energy-efficient residences in hot and humid climates because it demonstrates a methodology to maximize building energy savings by combining available techniques and design options, and evaluating their combined energy-saving potential. The combination of energy-efficient strategies includes many strategies that have been analyzed separately or have not been analyzed in combination with other strategies. By investigating the combined energy-saving potential, this study facilitates the selection of an optimum combination of energy-saving strategies that could minimize the building energy use.

3.2. Limitations of the Study

The limitations of this study are:

1) The analysis was performed using a DOE-2 simulation model of a house.
2) The simulation model of the basecase house was assumed to represent only certain aspects of a typical house in hot and humid climates. Selected features, such as a high pitch roof with a vented attic and a high ceiling were not included because they required special DOE-2 function commands which were beyond the scope of this thesis.
3) The basecase house is 2000 IECC compliant. Therefore, the energy savings from different measures were calculated against the basecase house.
4) The analysis was performed using a single-family detached house only in the hot and humid climate of Houston, Texas, and
5) The energy-saving options that were analyzed are limited to those that DOE-2 programs can simulate. This excluded the analysis of natural ventilation, air movement, dayligting and a high pitch roof with naturally vented attic.

4. METHODOLOGY

4.1. Introduction

The methodology adopted for this study included a survey of the previous studies as discussed in the literature review, determination of the characteristics of the basecase house, development of the DOE-2 simulation model, simulation of the house with basecase characteristics and with energy-efficient measures, and an economic analysis of those measures.

Figure 1 shows the steps that were followed in this study. First, the characteristics of the basecase house, which included: the size of the house, layout, occupancy, envelope, HVAC and DHW systems, lighting, and equipment, were determined. In the second step, these characteristic were incorporated into the DOE-2 simulation model of the house. The third step involved an analysis of the energy-saving potential of simulatable energy-efficient measures using the DOE-2 program. For this, the characteristics of the basecase house were improved by applying energy-efficient measures individually and in combination. The fourth step involved the development of the maximum energy-efficient house by applying potential energy-saving measures incrementally to the basecase house. The fifth step involved an economic analysis of those measures to assess the cost-effectiveness of their individual and combined application.

In all these steps, previous studies were reviewed to determine the characteristics of the basecase house; to investigate available energy-saving measures, their energy-saving potential, conditions for their optimal performance, and their ability to be simulated; and to determine various costs associated with them. The following sections describe these steps in detail.

4.2. Determination of the Characteristics of the Basecase House

This study targets single-family detached houses in the hot and humid climate of Houston, Texas in the United States. For this study, a DOE-2 simulation model of a 2000 International Energy Conservation Code (IECC) compliant house in Houston, Texas was selected as the basecase. The characteristics of the house were determined from the following sources:

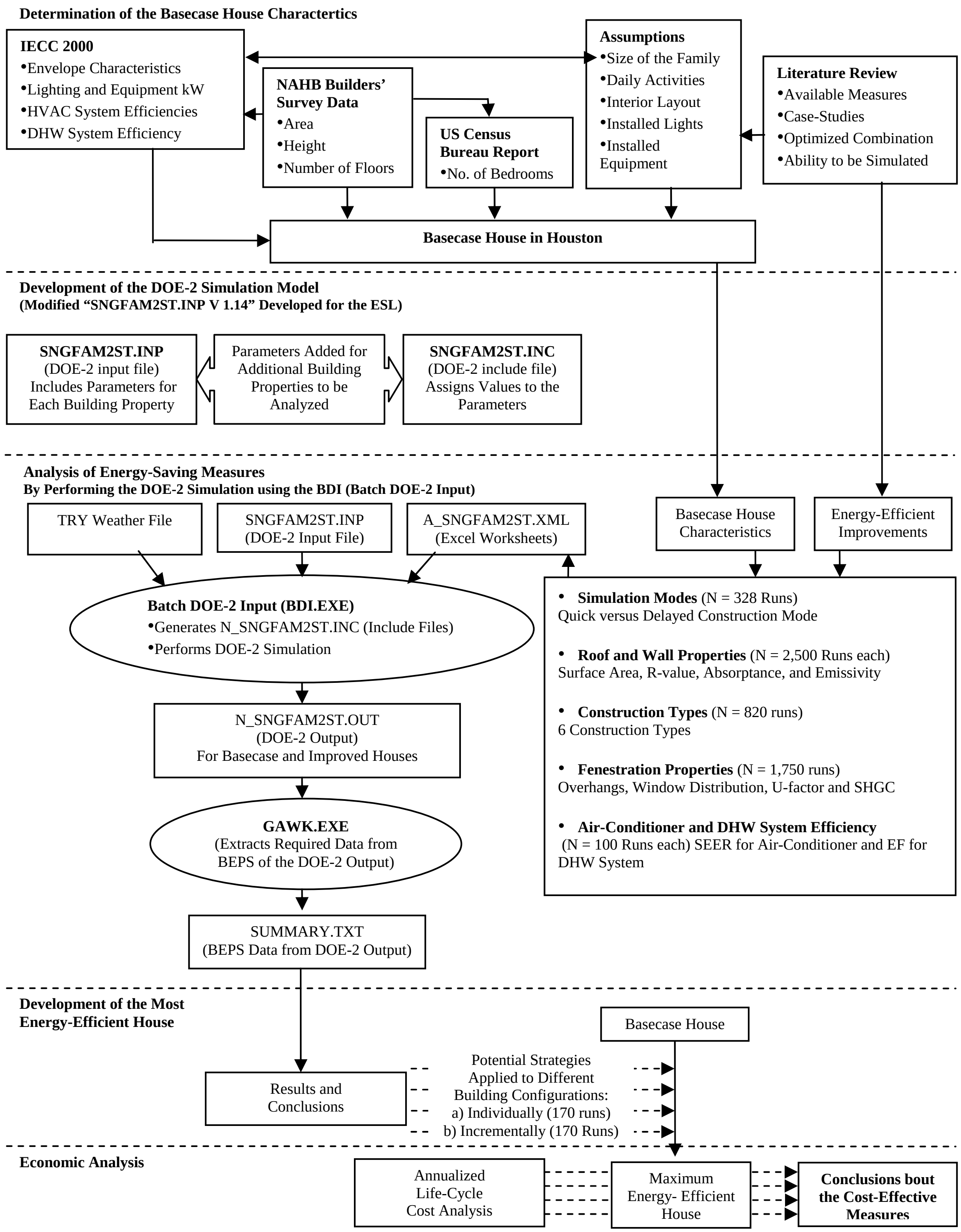


Figure 1: Methodology

1) The size of the house, in terms of its conditioned floor area, number of floors and floor height, was determined from survey data by the National Association of Home Builders (NAHB 2003).
2) The number of bedrooms was determined from the housing survey report by the U.S. Census Bureau (USCB 2002).
3) The characteristics of the building envelope, HVAC system, and DHW system were determined from the specifications given in the 2000 IECC, as modified by the 2001 Supplement (ICC 1999) for a house located in Houston, Texas.
4) Assumptions were made about the daily activities of the occupants. These assumptions were used to estimate the lighting load. The equipment loads were adopted from Energy Star (2002).
5) The total internal heat gain from lighting and equipment loads were set to match the constant load for the standard house as specified in Section 402.1.3.6 of the 2000 IECC.

A brief listing of the characteristics of the basecase house is included in Table 1. A detailed description of these characteristics is included in Section 5.

4.3. Development of the DOE-2 Simulation Model

<u>DOE-2 Input File</u>

The DOE-2 simulation model for this study was adopted from the input file – SNGFAM2ST.INP version 1.14, developed by the Energy Systems Laboratory (ESL). This input file was being developed to evaluate amendments above the building energy codes for single-family, one and two-story detached houses, and to quantify the resulting energy savings and emission reductions for the Senate Bill 5 (Senate Bill 5 2005). This input file used parameters instead of fixed values for various building characteristics, such as the building geometry, location, building envelope components, HVAC and DHW system, lighting, equipment, and occupancy. Values were assigned to these parameters using an external include file –

SNGFAM2ST.INC. The values of these parameters were modified to evaluate their effect on building energy use.

Modification to the DOE-2 Input File

To use the input file SNGFAM2ST.INP version 1.14, certain changes were made to incorporate the characteristics of the basecase house. Also, new parameters and macros for specifying construction type, airtightness level, lighting and equipment load, and different options for specifying the window distribution and window properties, were added to incorporate the simulatable energy-saving upgrades identified from the previous studies. The details of the modifications to the input file are provided in Section C.1, Appendix C.

4.4. Analysis of Energy-Saving Measures Using the DOE-2

The simulatable energy-saving measures for the building configuration, envelope and system characteristics were selected for the analysis. The energy-saving potential of these measures was analyzed using the DOE-2 simulation, supplemented by other programs and files. Section 6 presents the results of the simulations as graphs, and analyzes the energy use and savings. The analysis is supported by the tables in Appendix D that present the percent energy savings for the selected intermediate values of building parameters.

Supplementary Programs and Files

For performing the DOE-2 simulation and analyzing the results, the following supplementary programs and files that used: (a) WINDOW 5, a computer program, for creating DOE-2 window library entries for the basecase windows and the improved windows; (b) the TRY weather data for Houston, Texas for the year 1999; (c) the BDI (Batch DOE-2 Input) program, developed by the ESL, to perform the DOE-2 simulations in the batch mode; and (d) the GAWK program, to extract the desired data from the DOE-2 output. Section C.2, Appendix C includes the modified DOE-2 window library entries created by the WINDOW-5 program. Section C.3, Appendix C demonstrates the working of the BDI and the GAWK programs.

DOE-2 Simulations

The building properties whose effect on the building's energy use was analyzed are listed in Table 1 and are discussed in detail in the following section.

Table 1: List of Building Properties Analyzed

Properties	**Values Used for the Basecase**	**Values Used for the Analysis**	**Reference Table**
Building Configuration	1:1 Width-to-Depth Ratio, One-story (In Quick and Delayed Construction Modes)	1:3 to 3:1 Width-to-depth Ratio, One and Two-story (In Quick and Delayed Construction Modes)	Table 2
Roof and Wall Properties			Table 3
Absorptance	Roof: 0.82 (Aspen Gray Asphalt Shingles) Walls: 0.55 (Light-Buff Brick Facia)	0.25 (Light-Color Surfaces) to 0.85 (Dark-Color Surfaces)	
Emissivity	Roof: 0.9 (Aspen Gray Asphalt Shingles) Walls: 0.9 (Light-Buff Brick Facia)	0.1 (metallic surfaces/paints) to 0.9 (non-metallic surfaces)	
Insulation	Roof: R-30 (10" Thk. Fiberglass Batt Insulation) Walls: R-11 (3.5" Thk. Fiberglass Batt Insulation)	R-10 to R-55	
Construction Type	Wood-Frame with 2x4 Studs @ 16" o.c. for Walls and 2X10 Joists @ 16" o.c. for Roof	Basecase Construction Advanced Wall Framing for Walls and Roof Structural Insulated Panels for Walls and Roof Insulated Concrete Foam Walls Concrete-Filled Concrete Masonry Unit for Walls Perlite-Filled Concrete Masonry Unit for Walls	Table 6 and Table 7
Fenestration			Table 8
Window Distribution	Windows (18% of the Floor Area) Distributed Equally on All orientations	Different Windows Distributions to place up to 75% on South, 15% on North, 5% on East and 5% on West	
Exterior Shading	No Overhang	0 to 4 ft. Overhangs	
Glazing U-factor	0.47 (Double-Glazed Low-e Air-Flled Windows)	0.2 (Double-Pane, Low-e or Triple Pane) to 1.2 (Single Pane)	
Glazing SHGC	0.4 (Double-Glazed Low-e Air-Flled Windows)	0.25 (Tinted or Reflected Glazing) to 0.85 (Clear Glazing)	
Air-Conditioner and DHW Systems			Table 10
Air-Conditioner Efficiency	SEER-10	SEER-10 to SEER-18	
DHW System Efficiency	54.4 EF	45 to 90 EF	

For analyzing the effect of changing characteristics of different building systems and components, the corresponding parameters of the input file were assigned different values, as shown in Table 1, using the BDI spreadsheets. Five BDI spreadsheets were created corresponding to five building systems and components that includes: (a) building configuration, (b) roof and walls, (c) construction type, (d) fenestration and (e) air-conditioner and DHW system. Each row in a BDI spreadsheet corresponded to a distinct scenarios or a distinct set of values for various parameters related to one of the five building systems and components. These spreadsheets were used to perform the DOE-2 simulations in the batch mode using the BDI program. Simulations were performed according to the simulation plan as described in the following sections. Using the GAWK program, the annual energy use for different end-uses was extracted from the Building

Energy Performance Summary (BEPS) of the output files. Finally, the extracted data from the BEPS was plotted and analyzed. Also, the hourly outside air temperatures, room temperatures, heating fuel and cooling electricity use from the Hourly-Report for the peak summer and the peak winter days were plotted to analyze the effect of thermal mass associated with certain measures.

The following sections discuss the plans for performing DOE-2 simulation with changing characteristics of building systems and components, and for analyzing the results of the simulation.

4.4.1. Quick and Delayed Construction Modes

For the DOE-2 simulation, the construction for the exterior walls and roof can be specified using on of the two approaches: the quick method and the delayed method. The quick method uses U-value and pre-calculated ASHRAE weighting factors. This approach is used to specify a steady state, or “quick”, construction that has little heat capacitance and where heat flow is not delayed. The delayed method uses layered construction and custom weighting factors. This approach is used to specify a dynamic, or “delayed”, construction where the calculation of heat transfer considers time and thermal mass. Specifying a construction using the “delayed” method tends to produce more accurate results, especially with massive wall construction (DOE 1980).

This study used both, the quick and delayed methods, for the simulation. The quick method was used to analyze the effect of increasing the R-value, reflectance, and emissivity of the roof and exterior walls. It allowed specifying different values for these properties without having to change materials, thus, obtain the results of the simulation free from the effect of thermal mass of those materials. For analyzing other measures, the delayed method was used to obtain more accurate results. Therefore, prior to further analysis, the difference between the results of the simulation using quick and delayed methods was analyzed and quantified.

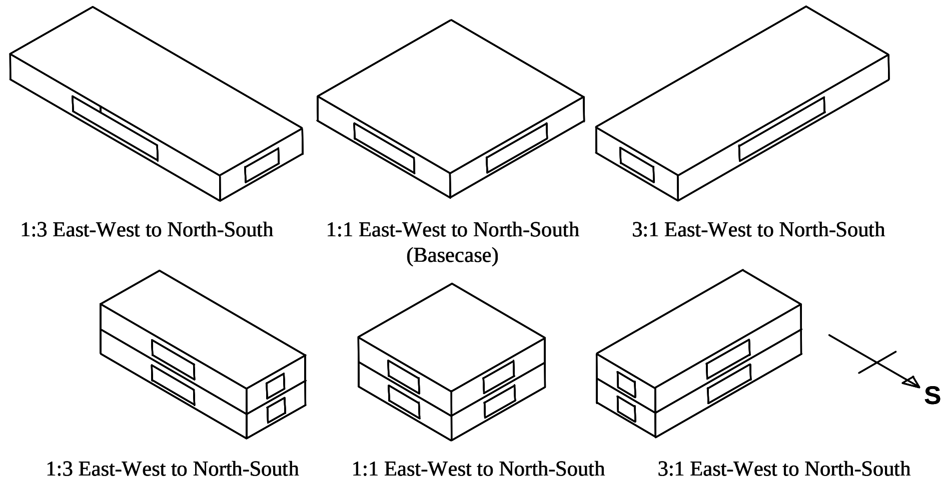
Plan for the Simulation

Table 2 shows the simulation plan for the analysis. Simulations were performed in quick and delayed modes for different building configurations of a fixed 2,500 ft^2 gross floor area of the basecase house. For this, the aspect ratio (east-west to north-south) of the house was changed from 1:3 to 3:1 in the increments of 0.1 for both, the one-story and the two-story configurations. In addition, one set of simulations was performed keeping the gross window area fixed to 18% of the conditioned floor area, as in the basecase house. Another set of simulations was performed keeping the window-to-wall area ratio on each orientation fixed to 28% that corresponds to 18% window-to-floor area ratio of the square-shape basecase house. The other characteristics were same as in the basecase house.

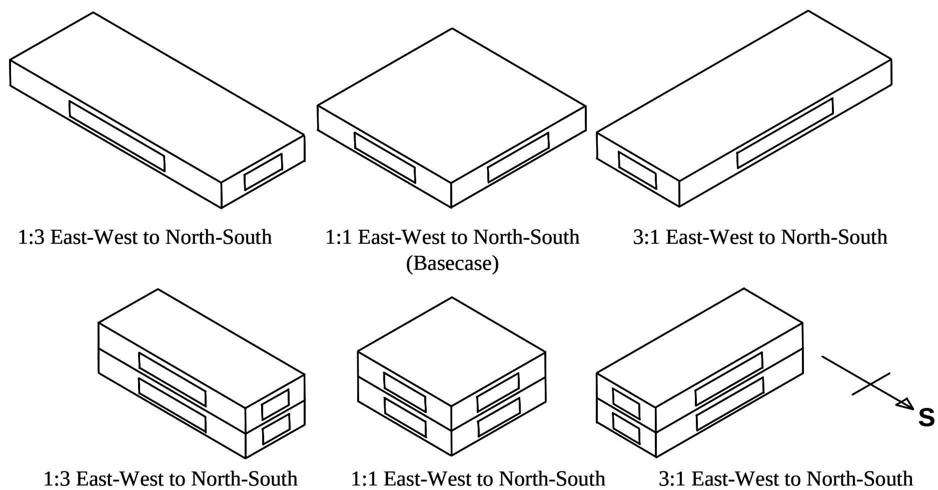
Table 2: Simulation Plan for Quick and Delayed Construction Modes

Window Area	Simulation Mode	Number of Floors	Aspect Ratio (East-West to North-South)	Number of Simulations
18% window to conditioned floor area	Quick Construction	One story	1:3 to 3:1 incrementally	41
		Two story		41
	Delayed Construction	One story		41
		Two story		41
28.125% window to wall area	Quick Construction	One story		41
		Two story		41
	Delayed Construction	One story		41
		Two story		41
			Total	328

Figure 2 shows the variation in the building shapes and window area for the east-west to north-south aspect ratio of 3:1, 1:1 and 1:3, respectively, for one and two-story configurations, keeping the (a) window-to-floor area ratio fixed to 18%, and (b) window-to-wall area ratio fixed to 28%. The first set with constant window-to-floor area ratio shows different building shapes having equal gross window area; whereas the second set with constant window-to-wall area ratio shows different building shapes with increased gross window area due to increased exterior wall area of elongated and/or two-story configurations. A total of 328 simulation runs were performed and the annual energy use was plotted for the analysis. In addition, the hourly outside air and room temperatures, and heating fuel and cooling electricity use for the peak summer and the winter days were plotted to analyze the effect of the thermal mass.



(a) Gross Window Area - 18% of the Conditioned Floor Area



(b) Gross Window Area - 28% of the Exterior Wall Area

Figure 2: Building Shapes for Different Aspect Ratio and Number-of-Floors (Floor Area = 2,500 ft^2)

4.4.2. Roof and Wall Properties

The amount of heat gain/loss through the building envelope depends on the R-value, absorptance and emissivity of the exposed surfaces. The roof and walls contribute to different amounts of heat gain/loss due to the difference in the angle of incident solar radiation. Therefore, the effect of R-value, absorptance and emissivity was analyzed for both, the roof and walls. Since the heat gain/loss through the building envelope depends on the exposed area of roof and walls, the analysis was performed using different building configurations of equal floor area that have different exposed area for the roof and walls. The effect of changing R-value, absorptance and emissivity for different building configurations was analyzed in combination to assess their thermal performance in different scenarios and identify the conditions for their optimal performance.

Plan for the Simulation

Table 3 shows the simulation plan for the analysis. The same simulation plan was used for analyzing both, the roof and the wall properties. First, the R-value of the roof/walls was changed from 10 Btu/hr-ft^2-ºF to 55 Btu/hr-ft^2-ºF in the increments of 5 Btu/hr-ft^2-ºF. The surface absorptance was changed from 0.25 to 0.85 in the increments of 0.15. The emissivity was changed from 0.1 to 0.9 in the increments of 0.2. For the range of values analyzed, higher R-values are achieved by using higher thickness of insulation. The lower values of emissivity are associated with metal surfaces and metallic paints, such as aluminum, copper, bronze paint, galvanized sheet, stainless steel etc.; whereas higher values are associated with non-metallic surfaces such as plaster, paint, brick, concrete, sand, asphalt etc. Similarly, the lower values of absorptance are associated with light-color surfaces, whereas higher values of absorptance are associated with dark-color surfaces. The values used for the properties of walls/roof are ranges to obtain a continuous curve. The properties of available materials and assemblies do not exactly match with all the combinations analyzed.

Simulations were performed for different building configurations of equal floor area, by changing the east-west to north-south aspect ratio from 1: 1 to 3:1 for one and two-story house. Simulations were performed in the quick mode to specify different values for these properties without having to change materials, thus, obtain the results of the simulation free from the effect of thermal mass of those materials. The other characteristics were same as in the basecase house.

Table 3: Simulation Plan for Roof and Wall Properties

Building Configuration	Surface Emissivity	Surface Absorptance	Insulation Level	Number of Simulations for Roof Properties	Number of Simulations for Wall Properties
1:1, 1-story (Basecase) 1:1, 2-story 1.5:1, 1-story 1.5:1, 2-story 2:1, 1-story 2:1, 2-story 2.5:1, 1-story 2.5:1, 2-story 3:1, 1-story 3:1, 2-story	0.9 (for Basecase Roof and Walls)	0.25	R-10 to R-55 incrementally (R-10, for Basecase Walls, R-30 for Basecase Roof)	100	100
		0.4		100	100
		0.55 (for Basecase Walls)		100	100
		0.7		100	100
		0.85 (for Basecase Roof)		100	100
	0.7	0.25	R-10 to R-55 incrementally	100	100
		0.4		100	100
		0.55		100	100
		0.7		100	100
		0.85		100	100
	0.5	0.25	R-10 to R-55 incrementally	100	100
		0.4		100	100
		0.55		100	100
		0.7		100	100
		0.85		100	100
	0.3	0.25	R-10 to R-55 incrementally	100	100
		0.4		100	100
		0.55		100	100
		0.7		100	100
		0.85		100	100
	0.1	0.25	R-10 to R-55 incrementally	100	100
		0.4		100	100
		0.55		100	100
		0.7		100	100
		0.85		100	100
			Total	2500	2500

A total of 2,500 simulation runs were performed for each, the roof and walls, and the annual energy use was plotted for the analysis.

Plan for the Analysis of the Results

Table 4 and Table 5 show the plan for analyzing the results of the simulation. Among the four variables, i.e. building configuration, R-value, absorptance and emissivity, the effect of changing each variable on the energy performance of the remaining three variables was analyzed. This was accomplished by selecting the scenarios where only two variables A and B were changed at a time, and the remaining two were constant as in the basecase house. For each value of variable A, the annual energy use was plotted against the variable B on the X-axis. The resulting graph shows the effect of changing variable A on the energy performance of variable B. The reference figures for these plots are listed in column 3. The reference tables quantifying the percent energy savings/penalty from the variable B, for different values of variable A, are listed in column 4.

Table 4: Plan for the Analysis of Roof Properties

Parameter 1 (Along X-axis)	Parameter 2 (Varied)	Reference Table (Appendix D)	Reference Figure (Section 6)
Roof Insulation	Building Configuration	Table D- 2	Figure 12
Roof Absorptance		Table D- 3	
Roof Emissivity		Table D- 4	
Building Configuration	Roof Insulation	Table D- 5	Figure 13
Roof Absorptance		Table D- 6	
Roof Emissivity		Table D- 7	
Building Configuration	Roof Absorptance	Table D- 8	Figure 14
Roof Insulation		Table D- 9	
Roof Emissivity		Table D- 10	
Building Configuration	Roof Emissivity	Table D- 11	Figure 15
Roof Insulation		Table D- 12	
Roof Absorptance		Table D- 13	

Table 5: Plan for the Analysis of Wall Properties

Parameter 1 (Along X-axis)	Parameter 2 (Varied)	Reference Table (Appendix D)	Reference Figure (Section 6)
Wall Insulation	Building Configuration	Table D- 14	Figure 16
Wall Absorptance		Table D- 15	
Wall Emissivity		Table D- 16	
Building Configuration	Wall Insulation	Table D- 17	Figure 17
Wall Absorptance		Table D- 18	
Wall Emissivity		Table D- 19	
Building Configuration	Wall Absorptance	Table D- 20	Figure 18
Wall Insulation		Table D- 21	
Wall Emissivity		Table D- 22	
Building Configuration	Wall Emissivity	Table D- 23	Figure 19
Wall Insulation		Table D- 24	
Wall Absorptance		Table D- 25	

For example, the basecase house was a square-shape, one-story house, with a roof R-value of R-30, roof absorptance of 0.85 and roof emissivity of 0.9. First, the scenarios with different building configurations and different R-values were selected. The absorptance and the emittance of the roof were same as in the basecase. Next, for each building configuration, the annual energy use was plotted against roof R-value on the X-axis. Similar steps were followed to plot the annual energy use against roof absorptance and roof emissivity on the X-axis. The reference figure on p. 75 shows three graphs, each includes several lines, each line showing the reduction in annual energy use from changing one property for one building configuration. A set of such lines demonstrates the effect of different building configuration on the thermal performance of that property.

4.4.3. Construction Type

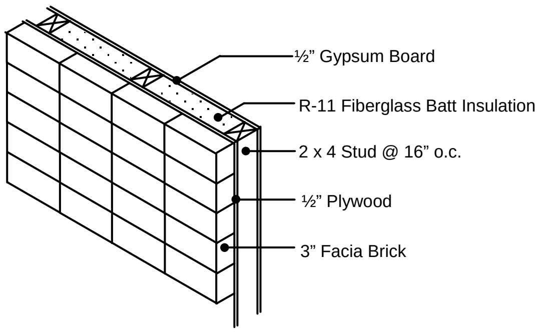
The effect of different construction types was analyzed for different building configurations to find the combination that could result in minimum annual energy use. Besides the basecase construction type, i.e. 2x4 wood-frame spaced at 16 on center (WL16), the other wall construction types that were analyzed include: better insulated 2x6 wood-frame spaced at 24 inch on center (WL24), structural insulated panels (SIPW), insulated concrete forms (ICFW), and 8 inch thick concrete-filled concrete blocks (CFCB) and 8 inch thick perlite-filled concrete blocks (PFCB). The exterior finish of the walls and roof was the same as the basecase house. The details of different construction types for exterior walls and roof, and their overall R-values are summarized in Table 6 and are shown in Figure 3 and Figure 4.

Plan for the Simulation

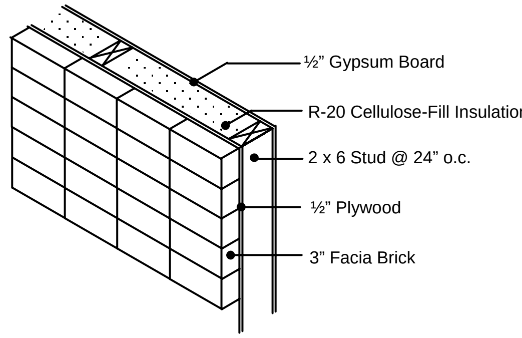
Table 7 shows the simulation plan for the analysis. Simulations were performed for different construction types, for different building configurations of 2,500 ft^2 gross floor area (which is same as the basecase house). For this, the aspect ratio (east-west to north-south) was changed from 1:3 to 3:1 in the increments of 0.1 for both, the one-story and two-story house. In addition, in order to incorporate the effect of reduced air infiltration achieved from airtight SIP and ICF construction, one set of simulations was performed assuming the airtightness of the building envelope equal to 0.46 ACH/hr, as specified in the 2000 IECC. Another set of simulations was performed assuming the building envelope to be 85% more airtight than the basecase construction, which corresponds to the airtight SIP house. A third set of simulations was performed assuming the building envelope to be 50% more airtight than the basecase construction, which corresponds to the airtight ICF construction for the walls. The other characteristics were same as in the basecase house. A total of 820 simulation runs were performed and the annual energy use was plotted for the analysis. In addition, the hourly outside air and room temperatures, and heating fuel and cooling electricity use for the peak summer and the winter days were plotted to analyze the effect of the thermal mass for each construction.

Table 6: Details of Different Construction Types for Exterior Walls and Roof

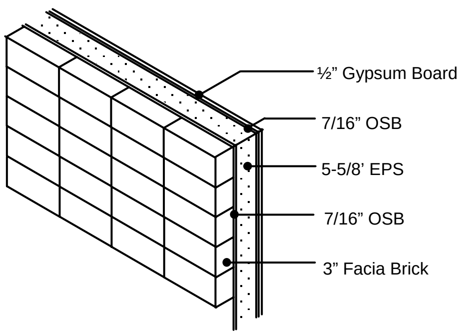
Name	Construction Type	Layers	Overall R-value
Exterior Wall Construction Type			
WL16	2x4 Wood Frame @ 16" o.c. (4.5" Thk.)	- BK04: 3" Brick (R = 0.33) - AL21: 3/4" - 4" Air Layer (R = 0.89) - PW03: 1/2" Plywood (R = 0.63) - IN02: 3.55" R-11 Fiberglass Batt Insulation (R = 11.83) (Insulation Part) or WD04: 3.5" Soft Wood (R = 4.37) (Stud) - GP01: 1/2" Gypsum Board (R = 0.45)	12.1
WL24	2x6 Wood Frame @ 24" o.c. (6.5" Thk.)	- BK04: 3" Brick (R = 0.33) - AL21: 3/4" - 4" Air Layer (R = 0.89) - PW03: 1/2" Plywood (R = 0.63) - IN14: 5.5" R-20 Cellulose-Fill Insulation (R = 20.37) (Insulation Part) or WD04 variation: 5.5" Soft Wood (R = 6.87) (Stud) - GP01: 1/2" Gypsum Board (R = 0.45)	19.27
SIPW	Structural Insulated Panels (7" Thk.)	- BK04: 3" Brick (R = 0.33) - AL21: 3/4" - 4" Air Layer (R = 0.89) - 7/16" OSB (R = 0.69) - IN37 Variation: 5-5/8" Expanded Polystyrene Insulation (R = 23.44) - 7/16" OSB (R = 0.69) - GP01: 1/2" Gypsum Board (R = 0.45)	26.49
ICFW	Insulated Concrete Forms (9.5" Thk.)	- BK04: 3" Brick (R = 0.33) - AL21: 3/4" - 4" Air Layer (R = 0.89) - IN37 Variation: 2.5" Expanded Polystyrene Insulation (R = 10.42) - CC24: 4" Medium-Weight Concrete (R = 1.6) - IN37 Variation: 2.5" Expanded Polystyrene Insulation (R = 10.42) - GP01: 1/2" Gypsum Board (R = 0.45)	24.11
CFCB	8" Concrete-Filled Medium-Weight Concrete Block	- BK04: 3" Brick (R = 0.33) - AL21: 3/4" - 4" Air Layer (R = 0.89) - IN35: 2" Expanded Polystyrene Insulation (R = 8.33) - CB32: 8" Concrete Filled Concrete Block (R = 1.34) - AL21: 3/4" - 4" Air Layer (R = 0.89) - GP01: 1/2" Gypsum Board (R = 0.45)	12.23
PFCB	8" Perlite-Filled Medium-Weight Concrete Block	- BK04: 3" Brick (R = 0.33) - AL21: 3/4" - 4" Air Layer (R = 0.89) - IN35: 2" Expanded Polystyrene Insulation (R = 8.33) - CB33: 8" Perlite-Filled Concrete Block (R = 5.84) - AL21: 3/4" - 4" Air Layer (R = 0.89) - GP01: 1/2" Gypsum Board (R = 0.45)	16.73
Roof Construction Type			
RF16	2x10 Wood Frame @ 16" o.c.	- AR02: Asphalt Shingle (R = 0.44) - BP01: Permeable Felt (R = 0.06) - PW05: 3/4" Plywood (R = 0.94) - IN05: 9.68" Fibreglass Batt Insulation (R = 32.26) (Insulation Part) or WD04 variation: 9.5" Soft Wood (R = 11.87) (Joist) - GP01: 1/2" Gypsum Board (R = 0.45)	29.74
RF24	2x10 Wood Frame @ 24" o.c.	- AR02: Asphalt Shingle (R = 0.44) - BP01: Permeable Felt (R = 0.06) - PW05: 3/4" Plywood (R = 0.94) - IN05: 9.68" Fibre Batt Insulation (R = 32.26) (Insulation Part) or WD04 variation: 9.5" Soft Wood (R = 11.87) (Joist) - GP01: 1/2" Gypsum Board (R = 0.45)	30.94
SIPR	SIP Roof	- AR02: Asphalt Shingle (R = 0.44) - BP01: Permeable Felt (R = 0.06) - 7/16" OSB (R = 0.69) - IN37 Variation: 9-3/8" EPS (R = 39.06) - 7/16" OSB (R = 0.69) - GP01: 1/2" Gypsum Board (R = 0.45)	41.39



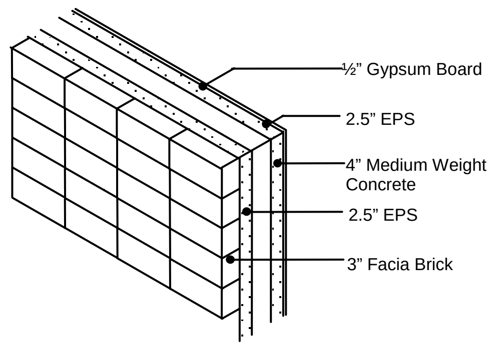
Basecase Construction
2x4 Wood-Frame @ 16" o.c. (4.5" Thk.)



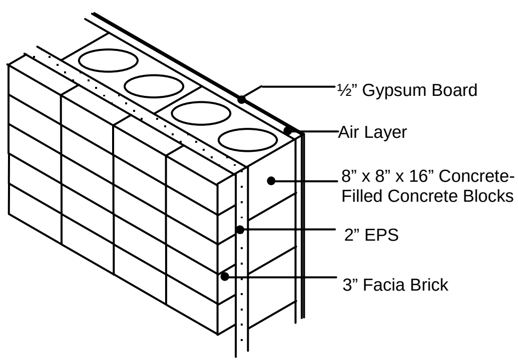
Advanced Wall Framing
2x6 Wood-Frame @ 24" o.c. (6.5" Thk.)



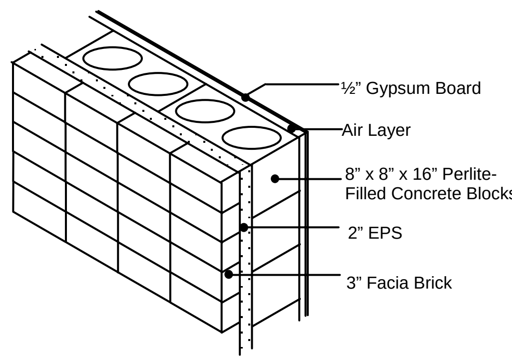
Structural Insulated Panels (7" Thk.)



Insulated Concrete Forms (9.5" Thk.)

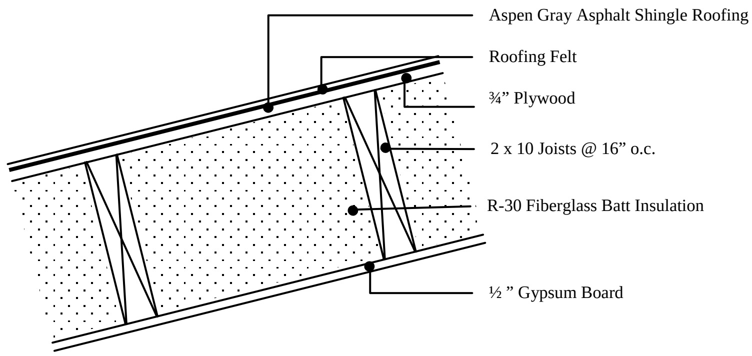


8" Concrete-Filled Concrete Blocks

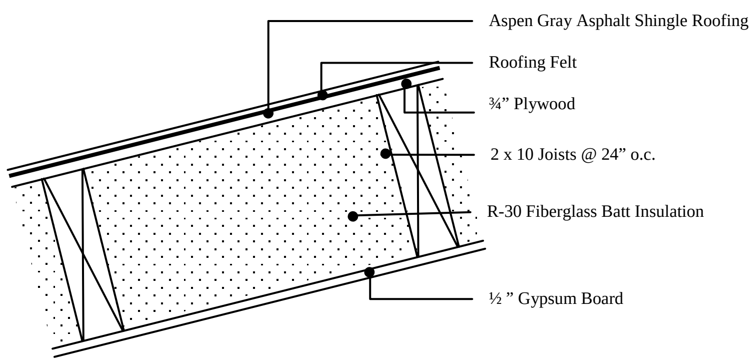


8" Perlite-Filled Concrete Blocks

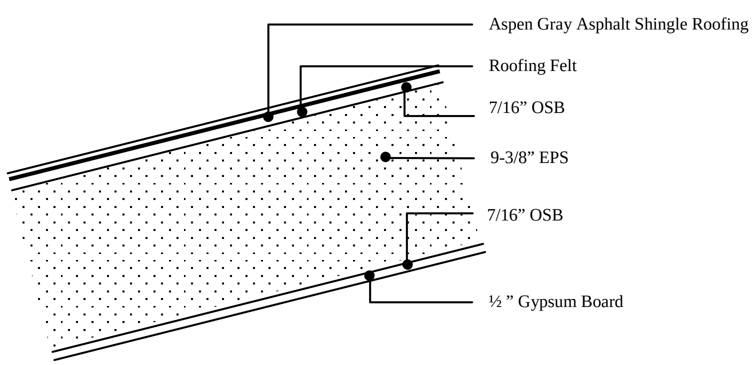
Figure 3: Details of Different Construction Types for Exterior Walls



Basecase Construction
2x10 Wood-Frame @ 16" o.c.



Advanced Wall Framing
2x10 Wood-Frame @ 24" o.c.



Structural Insulated Panels

Figure 4: Details of Different Construction Types for Roof

Table 7: Simulation Plan for Construction Types

Construction Type		Wall Type	Roof Type	ACH/hr	Number of Floors	Aspect Ratio (EW to NS)	Number of Simulations
A	2x6 Wood Frame @ 24" o. c. (Basecase)	WL16	RF16	0.46 (as specified in the 2000 IECC)	One-story (Basecase)	1:3 to 3:1 incrementally	41
					Two -story		41
B	2x4 Wood Frame @ 16" o. c.	WL24	RF24		One-story		41
					Two -story		41
C	Structural Insulated Panels (Only for Walls)	SIPW	RF24		One-story		41
					Two -story		41
D	Insulated Concrete Forms (Only for Walls)	ICFW	RF24		One-story		41
					Two -story		41
E	Concrete-Filled Concrete Block (for Walls)	CFCB	RF24		One-story		41
					Two -story		41
F	Perlite-Filled Concrete Block (for Walls)	PFCB	RF24		One-story		41
					Two -story		41
CC	Airtight SIP House	SIPW	SIPR	0.07 (Reduced by 85%)	One-story		41
					Two -story		41
AC	Equivalent Airtight Wood Frame House	WD16	RF24		One-story		41
					Two -story		41
DD	Airtight ICF House	ICFW	RF24	0.23 (Reduced by 50%)	One-story		41
					Two -story		41
AD	Equivalent Airtight Wood Frame House	WD16	RF24		One-story		41
					Two -story		41
						Total	820

4.4.4. Fenestration Properties

The heat gain/loss through the windows depends on the shading, window distribution on different orientations, U-factor and SHGC of the windows. The effect of improving these properties on annual energy use was analyzed to assess the individual performance and the impact of improving one property on the energy performance of other properties, and to find the optimum combination of fenestration properties that could result in minimum energy use.

Plan for the Simulation

Table 8 shows the simulation plan for the analysis. First, the U-factor was changed from 0.29 Btu/hr-ft^2-°F to 1.1 Btu/hr-ft^2-°F in the increments of 0.18, and SHGC was changed from 0.25 to 0.85 in the increments of 0.15. The lower values of U-factor are associated with double pane, low-e or triple pane glazing, and the higher values are associated with single pane glazing. Similarly, the lower values of SHGC are associated with reflected or tinted glazing, and the higher values are associated with clear glazing. The values used for the glass properties are ranges to obtain a continuous curve. The properties of available glass types do not exactly match with all the combinations analyzed. In addition to window U-value and SHGC, the window distribution was changed from equal windows on all four sides to the minimum windows on east, west and north, while keeping the window-to-floor area fixed at 18%. This was accomplished in two steps. First, the window area on east and west was reduced to 5% each and added to south, keeping the north window area fixed to 25% of the gross window area. Further, north window area was decreased to 15% to have 75% windows on the south. These combinations of fenestration properties were analyzed with different overhang depths on all four sides, starting from no overhang to a four-foot overhang, in increments of 1-foot. Simulations were performed using the shading coefficient method to be able to input different values for U-factor and SHGC. The other characteristics were same as in the basecase house. A total of 1,750 simulation runs were performed. The results from the BEPS were plotted for the analysis.

Table 8: Simulation Plan for Fenestration Properties

<table>
<tr><th>Overhang Depth</th><th>Window Distribution</th><th>U-factor</th><th>SHGC</th><th>Number of Simulations</th></tr>
<tr><td rowspan="25">0' to 6'
(0 feet, for the Basecase)</td><td rowspan="25">25,25,25,25
(Basecase)
35,25,20,20
45,25,15,15
55,25,10,10
65,25,5,5

75,15,5,5
65,25,5,5
55,35,5,5
45,45,5,5
35,55,5,5</td><td rowspan="5">0.29</td><td>0.25</td><td>70</td></tr>
<tr><td>0.4 (Basecase)</td><td>70</td></tr>
<tr><td>0.55</td><td>70</td></tr>
<tr><td>0.7</td><td>70</td></tr>
<tr><td>0.85</td><td>70</td></tr>
<tr><td rowspan="5">0.47 (Basecase)</td><td>0.25</td><td>70</td></tr>
<tr><td>0.4</td><td>70</td></tr>
<tr><td>0.55</td><td>70</td></tr>
<tr><td>0.7</td><td>70</td></tr>
<tr><td>0.85</td><td>70</td></tr>
<tr><td rowspan="5">0.65</td><td>0.25</td><td>70</td></tr>
<tr><td>0.4</td><td>70</td></tr>
<tr><td>0.55</td><td>70</td></tr>
<tr><td>0.7</td><td>70</td></tr>
<tr><td>0.85</td><td>70</td></tr>
<tr><td rowspan="5">0.83</td><td>0.25</td><td>70</td></tr>
<tr><td>0.4</td><td>70</td></tr>
<tr><td>0.55</td><td>70</td></tr>
<tr><td>0.7</td><td>70</td></tr>
<tr><td>0.85</td><td>70</td></tr>
<tr><td rowspan="5">1.1</td><td>0.25</td><td>70</td></tr>
<tr><td>0.4</td><td>70</td></tr>
<tr><td>0.55</td><td>70</td></tr>
<tr><td>0.7</td><td>70</td></tr>
<tr><td>0.85</td><td>70</td></tr>
<tr><td colspan="4">Total</td><td>1750</td></tr>
</table>

Plan for the Analysis of the Results

Table 9 shows the plan for analyzing the results of the simulation. Among the four variables, i.e. overhang depth, window distribution of all four orientations, U-value and SHGC, the effect of changing each variable on the energy performance of the remaining three variables was analyzed. This was accomplished by selecting the scenarios where only two variables A and B were changed at a time, and the remaining two were constant as in the basecase house. For each value of variable A, the annual energy use was plotted against the variable B on the X-axis. The resulting graph shows the effect of changing variable A on the energy performance of variable B. The reference figures for these plots are listed in column 3. The reference tables quantifying the percent energy savings/penalty from the variable B, for different values of variable A, are listed in column 4.

Table 9: Plan for the Analysis of Fenestration Properties

Parameter 1 (Along X-axis)	Parameter 2 (Varied)	Reference Table (Appendix D)	Reference Figure (Section 6)
Window Distribution	Overhang Depth	Table D- 27	Figure 22
U-factor		Table D- 28	
SHGC		Table D- 29	
Overhang Depth	Window Distribution	Table D- 30	Figure 23
U-factor		Table D- 31	
SHGC		Table D- 32	
Overhang Depth	U-factor	Table D- 20	Figure 24
Window Distribution		Table D- 21	
SHGC		Table D- 35	
Overhang Depth	SHGC	Table D- 36	Figure 25
Window Distribution		Table D- 37	
U-factor		Table D- 38	

For example, the basecase house had window area equal to 18% of the floor area, distributed equally on all sides. The window had 0.47 U-value and 0.4 SHGC. The windows had no exterior shading. First, the scenarios with different overhang depths and U-value were selected. The distribution of windows on all four sides and the SHGC were same as in the basecase house. Next, for each value of overhang depth, the annual energy use was plotted against the window U-value on the X-axis. Similar steps were followed to plot the annual energy use against window distribution and SHGC on the X-axis. The reference figure on p. 97 shows three graphs, each includes several lines, each line showing the reduction in annual energy use from changing one property for one value of overhang depth. A set of such lines demonstrates the effect of changing overhang depth on the thermal performance of that property.

4.4.5. Air-Conditioner and DHW Systems

The type and efficiency of the air-conditioner and DHW system affect the annual energy use. The gas heating and electric cooling systems have more site energy use but less source energy use, than the all electric system. For this study, only the gas space and water heating and electric cooling systems were considered. The DHW system with a standing pilot light that consumes 800 Btu/hr energy, continuously. By using the systems without pilot light energy use for water heating can be reduced significantly. For the analysis, the effect of systems with different efficiency was analyzed. The results of the analyses were used to develop the maximum energy-efficient house.

<u>Plan for the Simulation</u>

Table 10 shows the simulation plan for the analysis. Simulations with systems of different efficiencies were performed to analyze the effect of using more efficient systems on reducing energy use. In addition, simulations were performed for different building configurations to assess the impact of changing building configuration on the energy-saving potential of energy-efficient systems.

4.5. Development of the Maximum Energy-Efficient House

From the analysis of energy-saving potential of different measures that include: building configuration, walls and roof properties, construction type, fenestration properties, and efficiency of air-conditioner and DHW systems; the most energy-saving measures were selected and applied to the basecase house incrementally to achieve the maximum energy savings. For this, optimum values for all the parameters that resulted in maximum savings, when applied in combination, were chosen. These values were assigned to the parameters of the simulation model one by one to

Table 10: Simulation Plan for Analyzing Air-Conditioner and DHW System Efficiencies

Building Configuration	Air-conditioner Efficiency		Water Heater Efficiency	
	SEER	Number of Simulations	Energy Factor	Number of Simulations
1:1, 1-story (Basecase) 1:1, 2-story 1.5:1, 1-story 1.5:1, 2-story 2:1, 1-story 2:1, 2-story 2.5:1, 1-story 2.5:1, 2-story 3:1, 1-story 3:1, 2-story	**10 (Basecase)**	10	0.45	10
	11	10	0.50	10
	12	10	**0.55 (Basecase)**	10
	13	10	0.60	10
	14	10	0.65	10
	15	10	0.70	10
	16	10	0.75	10
	17	10	0.80	10
	18	10	0.85	10
	19	10	0.90	10
Total		**100**		**100**

Table 11: Simulation Plan for Developing Maximum Energy-Efficient Residence

Steps	Properties	Basecase characteristics	Energy-efficient Design Measures	Building Configurations Analyzed	Number of Simulations
1		Basecase	-		10
2	Construction	Wood frame construction	SIP Construction	1:1, one-story (Basecase) 1.5:1, one-story 2:1, one-story 2.5:1, one-story 1:1, two-story 1.5:1, two-story 2:1, two-story 2.5:1, two-story 3:1, one-story 3:1, two-story	10
3	Ventilation	No mechanical ventilation	Energy recovery ventilator		10
4	Roofing	Asphalt shingles (absorptance = 0.822)	White fiber cement shingles (absorptance = 0.234)		10
5	Exterior wall surface	Light buff brick (absorptance = 0.55)	White semi gloss paint (absorptance = 0.25)		10
6	Glazing	Double clear air-filled low-e windows, (U = 0.47, SHGC = 0.4)	Double clear argon-filled low-e windows (U = 0.29, SHGC = 0.28)		10
7	Window frame	Aluminium frames with thermal break	Vinyl frame		10
8	Exterior shading	No shading	4' overhangs on all sides		10
9	Window distribution	Equal window area on all sides	75% on south, 15% on north, 5% on east and 5% on west		10
10	Lighting	Incandescent lamps	Compact Fluorescent Lamps with electronic ballast		10
11	Refrigerator	660 kWh/yr	Kenmore 76942 (18.8 cu. ft. Top Freezer, 392 kWh/yr)		10
12	Freezer (upright)	900 kWh/yr	Wood's V10W 10.4 cu. ft., 353 kWh/yr		10
13	Dishwasher	696 kWh/yr	ASKO D3530 (181 kWh, < 4 gallons water use)		10
14	Clothes washer	816 kWh/yr	Bosch WFMC3200 Nexxr (3.03 cu.ft. 186 kWh/yr, 18.5 gallons water use)		10
15a	Domestic water heater	40 gallon tank, pilot ignition, EF = 0.487 (autosized)	Bosch AquaStar 250 SX Tankless hot water heater (a) not considering and (b) considering electronic ignition (EF = 0.85, 125 therms/yr)		10
15b					10
16	Air-conditioner	10 SEER	15 SEER		10
				Total	170

see their contribution to the maximum energy savings and identify the most energy-saving options. Table 11 lists these measures in the order they were applied. Simulations with each incremental application of the measures were performed for different building configurations.

4.6. Economic Analysis with Individual and Combined Application of Strategies

Next, an economic analysis was performed for the energy-efficient measures that were applied to the basecase house in order to develop the most energy-efficient house. The purpose of the analysis is to compare the cost-effectiveness of energy-saving measures applied individually as well as in combination. The analysis was based on the results of the simulation of the most energy-efficient house, as described in Section 7. The analysis is performed using the annualized life-cycle cost analysis method described in ASHRAE (2003) and Haberl (1993).

The analysis was performed by using two approaches. First, a life-cycle cost analysis of individual measures was performed. Second, the effect of the combined application to the basecase house was analyzed. For the combined application, the impact of incremental application of the measures was also observed.

5. CHARACTERISTICS OF THE BASECASE HOUSE

5.1. Introduction

Since this study targets single-family detached houses in hot and humid climates in the United States, a DOE-2 simulation model of a prototype house in Houston, Texas was selected as the basecase. The characteristics of the house were determined from the sources listed in Table A-5 and discussed in Section 4.2. The characteristics of the basecase house are described in the following sections and are summarized in Table 15.

5.2. General Characteristics

The basecase house is a standard house located in Houston, designed in accordance with the Chapter 4 of the 2000 IECC. The house is assumed to be a square-shaped single family one-story house having 2,500 ft^2 conditioned floor area (NAHB 2003), with the front of the house facing south. The floor to ceiling height of the building is 8 ft. (NAHB 2003). The house is assumed to have four bedrooms (USCB 2002), and occupied by a family of four people that includes a working father, a housewife, and two school-age children.

5.3. Building Envelope

The characteristics of the building envelope were determined from Chapter 4 of the 2000 IECC, for a standard design located in Houston that has 1,500 heating degree days (HDD_{65}).

5.3.1. Fenestration System

The gross window area, inclusive of the framed sash and the glazing area is equal to 18 percent of the conditioned floor area, conforming to Section 402.1.1. The windows are distributed equally on all the sides, conforming to Section 402.1.3.1. This corresponds to 28% of window to exterior wall area on four sides, assuming a wall height of 8 ft.

The windows are assumed to be 3 ft. in width, 5 ft. in height and are placed 2 ft. above the ground. The windows have no external shading, conforming to Section 402.1.3.1.3. The fenestration system solar heat gain coefficient (SHGC), inclusive of the framed sash and glazing area is 0.4 for all windows, conforming to Section 402.1.3.1.4. The fenestration system U-factor is 0.47 conforming to Section 402.1.1, Table 402.1.1(2), for a house located in Houston.

5.3.2. Opaque Components

The basecase house had a wall assembly U-factor of 0.085 Btu/hr-ft^2-ºF (Section 402.1.1), ceiling R-value of 30 hr-ft^2-ºF/Btu (Section 502.2.4) and floor-weight of 11.5 lb/ft^2 (Section 402.1.3.3), as specified in the 2000 IECC for a standard design with 18% window-to-conditioned floor area (or 28% window-to-wall area). To define the layers for the DOE-2 simulation in the delayed construction mode, while achieving the overall U-value of 0.085 for the wall assembly, an equivalent construction of lightweight wood frame with 2 x 4 studs spaced at 16 inch on center, and R-11 fiberglass batt insulation for wall cavities was assumed for the exterior walls. Similarly, an equivalent construction of light-weight wood frame with 2 x 10 joists spaced at 16 inch on center, and R-30 fiberglass batt insulation on the ceiling was assumed for the low-pitched roof. The exterior wall surface was assumed to be light buff brick with an absorptance of 0.55 and an emissivity of 0.9. The exterior roof surface was assumed to have aspen gray asphalt shingle roofing with an absorptance of 0.822 and an emissivity of 0.9. Such roofing type was considered even for the low-pitched roof of the basecase house, to model the thermal properties of typical roofing type. Figure 5 and Figure 6 show the details of the exterior wall and roof construction.

The floor of the basecase house was assumed to be slab-on-grade constructed with 4-inch heavy-weight concrete. Two doors (3 ft. wide by 6.67 ft. high), with a U-factor of 0.2 Btu/hr-ft^2-ºF (Section 402.1.3.4.3), are assumed to be on the front and the back of the house.

The types of construction and materials are determined to represent a typical single-family detached house in hot and humid climates of the U.S. Certain typical characteristics such as the sloping roof with ventilated attic and ducts in the attic space were not used for the simulation.

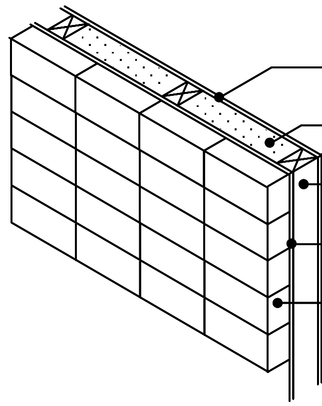


Figure 5: Construction Detail of the Exterior Wall

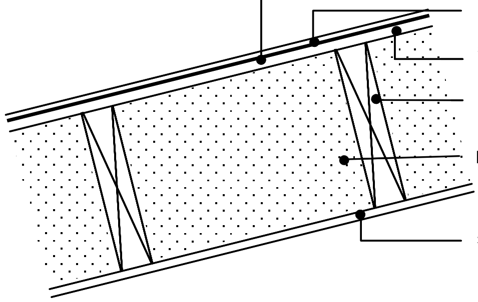


Figure 6: Construction Detail of the Roof

5.3.3. Air Infiltration

The average air changes (ACH) per hour for the basecase house were determined from the following equation, as given in Section 402.1.3.10 of the 2000 IECC:

ACH = normalized leakage (0.57) x weather factor

Based on the weather factor for Houston, which is 0.81, as specified in ASRAE Standard 136-1993 (ASHRAE 2001b), the estimated ACH per hour is 0.4617.

5.4. Interior Layout

Figure 7 shows the interior layout adopted for the 2,500 ft^2 square-shaped basecase house. Various spaces in the house include: a formal living room, a family room, kitchen and dining room, a pantry, a utility room, a master bedroom with an attached dress and an attached bath, two single-bedrooms for the two children, a guest-bedroom, a common bath, a half-bath, and some storage spaces for household items and building systems. Area allocation of these spaces is provided in Table 12.

5.5. Occupancy

The daily activities of the occupants of the house for weekdays and weekends were assumed to represent that of a typical family of four. This assumed a working father, a housewife and two school-age children. The daily routine was assumed to start at 5:30 AM on weekdays and at 8:00 AM on weekends. The children and the father leave the house at 7 AM and return at 2 PM and 6 PM on weekdays, respectively. On weekdays, the mother leaves for shopping from 11 PM to 1 PM. On Saturdays, the family goes out from 4 PM to 6 PM for shopping or extracurricular activities. The household cleaning and laundry was assumed to be done on Saturdays and Sundays. The major cooking was assumed to be done twice a day, except on Sundays. The daily activities of the family for the weekdays and the weekends are listed in Appendix B. These activities most affected the lighting and equipment loads.

5.6. Lighting

The basecase house was assumed to have incandescent lamps for general lighting as well as for most of the tasks. Fluorescent lamps were provided for special tasks in the kitchen. The lighting levels for the general illumination and special tasks are determined from the recommended lighting levels as specified in the IESNA (2000). The general illumination level in various spaces of the house was maintained at 50 lux (5 fc) that corresponds to a lighting load of 0.75 W/ft^2 for incandescent lamps. Higher lighting levels of up to 300 lux (30 fc) and 500 lux (50 fc) were provided for the dressing, reading and kitchen activities, using task lighting, which correspond to 4.25 W/ft^2 and 7 W/ft^2, respectively, for incandescent lamps.

The number of lamps in different spaces was estimated using the relation between the lighting load (W/ft^2) and the illumination level (lux) for incandescent and fluorescent lamps, to maintain the required illumination level. The lighting loads associated with

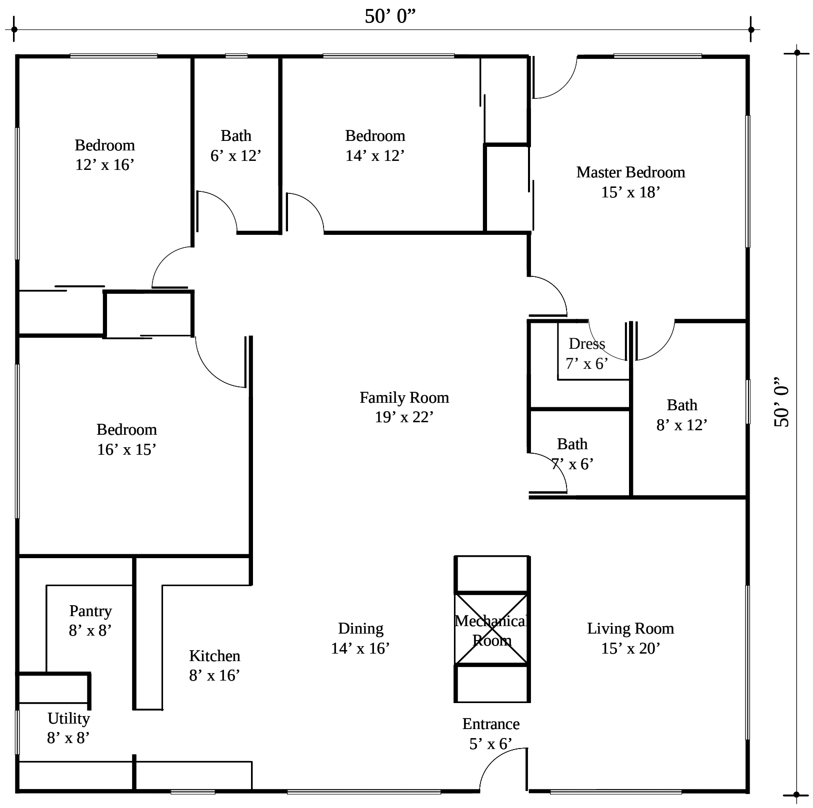


Figure 7: Interior Layout of the Basecase House (2,500 ft2 Floor Area, 18% Window-to-Floor Area)

Table 12: Area Allocation and Installed Lights in Various Spaces

Room	Width (ft.)	Depth (ft.)	Area (Sq. ft.)	Installed Lamps (0.75 W/sq. ft. for General Lighting[1])	Installed Wattage (W)
Formal Living	15	20	300	2-100 W Incand + 2-25 W Incand	250
Family room	19	22	418	3-100 W Incand + 2-25 W Incand	350
Dining	14	16	224	2-100 W Incand	200
Kitchen	8	16	128	1-32 W Fluor + 3-40 W Incand	152
Pantry	8	8	64	1-40 W Incand	40
Utility area	8	8	64	1-40 W Incand	40
Bedroom 1	15	18	270	2-100 W Incand + 2-25 W Incand	250
Bedroom 2	16	12	192	2-100 W Incand + 1-25 W Incand	225
Bedroom 3	14	12	168	2-100 W Incand + 1-25 W Incand	225
Bedroom 4	15	16	240	2-100 W Incand + 2-25 W Incand	250
Wardrobe 1	3	6	18	-	-
Wardrobe 2	3	6	18	-	-
Wardrobe 3	3	6	18	-	-
Wardrobe 4	3	6	18	-	-
Dress	7	6	42	1-40 W Incand	40
Toilet 1	8	12	96	2-40 W Incand	80
Toilet 2	6	12	72	1-40 W Incand	40
Toilet 3	6	7	42	1-40 W Incand	40
Lobby/hallway	7	4	28	1-40 W Incand	40
Entrance	6	5	30	1-40 W Incand	40
Storage	5	10	50	-	-
Total Floor Area			**2500**	**Total Installed Wattage**	**2262**

Table 13: Lighting Wattage Used at Different Hours of the Day

Hour	Weekdays	Saturdays	Sundays/ Holidays	Average Hourly Watts
0:00	0	0	0	0
0:30	0	0	0	0
1:00	0	0	0	0
1:30	0	0	0	0
2:00	0	0	0	0
2:30	0	0	0	0
3:00	0	0	0	0
3:30	0	0	0	0
4:00	0	0	0	0
4:30	0	0	0	0
5:00	0	0	0	0
5:30	80	0	0	57
6:00	800	0	0	571
6:30	872	0	0	623
7:00	272	0	0	194
7:30	72	0	0	51
8:00	280	120	120	234
8:30	240	120	120	206
9:00	25	200	200	75
9:30	25	120	120	52
10:00	0	0	0	0
10:30	0	0	0	0
11:00	0	200	40	34
11:30	0	200	40	34
12:00	0	240	40	40
12:30	0	240	40	40
13:00	160	120	120	149
13:30	160	120	120	149
14:00	0	0	0	0
14:30	0	0	0	0
15:00	0	0	0	0
15:30	0	0	0	0
16:00	50	0	50	43
16:30	50	0	50	43
17:00	50	0	50	43
17:30	50	0	50	43
18:00	652	692	572	646
18:30	532	532	532	532
19:00	927	452	800	841
19:30	927	452	800	841
20:00	732	732	200	656
20:30	732	732	200	656
21:00	975	525	975	911
21:30	1015	525	1015	945
22:00	250	750	250	321
22:30	290	790	290	361
23:00	0	250	0	36
23:30	0	290	0	41
Total kWh/day	**5.11**	**4.20**	**3.40**	**4.73**
Average Hourly kW	**0.21**	**0.18**	**0.14**	**0.20**

1 fc illumination level are 0.15 W/ft^2 for incandescent lamps and 0.034 W/ft^2 for fluorescent lamps (Stein and Reynolds 1992, p. 1070), shows the installed lights and wattage in different spaces of the basecase house.

The lighting use at different hours of weekdays and weekends was determined from the assumptions about the daily activities of the occupants, and is shown in Appendix B. The summary of the lighting load at different hours of weekdays and weekends is presented in Table 13. An average of 5 kWh, 4.04 kWh and 3.28 kWh daily lighting energy use was estimated for weekdays, Saturdays and Sundays/holidays. Based on these estimates, an equivalent constant lighting load of 0.20 kW was estimated to be used for the DOE-2 simulation.

5.7. Equipment

The house was assumed to have basic appliances for cooking, utility and entertainment. The wattage and the usage of these appliances were determined from Energy Star (2002). Table 14 lists the appliances installed in the house, their wattage, hours of use, and monthly and annual energy use. The total annual electricity use for equipment was estimated to be 6022 kWh/yr. Based on this estimate, an equivalent average equipment load of 0.69 kW was used for the DOE-2 simulation. The total internal heat gain from lighting and equipment was 0.88 kW, which is in line with the constant load of 879 W for the standard house, as specified in Section 402.1.3.6 of the 2000 IECC.

Table 14: Equipment Energy Use

Appliances	Typical Wattage		Hours in Use per Month	kWh/yr
	When On	In Stand-by Mode		
Refrigerator	146.67	-	375	660
Freezer	200	-	375	900
Electric Range	12200	-	6	900
Microwave oven	1500	-	7	120
Dishwasher	2000	-	25	696
Toaster	1100	-	3	36
Coffee maker	1100	-	8	108
Clothes Washer	8500	-	8	816
Clothes Dryer	5500	-	16	1056
Iron	1200	-	4	60
Vacuum cleaner	1000	-	6	72
Television	75	5.9	180	200.4
VCR	12.5	5.1	10	44.4
DVD	17.8	4.5	70	54
Stereo	51.9	3.2	30	45.6
Computer	55	-	150	99.6
Monitor	85	-	150	153.6
			Total	**6021.6**
			Average Electricity Demand (kW)	**0.69**

5.8. Space Heating and Cooling Systems

System Type and Efficiency

The house is assumed to have electric cooling and natural gas heating systems that include a SEER-10 air-cooled split-system air conditioner and a 0.78 AFUE gas-fired furnace. The types of systems for the basecase house were determined from the Builders' Survey data (NAHB 2003). The efficiencies of the equipment were determined from the minimum specified performance confirming Section 503.2 of the 2000 IECC. The systems were assumed to operate throughout the year.

Thermostat Setpoints

The thermostat setpoints for heating and cooling were assumed to be 68ºF and 78ºF, with a 5ºF setback/setup for 6 hours per day, conforming to Section 402.1.3.5 of the 2000 IECC. The heating and cooling systems were assumed to be available year around (i.e., they were assumed to operate automatically).

Ducts

Although, conventional practice of locating ducts is inside the vented attic, the ductwork in the basecase house was assumed to be located inside the conditioned space. Therefore, no penalty was assessed for duct location or R-value.

5.9. Domestic Hot Water System

This four bedroom and 2.5 bath house has a gas-fired water heater (NAHB 2003) with a 40-gallon storage tank (with 38 kBtu per hour input, 72 gallons of 1 hour draw and 32 gallons per hour recovery) (ASHRAE 2003). A daily hot water consumption of 70 gallons was used, as calculated from the following equation in Section 402.1.3.7 of the 2000 IECC:

$$\textit{Daily Hot Water Consumption} = (30 \times a) + (10 \times b)$$

where, a = Number of Living Units, b = Number of Bedrooms in Each Living Unit

A temperature setpoint of 120ºF was used for the simulation (Section 402.1.3.7, 2000 IECC). An energy factor of 0.54 was used for the water heater, which is the minimum performance for the storage type gas-water heating equipment, as determined from the following equation in Section 504.2.1 of the 2000 IECC:

Minimum Performance of Storage Type Gas Water Heating Equipment = 0.62 – 0.0019V

V= Rated Storage Volume is Gallons

5.10. Summary

Table 15 summarizes the main characteristics of the basecase house and the sources that helped in determining those characteristics.

Table 15: Summary of Basecase House Characteristics

Characteristics		**Source**
Building		
Location	Houston, Harris County, TX (HDD65 =1500), 29.98 lat., 95.37 long., 108 ft. alt.	Assumed
Orientation	Oriented in four cardinal directions, Front faces south (Azimuth = 0)	Assumed
Conditioned floor area	2,500 ft^2	NAHB 2003
Number of floors	One	NAHB 2003
Building configuration	Square shape (Aspect Ratio = 1:1)	Assumed
Height	8 ft. floor to ceiling	NAHB 2003
Number of bedrooms	Four bedrooms	NAHB 2003, www.census.gov
Other spaces	Formal living, family room, kitchen, dining, 2.5 bath,1 dress, utility, no garage	Assumed
Surroundings	No building shades, dry grass on surrounding ground (Reflectance = 0.24)	IECC 2000
Ground-temperature		From TRY Weather File
Construction		
Construction type	Light-weight wood-frame	NAHB 2003
Exterior walls	2 x 4 studs @ 16" o. c.	NAHB 2003
	R-11 fiberglass batt cavity insulation	IECC 2000
	1/2" plywood sheathing	NAHB 2003: 7/16" or 1/2" OSB
	3" brick fascia (e = 0.9, abs = 0.55, roughness = 1)	NAHB 2003
	1/2" gypsum board interior finish	Assumed
Roof	Low-pitched roof with cathedral ceiling	Assumed
	2 x 10 studs @ 16" o.c.	Assumed
	Aspen gray asphalt shingles (e = 0.9, abs = 0.822, roughness = 1),	Assumed
	R-30 ceiling insulation	IECC 2000
	1/2" gypsum board	Assumed
Interior floors	2 x 10 studs @ 16” o. c.	Assumed
	¾” plywood	Assumed
	Carpet and padding	Assumed
	½” gypsum board ceiling	Assumed
Windows	Gross window area: 18% of conditioned floor area (equivalent to 450 ft^2), distributed equally on all sides (i.e. 112.5 ft^2).	IECC 2000
	Double pane low-e air filled windows (U = 0.47, SHGC = 0.4),	IECC 2000, NAHB 2003
	Aluminum frames with thermal break (frame abs = 0.7, frame conductance = 1.245, frame width = 0.125),	NAHB 2003
	Spacer is taken from the library (default is AL)	Assumed
Doors	2 - 3 ft. x 6.67 ft. on front and back, U = 0.2	IECC 2000
Exterior shading	No shading and overhangs	IECC 2000

Table 15 (Cont.)

Characteristics		**Source**
Construction		
Underground floor	Slab-on-grade floor with 4” heavy weight concrete, no perimeter insulation	NAHB 2003
Floor-weight	11.5 for quick mode	IECC 2000
Furniture type and weight	Light, 0.6 lb/ft2	IECC 2000
Infiltration method	Air change	IECC 2000
	ACH per hour = 0.46 (ACH = Normalized air leakage x Weather factor)	IECC 2000
Internal loads		
Internal heat gain	3000 Btu/hr (0.88 kW)	IECC 2000
Lighting	Incandescent (0.19 kW)	
Equipment	Conventional models (Resulting in an equivalent constant load of 0.69 kW)	
Occupancy	Four people that includes a working father, a house-wife mother, two school-going children	Assumed
HVAC systems		
Type	Electric split air conditioner and natural gas furnace	NAHB 2003
System efficiency	10 SEER AC, 78% AFUE	IECC 2000
Duct location	In conditioned space	Assumed
Supply air	1 cfm/sqft	
Supply temperature	Max. supply T: 120; Min. supply T: 55	
	Single speed compressor, intermittent outside fan mode	NAHB 2003
Space condition	Temperature: 73	
Temperature set-point	Winter set-point = 68F, summer set-point = 78F	IECC 2000
Setup and setback	Morning 6 hr. setup and set back to 63 and 83F	
Thermostat type	Proportional, Throttling range: 5	
Supply static, supply efficiency	2, 0.75	
DHW heater		
Type	Gas water heater	Assumed
DHW load	70 gallons/day or 0.0486 gpm (30+10*no. of bedrooms)	IECC 2000
Rated volume	40-gallons	ASHRAE 2003
Efficiency	DHW-EF = 0.62-0.0019*DHW size (0.487)	IECC 2000
Supply temperature	120F	Assumed
Ignition	Pilot light	Assumed

6. RESULTS OF THE SIMULATIONS WITH IMPROVED HOUSE CHARACTERISTICS

6.1. Introduction

This section presents the results of the simulation of the house with improved building characteristics. The characteristics of the basecase house were improved individually and in combination. For this, different values were assigned to the parameters of the DOE-2 input that represented the characteristics of the building systems and components. By examining the change in the annual energy use from the Building Energy Performance Summary (BEPS) of the DOE-2 output, it was possible to determine the values of those parameters that resulted in maximum energy savings, when applied individually and in combination.

Simulations were performed following the simulation plans described in Section 4. The analysis was performed by plotting the annual energy use for different scenarios. The annual energy use and energy savings for selected scenarios are presented in Appendix D.

6.2. Format for Presenting the Results

A consistent format was followed in this section to present the results of the simulations. In general, line graphs were used to plot the annual energy use for different values of the parameters. Also, hourly energy use for a peak winter and a peak summer day were plotted for analyzing the effect of construction type.

In the line graphs, representing the impact of incremental change in building property shown on the X-axis on the annual energy use, different colors represent different end-use energy uses: red for the space heating; blue for the space cooling; orange for the domestic water heating; grey for other end-uses (that includes the remaining end-uses such as, lighting, appliances, heating/cooling fans, pumps and miscellaneous, and domestic water heating, if not shown separately on the graph); and green for the total energy use (that includes all the above end-uses).

The solid and dotted line types represent one-story and two-story configurations, respectively. Different shades of a color and/or different markers represent different values of the property under consideration: darker shades and/or solid markers for higher values and lighter shades and/or unfilled markers for lower values. The black circular marker on each set of the lines represents the basecase scenario (i.e., a square-shaped, one-story configuration with the building characteristics as specified in Table 15 of Section 5).

The same format is followed throughout this section with few exceptions. For example, in the graphs analyzing only one-story configuration, or analyzing one and two-story configurations side-by-side, the dotted lines, if used, do not represent the two-story configuration.

6.3. Analysis of the Results

6.3.1. Effect of Quick and Delayed Construction Modes

As discussed in Section 4.4.1, simulations were performed in the quick and delayed construction modes for different building configurations. Two sets of simulations were performed keeping the (a) window-to-floor area ratio fixed to 18%, and (b) window-to-wall area ratio fixed to 28%. The following sections provide the analysis of the results.

Results of the Simulations

Figure 8 shows the results of the simulations, following the format discussed in Section 6.2. The two graphs correspond to the two sets of simulation. The left graph corresponds to 18% window-to-floor area ratio and the right graph corresponds to 28% window-to-wall area ratio. The annual energy uses were plotted against different building configurations on the X-axis. The one-story and two-story configurations were analyzed side-by-side. For each, the east-west to north-south aspect ratio of the building was changed from 1:3 to 3:1. The darker lines correspond to the delayed mode, and the lighter lines of the same color correspond to the quick mode.

Table D- 1 shows the annual energy use and percent savings for the selected intermediate values of the aspect ratio for one and two-story configurations of the building, for all the four combinations of the two simulation modes and the two window area specification methods. The

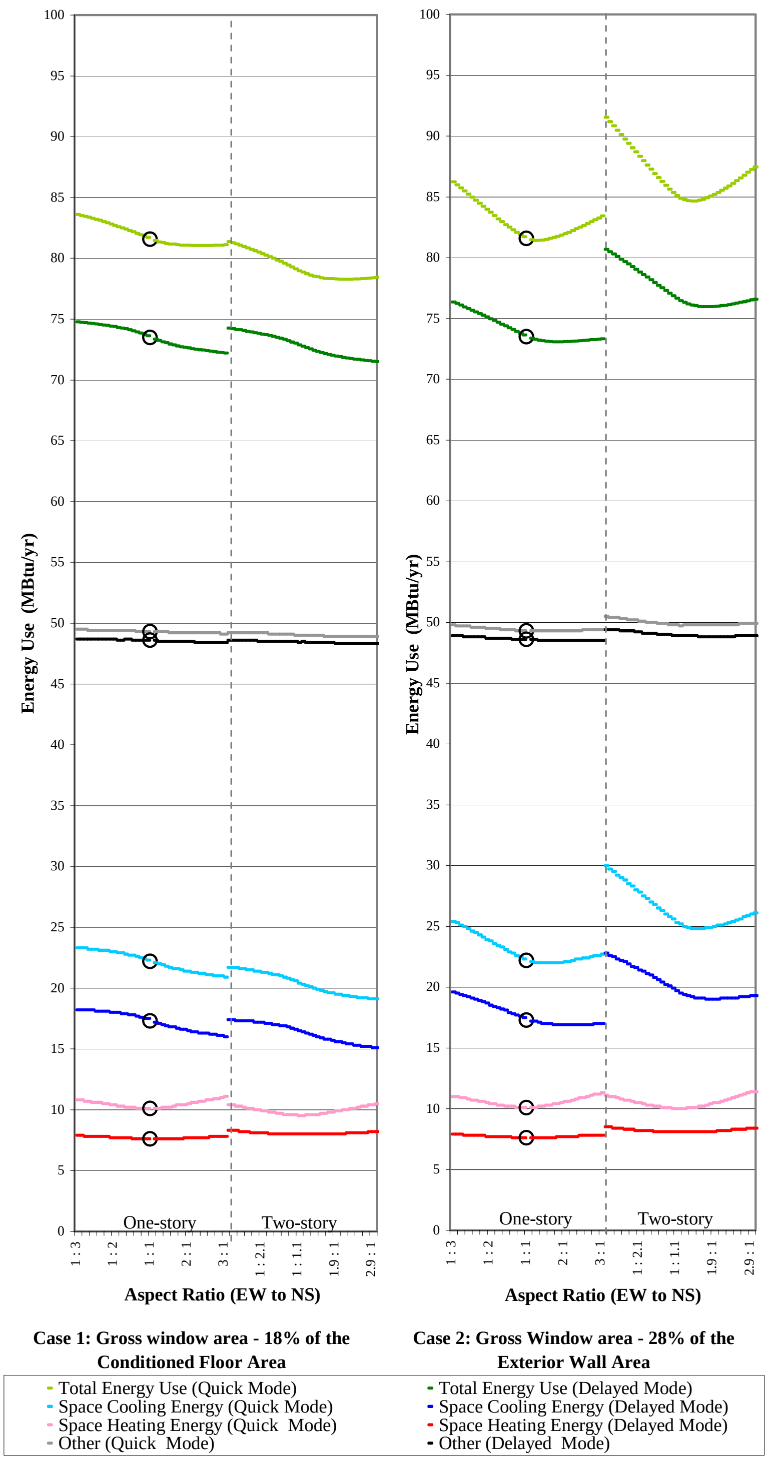


Figure 8: Annual Energy Use for Different Building Configurations in Quick and Delayed Construction Modes

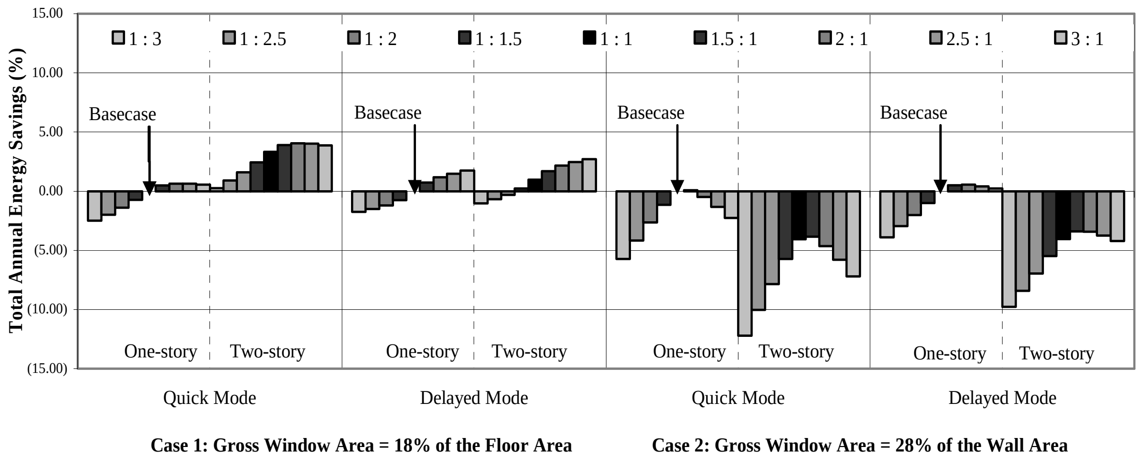


Figure 9: Annual Total Energy Savings from Changing Building Configurations

savings from changing building configurations, as calculated in this table is plotted in Figure 9. The percent savings were plotted against different building configurations in the quick and delayed modes, for each of the two cases – the 18% window-to-floor area ratio and the 28% window-to-wall area ratio. For each of the four scenarios, the one-story and two-story configurations were plotted side-by-side, and the east-west to north-south aspect ratio of the building was changed from 1:3 to 3:1.

From Figure 8 and Figure 9, it was observed that among the different configurations analyzed, the most energy-saving configuration was different for quick and delayed modes. For a window-to-floor area ratio fixed of 18%, which corresponds to a fixed window area for all the analyzed configurations distributed on different orientations in proportion to the corresponding wall area, the following points were observed:

1) The space cooling energy savings were higher for a two-story house elongated along the east-west axis in both the modes.

2) In the quick mode, space heating energy savings were higher for a square-shape, two-story house; whereas in the delayed mode, space heating energy savings were higher for a square-shape, one-story house.

3) For both the modes, total energy savings were higher for a two-story house elongated along the east-west axis.

4) Simulation in the quick mode showed the highest total energy savings of 4% for a 2:1, two-story configuration; whereas simulation in the delayed mode showed the highest total energy savings of 3% for a 3:1, two-story configuration.

For a window-to-wall area ratio fixed of 28% distributed on different orientations in proportion to the corresponding wall area, which resulted in an increased window area for elongated and two-story configurations, the following points were observed:

1) A two-story configuration was more energy consuming in both the modes, since it had higher heat gain and loss from an increased wall area and an increased window area.

2) Penalty for plans elongated along the east-west axis, was higher in quick mode than in delayed mode.

3) In the quick mode, the square-shape configuration was the least energy consuming, whereas in the delayed mode a nearly square-shape plan elongated along the east-west axis was the least energy consuming.

4) Simulation in the quick mode showed the highest energy savings of 0.09% for a 1.5:1, one-story configuration; whereas simulation in the delayed mode showed the highest savings of 0.54% for a 2:1, one-story configuration over the basecase house.

<u>Difference in the Quick and Delayed Mode</u>

Table D- 1 also shows the percent difference in annual energy use in quick and delayed modes for the selected intermediate values of the aspect ratio for one and two-story building configurations and the two window area specification methods. These percent differences in the annual energy use in quick and delayed modes were plotted against different building configurations on the X-axis in Figure 10, following the format described in Section 6.2. The differences for one-story and two-story configurations were plotted side-by-side. For each, the east-west to north-south aspect ratio of the building was changed from 1:3 to 3:1. The solid and dotted lines of the same color correspond to the two cases: the 18% window-to-floor area ratio, and the 28% window-to-wall area ratio, respectively. From Figure 10 the following points were observed:

1) In general, the quick mode over-predicted the total energy use by 8% to 14% over the delayed construction mode.
2) Considering the 18% window-to-floor area ratio, the differences were the least for the square-shaped plan (8% to 11%), than for the elongated plan (up to 12%). Considering the 28% window-to-wall area ratio, the differences were the least for the square-shaped plan (11%), than for the elongated plan (up to 14%).
3) Considering the 18% window-to-floor area ratio, the differences were less for the two-story configuration (8% to 10%) than for the one-story configuration (11% to 12%). Considering the 28% window-to-wall area ratio, the one and two-story configuration showed similar differences (11% to 14%).

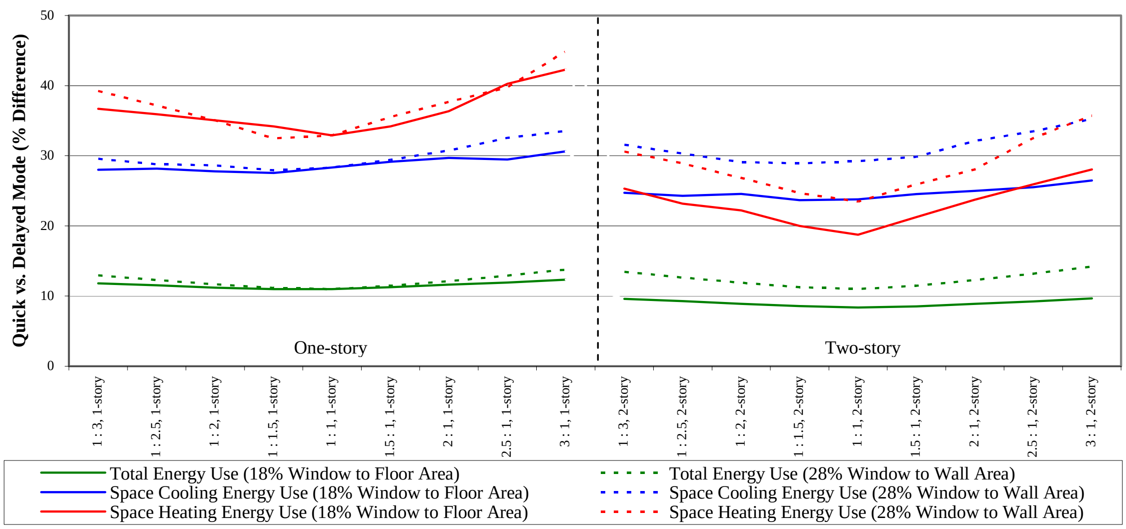


Figure 10: Percent Difference in Annual Energy Use in Quick and Delayed Construction Mode

Effect of Quick and Delayed Modes on the Peak Hourly Energy Use

Figure 11 compares the hourly inside temperature and energy use on the peak days, in the quick and delayed modes, which revealed more details about why there was a difference between quick and delayed construction modes. The graphs on the left correspond to the peak winter day (January 4), and the graph on the right correspond to the peak summer day (August 18). The top most graphs show the hourly outside air, inside and setpoint temperatures. The graphs in the middle show the heating fuel and the cooling electricity used during different hours of the peak winter and summer days. The lower most graphs show the scatter plot of hourly energy use versus the outside air temperature.

It is to be noted that for six hours in the morning (i.e., from 12:00 p.m. to 6:00 a.m.), the thermostat was setback and setup by 5ºF for winter and summer, respectively. These setback and setup are shown in the top most graphs for peak winter and summer days. From Figure 11 following points were observed:

1) The graph showing the temperatures for the peak winter day demonstrated that in delayed construction mode, the indoor temperature was more stable during afternoon hours when the outdoor temperature was very high, and the indoor temperature achieved the setpoint temperature sooner than in the quick construction mode.
2) From the similar graph corresponding to the peak summer day, no difference in the daytime indoor temperatures for quick and delayed construction mode were observed. However, during morning hours when the thermostat was setup, the indoor air temperature did not achieve the setback temperature in the quick construction mode. Whereas, in the quick mode, the indoor temperature increased with the setup.
3) The graph showing the heating fuel use during different hours of the peak winter day demonstrated that for the hour when thermostat changed from the 5ºF setback to the setpoint temperature, the heating fuel use in the quick mode was up to 2.64 times higher than in the

delayed mode. Therefore, using the simulation in the quick construction mode, the heating equipment may be oversized by a factor of 2.64.

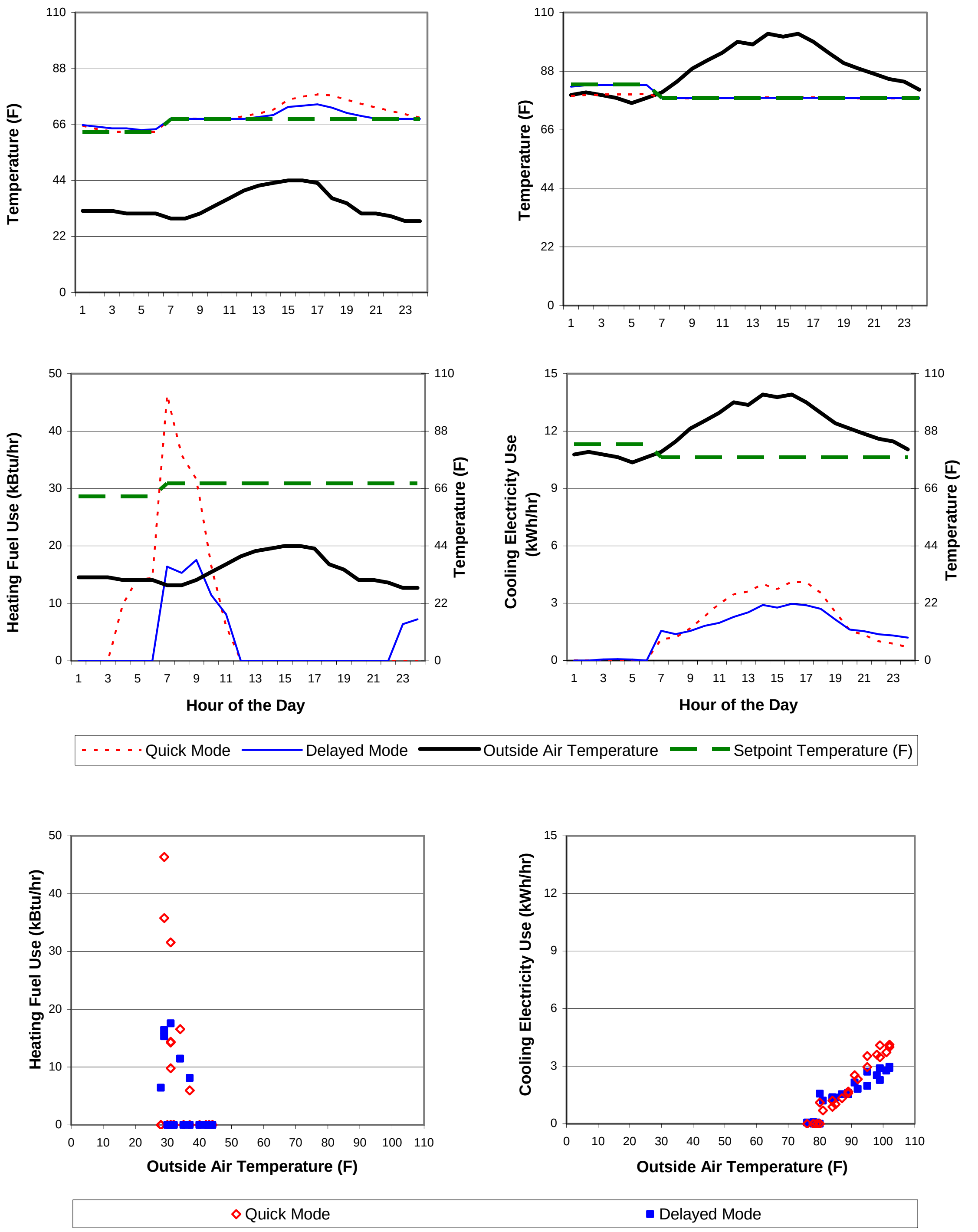


Figure 11: Hourly Plot for a Peak Winter and a Peak Summer Day in Quick and Delayed Modes

4) The similar graph corresponding to the peak summer day demonstrated that when the outside temperature was the highest, the cooling electricity use in the quick mode was 1.39 times higher than in the delayed mode. Therefore, using the simulation in the quick construction mode, the cooling equipment may be oversized by a factor of 1.39.

The scatter plot of cooling electricity use versus the outside air temperature on the peak summer days demonstrated that in the quick construction mode, the hourly cooling electricity use was more fluctuating with the change in the outside air temperature. Therefore, with the oversized equipment, the cooling system would achieve part load performance for most of the times.

Conclusion

This analysis implied that simulation in quick mode and delayed mode produced different results. The quick mode over-predicted the energy use by 8% to 14%. Also, in quick mode the heating and cooling equipment were oversized. Considering that the delayed mode produces more accurate results, the other measures were analyzed in delayed mode. Unfortunately, since most of the building codes define the wall and roof construction as R-values or U-values, and the floor-weight as a fixed value; this analysis implies that a re-evaluation of the published prescriptive tables may be warranted.

6.3.2. Effect of Roof and Wall Properties

As discussed in Section 4.4.2, simulations were performed to analyze the combined effect of R-value, absorptance and emissivity of the roof and walls for different building configurations. The following sections provide the analysis of the results.

Results of the Simulations

Figure 12 through Figure 15 show the results of the simulations with improved roof characteristics. Figure 16 through Figure 19 show the results of the simulations with improved wall characteristics. These figures follow the format as discussed in Section 6.2. Table D- 2 through Table D- 13 and Table D- 14 through Table D- 25 show the annual energy use and savings for selected intermediate values of the aspect ratio, R-value, absorptance and emissivity

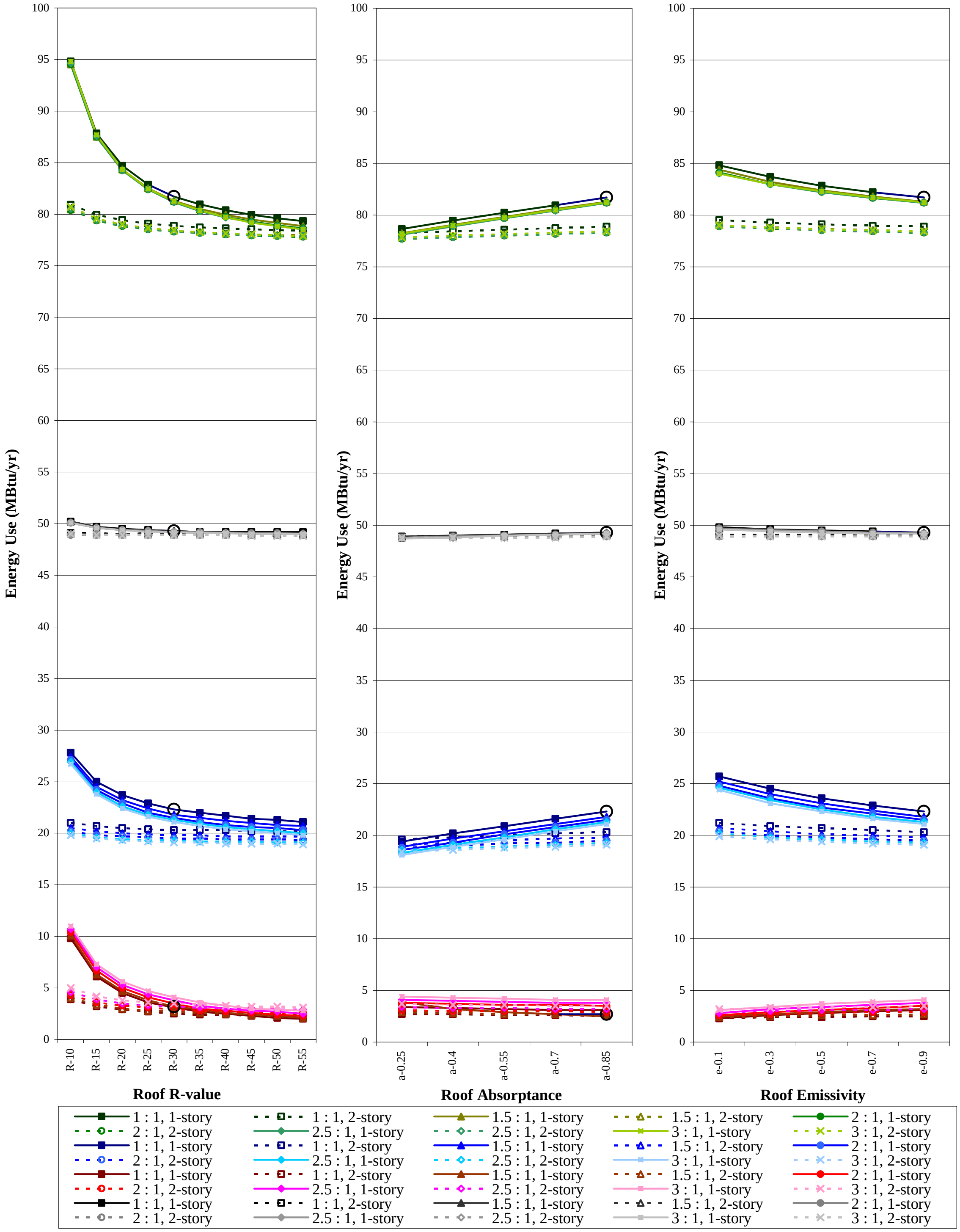


Figure 12: Effect of Building Configuration on Energy Savings from (a) Roof Insulation, (b) Roof Absorptance, and (c) Roof Emissivity

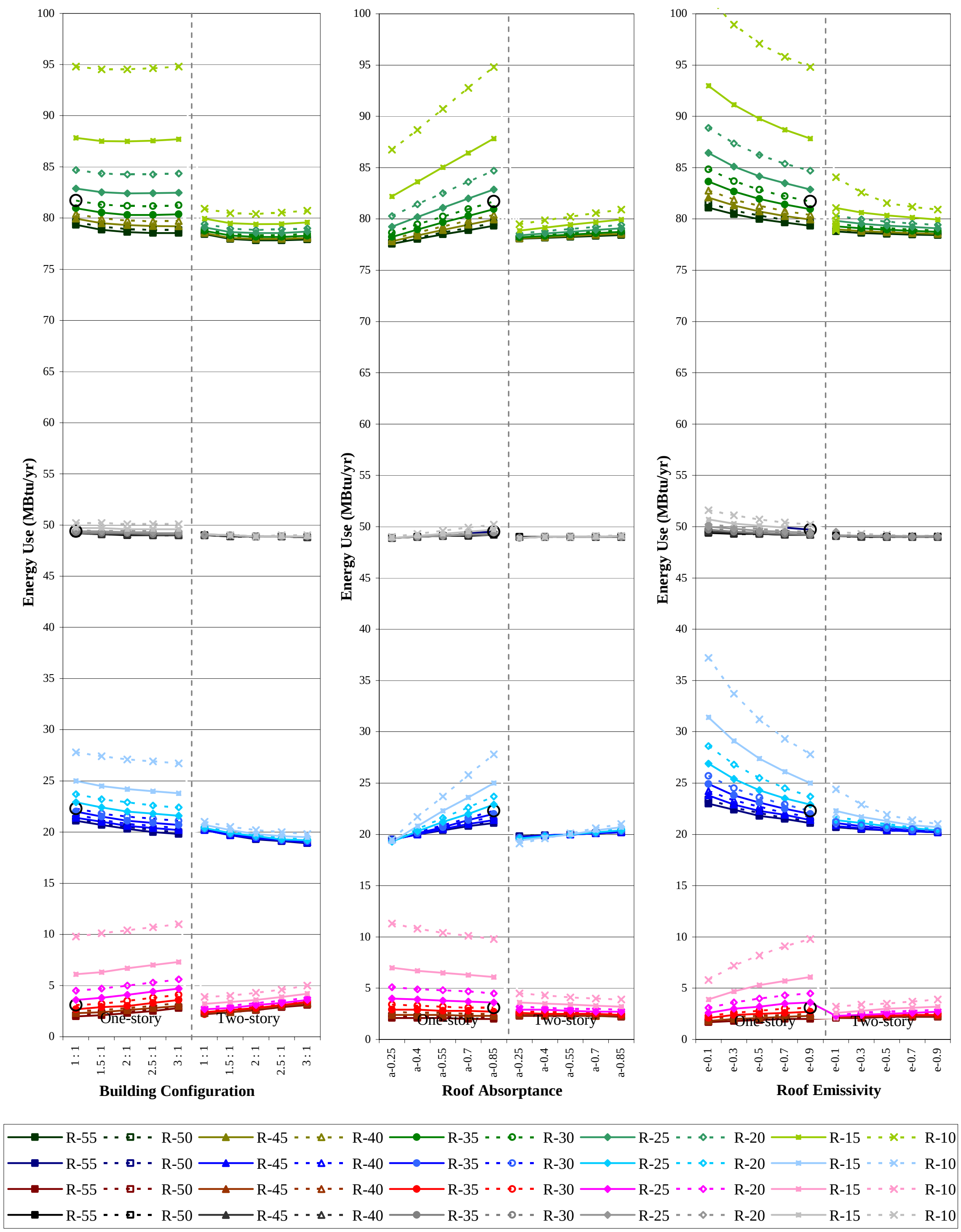


Figure 13: Effect of Roof Insulation on Energy Savings from (a) Building Configuration, (b) Roof Absorptance, and (c) Roof Emissivity

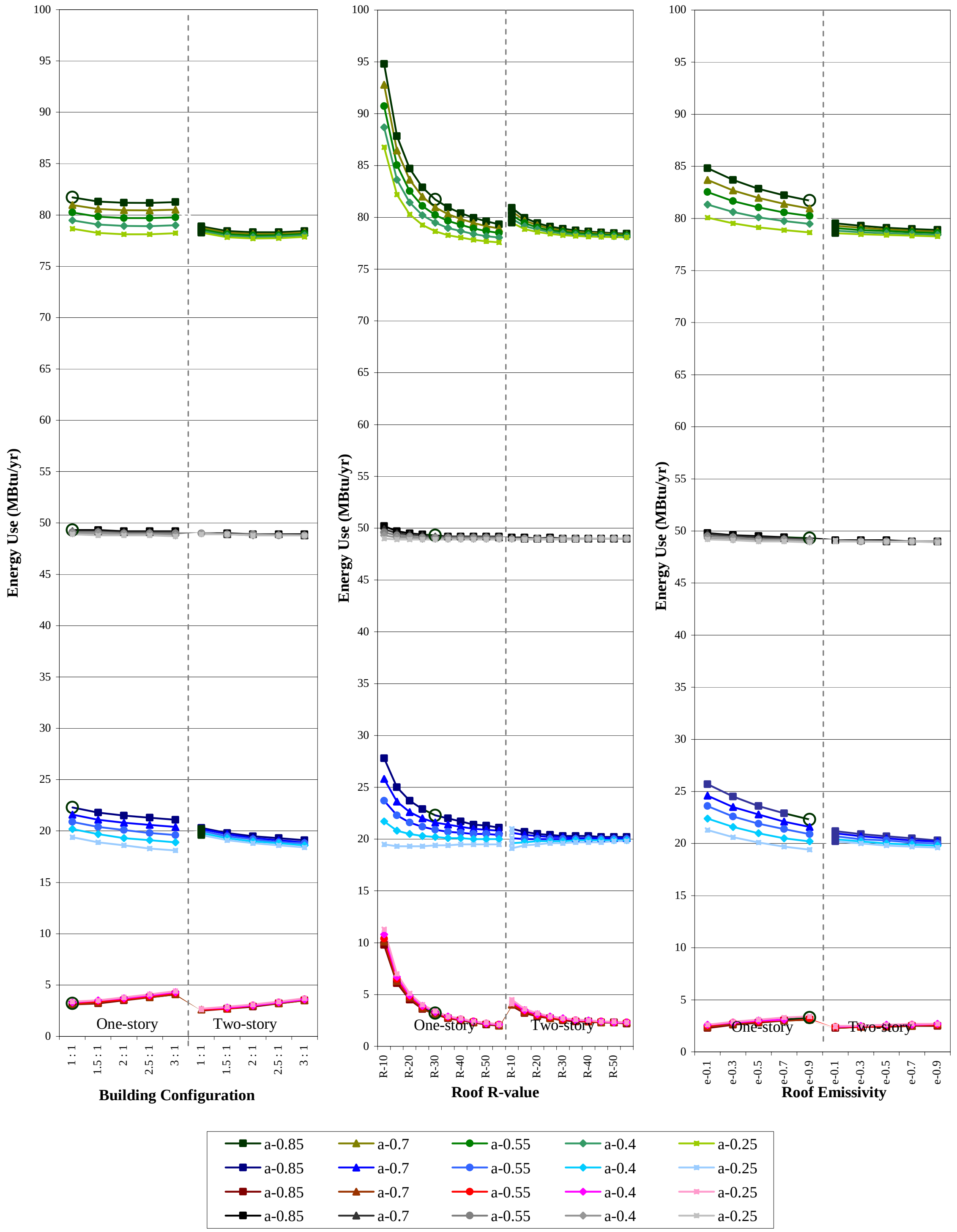


Figure 14: Effect of Roof Absorptance on Energy Savings from (a) Building Configuration, (b) Roof Insulation, and (c) Roof Emissivity

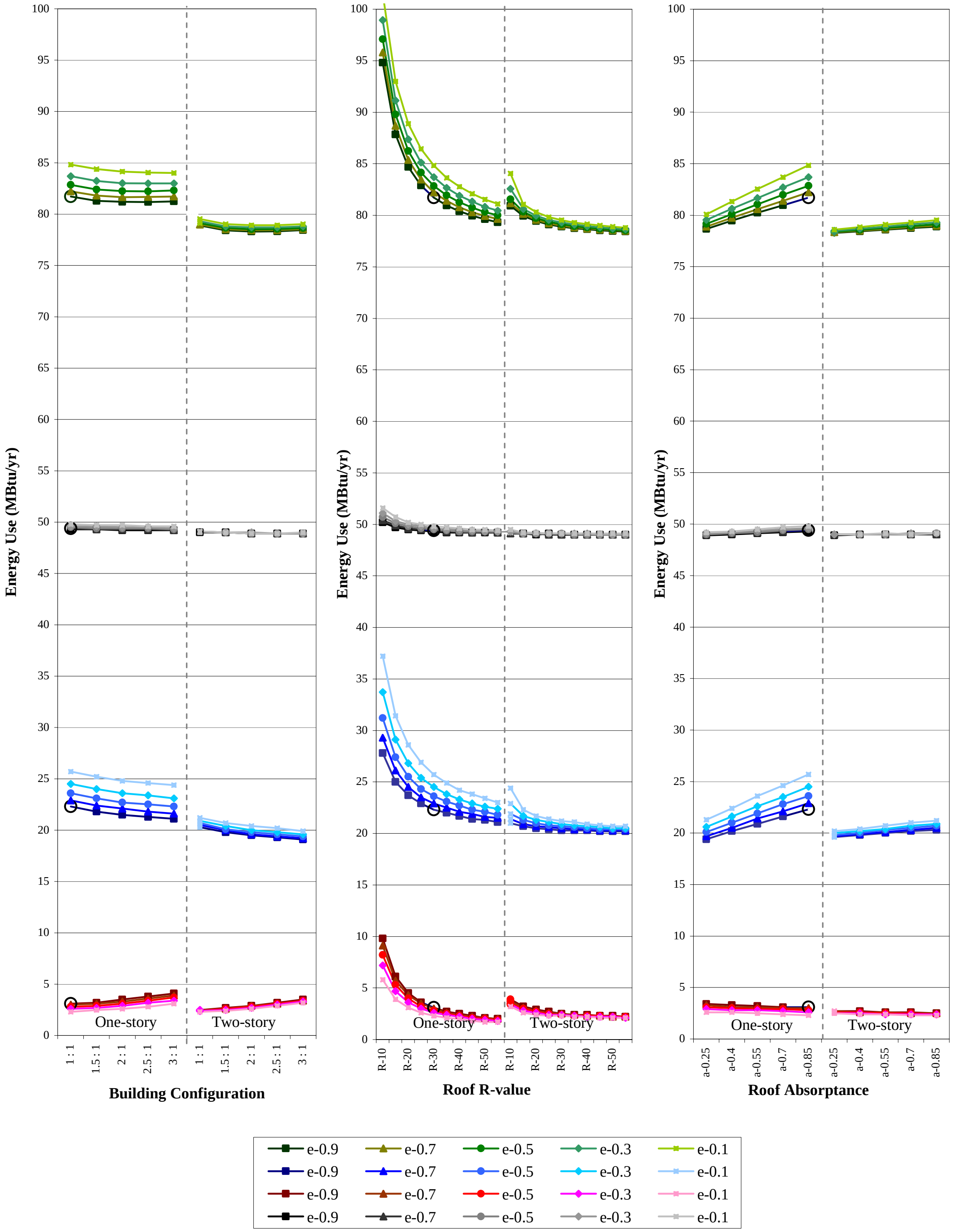


Figure 15: Effect of Roof Emissivity on Energy Savings from (a) Building Configuration, (b) Roof Insulation, and (c) Roof Absorptance

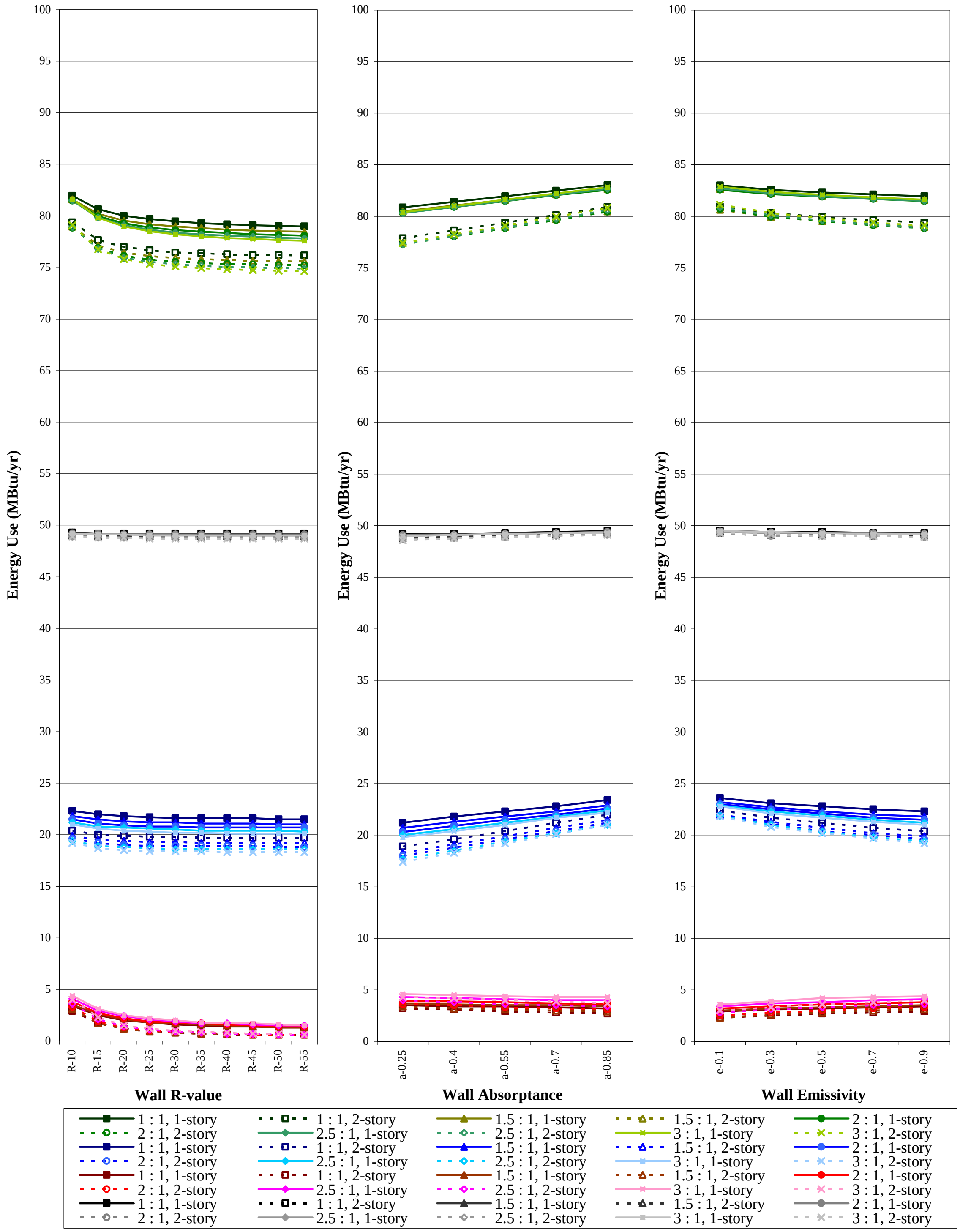


Figure 16: Effect of Building Configuration on Energy Savings from (a) Wall Insulation, (b) Wall Absorptance, and (c) Wall Emissivity

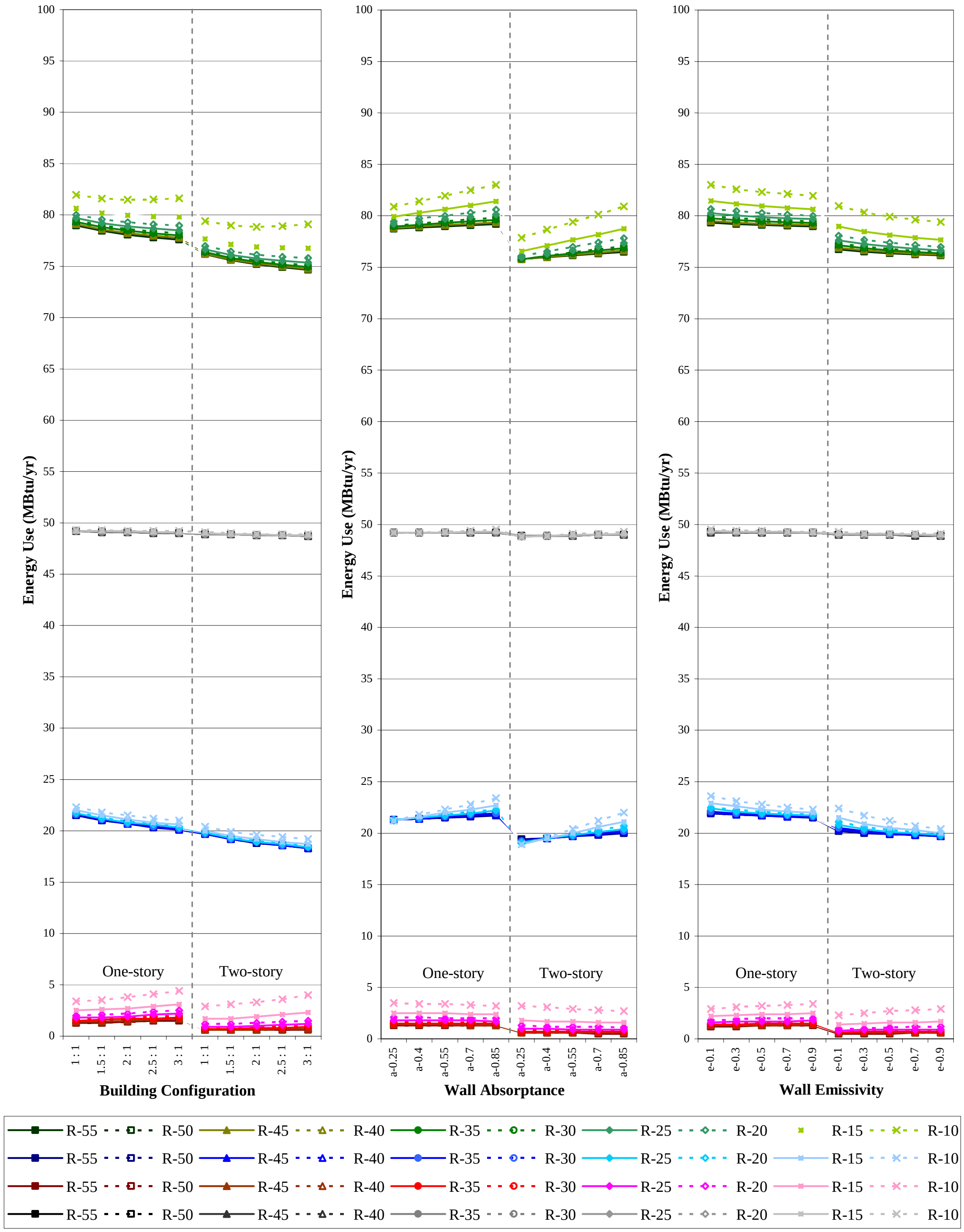


Figure 17: Effect of Wall Insulation on Energy Savings from (a) Building Configuration, (b) Wall Absorptance, and (c) Wall Emissivity

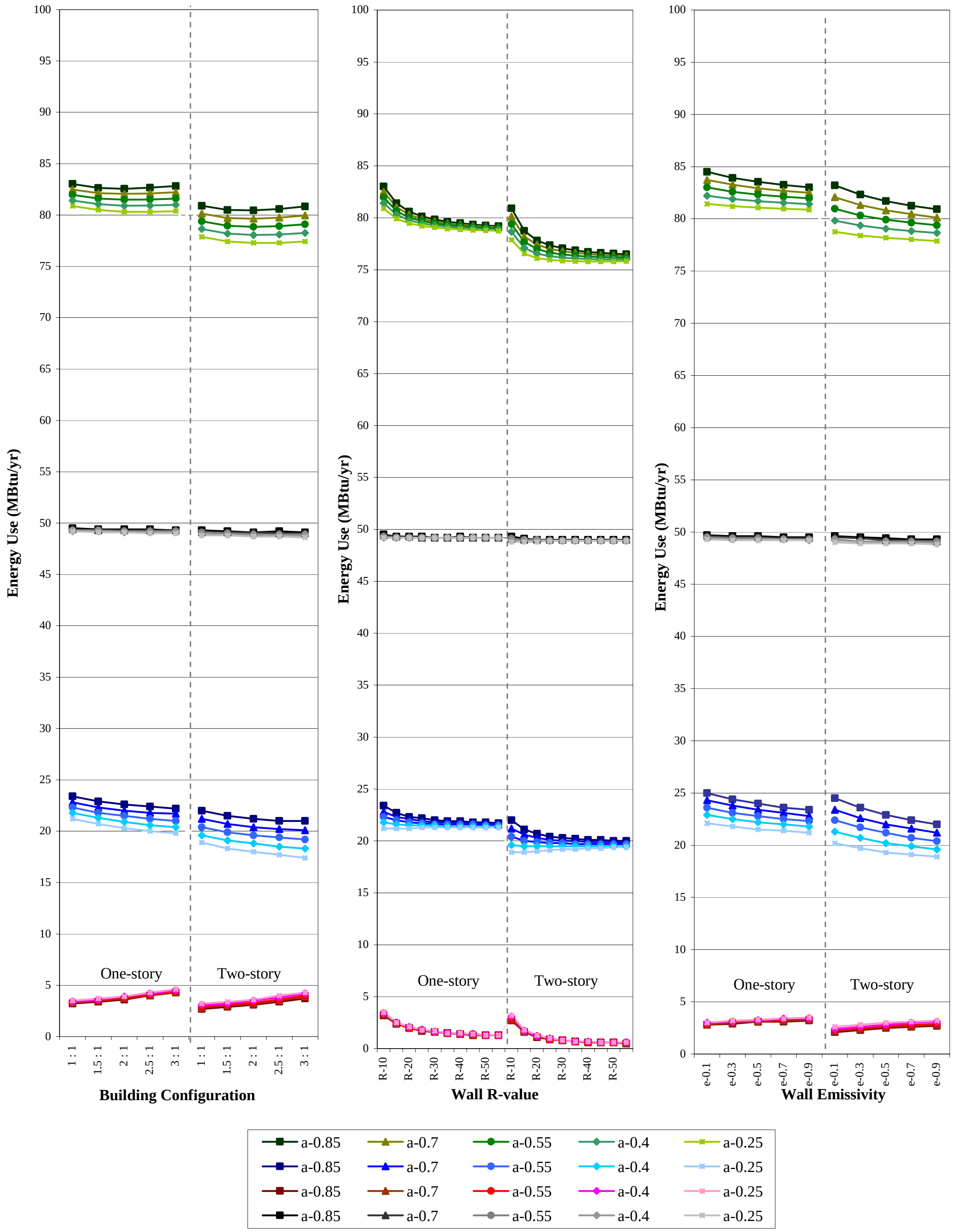


Figure 18: Effect of Wall Absorptance on Energy Savings from (a) Building Configuration, (b) Wall Insulation, and (c) Wall Emissivity

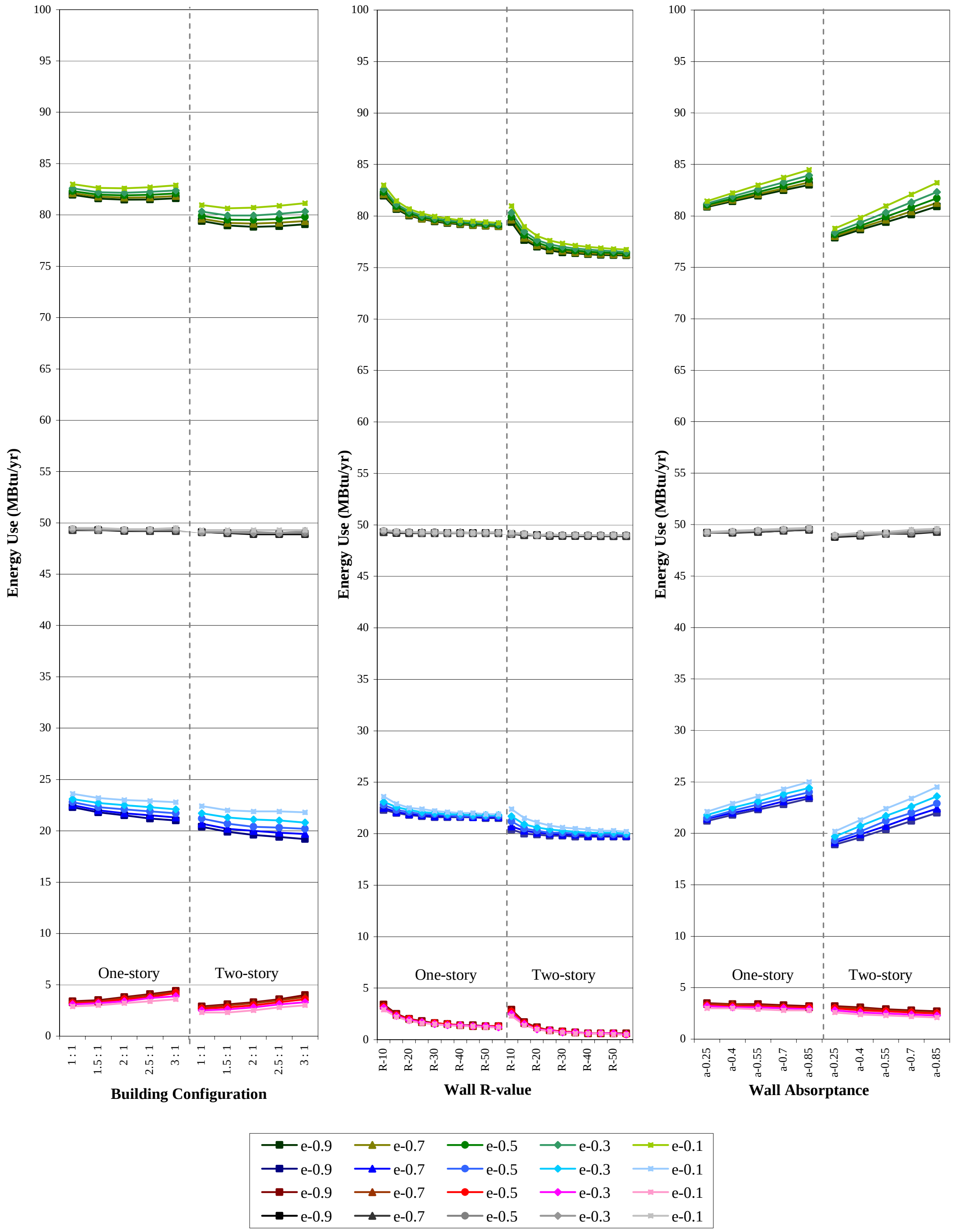


Figure 19: Effect of Wall Emissivity on Energy Savings from (a) Building Configuration, (b) Wall Insulation, and (c) Wall Absorptance

of the roof and of the walls, respectively. The following sections discuss the results of the simulations.

Analysis of Roof Properties

In general, increasing the roof insulation and changes to the reflectance and emissivity of the roof surface resulted in significant savings. Increasing the roof insulation resulted in a cooling as well as a heating energy savings; whereas, increasing the roof reflectance and emissivity showed that the cooling energy savings were offset by a small amount of heating energy penalty. In all these cases, there were also small reductions in energy used by the heating/cooling fans. Changing the building plan from a square shape to a shape elongated along the east-west axis resulted in a cooling energy savings as well as a heating energy penalty.

Effect of Building Configuration

Figure 12 includes three graphs that show the effect of building configuration on energy savings from (a) increasing roof insulation, (b) decreasing roof absorptance, and (c) increasing roof emissivity. The configurations analyzed include one-story and two-story houses with aspect ratio changing from 1:1 to 3:1 east-west to north-south. In the first graph, the annual energy use was plotted against roof R-values ranging from R-10 to R-55. In the second graph, the annual energy use was plotted against roof absorptance ranging from 0.25 to 0.85. In the third graph, the annual energy use was plotted against roof emissivity ranging from 0.1 to 0.9. The properties of the house other than those shown in the respective graphs were the same as in the basecase house. From Figure 12 and Table D- 2 through Table D- 4, the following points were observed:

1) Savings from increasing the roof insulation, increasing the reflectance and increasing the emissivity of the roof surface were higher in a one-story configuration than in a two-story configuration of equal floor area, due to increased roof area. Table D- 2 and Table D- 3 show 3% to 4% total energy savings in a one-story configuration and less than 1% total energy savings in a two-story configuration from increasing the roof R-value from R-30 to R-55 or decreasing the absorptance from 0.85 to 0.25.

2) Savings from increasing the roof insulation were up to 1% higher in buildings elongated along the east-west axis than in square shaped buildings. Table D- 2 shows that increasing the roof R-value from R-30 to R-55 resulted in 2.91% savings in a square-shaped, one-story house; and 3.35% savings in an elongated house with a 3:1 east-west to north-south aspect ratio. However, no such relation is found for roof absorptance and emissivity.

Effect of Roof R-value

Figure 13 includes three graphs that show the effect of roof insulation on energy savings from (a) changing building configuration, (b) decreasing roof absorptance, and (c) increasing roof emissivity. The R-values analyzed ranged from R-10 to R-55. In all the graphs, one story and two-story configurations were analyzed side-by-side. In the first graph, the annual energy use was plotted against changing aspect ration from 1:1 to 3:1 east-west to north-south. In the second graph, the annual energy use was plotted against the roof absorptance ranging from 0.25 to 0.85. In the third graph, the annual energy use was plotted against the roof emissivity ranging from 0.1 to 0.9. The properties of the house other than those shown in the respective graphs were the same as in the basecase house. From Figure 13 and Table D- 5 through Table D- 7, the following points were observed:

1) Changing the building plan from a square-shape to a shape elongated along the east-west axis resulted in a cooling energy savings as well as a heating energy penalty. In the house with a less insulated roof, the heating energy penalty was higher than the cooling energy savings. In a house with a high insulated roof, an elongated plan resulted in a small savings; whereas for a less insulated roof, an aspect ratio of 2:1 was found to be optimum beyond which any further change in the building plan resulted in the heating energy penalty higher than the cooling energy savings. Table D- 5 shows that the maximum total energy savings of 0.31%, 0.66% and 0.97% could be achieved from changing the aspect ratio to 2:1, 2.5: 1 and 3:1 for the roof insulation levels of R-10, R-30 and R-50, respectively.

2) Savings from changing the building plan from a one-story to a two-story resulted in significant savings for a less insulated roof, and very small savings for a highly insulated roof. Table D- 5 shows 14.65%, 3.45% and 1.43% total energy savings from changing the building plan from a one-story to a two-story for the roof insulation levels of R-10, R-30 and R-50, respectively.

3) Savings from increasing the roof reflectance (i.e., decreasing the roof absorptance) and increasing the emissivity were higher for a less insulated roof. These savings were less pronounced for a two-story house. Table D- 6 shows 8.5%, 3.73% and 2.42% total energy savings from decreasing the roof absorptance from 0.85 to 0.25 for the roof insulation levels of R-10, R-30 and R-50, respectively, in a one-story house.

Effect of Roof Absorptance

Figure 14 includes three graphs that show the effect of roof absorptance on energy savings from (a) changing building configuration, (b) increasing roof insulation, and (c) increasing roof emissivity. The absorptance analyzed ranged from 0.25 to 0.85. In all the graphs, one story and two-story configurations were analyzed side-by-side. In the first graph, the annual energy use was plotted against changing aspect ration from 1:1 to 3:1 east-west to north-south. In the second graph, the annual energy use was plotted against the roof R-value ranging from R-10 to R-55. In the third graph, the annual energy use was plotted against the roof emissivity ranging from 0.1 to 0.9. The properties of the house other than those shown in the respective graphs were the same as in the basecase house. From Figure 14 and Table D- 8 through Table D- 10, the following points were observed:

1) Savings from changing the building plan from a square-shape to the one elongated along the east-west axis were the same, irrespective of the roof absorptance value. Savings from changing the building configuration from a one-story to a two-story were higher for dark roofs. Table D- 8 shows equal total energy savings of 0.56% from changing the aspect ratio of the one-story basecase house to a 3:1 east-west to north-south for the roof absorptance

value of 0.25, 0.55 and 0.85. For the same values of roof absorptance, total energy savings of 0.48%, 2.83% and 3.45%, respectively, were observed from changing the building plan from a one-story to a two-story.

2) Savings from increasing roof insulation and emissivity were higher for dark roofs. These savings were less pronounced for a two-story house. Table D- 9 shows 1.37%, 2.17% and 2.91% total energy savings from increasing the roof R-value from R-30 to R-55 for the roof absorptance value of 0.25, 0.55 and 0.85, respectively, in a one-story house.

<u>Effect of Roof Emissivity</u>

Figure 15 includes three graphs that show the effect of roof emissivity on energy savings from (a) changing building configuration, (b) increasing roof insulation, and (c) decreasing roof absorptance. The emissivity analyzed ranged from 0.1 to 0.9. In all the graphs, one story and two-story configurations were analyzed side-by-side. In the first graph, the annual energy use was plotted against changing aspect ratio from 1:1 to 3:1 east-west to north-south. In the second graph, the annual energy use was plotted against the roof R-value ranging from R-10 to R-55. In the third graph, the annual energy use was plotted against the roof absorptance ranging from 0.25 to 0.85. The properties of the house other than those shown in the respective graphs were the same as in the basecase house. From Figure 15 and Table D- 11 through Table D- 13, the following points were observed:

1) Savings from changing the building plan from a square-shape to the one elongated along the east-west axis were slightly higher for a less emissive roof. Savings from changing the building shape from a one-story to a two-story were higher for a less emissive roof. Table D-11 shows total energy savings of 0.97%, 0.66% and 0.56% from changing the aspect ratio of the one-story basecase house to a 3:1 east-west to north-south for the roof emissivity values of 0.1, 0.5 and 0.9. For the same values of roof emissivity, total energy savings of 6.26%, 4.51% and 3.45%, respectively, were observed from changing the building plan from a one-story to a two-story.

2) Savings from increasing the roof insulation and reflectance were higher for a less emissive roof. These savings were less pronounced for a two-story house. Table D- 12 shows 3.45%, 3.14% and 2.91% total energy savings from increasing the roof R-value from R-30 to R-55 for the roof emissivity values of 0.1, 0.5 and 0.9, respectively, in a one-story house. For the same values of roof emissivity, Table D- 13 shows total energy savings of 5.61%, 4.47% and 3.73%, respectively, from decreasing the roof absorptance from 0.85 to 0.25, in a one-story house.

Analysis of Wall Properties

In general, increasing the wall insulation, and changes to the reflectance and emissivity of the wall surface resulted in a smaller savings than with the similar improvements for the roof. Increasing the wall insulation resulted in a cooling as well as a heating energy savings; whereas, increasing the wall reflectance and emissivity showed that the cooling energy savings were offset by a small amount of heating energy penalty. In all these cases, there were also small reductions in energy used by the heating/cooling fans. Changing the building plan from a square-shape to a shape elongated along the east-west axis resulted in a cooling energy savings as well as a heating energy penalty.

Effect of Building Configuration

Figure 16 includes three graphs that show the effect of building configuration on energy savings from (a) increasing wall insulation, (b) decreasing wall absorptance, and (c) increasing wall emissivity. The configurations analyzed include one-story and two-story houses with aspect ratio changing from 1:1 to 3:1 east-west to north-south. In the first graph, the annual energy use was plotted against the wall R-values ranging from R-10 to R-55. In the second graph, the annual energy use was plotted against the wall absorptance ranging from 0.25 to 0.85. In the third graph, the annual energy use was plotted against wall emissivity ranging from 0.1 to 0.9. The properties of the house other than those shown in the respective graphs were the same as in the basecase house. From Figure 16 and Table D- 14 through Table D- 16, the following points were observed:

1) Savings from increasing wall insulation, and reflectance and emissivity of the wall surface were slightly higher in a two-story configuration than in a one-story configuration of equal floor area. Table D- 14 shows 3% to 4% total energy savings in a one-story configuration and up to 5% total energy savings in a two-story configuration from increasing the wall R-value from R-10 to R-30. Table D- 15 shows up to 1.5% total energy savings in a one-story configuration and more than 2% total energy savings in a two-story configuration from decreasing the wall absorptance from 0.55 to 0.25.
2) Savings from increasing wall insulation and absorptance were slightly higher in buildings elongated along the east-west axis than in square shaped buildings. Table D- 2 shows that increasing the roof R-value from R-10 to R-30 resulted in 3.04% savings in a square-shaped, one-story house; and 4.15% savings in an elongated house with a 3:1 east-west to north-south aspect ratio. However, impact of building shape on energy savings from wall absorptance and emissivity were insignificant.

<u>Effect of Wall R-value</u>

Figure 17 includes three graphs that show the effect of wall insulation on energy savings from (a) changing building configuration, (b) decreasing wall absorptance, and (c) increasing wall emissivity. The R-values analyzed range from R-10 to R-55. In all the graphs, one story and two-story configurations were analyzed side-by-side. In the first graph, the annual energy use was plotted against changing aspect ratio from 1:1 to 3:1 east-west to north-south. In the second graph, the annual energy use was plotted against the wall absorptance ranging from 0.25 to 0.85. In the third graph, the annual energy use was plotted against the wall emissivity ranging from 0.1 to 0.9. The properties of the house other than those shown in the respective graphs were the same as in the basecase house. From Figure 17 and Table D- 17 through Table D- 19, the following points were observed:

1) Changing building plan from square shape to the one elongated along the east-west axis results in cooling energy savings as well as heating energy penalty. House with less insulated

walls, heating energy penalty are higher than cooling energy savings. Therefore, with high insulated walls, elongated plan resulted in some (however, small) savings; whereas, for less insulated walls, an aspect ratio of 2:1 was found to be optimum beyond which any further change in building plan resulted in heating energy penalty higher than cooling energy savings. Table D- 17 shows that the maximum total energy savings of 0.59% and 1.57% could be achieved from changing the aspect ratio to 2:1and 3:1 for the wall insulation levels of R-10 and R-30, respectively.

2) Savings from changing the building configuration from one-story to two-story resulted in slightly higher savings for high insulated walls than for less insulated walls. Table D- 17 shows 3.14% and 3.79% total energy savings from changing the building plan from a one-story to a two-story for the wall insulation levels of R-10 and R-30, respectively.

3) Savings from increasing wall reflectance and emissivity are higher for less insulated walls. Table D- 19 shows 1.32% and 0.49% total energy savings from decreasing the wall absorptance from 0.55 to 0.25 for the wall insulation levels of R-10 and R-30, respectively, in a one-story house.

<u>Effect of Wall Absorptance</u>

Figure 18 includes three graphs that show the effect of wall absorptance on energy savings from (a) changing building configuration, (b) increasing wall insulation, and (c) increasing wall emissivity. The absorptance analyzed ranged from 0.25 to 0.85. In all the graphs, one story and two-story configurations were analyzed side-by-side. In the first graph, the annual energy use was plotted against changing aspect ratio from 1:1 to 3:1 east-west to north-south. In the second graph, the annual energy use was plotted against the wall R-value ranging from R-10 to R-55. In the third graph, the annual energy use was plotted against the wall emissivity ranging from 0.1 to 0.9. The properties of the house other than those shown in the respective graphs were the same as in the basecase house. From Figure 18 and Table D- 20 through Table D- 22, the following points were observed:

1) Savings from changing building plan from square shape to the one elongated along the east-west axis were slightly higher for light walls. Savings from changing building configuration from one-story to two-story were higher for light walls. Table D- 20 shows total energy savings of 0.61%, 0.43% and 0.24% from changing the aspect ratio of the one-story basecase house to a 3:1 east-west to north-south for the wall absorptance value of 0.25, 0.55 and 0.85. For the same values of wall absorptance, total energy savings of 3.72%, 3.14% and 2.54%, respectively, were observed from changing the building plan from a one-story to a two-story.
2) Savings from increasing wall insulation and emissivity were higher for dark walls. These savings were more pronounced for a two-story house, which has more wall area. Table D- 21 shows 2.23%, 3.04% and 3.84% total energy savings from increasing the wall R-value from R-10 to R-30 for the wall absorptance value of 0.25, 0.55 and 0.85, respectively, in a one-story house.

Effect of Wall Emissivity

Figure 19 includes three graphs that show the effect of wall emissivity on energy savings from (a) changing building configuration, (b) increasing wall insulation, and (c) decreasing wall absorptance. The emissivity analyzed ranged from 0.1 to 0.9. In all the graphs, one story and two-story configurations were analyzed side-by-side. In the first graph, the annual energy use was plotted against changing aspect ration from 1:1 to 3:1 east-west to north-south. In the second graph, the annual energy use was plotted against the wall R-value ranging from R-10 to R-55. In the third graph, the annual energy use was plotted against the wall absorptance ranging from 0.25 to 0.85. The properties of the house other than those shown in the respective graphs were the same as in the basecase house. From Figure 19 and Table D- 23 through Table D- 25, the following points were observed:

1) Savings from changing building plan from a square shape to the one elongated along the east-west axis were slightly higher for high emissive walls. Savings from changing building shape from a one-story to a two-story were higher for high emissive walls. Table D- 23

shows a total energy savings of 0.16%, 0.28% and 0.43% from changing the aspect ratio of the one-story basecase house to a 3:1 east-west to north-south for the wall emissivity values of 0.1, 0.5 and 0.9. For the same values of wall emissivity, total energy savings of 2.46%, 2.92% and 3.14%, respectively, were observed from changing the building plan from a one-story to a two-story.

2) Savings from increasing wall reflectance are higher for less emissive roof. These savings are more pronounced for a two-story house than for a one-story house. No such dependence is found for savings from increasing wall insulation. Table D- 24 shows total energy savings of 3.23%, 3.13% and 3.04% from increasing the wall R-value from R-10 to R-30 for the wall emissivity values of 0.1, 0.5 and 0.9, respectively, in a one-story house. For the same values of wall emissivity, Table D- 25 shows total energy savings of 1.88%, 1.51% and 1.32%, respectively, from decreasing the wall absorptance from 0.55 to 0.25, in a one-story house.

Conclusions

The heat gain and loss from roof contribute to a higher portion of building energy use in a one-story house than in a two-story house with an equal floor area, because a one-story configuration has a larger roof area than a two-story configuration. Therefore, improving roof has a higher energy-saving potential in a one-story building. On the other hand, the heat gain and loss from walls contribute to a higher portion of building energy use in a two-story house than in a one-story house with equal floor area, because a two-story configuration has a larger wall area than a one-story configuration. Therefore, improving walls has a higher energy-saving potential in a two-story building.

In general, buildings with less surface area, high insulation value and low absorptance and high emittsivity surfaces are less energy consuming. Building configuration is critical for houses with a less insulated envelope, and high absorptance and low emissivity surfaces. Increasing insulation is more effective energy-saving measure for surfaces with a high absorptance and a low emissivity. Low absorptance surfaces are more effective for less insulated envelope and low emissivity surfaces.

6.3.3. Effect of Construction Type

As discussed in Section 4.4.3, simulations were performed for six construction types that include: 2x4 wood frame spaced at 16 inch on center, 2x6 wood frame spaced at 24 inch on center, structural insulated panels, insulated concrete forms, concrete-filled concrete blocks and perlite-filled concrete blocks, for different building configurations.

<u>Annual Energy Use</u>

Figure 20 shows the results of the simulations, following the format discussed in Section 6.2. The three graphs correspond to the three sets of simulation with different levels of airtightness. The first graph corresponds to the air infiltration of 0.46 ACH/hr. and shows all the construction types. In the second graph, only the SIP construction was compared with the basecase construction, for the air infiltration same as the basecase house and when it was reduced by 85% corresponding to the airtight SIP construction. In the third graph, only the ICF construction was compared with the basecase construction, for the air infiltration same as the basecase and when it was reduced by 50% corresponding to airtightness achieved in ICF construction. The annual end-use energy uses were plotted against different building configurations on the X-axis. The one-story and two-story configurations were analyzed side-by-side. For each, the east-west to north-south aspect ratio of the building was changed from 1:3 to 3:1. The different lines correspond to the different construction types.

Table D- 26 shows the annual energy use and percent savings for the selected intermediate values of the aspect ratio for one and two-story configurations of the building, for different construction types and air tightness levels.

From Figure 20 and Table D- 26 the following points were observed:

1) The highest total energy savings of 2.47% were resulted from the air tight SIP construction for 3:1, one-story configuration.

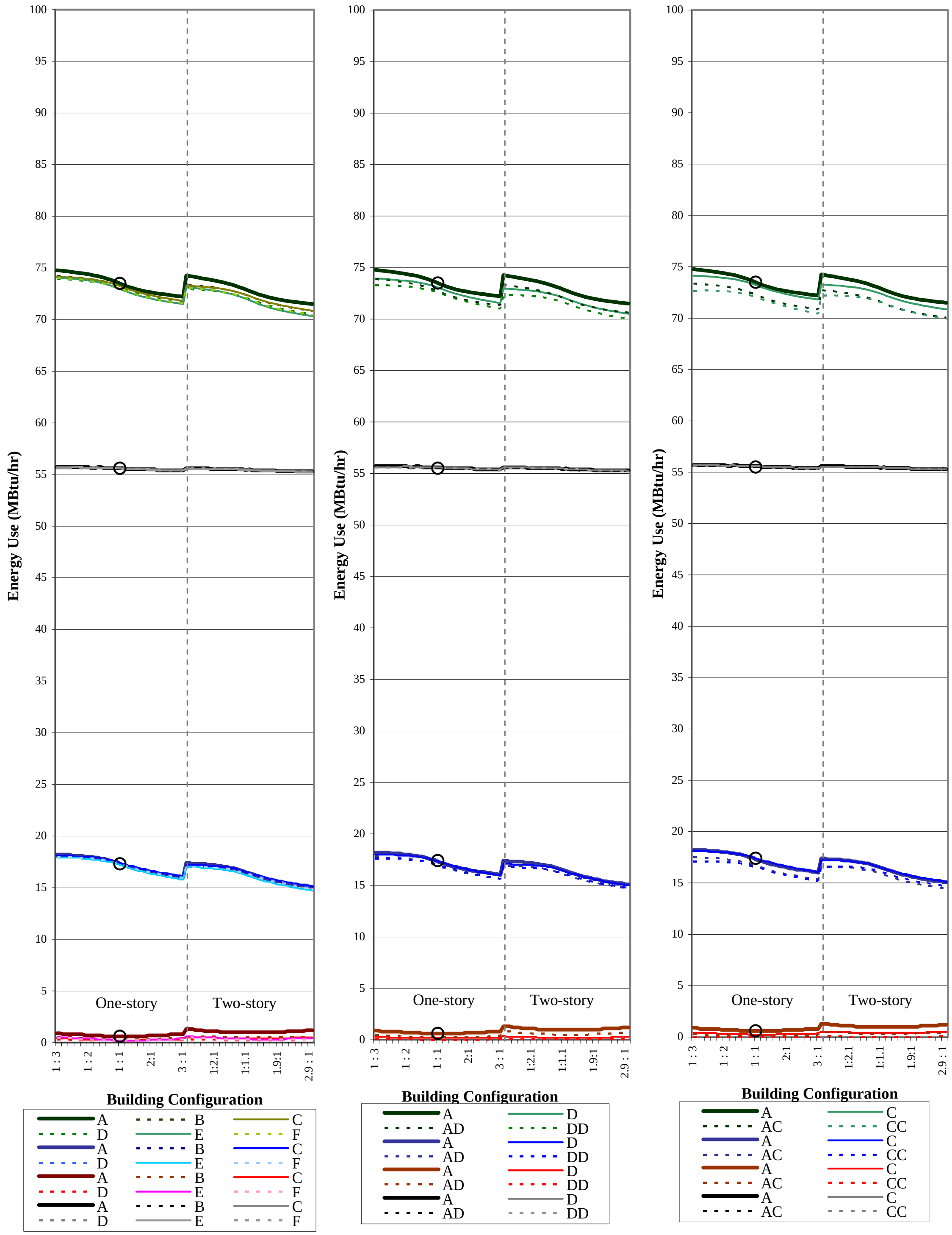


Figure 20: Annual Energy Use for Different Construction Types

2) The energy savings from different construction types were higher for a two-story configuration except for the air tight SIP construction. The energy savings from the air tight SIP construction ranged from 1.96% to 2.47% in a one-story house and from 1.83% to 2.20% in a two-story house for 1:1 to 3:1 east-west to north-south aspect ratio, respectively.

3) In a one-story configuration, the highest space cooling energy savings of up to 5% were resulted with the air tight SIP construction, whereas for a two-story configuration, the highest cooling energy savings of up to 5% were resulted with an air tight ICF construction.

4) The space heating energy use could be eliminated with air tight SIP or ICF construction.

Hourly Plots for Peak Winter and Summer Days

Figure 21 compares the hourly inside temperature and energy use on the peak days, for different construction types. The graphs on the left correspond to the peak winter day, and the graph on the right correspond to the peak summer day. The top most graphs show the hourly outside air, inside and setpoint temperatures. The graphs in the middle show the heating fuel and the cooling electricity used during different hours of the peak winter and summer days. The lower most graphs show the scatter plot of hourly energy use versus the outside air temperature.

It is to be noted that for six hours in the morning (i.e., from 12:00 p.m. to 6:00 a.m.), the thermostat was setback and setup by 5ºF for winter and summer, respectively. These setback and setup are shown in the top most graphs for peak winter and summer days. From the figure following observations were made:

1) The graph showing the temperatures for the peak winter day demonstrated that the indoor temperature the basecase construction was the closest to the setpoint temperature. The airtight SIP house demonstrated the most stable indoor temperature; however, the temperature was highest and the least close to the setpoint temperature when compared to other construction types.

2) From the similar graph corresponding to the peak summer day, no difference in the daytime indoor temperatures was observed for all the construction types.

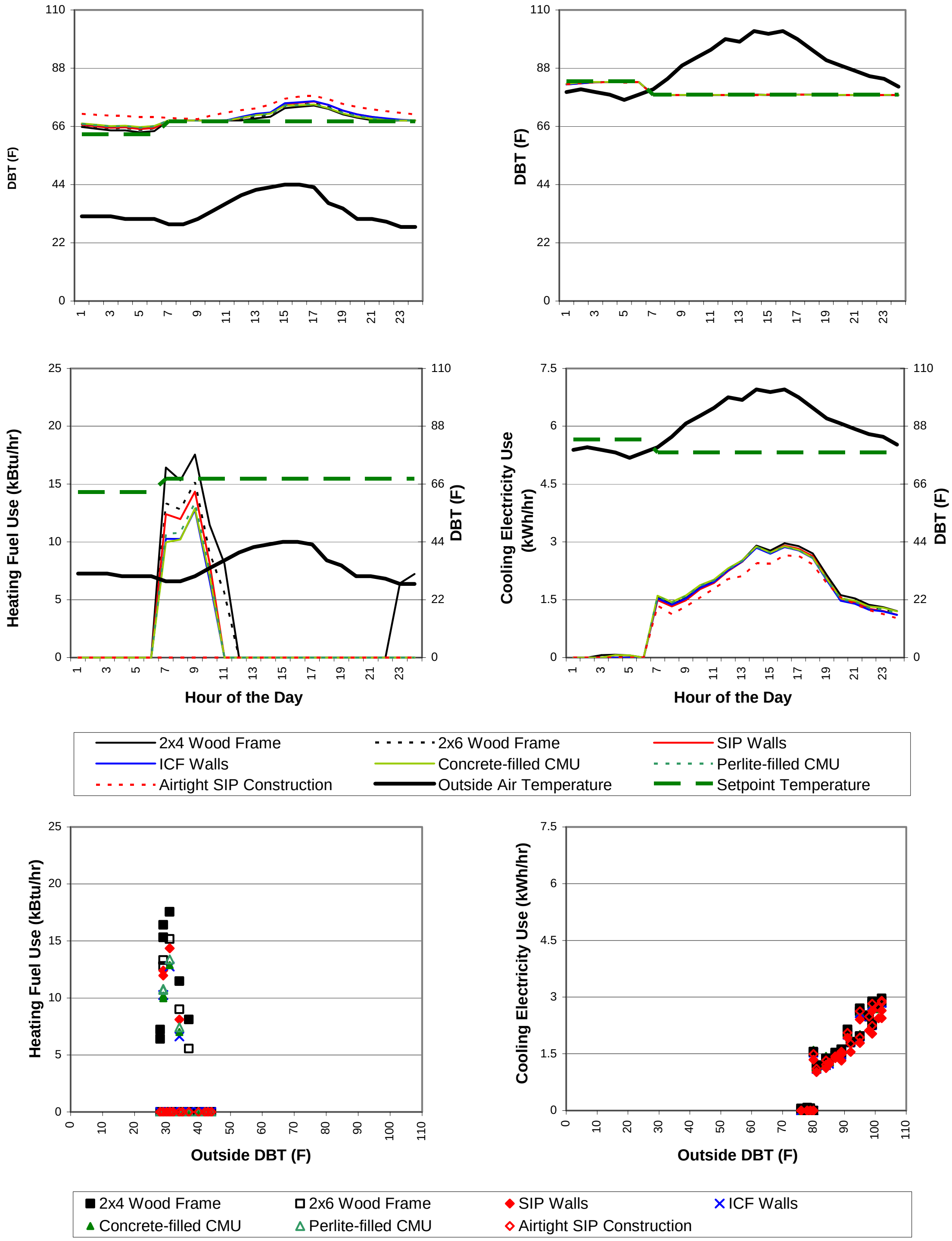


Figure 21: Hourly Plots for a Peak Winter and a Peak Summer Day for Different Construction Types

3) The graph showing heating fuel use during different hours of the peak winter day demonstrated that the heating load for the basecase construction with 2x4 studs and R-11 insulation had the largest peak heating loads. Other construction types had significant effect on reducing heating load. The airtight SIP house did not require heating even during the peak winter day.

4) The similar graph corresponding to the peak summer day demonstrated that airtight SIP construction had the smallest cooling load. The other construction types did not have a significant effect on reducing cooling load.

5) The scatter plot of heating and cooling load versus the outside air temperature on the peak days confirmed the observations made in the step 3 and 4.

6.3.4. Effect of Fenestration Properties

As discussed in Section 4.4.4, simulations were performed to analyze the combined effect of shading, window distribution, U-factor and SHGC of the windows.

Results of the Simulations

Figure 22 through Figure 25 show the results of the simulations with improved fenestration characteristics. These figures follow the format as discussed in Section 6.2. Figure 22 shows the effect of overhang on the energy savings from window redistribution, reducing window U-value and reducing SHGC. Figure 23 shows the effect of window distribution on the energy savings from increasing overhang depth, reducing window U-value and reducing SHGC. Figure 24 shows the effect of window U-value on the energy savings from increasing overhang depth, window redistribution, and reducing SHGC. Figure 25 shows the effect of SHGC on energy savings from increasing overhang depth, window redistribution, and reducing window U-value. Table D- 27 through Table D- 38 show the annual energy use and savings for selected intermediate values of the overhang depth, window distribution, U-factor and SHGC of the windows. The following sections discuss the results of the simulations.

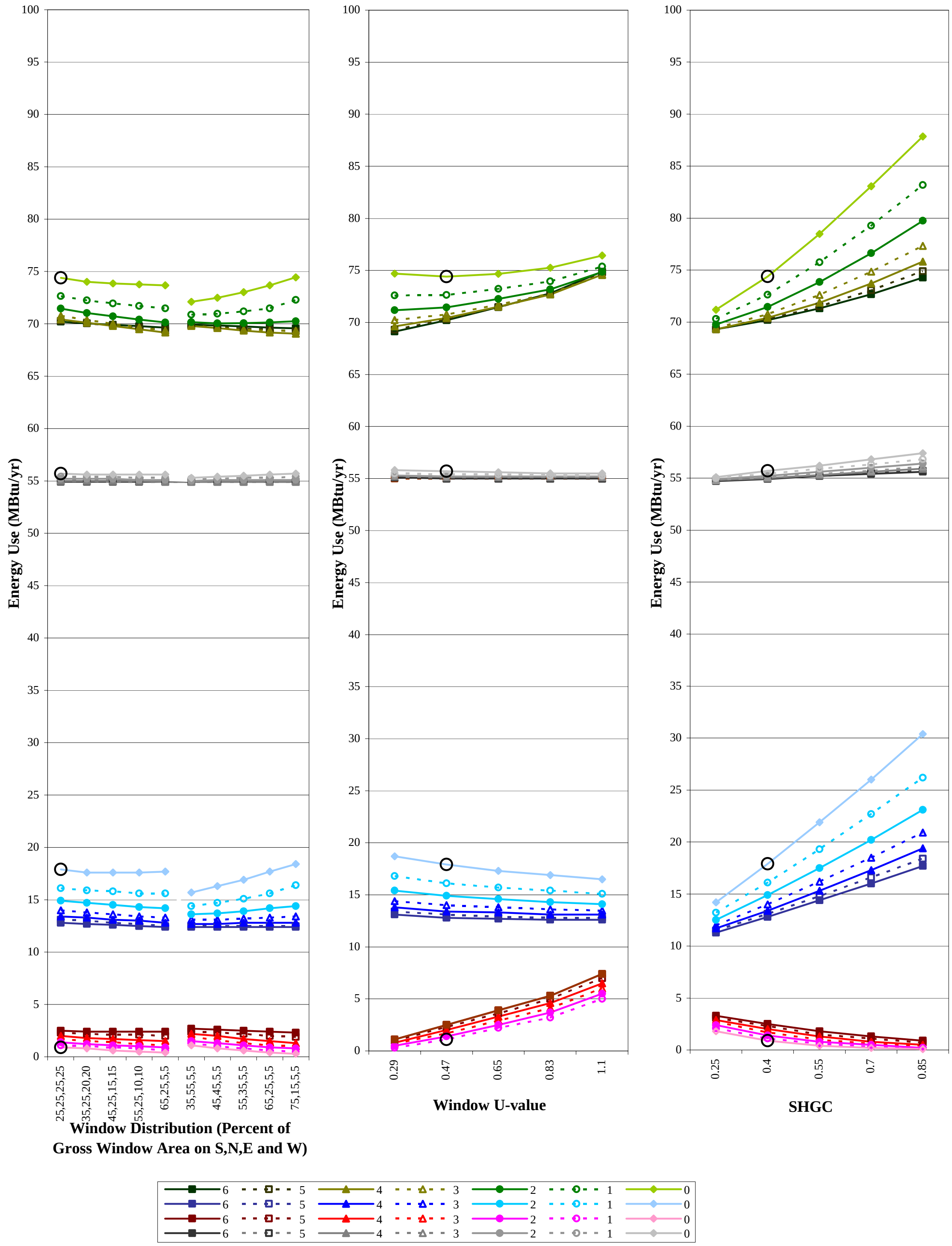


Figure 22: Effect of Overhang Depth on Energy Savings from (a) Window Redistribution, (b) Window U-factor, and (c) SHGC

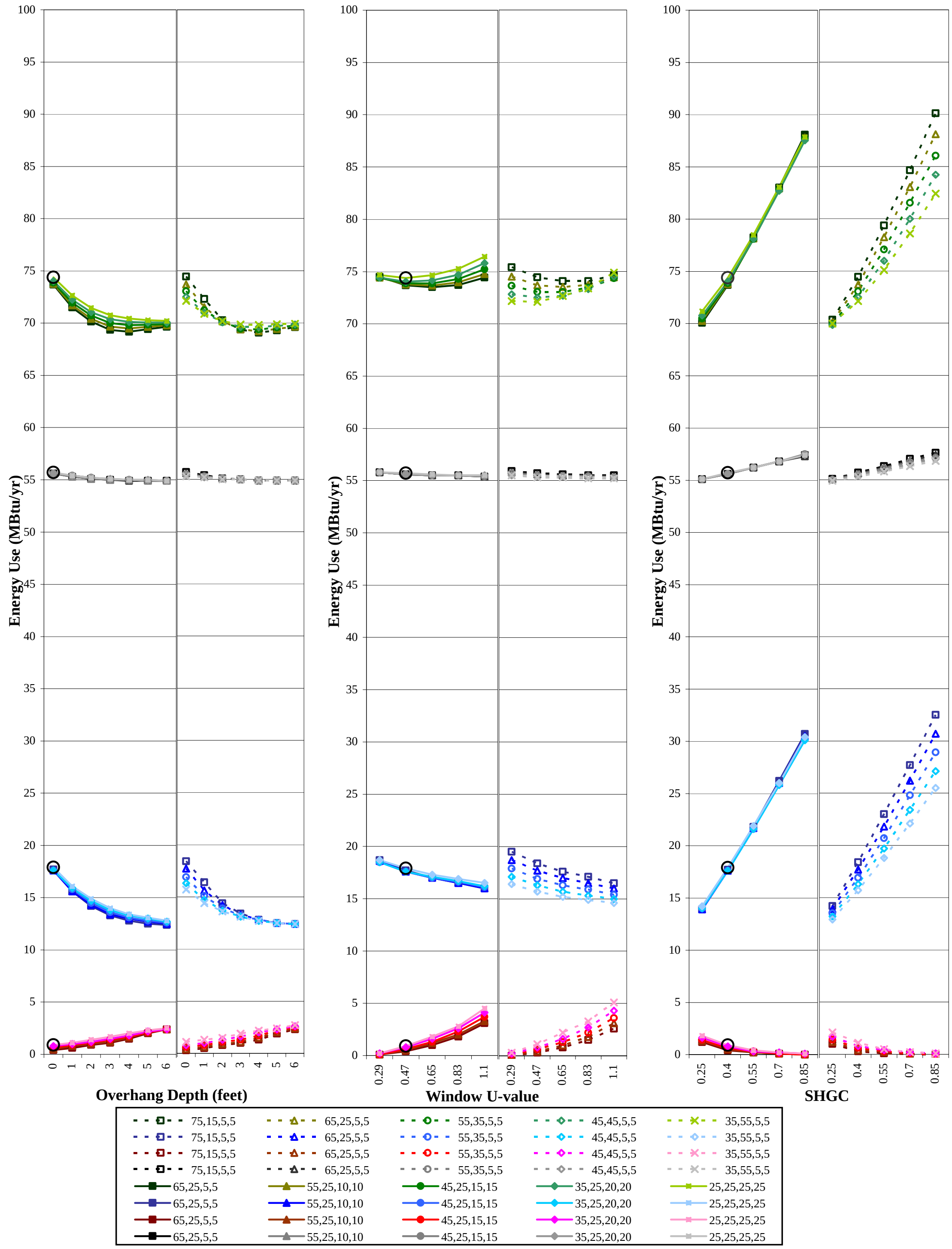


Figure 23: Effect of Window Redistribution on Energy Savings from (a) Overhangs, (b) Window U-factor, and (c) SHGC

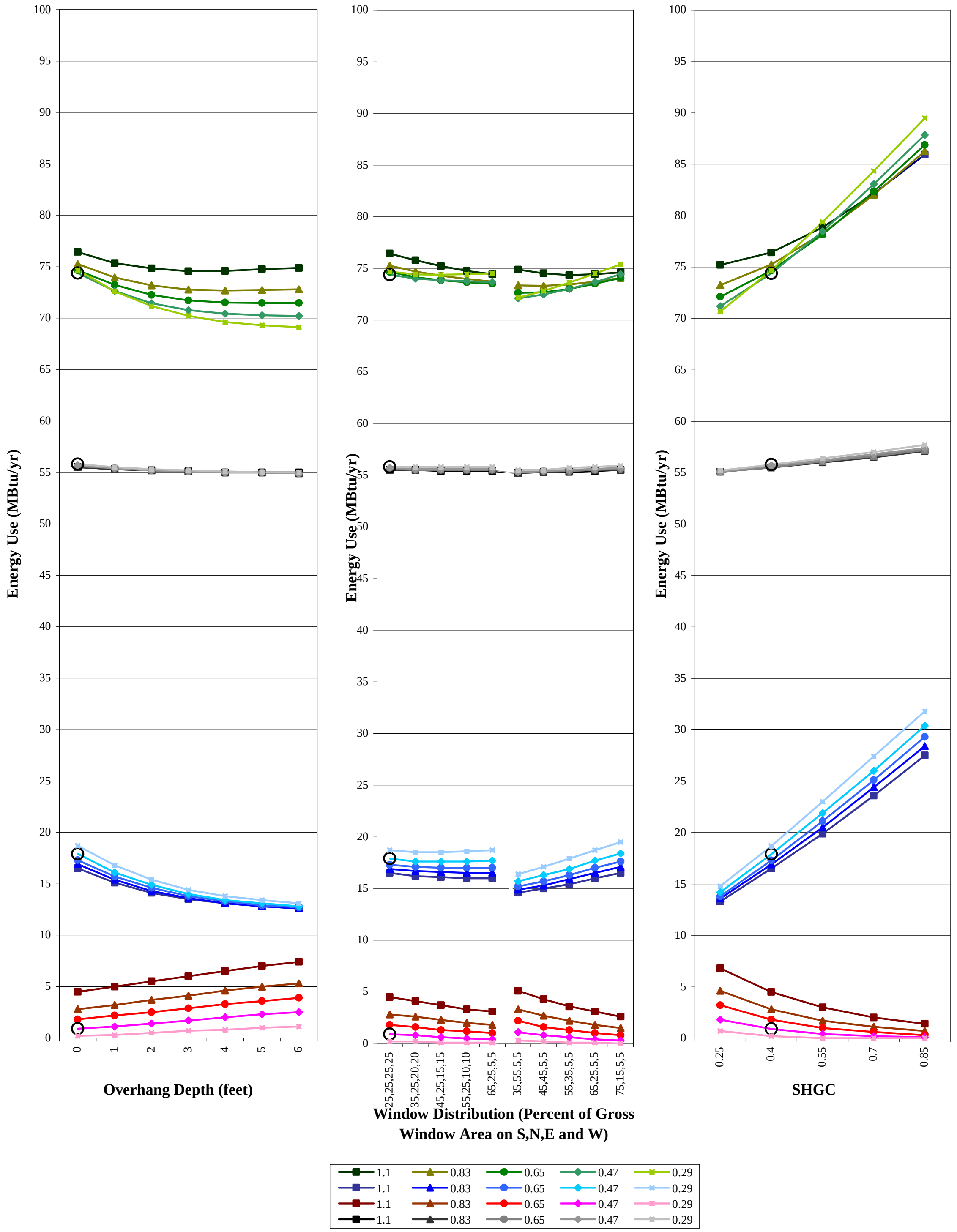


Figure 24: Effect of Window U-factor on Energy Savings from (a) Overhangs, (b) Window Redistribution, and (c) SHGC

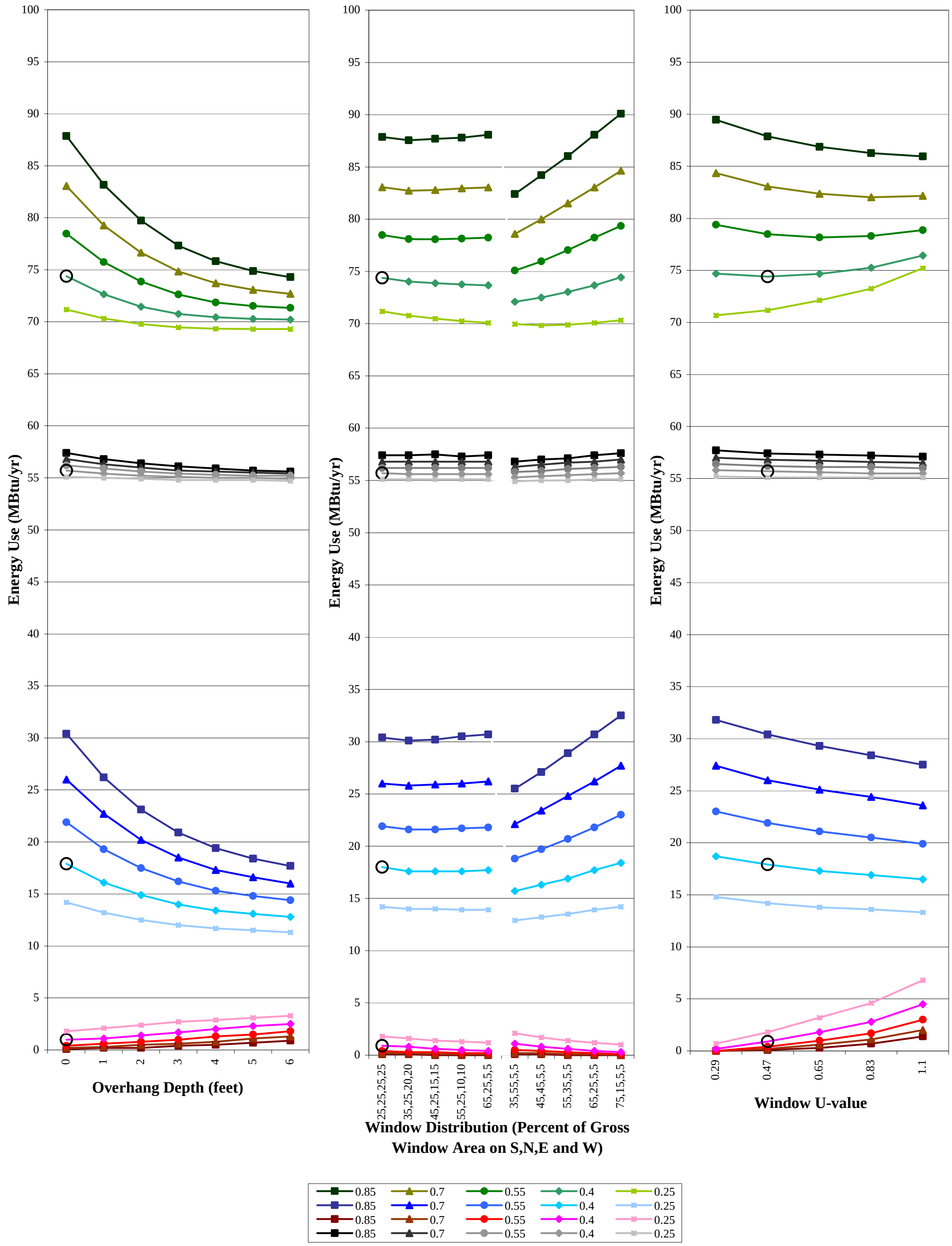


Figure 25: Effect of SHGC on Energy Savings from (a) Overhangs, (b) Window Redistribution, and (c) Window U-factor

Analysis of Fenestration Properties

In general, increasing the overhang depth resulted in a cooling energy savings and a heating energy penalty. Decreasing the window U-value resulted in a cooling energy penalty comparable to the heating energy savings. Decreasing the SHGC resulted in a high cooling energy savings and a relatively small heating energy savings, thus, a significant total energy savings, always. Redistributing the east and west windows to the south resulted in a small heating and a small cooling energy savings, thus, a small total energy savings. Redistributing the north windows to the south resulted in a cooling energy penalty and a heating energy savings.

Effect of Overhang Depth

Figure 22 includes three graphs that show the effect of overhang on the energy savings from (a) window redistribution, (b) reducing window U-value and (c) reducing SHGC. In the first graph, the annual energy use was plotted against the window percent on the four orientations (south, north, east, and west). The X-axis was divided in two parts. First the window area on the east and west was decreased from 25% to 5% of the gross window area; and then, the north window area was decreased to 5%. In the second graph, the annual energy use was plotted against the window U-values ranging from 0.29 to 1.1. In the third graph, the annual energy use was plotted against the SHGC ranging from 0.25 to 0.85. The properties of the house other than those showen in the respective graphs were the same as in the basecase house. From Figure 22 and Table D- 27 through Table D- 29, the following points were observed:

1) For a house with no overhang, redistributing east and west windows to the north showed higher savings than to the south. Table D- 27 shows that more than 3% savings were resulted from a window distribution of 35%, 55%, 5% and 5% on the south, north, east and west. For 2-foot overhang, these savings were reduced to less than 2%. For more than 4-foot overhang, these savings were further reduced; however, maximum windows on the south produced the highest savings.

2) Redistributing the north windows on the south resulted in the cooling energy penalty higher than the heating energy savings for up to 2-foot overhang depth. Beyond 2-foot, a small total energy savings were resulted from redistributing the north windows to the south. Table D-27 shows that for a house with no overhangs, more windows on the north could result in up to 3% total energy savings. For a house with more than 2-foot overhang, redistributing windows to the south resulted in up to 2% energy savings.

3) Savings from decreasing the window U-value were higher for increased overhang depth. Table D- 28 shows -0.39%, 0.39%, 1.15% and 1.54% total energy savings from decreasing U-value from 0.47 to 0.29 for 0 ft., 2 ft., 4 ft. and 6 ft. overhang depths. Therefore, for shaded windows, less conductive windows showed higher energy savings potential.

4) Savings from decreasing the window SHGC were higher for windows with no overhangs. Table D- 29 shows 4.32%, 2.35%, 1.58% and 1.27% total energy savings from decreasing SHGC from 0.4 to 0.25 for 0 ft., 2 ft., 4 ft. and 6 ft. overhang depths. Therefore, for unshaded windows, low SHGC windows showed higher energy savings potential.

Effect of Window Distribution

Figure 23 includes three graphs that show the effect of window distribution on the energy savings from (a) increasing overhang depth, (b) reducing window U-value, and (c) reducing SHGC. In all the graphs, the X-axis was divided in two parts. The left half corresponds to the case where the effect of redistributing the east and west windows to the south was analyzed, keeping the north window area constant to 25% of the gross window area. The right half corresponds to the case where the effect of redistributing the north windows to the south was analyzed, keeping the east and west window area constant to 5% of the gross window area.

In the first graph, the annual energy use was plotted against the overhang depths ranging from 0-foot to 6-foot. In the second graph, the annual energy use was plotted against the window U-values ranging from 0.29 to 1.1. In the third graph, the annual energy use was plotted against SHGC ranging from 0.25 to 0.85. The properties of the house other than those shown in the respective graphs were the same as in the basecase house. From Figure 23 and Table D- 30 through Table D- 32, the following points were observed:

1) Savings from increasing the overhand depth were higher for a house with more windows on south. For most of the east and west windows redistributed on the south, an overhang depth of 4 ft. was found optimum. Table D- 30 shows more than 7% energy savings in a house with 4-foot overhang and 75% windows on the south. For a house with the windows having no overhangs, the redistribution of the north windows to the south resulted in the cooling energy penalty higher than the heating energy savings. The redistribution of the north windows to the south was the most advantageous for an overhang depth of 4-foot, beyond which less total energy savings were achieved.
2) Savings/penalty from decreasing the window U-value was higher for the windows distributed equally on all four sides. For a house with the east and west windows distributed to the south, a window U-value of 0.65 was found optimum, whereas for a house with equal windows on all four sides, a window U-value of 0.47 was found optimum. For a house with more north windows, decreasing the window U-value resulted in energy savings; whereas for a house with more south windows, a window U-value of 0.65 to 0.83 was found optimum, beyond which, the cooling energy penalty was higher than the heating energy savings.
3) Savings from decreasing the window SHGC were higher for a house with more windows on the south. However, redistributing the north windows on the south had more effect on these savings than redistributing the east and west windows to the south. Therefore, decreasing SHGC was more effective for a house with less north windows. Up to 5% energy savings could be achieved from decreasing the SHGC from 0.4 to 0.25.

Effect of Window U-value

Figure 24 includes three graphs that show the effect of window U-value on the energy savings from (a) increasing overhang depth, (b) window redistribution, and (c) reducing SHGC.

In the first graph, the annual energy use was plotted against overhang depths ranging from 0-foot to 6-foot. In the second graph, the annual energy use was plotted against window percent on the four orientations (south, north, east, and west). The X-axis was divided in two parts. First the window area on the east and west was decreased from 25% to 5% of the gross window area; and then, the north window area was decreased to 5%. In the third graph, the annual energy use was plotted against SHGC ranging from 0.25 to 0.85. The properties of the house other than those shown in the respective graphs were the same as in the basecase house. From this figure, the following points were observed:

1) Savings from increasing overhang depth were higher for less conductive windows. From increasing overhangs depths, 5.63%, 4.27% and 3.28% total energy savings could be achieved for window U-values of 0.47, 0.65 and 0.83.
2) Savings from redistributing east and west and north windows to the south were higher for more conductive windows; whereas savings from redistributing north windows to the south were higher for less conductive window.
3) Savings from decreasing SHGC were higher for less conductive windows. Also, for less conductive windows, a low SHGC was desirable; whereas for high conductance windows, a high SHGC was desired to achieve energy savings.

Effect of SHGC

Figure 25 includes three graphs that show the effect of SHGC on energy savings from (a) increasing overhang depth, (b) window redistribution, and (c) reducing window U-value In the first graph, the annual energy use was plotted against overhang depths ranging from 0-foot to 6-foot. In the second graph, the annual energy use was plotted against window percent on the four orientations (south, north, east, and west). The X-axis was divided in two parts. First the window area on the east and west was decreased from 25% to 5% of the gross window area; and then, the north window area was decreased to 5%. In the third graph, the annual energy use was plotted against the window U-value ranging from 0.29 to 1.1. The properties of the house other than those shown in the respective graphs were the same as in the basecase house. From this figure, the following points were observed:

1) Savings from increasing the overhang depth were higher for the windows with a high SHGC. From increasing overhangs depths, 5.63%, 9.11% and 12.48% total energy savings could be achieved for SHGC values of 0.4, 0.55 and 0.7.
2) Redistributing the east and west windows to the south resulted in a small heating energy savings and a small cooling energy penalty. These resulted in a small savings for a low SHGC window and a small penalty for a high SHGC window. Such measure resulted in 0.95%, 0.32% and 0.04% total energy savings for SHGC values of 0.4, 0.55 and 0.7.
3) On the other hand, redistributing north window on the south resulted in a small heating energy savings and a high cooling energy penalty – higher for high SHGC windows. These resulted in a high energy penalty for a high SHGC windows and a small penalty for a low SHGC windows.
4) Decreasing the window U-value resulted in energy savings for low SHGC and in energy penalty for high SHGC.

6.3.5. Effect of Air-Conditioner and DHW System Efficiency

As discussed in Section 4.4.5, two sets of simulations were performed by changing the efficiencies of the air-conditioner and DHW system. Each set of simulations analyzed the effect of different building configurations on energy savings from efficient systems.

<u>Results of the Simulations</u>

Figure 26 shows the results of the simulations with varying space cooling, space heating and water heating system efficiencies. The first graph corresponds to the changing air-conditioner efficiency (seasonal energy-efficiency ratio) from SEER-10 to SEER-19. The second graph corresponds to the changing DHW system energy factor (EF) from 0.45 to 0.9.

Table D- 39 and Table D- 40 show the annual energy use and percent savings for the selected intermediate values of the aspect ratio for one and two-story configurations of the

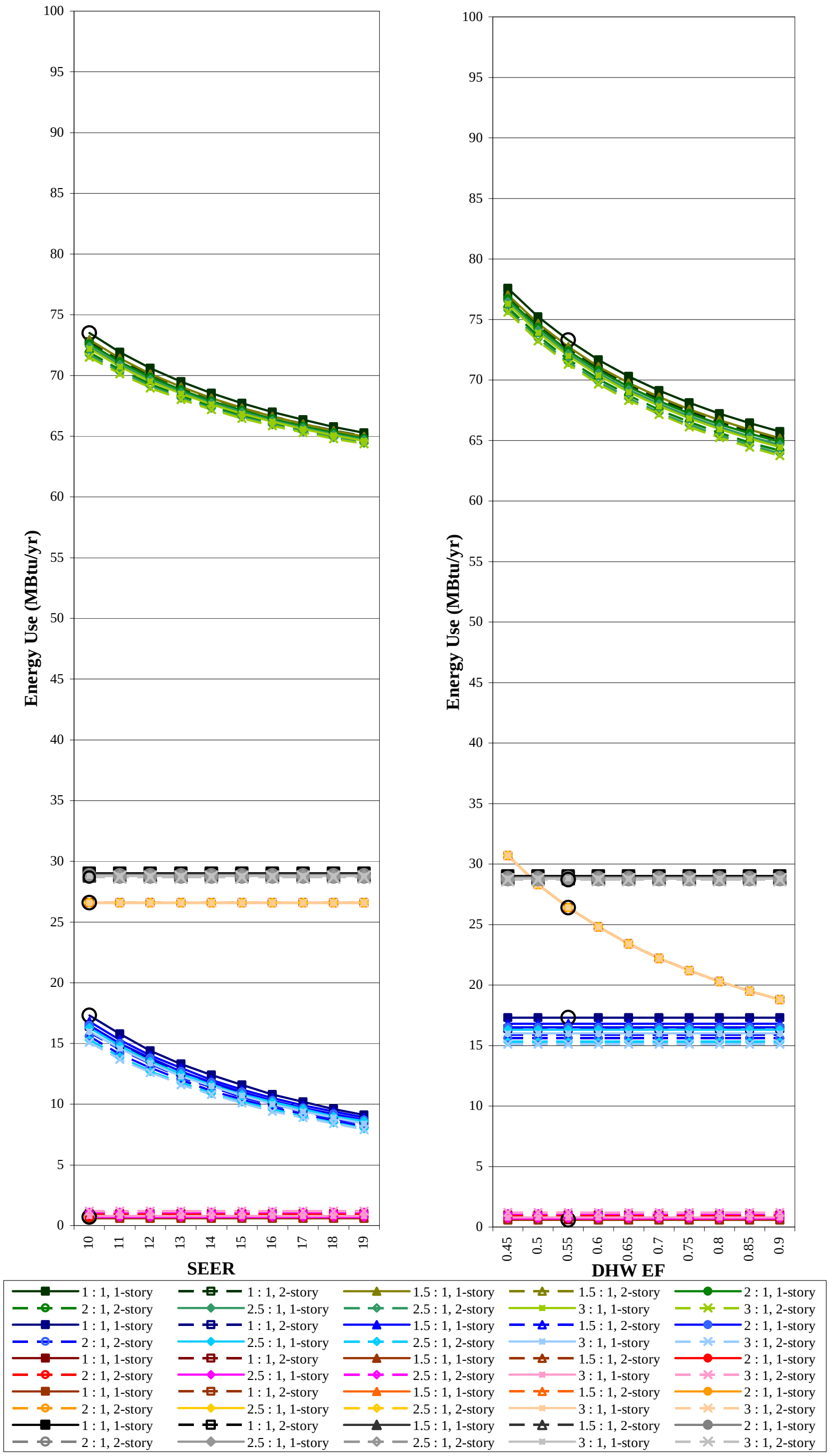


Figure 26: Effect of Air-Conditioner and DHW System Efficiency on Annual Energy Use

building for all the analyzed values of air-conditioner efficiency and DHW system EF. The following sections discuss the results of simulations.

Analysis of Air-Conditioner Efficiency

Energy-efficient air-conditioners have significant energy-saving potential in reducing space cooling energy use. Compared to the basecase SEER-10 air-conditioner, a SEER-12 air-conditioner resulted in a cooling energy savings of 16% to 17% and a total annual energy savings of 3% to 4%. With a SEER-15 air-conditioner cooling energy savings of 32% to 34% and a total annual energy savings of 7% to 8% could be achieved for different building configurations.

Analysis of Water Heater Efficiency

Energy-efficient water heaters have significant energy-saving potential in reducing water heating energy use. A 0.65 EF water heater resulted in 12% water heating energy savings and up to 4% total energy savings. With a 0.85 EF water heater up to 28% water heating energy savings and up to 10% total energy savings could be achieved. Further decrease in energy use is expected by using DHW system without a standing pilot light that consumes up to 800 Btu/hr energy, continuously.

6.4. Development of the Maximum Energy-Efficient House

As discussed in Section 4.5, simulations were performed to analyze the individual and combined effect of energy-efficient measures and determine the maximum energy savings that could be achieved using the analyzed simulatable measures.

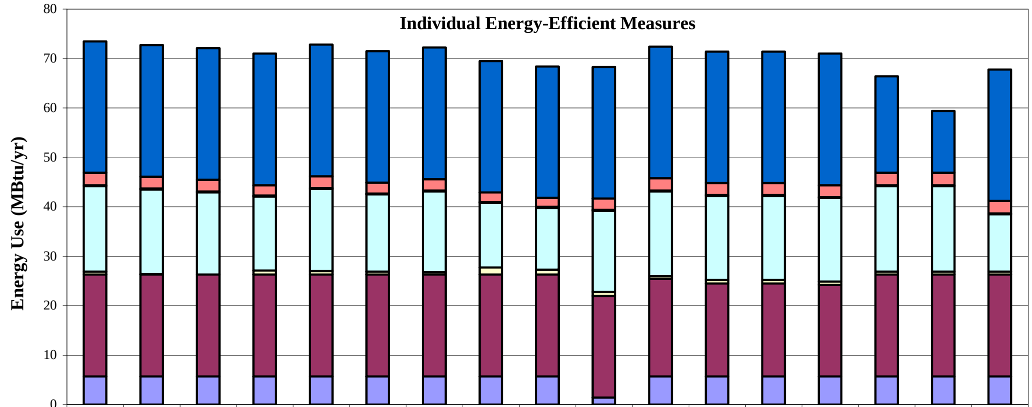
Table 11 in Section 4 lists these measures in the order they were applied. The analysis of the impact of applying these measures was performed using two approaches. First, the impact of each measure was assessed separately. Second, the impact of combined application of these measures was assessed in a cumulative fashion. The following section describes the effect of individual and combined application of these measures. Table D- 41 and Table D- 42 show the annual energy use and savings for different end uses for individual and combined application of measures. Also, for combined application of measures, incremental savings from each measure was calculated and compared to the individual savings from the corresponding measure. The cumulative energy savings shows the maximum energy savings that could be achieved using the selected strategies, in a single-family detached house in a hot and humid climate.

Annual Energy Use for Individual Application of Energy-Efficient Measures

Figure 27 shows the annual energy use for the individual application of the selected energy-saving measures to the basecase house. The stacked bars showing the annual end-use energy use demonstrate that the largest savings in space cooling was achieved from the SEER-15 air-conditioner (33% savings), followed by overhangs with window redistribution (28% savings). The largest savings in space heating was achieved from the airtight SIP construction with ERV (100% savings). The largest savings for domestic water heating was achieved from the efficient tankless water heater with pilot lights (53% savings). The largest savings in equipment energy was achieved from the horizontal-axis clothes washer (20% savings). CFLs saved 75% lighting energy use. Among all the measures applied individually, tankless water heater without pilot light had the highest total energy-saving potential (19% savings), followed by overhangs with window redistribution and CFLs.

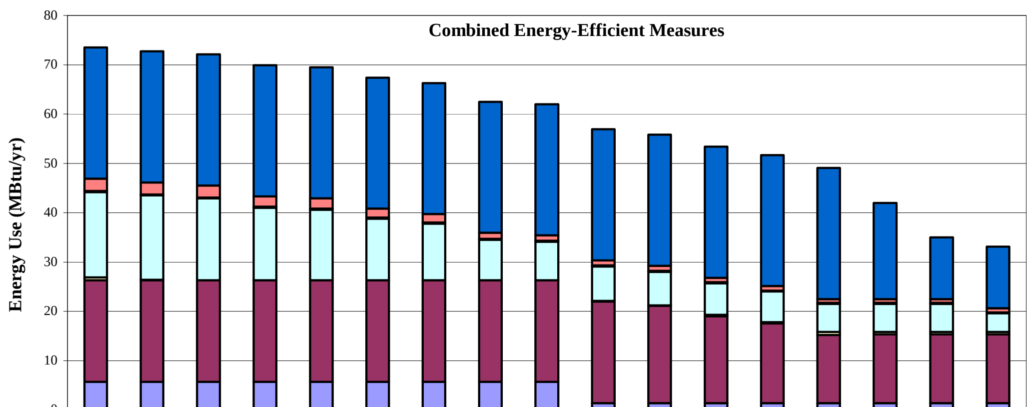
Annual Energy Use for Combined Application of Energy-Efficient Measures

Figure 28 shows the annual energy use for the combined application of the energy-saving measures to the basecase house. The stacked bars showing the annual end-use energy use demonstrate that, for the basecase house, the space cooling, domestic water heating and equipment energy use comprised a significant part of the total energy use (24%, 36% and 28%, respectively) and the space heating and lighting energy use were only 10% and 8% of the total energy use; whereas after the combined application of all the measures to achieve the maximum energy-efficient house, the space cooling, domestic water heating energy use could be reduced significantly and the equipment energy contributed the most to the total energy use (42% of the total).



	Basecase	SIP Construction	SIP (airtight) + ERV	High-albedo Roof	High-albedo Walls	Ar-Fill Low-e Windows	Vinyl Frame	Overhangs	+ 75% Windows on South	CFL	Efficient refrigerator	Efficient Freezer	Efficient Dishwasher	Horizontal Axis CW	Tankless Water Heater	+ Electronic Ignition	High SEER AC
DHW	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	19.5	12.5	26.6
Vent Fans	2.5	2.4	2.4	2.1	2.4	2.2	2.3	1.9	1.8	2.3	2.5	2.4	2.4	2.4	2.5	2.5	2.5
Pumps & Misc.	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Space Cool (Mbtu)	17.3	17.1	16.6	15	16.6	15.6	16.3	13.1	12.5	16.4	17.1	17	17	16.9	17.3	17.3	11.6
Space Heat (Mbtu)	0.6	0.1	0	0.8	0.7	0.6	0.5	1.4	1	0.8	0.6	0.7	0.7	0.7	0.6	0.6	0.6
Misc Equip	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	19.7	18.8	18.8	18.5	20.6	20.6	20.6
Area Lights	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	1.4	5.7	5.7	5.7	5.7	5.7	5.7	5.7

Figure 27: Annual Energy Use for Individual Application of Energy-Efficient Measures



	Basecase	SIP Construction	SIP (airtight) + ERV	+ High-albedo Roof	+ High-albedo Walls	+ Ar-Fill Low-e Windows	+ Vinyl Frame	+ Overhangs	+ 75% Windows on South	+ CFL	+ Efficient Refrigera	+ Efficient Freezer	+ Efficient Dishwasher	+ Horizontal Axis	+ Tankless Water	+ Electronic Ignition	+ High SEER AC
DHW	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	19.5	12.5	12.5
Vent Fans	2.5	2.4	2.4	2.1	2.1	1.8	1.7	1.2	1.1	1	1	0.9	0.9	0.8	0.8	0.8	0.8
Pumps & Misc.	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Space Cool (Mbtu)	17.3	17.1	16.6	14.7	14.3	12.5	11.5	8.2	7.8	7	6.8	6.4	6.2	5.7	5.7	5.7	3.8
Space Heat (Mbtu)	0.6	0.1	0	0	0	0	0	0	0	0.1	0.1	0.3	0.3	0.6	0.5	0.5	0.5
Misc Equip	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	19.7	17.6	16.1	13.8	13.9	13.9	13.9
Area Lights	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4

Figure 28: Annual Energy Use for Combined Application of Energy-Efficient Measures

Effect of Combined Application of Energy-Efficient Measures

Figure 29 shows the impact of the combined application of the selected measures on the space heating, space cooling, domestic water heating, other end-uses, and total energy use using a common Y-axis versus the stacked bar chart shown in Figure 28. The graph includes the results of the simulation for different building configurations. This figure follows the format as discussed in Section 6.2. In this figure, measures with the highest incremental savings have the steepest slope. Form this figure, following observation were made:

1) As compared to a square-shaped, one-story, basecase house, a two-story house elongated along the east-west axis saved cooling energy. However, with a high reflectance roof, two-story house became more energy consuming than a one-story house because of the increased wall area.
2) The impact of changing building configuration on the energy use diminished as more efficient building systems and components were incorporated in the house.
3) The efficient tankless water heater without a pilot light was the most effective strategy, followed by CFLs. Other measures providing significant energy savings included the addition of overhangs, high reflectance roof, efficient windows, and efficient appliances.
4) By applying energy-efficient measures to the basecase house, the maximum reduction of 78% was achieved in space cooling energy use, followed by 53% reduction in domestic water heating energy use, 44% for other end-use that includes lighting, equipment, heating/cooling fans, and pump and miscellaneous; and 17% reduction in space heating. The space heating energy savings were less because some of the measures resulted in small heating energy penalty. The heating/cooling fan energy use was also reduced due to less heating and cooling energy consumption. A maximum of 55% total energy savings could be achieved from combining all the measures.

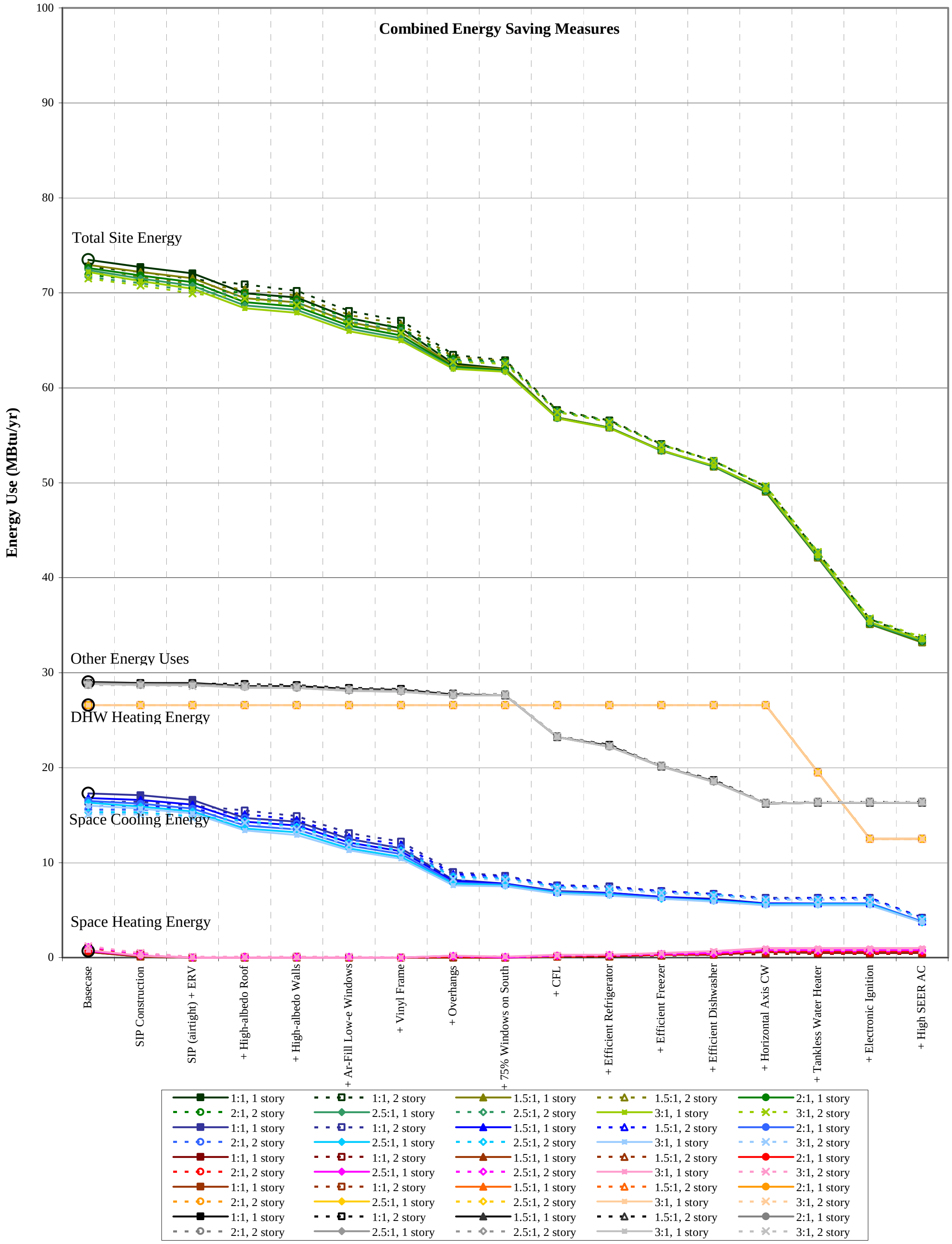


Figure 29: Effect of Combined Application of Energy-Efficient Measures on Annual Energy Use

7. ECONOMIC ANALYSIS

7.1. Introduction

This section presents an economic analysis of the house with energy-efficient measures that were applied to the basecase house in order to develop the most energy-efficient house. The purpose of the analysis was to compare the cost-effectiveness of the energy-saving measures applied individually as well as in combination. The analysis was based on the results of the simulation of the most energy-efficient house, as described in Section 6. The analysis was performed using the annualized life-cycle cost analysis method described in ASHRAE (2003) and Haberl (1993). The details of this technique are provided in Appendix E.

The analysis was performed using the following two approaches. The first approach was focused on the life-cycle cost analysis of individual measures. In the second approach, the effect of their combined application to the basecase house on the annualized life-cycle cost was analyzed.

7.2. Inputs for the Economic Analysis

The primary input data for the economic analysis included the first year costs, operating costs, and maintenance and replacement costs. Other factors that were defined to calculate the annualized costs included: the study period length, discount rate (i_d), inflation rate (j), mortgage rate (i_m), and periodic costs such as insurance and property tax. These factors are discussed in the following sections:

First Year Costs

Table 16 shows the initial cost of the basecase house and the increased costs due to energy-efficient upgrades. The first year cost of the basecase house was $224,598 that includes $220,650 for the construction and $3,948 for the installation of HVAC and DHW systems, and appliances. The total first year cost of applying individual measures is the summation of the first year cost of the basecase house and the increased cost of each measure. Similarly, the total first

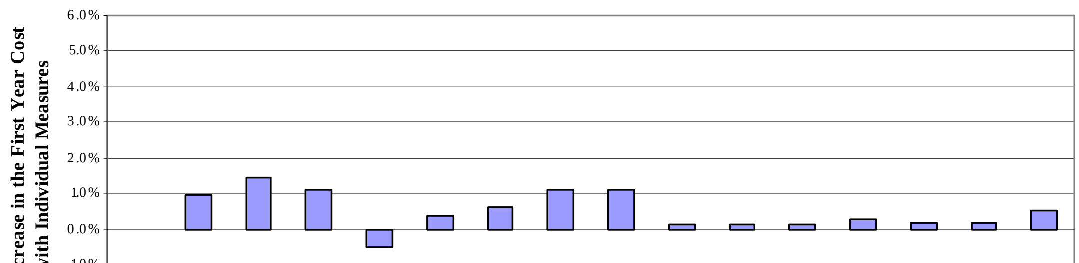
Table 16: Total First Year Costs

Item No.	Basecase Characteristics		Energy-Efficient Measures				Total First Year Cost ($)	
	Items	Cost ($)	Items	Cost ($)	Increased Cost ($)	Percent Increase in Cost (%)	Individual Application	Incremental Application
1	Basecase House	$224,598	-	-	-	-	$224,598	$224,598
2a	Wood-Frame Construction	$220,650	SIP Construction	$222,857	$2,207	0.98%	$226,805	$226,805
2b	No Mechanical Ventilation	$0	Energy Recovery Ventilator	$1,099	$1,099	0.49%	$227,904	$227,904
3	Gray Asphalt Shingle Roofing	$2,500	White Fiber-Cement Shingle Roofing	$5,000	$2,500	1.11%	$227,098	$230,404
4	Light Buff Facia Brick on the Exterior Walls	$7,475	White Semi-Gloss Paint on Stucco Walls	$6,325	($1,150)	-0.51%	$223,448	$229,254
5	Double Pane Air-Filled Low-e Windows	$5,300	Double Pane Argon-Filled Low-e Windows	$6,096	$796	0.35%	$225,394	$230,049
6	Aluminium Window Frames with Thermal Break	$6,096	Vinyl Window Frames	$7,500	$1,405	0.63%	$226,003	$231,454
7a	No Shading	$0	4 ft. Overhangs on All Sides	$2,520	$2,520	1.12%	$227,118	$233,974
7b	Equal Window Area on All Sides	$0	75% Windows on the South	$0	$0	0.00%	$227,118	$233,974
8	Incandescent Lamps	$26	CFLs with Electronic Ballast	$279	$252	0.11%	$224,850	$234,226
9	Conventional Refrigerator (660 kWh/yr)	$550	Kenmore Refrigerator (392 kWh/yr)	$800	$250	0.11%	$224,848	$234,476
10	Conventional Freezer (900 kWh/yr)	$300	Woods Freezer (353 kWh/yr)	$530	$230	0.10%	$224,828	$234,706
11	Conventional Dishwasher (696 kWh/yr)	$500	ASKO Dishwasher (181 kWh)	$1,149	$649	0.29%	$225,247	$235,355
12	Conventional Clothes Washer (816 kwh/yr)	$600	Bosch Clothes Washer (186 kWh/yr)	$950	$350	0.16%	$224,948	$235,705
13	Tanktype DWH with Pilot Ignition (EF = 0.54)	$550	Bosch AquaStar Tankless DWH (EF = 0.85)	$950	$400	0.18%	$224,998	$236,105
14	SEER-10 Air-Conditioner	$1,448	Goodman SEER-15 Air-Conditioner	$2,637	$1,189	0.53%	$225,787	$237,294
				Total	**$12,696**	**5.65%**		**$237,294**

year cost of applying measures in combination is the summation of the first year cost of the basecase house and the cumulative increased cost of applying those measures. Product details and cost data for the basecase house and the energy-efficient upgrades are presented in Table A-6.

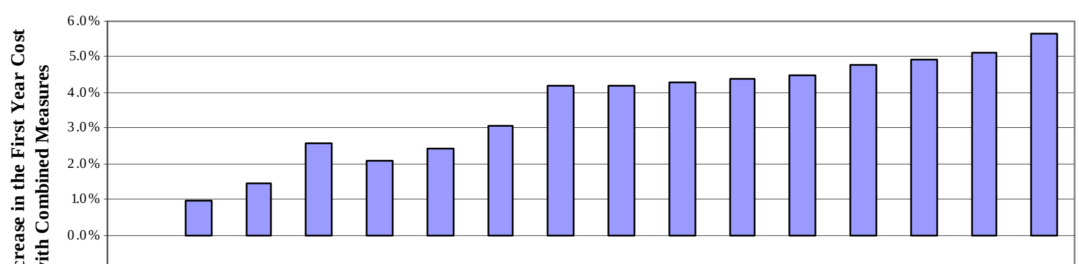
The percent increase in the first year cost of the house with individual application of energy-efficient measures is shown in Figure 30. It was found that the first year costs of the house with individual application of measures were not significantly different from the first year cost of the basecase house. Among all the measures, the addition of overhangs, white fiber-cement roofing, and SIP construction with an energy recovery ventilator had the highest first year costs; however, each added only up to 1.5% to the basecase cost. Argon-filled low-e windows and vinyl window frames added 0.35% and 0.63% to the basecase cost. A SEER-15 air-conditioner added 0.53% to the basecase cost. Energy-efficient lighting, different appliances and DHW system added 0.10% to 0.29%, each, to the basecase cost. White semi-gloss acrylic paint on the stucco walls reduced the first year cost by 0.51%.

Figure 31 presents the cumulative percent increase in the first year cost of the house with the combined application of energy-efficient measures. It shows that the combined application of these measures to the basecase house increased the first year cost by 5.65%.



	Base-case	SIP Const.	SIP + ERV	High-Albedo Roof	High-Albedo Walls	Ar-Fill Low-e Glazing	Vinyl Window Frames	Over-hangs	+75% Glaz. on South	CFL	Efficient Refri-gerator	Efficient Freezer	Efficient Dish-washer	Efficient Clothes Washer	Tank-less DWH	SEER-15 AC
Individual %Increase	0.00%	0.98%	1.47%	1.11%	-0.51%	0.35%	0.63%	1.12%	1.12%	0.11%	0.11%	0.10%	0.29%	0.16%	0.18%	0.53%

Figure 30: Percent Increase in the First Year Cost due to Individual Application of Energy-Efficient Measures



	Base-case	SIP Const.	SIP + ERV	High-Albedo Roof	High-Albedo Walls	Ar-Fill Low-e Glazing	Vinyl Window Frames	Over-hangs	+75% Glaz. on South	CFL	Efficient Refri-gerator	Efficient Freezer	Efficient Dish-washer	Efficient Clothes Washer	Tank-less DWH	SEER-15 AC
Cumulative %Increase	0.00%	0.98%	1.47%	2.58%	2.07%	2.43%	3.05%	4.17%	4.17%	4.29%	4.40%	4.50%	4.79%	4.95%	5.12%	5.65%

Figure 31: Cumulative Percent Increase in the First Year Cost due to Combined Application of Energy-Efficient Measures

Annual Energy Cost

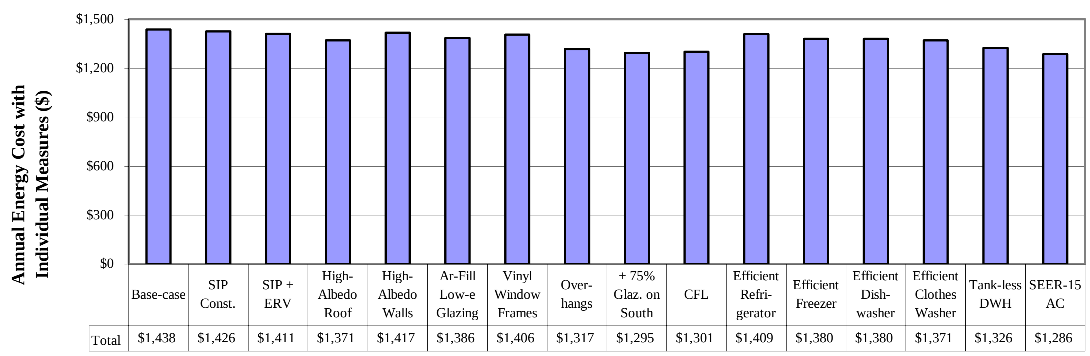
Table 17 shows the annual energy cost of the house with individual and combined application of energy-efficient measures. The utility rates were assumed to be 0.09 $/kWh for the electricity and 0.8 $/therm for the natural gas. The annual energy costs were calculated using these utility rates, and the annual electricity use (in kWh) and natural gas use (in therms) obtained from the building energy performance summary in utility units (BEPU) of the DOE-2 output.

Figure 32 shows the annual energy cost and percent reduction in annual energy cost of the house with individual application of energy-efficient measures. It was found that the SEER-15 air-conditioner, CFLs, and overhangs with 75% windows on south, each reduced the annual energy cost by approximately 10%. Approximately 8% reduction in the annual energy cost was estimated from the tankless water heater, followed by a 5% reduction from the high-reflectance roof and a 4% reduction from and argon-filled, low-e windows. Energy-efficient appliances reduced the annual energy cost by 2% to 5%. The airtight SIP construction with an energy recovery ventilator reduced the annual energy cost by 2%.

Figure 33 shows the annual energy cost and percent reduction in the annual energy cost of the house with combined application of energy-efficient measures. The energy cost saving potential of these measures, when applied to the basecase house with other measures added, was different from their individual application. The summation of percent savings from individual application of measures, as seen in Table 17 was 76%; whereas the actual total savings with combined application of measures was 56%. This was because the energy performance of one measure depends on the other characteristics of the house. This difference in the energy performance of measures is demonstrated by comparing the individual percent reduction in the annual energy cost in Figure 32 for each measure with the incremental percent reduction in Figure 33 for the same measure.

Table 17: Annual Energy Costs with the Energy-Efficient Measures

Item No.	Energy-Efficient Measures	Individual Application		Incremental Application		
		Annual Energy Cost ($)	Percent Decrease in Cost (%)	Annual Energy Cost ($)	Incremental Percent Decrease in Cost (%)	Cumulative Percent Decrease in Cost (%)
1	Basecase House	$1,438		$1,438		
2a	SIP Construction	$1,426	-0.85%	$1,426	-0.85%	-0.85%
2b	+ Energy Recovery Ventilator	$1,411	-1.89%	$1,411	-1.89%	-1.89%
3	High-Albedo Roofing	$1,371	-4.72%	$1,356	-3.93%	-5.75%
4	High-Albedo Exterior Walls	$1,417	-1.48%	$1,344	-0.86%	-6.57%
5	Argon-Filled Low-e Windows	$1,386	-3.62%	$1,287	-4.25%	-10.53%
6	Vinyl Window Frames	$1,406	-2.23%	$1,259	-2.20%	-12.50%
7a	Overhangs	$1,317	-8.43%	$1,160	-7.84%	-19.37%
7b	+ 75% Windows on the South	$1,295	-9.95%	$1,146	-8.95%	-20.33%
8	Efficient Lighting	$1,301	-9.57%	$1,010	-11.88%	-29.79%
9	Efficient Refrigerator	$1,409	-2.05%	$981	-2.83%	-31.78%
10	Efficient Freezer	$1,380	-4.04%	$915	-6.71%	-36.36%
11	Efficient Dishwasher	$1,380	-4.04%	$869	-5.11%	-39.62%
12	Efficient Clothes Washer	$1,371	-4.72%	$794	-8.55%	-44.78%
13	Tankless Water Heater	$1,326	-7.84%	$686	-13.66%	-52.32%
14	SEER-15 AC	$1,286	-10.60%	$635	-7.37%	-55.84%
		Total	**-76.05%**			**-55.84%**



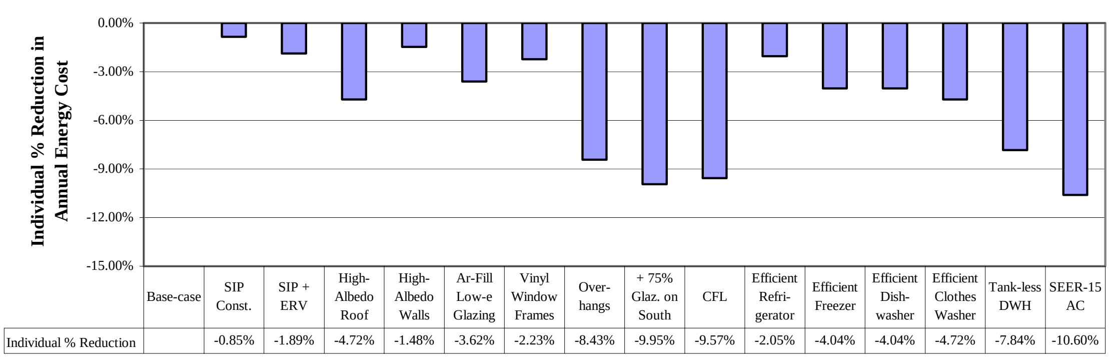
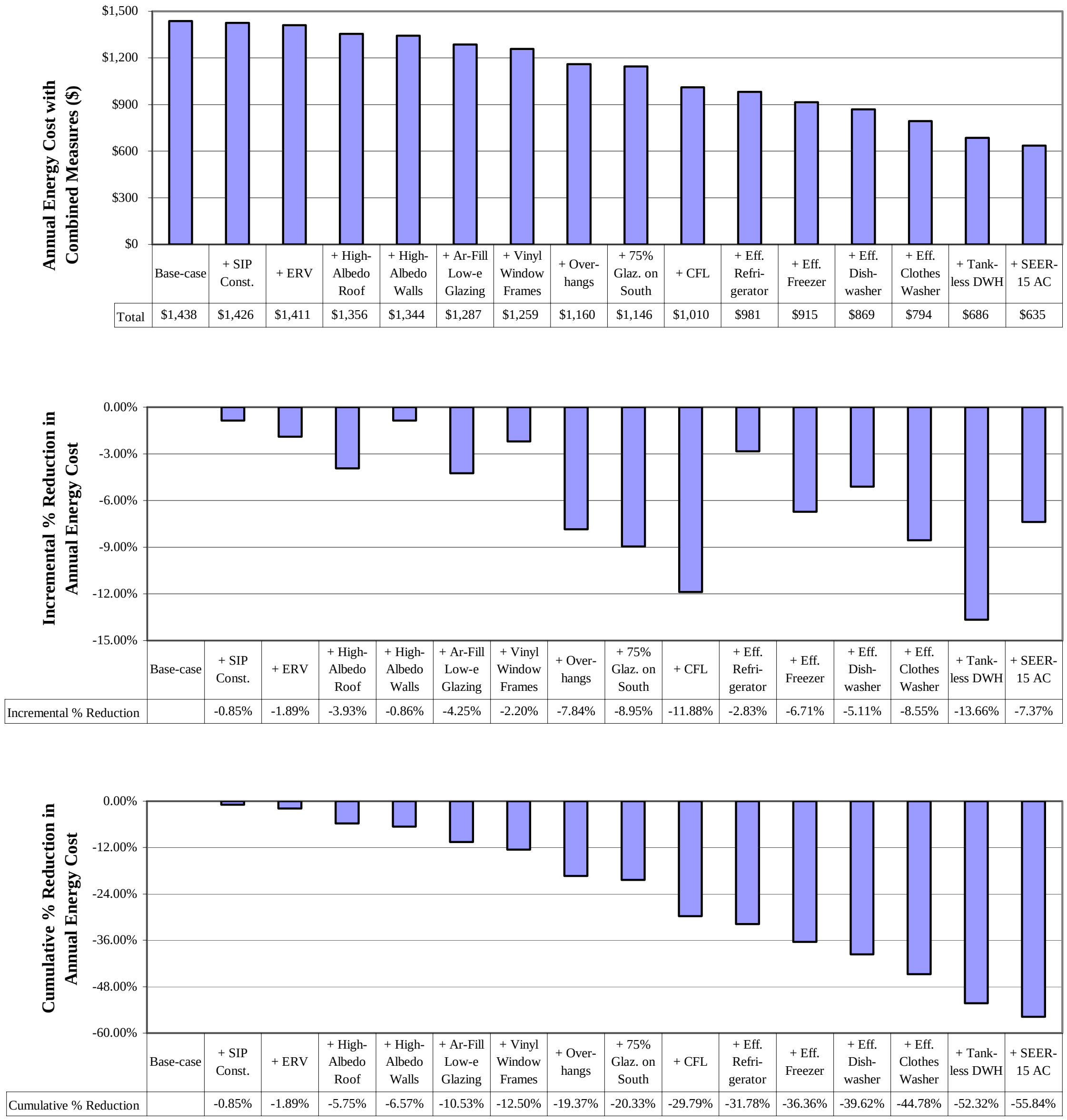


Figure 32: Annual Energy Costs and Percent Reduction in the Annual Energy Costs due to Individual Application of Energy-Efficient Measures



	Base-case	+ SIP Const.	+ ERV	+ High-Albedo Roof	+ High-Albedo Walls	+ Ar-Fill Low-e Glazing	+ Vinyl Window Frames	+ Over-hangs	+ 75% Glaz. on South	+ CFL	+ Eff. Refri-gerator	+ Eff. Freezer	+ Eff. Dish-washer	+ Eff. Clothes Washer	+ Tank-less DWH	+ SEER-15 AC
Total	$1,438	$1,426	$1,411	$1,356	$1,344	$1,287	$1,259	$1,160	$1,146	$1,010	$981	$915	$869	$794	$686	$635

	Base-case	+ SIP Const.	+ ERV	+ High-Albedo Roof	+ High-Albedo Walls	+ Ar-Fill Low-e Glazing	+ Vinyl Window Frames	+ Over-hangs	+ 75% Glaz. on South	+ CFL	+ Eff. Refri-gerator	+ Eff. Freezer	+ Eff. Dish-washer	+ Eff. Clothes Washer	+ Tank-less DWH	+ SEER-15 AC
Incremental % Reduction		-0.85%	-1.89%	-3.93%	-0.86%	-4.25%	-2.20%	-7.84%	-8.95%	-11.88%	-2.83%	-6.71%	-5.11%	-8.55%	-13.66%	-7.37%

	Base-case	+ SIP Const.	+ ERV	+ High-Albedo Roof	+ High-Albedo Walls	+ Ar-Fill Low-e Glazing	+ Vinyl Window Frames	+ Over-hangs	+ 75% Glaz. on South	+ CFL	+ Eff. Refri-gerator	+ Eff. Freezer	+ Eff. Dish-washer	+ Eff. Clothes Washer	+ Tank-less DWH	+ SEER-15 AC
Cumulative % Reduction		-0.85%	-1.89%	-5.75%	-6.57%	-10.53%	-12.50%	-19.37%	-20.33%	-29.79%	-31.78%	-36.36%	-39.62%	-44.78%	-52.32%	-55.84%

Figure 33: Annual Energy Costs and Percent Reduction in the Annual Energy Costs due to Combined Application of Energy-Efficient Measures

The comparison of Figure 32 and Figure 33 show that the measures related to building envelope showed higher percent reduction in annual energy cost on their individual application to the basecase house; whereas efficient windows, lighting, appliances and DHW system showed higher percent reduction in annual energy cost of the house with improved envelope characteristics. This was because, in a house with improved envelope and reduced heating and cooling energy requirements; the lighting, equipment and water heating energy constituted a larger part of the total energy use of the house. Therefore, the same lighting, equipment and water heating energy cost savings were a higher percent of the smaller annual energy cost of the house with improved envelope characteristics.

For example, the high-reflectance roof reduced the annual energy cost by 3.93% in the airtight SIP house, as opposed to 4.72% from its individual application to the basecase house. Similarly, high-reflectance walls reduced annual energy cost by 0.86% in an airtight SIP house with high-reflectance roof, as opposed to 1.48% in the basecase house. The addition of overhangs with the redistribution of windows to the south showed a 9.95% savings from their individual application and 8.95% savings in the airtight SIP house with improved roof, walls and windows.

On the other hand, the energy cost savings from the argon-filled, low-e windows increased from 3.62% for their individual application, to 4.25% for their installation in the airtight SIP house with high-reflectance roof and walls. Also, energy cost savings from CFLs, efficient clothes washer, and efficient DHW system increased from 9.57%, 4.72% and 7.84% for their individual application, to 11.88%, 8.55% and 13.66%, respectively, for their application to the house with improved characteristics.

However, the energy cost saving potential of the high SEER air-conditioner reduced from 10.60% for its individual application to the basecase house to 7.37% in the energy-efficient house, because of the reduced air-conditioning requirement. Overall, up to 56% annual energy cost savings could be achieved from the combined application of all these measures to the basecase house.

Maintenance and Replacement Cost

Table 18 shows the annual maintenance and replacement costs of the house. The annual maintenance cost of the basecase house was assumed to be $100 for the air conditioning system that needs regular maintenance such as filter cleaning. The annual replacement cost of the basecase house was $14 for the replacement of incandescent lamps, which was determined using

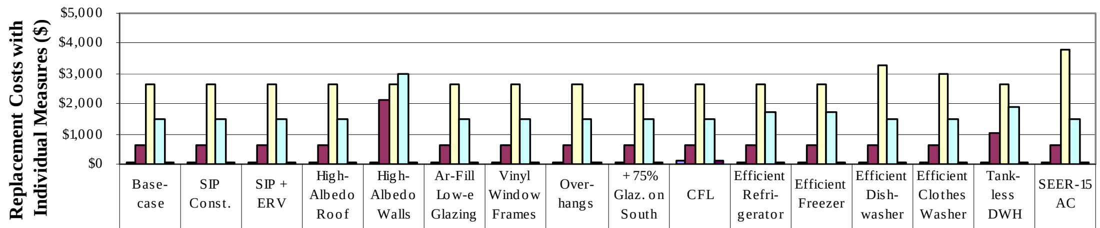
Table 18: Maintenance and Replacement Costs with the Energy-Efficient Measures

Item No.	Energy-Efficient Measures	Annual Maintenance Cost ($)	Replacement Costs ($)	Replacement Year
1	Basecase House	$100	$14	Annually (for Lighting)
			$550	10 (for DHW System)
			$2,548	15 (for AC, Clothes Washer and Dishwasher)
			$850	20 (for Refrigerator and Freezer)
2a	SIP Construction	$0	As above	
2b	+ Energy Recovery Ventilator	$0	As above	
3	High-Albedo Roofing	$0	As above	
4	High-Albedo Exterior Walls	$0	$1,500	10 (for Repainting the Walls)
5	Argon-Filled Low-e Windows	$0	As above	
6	Vinyl Window Frames	$0	As above	
7a	Overhangs	$0	As above	
7b	+ 75% Windows on the South	$0	As above	
8	Efficient Lighting	$0	$6	Added to the Annual Lighting Replacement Cost
9	Efficient Refrigerator	$0	$250	Added to the 20th Year Replacement Cost
10	Efficient Freezer	$0	$230	Added to the 20th Year Replacement Cost
11	Efficient Dishwasher	$0	$649	Added to the 15th Year Replacement Cost
12	Efficient Clothes Washer	$0	$350	Added to the15th Year Replacement Cost
13	Tankless Water Heater	$0	$400	Added to the10th Year Replacement Cost
14	SEER-15 AC	$0	$1,189	Added to the15th Year Replacement Cost

Table B- 3. The basecase house replacement cost at the end of 10th year was $550 for the water heater; at the end of 15th year was $2548 for the air conditioner, clothes washer and dishwasher; and at the end of 20th year was $850 for the replacement of the refrigerator and freezer. The replacement year for these equipment and appliances was determined based on their average life as found from different sources, listed in Table A-6.

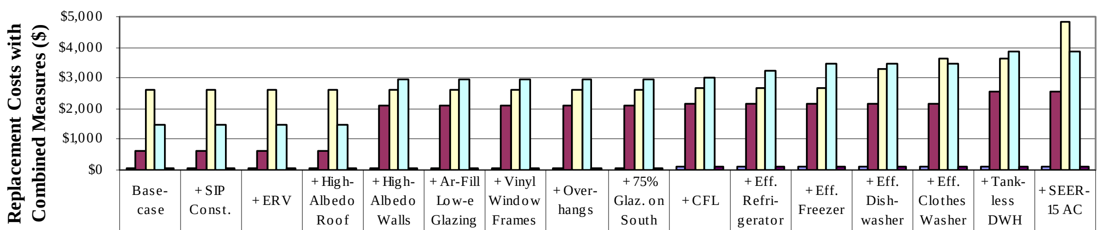
To account for the replacement costs of the house with energy-efficient measures, the differences between the basecase cost and the cost of energy-efficient upgrade, as shown in Table 16, were added to the replacement costs for the corresponding years. Also, $1,500 cost of repainting the high-reflectance walls, every 10 years, was added to the 10th year replacement cost. However, for the CFLs, the average annual replacement cost of $20 was taken into account as shown in Table B- 3, as opposed to their installation cost of $279, as shown in Table 16.

Figure 34 and Figure 35 compare the replacement costs of the individual and combined application of the energy-efficient measures at the end of every 5 years of the 25-year study period length. The energy-efficient measures required no extra maintenance, other than those



	Base-case	SIP Const.	SIP + ERV	High-Albedo Roof	High-Albedo Walls	Ar-Fill Low-e Glazing	Vinyl Window Frames	Over-hangs	+75% Glaz. on South	CFL	Efficient Refri-gerator	Efficient Freezer	Efficient Dish-washer	Efficient Clothes Washer	Tank-less DWH	SEER-15 AC
5th Year	$72	$72	$72	$72	$72	$72	$72	$72	$72	$102	$72	$72	$72	$72	$72	$72
10th Year	$622	$622	$622	$622	$2,122	$622	$622	$622	$622	$652	$622	$622	$622	$622	$1,022	$622
15th Year	$2,620	$2,620	$2,620	$2,620	$2,620	$2,620	$2,620	$2,620	$2,620	$2,650	$2,620	$2,620	$3,269	$2,970	$2,620	$3,809
20th Year	$1,472	$1,472	$1,472	$1,472	$2,972	$1,472	$1,472	$1,472	$1,472	$1,502	$1,722	$1,702	$1,472	$1,472	$1,872	$1,472
25th Year	$72	$72	$72	$72	$72	$72	$72	$72	$72	$102	$72	$72	$72	$72	$72	$72

Figure 34: Replacement Costs of Individual Application of the Energy-Efficient Measures



	Base-case	+SIP Const.	+ERV	+High-Albedo Roof	+High-Albedo Walls	+Ar-Fill Low-e Glazing	+Vinyl Window Frames	+Over-hangs	+75% Glaz. on South	+CFL	+Eff. Refri-gerator	+Eff. Freezer	+Eff. Dish-washer	+Eff. Clothes Washer	+Tank-less DWH	+SEER-15 AC
5th Year	$72	$72	$72	$72	$72	$72	$72	$72	$72	$102	$102	$102	$102	$102	$102	$102
10th Year	$622	$622	$622	$622	$2,122	$2,122	$2,122	$2,122	$2,122	$2,152	$2,152	$2,152	$2,152	$2,152	$2,552	$2,552
15th Year	$2,620	$2,620	$2,620	$2,620	$2,620	$2,620	$2,620	$2,620	$2,620	$2,650	$2,650	$2,650	$3,299	$3,649	$3,649	$4,838
20th year	$1,472	$1,472	$1,472	$1,472	$2,972	$2,972	$2,972	$2,972	$2,972	$3,002	$3,252	$3,482	$3,482	$3,482	$3,882	$3,882
25th Year	$72	$72	$72	$72	$72	$72	$72	$72	$72	$102	$102	$102	$102	$102	$102	$102

Figure 35: Replacement Costs of Combined Application of the Energy-Efficient Measures

required in the basecase house. However, the replacement costs of the house with energy-efficient measures were increased due to the high cost of certain upgrades.

<u>Economic Factors</u>

The economic factors that affect the annualized energy costs are: study period length, discount rate (i_d), inflation rate (j), mortgage rate (i_m), and periodic costs such as insurance and property tax. These factors are determined using various sources of information as listed in Table A-7. Table 19 shows the values of these factors.

Table 19: Economic Factors for the Annualized Life-Cycle Cost Analysis

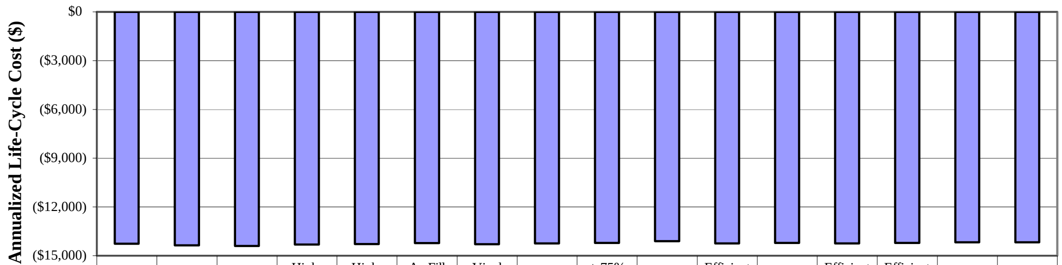
Economic Factors	Value	Source
Investment Tax Credit	$0.00	Assuming No Incentive
Life	25	Assumed
Discount Rate	4.00%	Bankrate, 2005
Inflation Rate	2.80%	Inflationdata, 2005
Fuel Inflation Rate	4.80%	FAS, 2005
Mortgage Rate	5.14%	Bankrate, 2005
Annual Insurance	$50.00	Kootin-Sanwu, 2004
Depreciation	7.00%	Kootin-Sanwu, 2004
Income Tax	5.00%	Kootin-Sanwu, 2004
Property Tax	1.00%	Kootin-Sanwu, 2004

7.3. Results of the Annualized Life-Cycle Cost Analysis

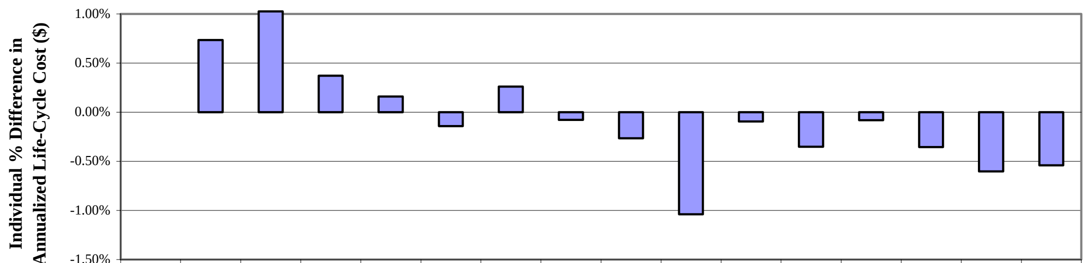
The energy-efficient measures that were evaluated using the life-cycle cost analysis are listed below:

1) Airtight SIP Construction and Installation of an Energy Recovery Ventilator
2) High-Reflectance Roof and Walls
3) Argon-Filled, Low-e Windows and Vinyl Window Frames
4) Overhangs and 75% Windows on the South
5) Compact Fluorescent Lamps with Electronic Ballast
6) Efficient Refrigerator and Freezer
7) Efficient Dishwasher
8) Horizontal-Axis Clothes Washer
9) Tankless Domestic Water Heater with Electronic Ignition
10) SEER-15 Air-Conditioner

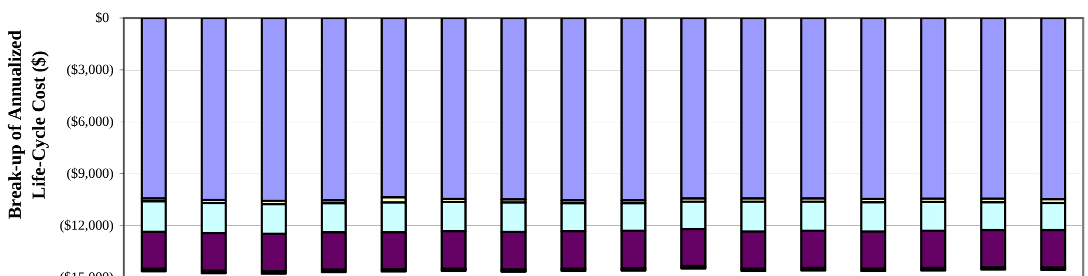
These measures were applied to the basecase house in the order listed. An economic analysis was performed for the house with individual and combined application of these measures. For the combined application, the impact of incremental application of these measures was also observed. The input and output details of the analysis are summarized in Appendix E. The results of the analysis with both of these approaches are shown in Figure 36 and Figure 37, and are discussed below.



	Base-case	SIP Const.	SIP + ERV	High-Albedo Roof	High-Albedo Walls	Ar-Fill Low-e Glazing	Vinyl Window Frames	Over-hangs	+ 75% Glaz. on South	CFL	Efficient Refri-gerator	Efficient Freezer	Efficient Dish-washer	Efficient Clothes Washer	Tank-less DWH	SEER-15 AC
Total	($14,252)	($14,357)	($14,398)	($14,305)	($14,275)	($14,232)	($14,289)	($14,241)	($14,214)	($14,104)	($14,238)	($14,202)	($14,240)	($14,201)	($14,166)	($14,175)

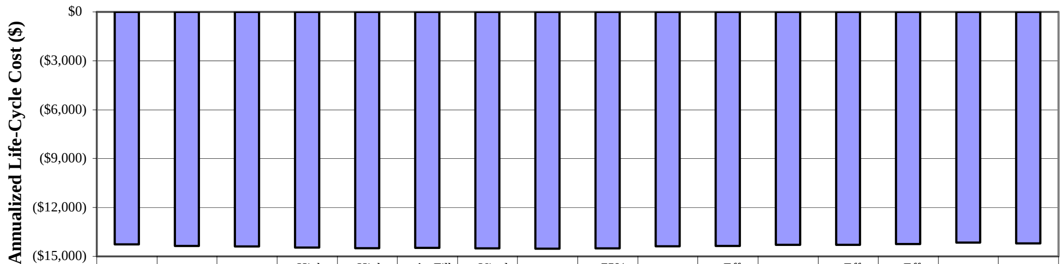


	Base-case	SIP Const.	SIP + ERV	High-Albedo Roof	High-Albedo Walls	Ar-Fill Low-e Glazing	Vinyl Window Frames	Over-hangs	+ 75% Glaz. on South	CFL	Efficient Refri-gerator	Efficient Freezer	Efficient Dish-washer	Efficient Clothes Washer	Tank-less DWH	SEER-15 AC
Individual % Difference	0.00%	0.73%	1.03%	0.37%	0.16%	-0.14%	0.26%	-0.08%	-0.26%	-1.04%	-0.10%	-0.35%	-0.08%	-0.36%	-0.60%	-0.54%

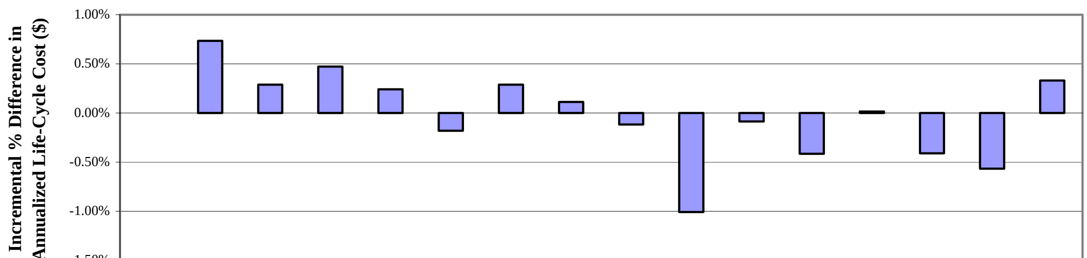


	Base-case	SIP Const.	SIP + ERV	High-Albedo Roof	High-Albedo Walls	Ar-Fill Low-e Glazing	Vinyl Window Frames	Over-hangs	+ 75% Glaz. on South	CFL	Efficient Refri-gerator	Efficient Freezer	Efficient Dish-washer	Efficient Clothes Washer	Tank-less DWH	SEER-15 AC
Depreciation Deduction	$169	$171	$171	$171	$168	$169	$170	$171	$171	$169	$169	$169	$169	$169	$169	$170
Interest Deduction	$196	$198	$199	$198	$195	$196	$197	$198	$198	$196	$196	$196	$196	$196	$196	$197
Insurance	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)
Maintenance	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)
Property Tax	($2,134)	($2,155)	($2,165)	($2,157)	($2,123)	($2,141)	($2,147)	($2,158)	($2,158)	($2,136)	($2,136)	($2,136)	($2,140)	($2,137)	($2,137)	($2,145)
Operating Costs	($1,752)	($1,737)	($1,719)	($1,669)	($1,726)	($1,689)	($1,713)	($1,604)	($1,578)	($1,584)	($1,716)	($1,681)	($1,681)	($1,669)	($1,615)	($1,566)
Replacements	($178)	($178)	($178)	($178)	($289)	($178)	($178)	($178)	($178)	($184)	($187)	($186)	($202)	($191)	($208)	($222)
Salvage Value	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Capital & Interest	($10,410)	($10,513)	($10,564)	($10,526)	($10,357)	($10,447)	($10,476)	($10,527)	($10,527)	($10,422)	($10,422)	($10,421)	($10,441)	($10,427)	($10,429)	($10,466)

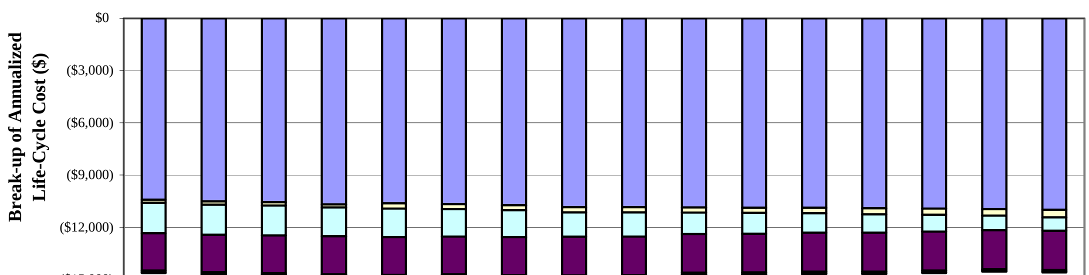
Figure 36: Annualized Life-Cycle Costs for Individual Application of the Energy-Efficient Measures



	Base-case	+ SIP Const.	+ ERV	+ High-Albedo Roof	+ High-Albedo Walls	+ Ar-Fill Low-e Glazing	+ Vinyl Window Frames	+ Over-hangs	+ 75% Glaz. on South	+ CFL	+ Eff. Refri-gerator	+ Eff. Freezer	+ Eff. Dish-washer	+ Eff. Clothes Washer	+ Tank-less DWH	+ SEER-15 AC
Total	($14,252)	($14,357)	($14,398)	($14,466)	($14,501)	($14,474)	($14,516)	($14,532)	($14,515)	($14,369)	($14,357)	($14,297)	($14,299)	($14,240)	($14,160)	($14,206)



	Base-case	+ SIP Const.	+ ERV	+ High-Albedo Roof	+ High-Albedo Walls	+ Ar-Fill Low-e Glazing	+ Vinyl Window Frames	+ Over-hangs	+ 75% Glaz. on South	+ CFL	+ Eff. Refri-gerator	+ Eff. Freezer	+ Eff. Dish-washer	+ Eff. Clothes Washer	+ Tank-less DWH	+ SEER-15 AC
Incremental % Difference	0.00%	0.73%	0.29%	0.47%	0.24%	-0.18%	0.29%	0.11%	-0.12%	-1.01%	-0.09%	-0.42%	0.02%	-0.41%	-0.57%	0.33%



	Base-case	+ SIP Const.	+ ERV	+ High-Albedo Roof	+ High-Albedo Walls	+ Ar-Fill Low-e Glazing	+ Vinyl Window Frames	+ Over-hangs	+ 75% Glaz. on South	+ CFL	+ Eff. Refri-gerator	+ Eff. Freezer	+ Eff. Dish-washer	+ Eff. Clothes Washer	+ Tank-less DWH	+ SEER-15 AC
Depreciation Deduction	$169	$171	$171	$173	$172	$173	$174	$176	$176	$176	$176	$176	$177	$177	$178	$178
Interest Deduction	$196	$198	$199	$201	$200	$200	$202	$204	$204	$204	$204	$204	$205	$205	$206	$207
Insurance	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)
Maintenance	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)
Property Tax	($2,134)	($2,155)	($2,165)	($2,189)	($2,178)	($2,185)	($2,199)	($2,223)	($2,223)	($2,225)	($2,228)	($2,230)	($2,236)	($2,239)	($2,243)	($2,254)
Operating Costs	($1,752)	($1,737)	($1,719)	($1,651)	($1,637)	($1,568)	($1,533)	($1,413)	($1,396)	($1,230)	($1,195)	($1,115)	($1,058)	($968)	($835)	($774)
Replacements	($178)	($178)	($178)	($178)	($289)	($289)	($289)	($289)	($289)	($295)	($304)	($312)	($336)	($349)	($378)	($422)
Salvage Value	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Capital & Interest	($10,410)	($10,513)	($10,564)	($10,680)	($10,626)	($10,663)	($10,728)	($10,845)	($10,845)	($10,857)	($10,868)	($10,879)	($10,909)	($10,925)	($10,944)	($10,999)

Figure 37: Annualized Life-Cycle Costs for Combined Application of the Energy-Efficient Measures

7.3.1. Basecase Scenario

The basecase scenario represents a one-story detached single family house designed in accordance with Chapter 4 of the 2000 IECC, as modified by the 2001 Supplement. The characteristics of the basecase house are discussed in Section 5 of this thesis. The different costs associated with the basecase scenario are listed in Appendix C. The basecase first year cost was estimated as $224,598. The annual energy cost for the house was $1,438. The annualized life-cycle cost of the basecase house was $14,252.

7.3.2. Airtight SIP Construction with Installation of an Energy Recovery Ventilator

Constructing the house with structural insulated panels added $2,207 (or 1% of the construction cost of the basecase house) to the basecase first year cost. Assuming that a SIP house requires mechanical ventilation because of the increased air tightness, installation of an energy recovery ventilator was included as an energy-efficient measure. This further increased the first year cost by $1,099. The annual energy cost of this house was $1,411, which was $27 less than the basecase scenario. The annualized life-cycle cost was $14,398, which was $146 more than the basecase house.

7.3.3. High-Reflectance Roof and Walls

A high-reflectance roof with white fiber-cement shingles roofing instead of asphalt shingles added $2,500 to the first year cost. The annual energy cost decreased to $1,371 and the annualized life-cycle cost increased to $14,305. The same measure applied to the airtight SIP house reduced the annual energy cost further to $1,356, whereas increased the annualized life-cycle cost to $14,466.

High-reflectance walls with white semi-gloss acrylic paint on stucco instead of light-buff brick facia decreased the first year cost by $1,150. This measure applied to the basecase house decreased both, the annual energy cost to $1,417 and the annualized life-cycle cost to $14,275. Application of this measure to the airtight SIP house with high-reflectance roof decreased the annual energy cost to $1,344, whereas increased the annualized life-cycle cost to $14,501.

7.3.4. Argon-Filled, Low-e Windows with Vinyl Window Frames

Installing low-e windows with argon-fill instead of air-fill increased the first year cost by $796. This measure decreased both, the annual energy cost to $1,386 and the annualized life-cycle cost to $14,232. Applying this measure in combination with previously discussed measure i.e. the airtight SIP construction and high-reflectance roof and walls, decreased both, the annual energy cost to $1,287 and the annualized life-cycle cost to $14,474.

Installing vinyl window frames instead of aluminum frames with thermal break increased the first year cost by $1,405. The individual application of this measure decreased the annual energy cost to $1,406, whereas increased the annualized life-cycle cost to $14,289. Installing vinyl window frames to the SIP house with argon-filled, low-e windows, high-reflectance roof and walls decreased the annual energy cost to $1,259 and increased the annualized life-cycle cost to $14,516.

7.3.5. Overhangs and 75% Windows on the South

Adding four-foot overhangs to the basecase house in the form of eaves on the roof added $2,520 to the first year cost. This decreased both, the annual energy cost to $1,332 and the annualized life-cycle cost to $14,241. The redistribution of windows to the south did not increase the first year cost. However, it further decreased the annual energy cost to $1,295 and the annualized life-cycle cost to $14,214.

Adding overhangs to a house having previously listed measures decreased the annual energy cost to $1,160 and increased the annualized life-cycle cost to $14,532. The redistribution of windows decreased both, the annual energy cost to $ 1,146 and the annualized life-cycle cost to $14,515.

7.3.6. Compact Fluorescent Lamps with Electronic Ballast

Installing compact fluorescent lamps with electronic ballast instead of the incandescent lamps in the basecase house increased the first year cost by $252. This decreased both, the annual energy cost to $1,301 and the annualized life-cycle cost to $14,104. This measure in a house with previously discussed measures decreased both, the annual energy cost to $1,010 and the annualized life-cycle cost to $14,369.

7.3.7. Efficient Refrigerator and Freezer

Installing an efficient refrigerator in the basecase house increased the first year cost by $250. This decreased both, the annual energy cost to $1,409 and the annualized life-cycle cost to $14,238. This measure in a house with the previously discussed measures decreased both, the annual energy cost to $981 and the annualized life-cycle cost to $14,357.

Installing an efficient freezer in the basecase house increased the first year cost by $230. This decreased the annual energy cost to $1,380 and increased the annualized life-cycle cost to $14,202. This measure in a house with all the previously discussed measures (including the efficient refrigerator) decreased both, the annual energy cost to $915 and the annualized life-cycle cost to $14,297.

7.3.8. Efficient Dishwasher

Installing an efficient dishwasher in the basecase house increased the first year cost by $649. This decreased both, the annual energy cost to $1,380 and the annualized life-cycle cost to $14,240. This measure in a house with the previously discussed measures decreased the annual energy cost to $869 and increased the annualized life-cycle cost to $14,299.

7.3.9. Horizontal-Axis Clothes Washer

Installing a horizontal-axis clothes washer in the basecase house increased the first year cost by $250. This decreased both, the annual energy cost to $1,371 and increased the annualized life-cycle cost to $14,201. This measure in a house with all the previously discussed measures decreased both, the annual energy cost to $794 and the annualized life-cycle cost to $14,240. Additional savings are expected from the reduced water use and reduced drying energy requirement.

7.3.10. Tankless Domestic Water Heater with Electronic Ignition

Installing an efficient tankless water heater with electronic ignition in the basecase house increased the first year cost by $400. This decreased both, the annual energy cost to $1,326 and the annualized life-cycle cost to $14,166. This measure in a house with the previously discussed measures decreased both, the annual energy cost to $686 and the annualized life-cycle cost to $14,160.

7.3.11. SEER-15 Air-Conditioner

Installing a SEER-15 air conditioner in the basecase house increased the first year cost by $1,189. This decreased both, the annual energy cost to $1,286 and the annualized life-cycle cost to $14,175. This measure in a house with the previously discussed measures decreased the annual energy cost be $635 and increased the annualized life-cycle cost to $14,206. However, a smaller air-conditioner, having a less installation cost, in an energy-efficient house with a smaller cooling load, is expected to reduce annualized life-cycle cost.

7.4. Comparison of the Annualized Life-Cycle Costs of the Energy-Efficient Measures

This section compares the results of the life-cycle cost analysis of the house with individual and combined application of energy-efficient measures. The comparison of percent increase in the annualized life-cycle cost shows that the SIP construction with ERV, white fiber-cement shingle roofing, white semi-gloss paint on stucco walls, and vinyl window frames increased the annualized life-cycle cost by 1.03%, 0.37%, 0.16% and 0.26%, when applied individually. The individual application of all the other measures decreased the annualized life-cycle cost. Among these measures, CFLs was the most cost-effective measure that decreased the life-cycle cost by 1.04%, followed by a tankless water heater, high SEER air-conditioner, and efficient freezer and horizontal-axis clothes washer, which decreased the annualized life-cycle cost by 0.60%, 0.54, 0.35% and 0.36%. Argon-filled, low-e windows and overhangs with window redistribution decreased the annualized life-cycle cost by 0.14% and 0.26%. Installing efficient refrigerator and dishwasher decreased the annualized life-cycle cost by up to 0.1%.

The combined application of these measures had different impact on annualized life-cycle costs. The high-reflectance roofing increased the life-cycle cost to 0.37% and 0.47% when applied to the basecase house and to the SIP house, respectively. Also, high-reflectance walls increased the life-cycle cost to 0.16% and 0.24% for the two houses. This suggested that such measures were not cost-effective, especially in a house with improved characteristics. Less expensive alternatives requiring less maintenance should have been considered as cost-effective measures for improving envelope characteristics. Vinyl window frames increased the life-cycle cost by 0.26% of the basecase and by 0.38% when installed with the low-e, argon-fill windows in the SIP house with high-reflectance roof and walls.

Among those measures that were found cost-effective on individual application, the installation of CFLs resulted in slightly less reduction in annualized life-cycle cost (1.01% as compared to 1.04% for individual application) when applied to the SIP house with improved walls, roof and windows. Argon-filled, low-e windows and the tankless water heater performed nearly the same in both the scenarios - the basecase house and the SIP house. They decreased annualized life-cycle cost by 0.14% and 0.60% from individual application, and 0.18% and 0.57% from application to the SIP house. Overhangs with window redistribution showed 0.26% reduction from individual application, and 0.12% reduction from application to the SIP house with improved roof. Energy-efficient appliances were less effective in reducing annualized life-cycle cost, in the energy-efficient house than in the basecase house. The high SEER air-conditioner that was found to be cost-effective measure for the basecase house, increased the annualized life-cycle cost by 0.33%.

7.5. Conclusions

From the comparisons discussed in Section 7.4, the following conclusions were made:

1) The high-reflectance roofing was a cost-effective energy-saving measure only when less expensive alternatives were considered.

2) The high SEER air-conditioner was a cost-effective energy-saving measure. However, for a house with high-performance envelope and reduced cooling requirement, such installation is cost-effective only when system downsizing is considered.

3) The CFLs and tankless water heater with electronic ignition were cost-effective energy-saving measures irrespective of the other building characteristics, since their performance were not affected by space heating or cooling loads.

4) Among home appliances, efficient refrigerator, freezer and clothes washer were cost-effective measures. Considering only the equipment energy use, efficient dishwasher was not a cost-effective measure due to its high initial cost. Selecting less expensive models and considering water savings from efficient models could demonstrate a cost-effective installation of such models.

5) The addition of overhangs was a cost-effective measure. However, this measure was less cost-effective in a house with other energy-efficient upgrades. Considering this measure in design stage could be very cost-effective where the cost of constructing overhangs would be included in the overall construction cost, and would not increase the first year cost, significantly.

6) Installation of argon-filled, low-e windows was a cost-effective energy-saving measure, whereas the same measure with vinyl frame reduced the cost-effectiveness of this measure.

8. CONCLUSIONS AND RECOMMENDATIONS

This section provides conclusion and proposes recommendations for future research in this area. The conclusions are presented to form guidelines to achieve maximum residential energy-efficiency in hot and humid climates.

8.1. Conclusions

From the analysis of results presented in Section 6 and Section 7, the following points were concluded for achieving maximum residential energy-efficiency in single-family detached houses in hot and humid climates:

1) Changing the building configuration, that is designing the building as a two-story house and/or orienting it along the east-west axis, is an effective energy-saving strategy for houses that do not have highly efficient building components, systems and appliances. Up to 3% total annual energy could be saved from changing the basecase building configuration to an east-west elongated, two-story configuration.
2) SIP construction performs the best in terms of minimizing the peak heating and cooling energy use, and the annual energy use. Compared to the conventional 2x4 wood frame construction, SIP construction resulted in 2.5% energy savings due to its airtight construction. Since, the analysis performed in this study assumed the same size of the air-conditioner for the basecase house and the improved house, the savings that could have resulted from the reduced cost of installation of a smaller air-conditioner were not taken into account.
3) Increased R-value, high reflectance and emissivity are the most desired for the roof. Up to 5% energy savings could be achieved from improving roof of the basecase house. Such improvements for walls do not produce significant savings.
4) Window shading is a potential energy-saving strategy for reducing energy use. This strategy gives the best results when the majority of the windows are placed on the south and the

window area is reduced on the east and west. For south windows, a 4-foot overhang is the optimum, beyond which an increase in heating energy penalty outweighs the cooling energy savings. Up to 10% total energy savings could be achieved from adding overhangs and placing maximum windows to the south.

5) Compact fluorescent lamps have a significant energy-saving potential, and are cost-effective. They resulted in up to 10% total annual energy savings in the basecase house.

6) Among the efficient household appliances, the horizontal-axis clothes washer is the most cost-effective energy-saving measure, followed by efficient refrigerator and freezer. In the basecase house it resulted in up to 5% total annual energy savings. Additional savings from horizontal-axis clothes washers are expected from reduced water use and reduced drying energy requirement.

7) An instantaneous domestic water heating system without pilot light has the highest energy-saving potential of all energy-saving measures. In the basecase house it resulted in up to 8% total annual energy savings. Using a solar water heating system supplemented by a small instantaneous water heater is expected to maximize the energy savings, cost-effectively.

8) High efficiency furnaces are not cost-effective in hot and humid climates where heating energy use is small.

9) High SEER air-conditioners have a significant energy-saving potential. For a highly energy-efficient house, this strategy is not cost-effective. However, a cost-effective installation is expected when the downsizing of the system due to the reduced cooling energy requirement in an energy-efficient house is considered. A SEER -15 air-conditioner showed up to 11% total annual energy savings.

10) Up to 55% energy savings could be achieved from the application of the ten energy-saving measures analyzed in this study.

Considering the annualized life-cycle cost that accounts for the costs of installation, replacement and maintenance, cost of saved energy, and other economic factors; the order of preference while selecting measures for achieving energy-efficiency in a single-family house in a hot and humid climate should be: an airtight SIP construction, CFLs, tankless DHW system with electric ignition, high-efficiency air-conditioner, efficient appliances, argon-filled low-e windows, and maximum windows on south with overhangs. These measures showed a reduction in the annualized life-cycle cost, and thus, are cost-effective. Less expensive alternatives for upgrading the envelope can be considered, since the measures analyzed in this study showed an increase in the life-cycle cost.

8.2. Recommendations for Future Research

This thesis analyzed the energy-saving measures that are simulatable with the DOE-2 simulation program. This excluded the analysis of many other energy-saving measures such as, daylighting, natural ventilation, solar thermal and photovoltaics, rain water harvesting, landscaping etc. These measures can be analyzed using other simulation programs in conjunction with the DOE-2, to fully realize the potential of renewable energy sources available on the site and maximize savings.

The simulation model used for this thesis did not include a high-pitch roof, vented attic and ducts inside the vented attic, which are typical characteristics of residences in the hot and humid climate of the US. To perform a more accurate analysis, an attic model with ducts inside the attic can be incorporated. A duct model for the DOE-2 simulation program proposed by Kim (2005) is under development that can be used for an accurate analysis of a house with an attic. However, the proposed duct model is in a verification process. While using such model, orientation and slope of the roof can be another factor to be analyzed that affects the energy use. However, 2000 IECC does not include any specification for orientation and slope of the roof.

The analysis of HVAC system was performed only for the typical air distribution residential HVAC system with natural gas space and water heating, and electric cooling. Other types of HVAC systems such as, heat pumps, radiant heating systems, combo systems etc. can be analyzed that have higher energy-saving potential.

For this analysis, only space heating, cooling, lighting and appliance energy use and savings were considered. Water savings and the resulting water heating energy savings that could be achieved from efficient home appliances were not considered. Also, energy-efficient models of only major home appliances were included in the analysis. Efficient models of other home appliances that consume significant amount of energy in operating and/or in standby mode, such as television, VCR, audio system, cooking top, vacuum cleaner etc. are also expected to result in significant savings.

REFERENCES

ACCA. 2004. *Manual J Residential Load Calculation,* 8th Edition, Fifth Printing, Version 1.11. Arlington, VA: Air Conditioning Contractors of America.

AcDirect. 2005. Goodman & Rudd Cooling Only Air Conditioning Systems. AcDirect, Inc. Retrieved July 9, 2005, from: www.acdirect.com.

ACEEE. 2004. *The Most Energy-Efficient Appliances.* Washington, DC: American Council for an Energy Efficient Economy.

Akbari, H., and S.J. Konopaki. 1998. The Impact of Reflectivity and Emissivity of Roofs on Building Cooling and Heating Energy Use. *Thermal Performance of the Exterior Envelopes of Buildings VII,* December: 29-39.

ASHRAE. 2001a. *2001 ASHRAE Handbook—Fundamentals.* Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

ASHRAE. 2001b. *ANSI/ASHRAE 136-1993, A Method of Determining Air Change Rates in Detached Dwellings (RA 2001).* Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

ASHRAE. 2003. *2003 ASHRAE Handbook—HVAC Applications.* Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Bankrate. 2005. Federal Discount Rate. Bankrate, Inc. Retrieved June 23, 2005, from: www.bankrate.com.

Berdahl, P., and S.E. Bretz. 1997. Preliminary Survey of Solar Reflectance of High Albedo Roof Coating. *Energy and Buildings* 25(2): 149-158.

Brown, G. Z. and M. DeKay. 2001. *Sun, Wind and Light: Architectural Design Strategies,* 2nd Edition. New York: John Wiley & Sons, Inc.

Building America. 2004. Building America Case Studies. Building Science Corporation. Retrieved July 11, 2005, from: www.buildingscience.com/buildingamerica/casestudies/default.htm.

Building Journal. 2005. Construction Cost Calculators—Residential—New Homes. Retrieved June 4, 2005, from: www.buildingjournal.com/residential-estimating.asp.

Casebolt, C. 1993. Home Alone—Living Off the Grid. *Home Energy Magazine* 10(3): 13-19.

Christensen, C., S. Horowitz, T. Gilver, A. Courtney and G. Barker. 2005. BEopt: Software for Identifying Optimal Building Designs on the Path to Zero Net Energy. NREL/CP-550-37733. Golden, CO: National Renewable Energy Laboratory.

Christian, J. 2005. Ultra-Low Energy Residences. *ASHRAE Journal* 47(1): 22-27.

Christian, J., P.Kerrigan and D. Beal. 2003. Livable and Affordable Zero Energy Habitats. Oak Ridge National Laboratory. Presented to EERE Oak Ridge Programs Brown Bag Luncheon, July 29, 2003. Retrieved July 11, 2005, from: www.ornl.gov/sci/eere/PDFs/christian_seminar072903.pdf.

Chulsukon, P. 2002. Development and Analysis of a Sustainable, Low Energy House in a Hot and Humid Climate. Ph.D. Dissertation. College Station, TX: Texas A&M University.

Cohen's. 2005. Appliances. Cohen's Home Furnishings. Retrieved July 9, 2005, from: www.cohens.ca/shop/default.htm.

Consumer Guide. 2005. Consumer Guide Products. Retrieved July 9, 2005, from: products.consumerguide.com.

Conway K. M. 1994. Lighting Makeovers: The Best is Not Always the Brightest. *Home Energy Magazine* 11(6): 20-25.

DOE. 1980. *DOE-2 Reference Manual, Part 1, Version 2.1,* p. III-34. Los Alamos, NM: Los Alamos Scientific Laboratory.

DOE. 1996. Residential Lighting: Use and Potential Savings. DOE/EIA-0555(96)/2. Washington, DC: Energy Information Administration, U. S. Department of Energy.

DOE. 1997. What's New in Building Energy Efficiency: Selecting Windows for Energy Efficiency. DOE/GO-DE-AC03-76SF00098. PUB-788 January 1997 - 5000. Washington, DC: U. S. Department of Energy.

DOE. 2000. Advanced Wall Framing. Office of Building Technology, State and Community Programs (BTS) Technology Fact Sheet. DOE/GO-102000-0770. Washington, DC: Energy Information Administration, U. S. Department of Energy.

DOE. 2001a. Energy-Efficient Appliances. Office of Building Technology, State and Community Programs (BTS) Technology Fact Sheet. DOE/GO-102001-0788. Washington, DC: Energy Information Administration, U. S. Department of Energy.

DOE. 2001b. Heat Recovery from Wastewater Using a Gravity-Film Heat Exchanger. DOE/EE-0247. Prepared for the U. S. Department of Energy. Oak Ridge, TN: Oak Ridge National Laboratory.

DOE. 2004. Building Energy Databook. Energy Efficiency and Renewable Energy, U.S. Department of Energy. Retrieved July 9, 2005, from: buildingsdatabook.eren.doe.gov/docs/bed2004.pdf.

EERE. 2005. Building Energy Software Tools Directory. Energy Efficiency and Renewable Energy, U.S. Department of Energy. Retrieved July 9, 2005, from: www.eere.energy.gov/buildings/tools_directory.

Energy Star. 2002. Reducing Appliance Energy Use Fact Sheet. RES-2010-1002. 2002 Wisconsin Focus on Energy. Retrieved July 10, 2005, from: www.focusonenergy.com/data/common/pageBuilderFiles/Appliances.pdf.

Farrar-Nagy, S., P. Reeves, C.E. Hancock, and R. Anderson. 2000. Impacts of Shading and Glazing Combination on Residential Energy Use in a Hot Dry Climate. *Proceedings of the 2000 ACEEE Summer Study of Energy Efficiency in Buildings*: 1.63-1.76.

FAS. 2005. Fuel Inflation Rate. Federation of American Scientists. Retrieved June 23, 2005, from: www.fas.org.

Fine, H.A. and D.L. McElroy. 1989. Assessment of the Energy Conservation Potential of Active (Variable Thermal Resistance and Switchable Absorptance) Systems for Residential Building Thermal Envelopes and Fenestration. *Thermal Performance of the Exterior Envelopes of Buildings IV,* December: 639-653.

Friedman, A. 2000. Design Secrets for Affordable Efficiency. *Home Energy Magazine* 17(1): 24-27.

Gamble, D., D. Meisegeier and J. Hall. 2004. Building a Path Towards Zero Energy Homes with Energy Efficiency Upgrades. *Proceedings of the 2004 ACEEE Summer Study of Energy Efficiency in Buildings*: 1.95-1.106.

Geltz, C. 1993. Building an Energy-Efficient Home Office. *Home Energy Magazine* 10(3): 35-37.

Givoni, B. 1998. *Climate Considerations in Building and Urban Design.* New York: Van Nostrand Reinhold.

Haberl, J.S. 1993. Economic Calculations for ASHRAE Handbook. EST-TR-93-04-07. College Station, TX: Energy Systems Laboratory, Texas A&M University.

Hayden, A.C.S. 1996. Choosing a Heating System That Saves Energy. *Home Energy Magazine* 13(2): 27-35.

Hedrick, R. 2003a. Home Builders Guide to Ducts in Conditioned Space: Design Guidelines. Report No. 500-03-082-A-18. October 2003. Sacramento, CA: California Energy Commission.

Hedrick, R. 2003b. Costs and Savings for Houses with Ducts in Conditioned Space: Technical Information Report. Report No. 500-03-082-A-31. October 2003. Sacramento, CA: California Energy Commission.

HouseNeeds. 2005. Water Heaters. HouseNeeds, Inc. Retrieved July 9, 2005, from: www.houseneeds.com.

ICC. 1999. *2000 International Energy Conservation Code*. Falls Church, VA: International Code Council, Inc.

ICFA. 2004. Product Info. Insulated Concrete Form Association. Retrieved July 9, 2005, from: www.forms.org/product_info/index.html.

IESNA. 2000. *The IES Lighting Handbook, Reference and Application,* 9th Edition. New York: Illuminating Engineering Society of North America.

Inflationdata. 2005. Current Inflation Rate. Financial Trend Forecaster®. Retrieved June 23, 2005, from: inflationdata.com/inflation.

Johnson, D. and E. Wyatt. 1997. Dampers, Reclaimers and Pumps-Oh My! *Home Energy Magazine* [Online], July/August. Retrieved November 20, 2005, from: homeenergy.org/archive/hem.dis.anl.gov/eehem/97/970714.html.

Kent, J. 2003. Some Research Begins at Home. *Home Energy Magazine* 20(6): 38-42.

Kim S. 2005. An Analysis of International Energy Conservation Code (IECC)-Compliant Single-Family Residential Energy Use. Ph.D. Dissertation. College Station, TX: Texas A&M University.

Kootin-Sanwu, V. 2004. An Analysis of Low Cost, Energy Efficient Housing for Low Income Residents of Hot and Humid Climates. Ph.D. Dissertation College Station, TX: Texas A&M University.

Kosny, J., E. Kossecka, A.O. Desjarlais and J.E. Christian. 1998. Dynamic Thermal Performance of Concrete and Masonry Walls. *Thermal Performance of the Exterior Envelopes of Buildings VII*, December: 629-643.

Kosny, J., T. Petrie, D. Gawin, P. Childs, A. Desjarlais and J. Christian. 2001. Thermal Mass - Energy Savings Potential in Residential Buildings. Building Technology Center, Oak Ridge National Laboratory. Retrieved July 9, 2005, from: www.ornl.gov/sci/roofs+walls/research/detailed_papers/thermal.

Kossecka, E. and J. Kosney. 1998. Effect of Insulation and Mass Distribution in Exterior Walls on Dynamic Thermal Performance of Whole Buildings. *Thermal Performance of the Exterior Envelopes of Buildings VII,* December: 721-731.

LBNL. 2005. Home Energy Saver: The First Web Based Do-It-Yourself Energy Audit Tool. Lawrence Berkeley National Laboratory. Retrieved July 10, 2005, from: hes.lbl.gov.

Lechner, N. 2001. *Heating, Cooling, Lighting: Design Methods for Architects,* 2nd Edition. New York: John Wiley & Sons, Inc.

Lightbulbsdirect. 2005. Light Bulbs Etc, Inc. Retrieved July 9, 2005, from: www.lightbulbsdirect.com.

Liz Madison. 2005. Large Appliances. LizMadison.com. Retrieved July 9, 2005, from: www.lizmadison.com.

Lowe’s. 2005. Cost of Window Products. Lowe’s Home Improvement Warehouse of Bryan.

Marsh, L. 1998. Taking Control of Energy Use. *Home Energy Magazine* 15(3): 23-27.

Mayfield, J. 2000. Snapshots of Shading Options. *Home Energy Magazine* 17(5): 20-23.

Miller, W.A., K.T. Loye, A.O. Desjarlais and R.P. Blonski. 2002. Cool Roofs with Complex Inorganic Color Pigments. *Proceedings of the 2002 ACEEE Summer Study on Energy Efficiency in Buildings*: 1.195-1.206.

Mitchell-Jackson J. and A. Meier. 2001. Cooking with Less Gas. *Home Energy Magazine* 18(3): 34-36.

Moloney K. 2005. Roofing Riddle. This Old House Ventures, Inc. Retrieved July 9, 2005, from: www.thisoldhouse.com/toh/print/0,17071,213518,00.html.

Mukhopadhyay J. 2005. Analysis of Improved Fenestration for Code-Compliant Residential buildings in Hot and Humid Climates. M.S. Thesis. College Station, TX: Texas A&M University.

Nadel, S., L. Rainer, M. Shepard, M. Suozzo and J. Thorne. 1998. Emerging Energy Saving Technologies and Practices for the Building Sector. Report No. A985. Washington, DC: American Council for an Energy Efficient Economy.

NAHB. 2003. The Builders Practices Survey Reports. National Association of Home Builders. Upper Marlboro, MD: NAHB Research Center.

Nayarat, R. 2003. An Analysis of Energy Reductions from the Use of Daylighting in Low-Cost Housing. M.S. Thesis. College Station, TX: Texas A&M University.

Olgyay, V. 1963. *Design with Climate: Bioclimatic Approach to Architectural Regionalism*. Princeton, NJ: Princeton University Press.

ORNL. 2002. DOE Insulation Fact Sheet. DOE/CE-0180/ with Addendum 1. Oak Ridge, TN: Oak Ridge National Laboratory.

Parker, D.S., and S.F. Barkaszi. 1997. Roof Solar Reflectance and Cooling Energy Use: Field Research Results from Florida. *Energy and Buildings* 25(2): 105-115.

Parker, D. and L. Schrum. 1997. Florida House Aglow with Lighting Retrofit. *Home Energy Magazine* 14(1): 21-27.

Parker, D., P. Broman, J. Grant, L. Gu, M. Anello, R. Vieira and H. Henderson. 1999. EnergyGauge USA: A Residential Building Energy Design Tool. *Proceedings of Building Simulation '99, Sixth International IBPSA Conference* 1: 73-79.

Parker, D.S., J.E.R. McIlvaine, S.F. Barkaszi, D.J. Beal and M.T. Anello. 2000. Laboratory Testing of the Reflectance Properties of Roofing Material. FSEC-CR670-00. Cocoa, FL: Florida Solar Energy Center.

Parker, D.S., J.K. Sonne and J.R. Sherwin. 2002. Comparative Evaluation of the Impact of Roofing Systems on Residential Cooling Energy Demand in Florida. *Proceedings of the 2002 ACEEE Summer Study on Energy Efficiency in Buildings*: 1.219-1.234.

Pletzer, R.K., J.W Jones. and B.D. Hunn. 1987. Energy Savings Resulting from Shading Devices on Single Family Residences in Austin, Texas. *Fourth Annual Symposium on Improving Building Energy Efficiency in Hot and Humid Climates*: 112-121.

Proctor, J., Z. Katsnelson and B. Wilson. 1995. Bigger Is Not Better: *Home Energy Magazine* 12(3): 19-26.

Proctor, J. and P. Albright. 1996. Sizing Air Conditioner: If Bigger Is Not Better, What Is? *Home Energy Magazine* 13(5): 13-18.

Rasisuttha, S. and J. Haberl. 2004. The Development of Improved Energy Efficient Housing for Thailand Utilizing Renewable Energy Technology. *Presented at SimBuild 2004, First National Conference of IBPSA-USA.* Boulder, CO.

Reilly, M.S., F.C. Winkelmann, D.K. Arasteh, and W.L. Caroll. 1995. Modeling Windows in DOE-2.1e. *Energy and Buildings* 22(1): 59-66.

RMI. 1994. Household Energy Efficiency—Home Energy Briefs. Rocky Mountain Institute. Retrieved July 9, 2005, from: www.rmi.org/sitepages/pid171.php.

RONA. 2005. Exterior Siding Products. RONA, Inc. Retrieved July 9, 2005, from: www.rona.ca/webapp/wcs/stores/servlet/ContentServlet?assetId=203&langId=-1&parentAssetId=64&parentAssetId=31&parentAssetId=5.

Rosen, K. and A. Meier. 2000. Energy Use of U. S. Consumer Electronics at the End of 20th Century. LBNL-46212. Berkeley, CA: Lawrence Berkeley National Laboratory.

Ross, J.P. and A. Meier. 2000. Whole House Measurements of Standby Power Consumption. LBNL-45967. Berkeley, CA: Lawrence Berkeley National Laboratory.

Sears. 2005. Appliances. 2005 Sears Brands LLC. Retrieved July 9, 2005, from: www.sears.com.

Senate Bill 5. 2005. Texas – Senate Bill 5. Retrieved July 9, 2005, from: energysystems.tamu.edu/sb5/documents/senatebill5.htm.

Simpson, J.R. and E.G. McPherson. 1997. The Effect of Roof Albedo Modifications on Cooling Loads of Scale Model Residences in Tucson, Arizona. *Energy and Buildings* 25(2): 127-137.

SIPA. 2004. Structural Insulated Panel Association. Retrieved July 9, 2005, from: www.sips.org.

Smith, M.W. 2001. Analysis of Thermal Performance of Tierra I- A Low-Energy High-Mass Residence. NREL/TP-550-25873. Golden, CO: National Renewable Energy Center.

Stein, B. and J.S. Reynolds. 1992. *Mechanical and Electrical Equipment for Buildings,* 8th Edition. New York: John Wiley & Sons, Inc.

Sullivan, B. 1995. Remodeling Kitchens: A Smorgasbord of Energy Savings. *Home Energy Magazine* 12(5): 11-16.

Ternes, M.P., K.E. Wilkes and A. McLain. 1994. Cooling Benefits from Exterior Masonry Wall Insulation. *Home Energy Magazine* 11(2): 33-35.

Thermapan. 2005. Thermapan Structural Insulated Panels. Retrieved July 9, 2005, from: www.thermapan.com.

Thorne, J. 1998. Integrated Hot Water Heating Systems: One system Is Often Better Than Two. Report No. A982. Washington, DC: American Council for an Energy Efficient Economy.

ToolBase. 2005. SIP Modular Housing. ToolBase Services. NAHB Research Center. Retrieved July 9, 2005, from: www.toolbase.org/tertiaryT.asp?TrackID=&DocumentID=2150& CategoryID=987.

Tribwell, L. 1997. Shedding Light on Home Lighting Use. *Home Energy Magazine* 14(1): 15-19.

Turrell, C. 2000. Storm Windows Save Energy. *Home Energy Magazine* 17(4): 20-23.

UltimateAir. 2005. Compare the RecoupAerator®. Stirling Technology. Retrieved July 9, 2005, from: www.ultimateair.com/products/compare.html.

UCLA. 2005. HEED, Version 2.0, Build 9 [Computer Software]. University of California in Los Angeles. Retrieved April 19, 2005, from: www.aud.ucla.edu/energy-design-tools.

USCB. 2002. Square Footage by Household and Unit Size, Income, and Costs—Occupied Units. *American Housing Survey for the United States: 2001*, p. 84. U.S. Census Bureau, Current Housing Reports, Series H150/01. Washington, DC: U.S. Government Printing Office.

Vieira, R.K., and K.G. Sheinkopf. 1992. *Energy-Efficient Florida Home Building Manual.* Revised, 3rd Printing. FSEC-GP-33-88. Cape Canaveral, FL: Florida Solar Energy Center.

Watson, D. and K. Labs. 1983. *Climatic Design: Energy-Efficient Building Principles and Practices.* New York: McGraw-Hill.

Weingarten, L. and S. Weingarten. 1996. Water Heaters and Energy Conservation- Choices, Choices! *Home Energy Magazine* 13(3): 15-21.

Wilson, A., J. Thorne and J. Morrill. 2003. *Consumer Guide to Home Energy Savings*, 8th Edition. Washington, DC: American Council for an Energy Efficient Economy.

APPENDIX A

SUMMARY OF LITERATURE REVIEW

Summary of Literature Review

This section of the appendix contains a summary of the literature review performed during different stages of this study. The summary is organized in a tabular format listing the sources used, the context in which they were used, the special importance to this study, and highlights of the findings. The sources of literature are grouped according to their relevance to a specific purpose, and are presented under following categories:

1) The building systems and components that affect building energy use
2) Optimized combination of strategies
3) Case-studies of high-performance homes
4) Simulation software for energy-efficient building design
5) The basecase house characteristics
6) Product detail and cost data for the basecase house and the energy-efficient upgrades
7) Economic factors affecting the life-cycle cost

Table A- 1: Building Systems and Components Affecting Residential Energy Use

Source	Context	Special Importance	Summary
Akbari and Konopaki 1998	Roof reflectivity and emissivity	Impact of roof reflectivity and emissivity on building cooling and heating energy use for several residential and commercial prototypical buildings	o Reflective roofs provided greater opportunities for energy savings in warm climates than in cold climates. o Coating roofs white reduced cooling energy use between 10-50% depending on the roof insulation. o Low emissivity roofs resulted in heating energy savings in very cold climates and cooling energy penalty in hot climates. o Decreasing roof emissivity from 0.9 to 0.25 resulted in net 10% increase in annual energy use in hot climates, no savings in cold climates, and up to 3% heating energy savings in very cold climates.
ASHRAE 2001a	Building envelope	Fundamentals of heat transfer through the building envelope; and thermal and optical properties of insulation and fenestration materials	o Recommended having a reasonably tight building envelope, and a properly designed and operated mechanically ventilated system for residences, to avoid possible difficulties of lack of control of ventilation rates, poor humidity control, air moisture infiltration and lack of opportunity to recover the energy used to condition the ventilation air. o Recommended using daylighting, passive solar heat gain, glazing with special transmission properties, and insulated glazing with low air leakage to optimize the energy impacts of fenestration. o Recommended using single or multiple (insulating) glazings, interior and exterior shading, and spectrally-selective coatings and tinted glass to control the heat flow through fenestration.
Berdahl and Bretz 1997	Roof reflectivity	Provided solar reflectance for different materials; discussed effects of material composition, roughness, purity, infrared (IR) emittance and convection on solar reflectance	o High solar reflectance, thermal emittance and convection coefficient were recommended for keeping surfaces cool, since materials with low emittance showed higher temperature rise, due to their reduced ability to radiate heat by IR radiation. o Roughness or corrugation on the surface lowered reflectance. o Temperature measurements in sunlight illustrated a strong correlation between solar absorptance and roof temperature for materials with IR emittance of about 0.9.
Brown and DeKay 2001	Building envelope	Listed strategies for design development stage	o The strategies included: organization, shape, orientation and location of building groups, building spaces, and building envelop components. o Recommends compact and/or combined organizations and buffer zones for heating and cooling energy savings; and thin building organization, light shelves and daylighting enhancing shades for daylighting.
Conway 1994	Lighting	Reported lighting energy savings from various energy-efficient lighting measures	o Motion detectors can save lighting electricity by 40% in bathrooms, 30% in bedrooms and kitchens, and 20% in living rooms and kitchen/dining areas. o An average of 26% annual operating cost savings were found from replacement with more efficient lamps, 45% from typical manual on/off controls with dimmers, timers, or sensors, 57% from an integrated system of efficient lamps, efficient luminaries and appropriate controls.
DOE 1996	Lighting	Energy end use data for lighting in residences	o Lighting energy consumption was only 9.4% of all electricity consumption in the residential sector, in 1993. o Replacement of incandescent lights with CFL had one of the highest (35%) energy-saving potential.
DOE 2000	Advanced wall framing	Design considerations, construction specifications, details, and benefits of advanced framing techniques	o Reduced thermal bridging in advanced wall framing results in improved whole-wall R-value, and elimination of cold spots that are susceptible to condensation, and mold growth. o Material and cost savings of about $500 or $1000 (for a 1200 and 2400 ft2 house), labor cost savings of between 3 to 5%, and annual heating and cooling cost savings of up to 5% can be achieved.
DOE 2001a	Appliances	Provided energy end use data for different home appliance, discussed factors affecting appliance energy use, and provided energy savings estimates from efficient appliances	o Water saving models of washing machines can cut water and energy usage by more than 40%. o Gas dryer costs 15-25 cents/load, compared to 31-40 cents in an electric one. Energy-efficient measures for clothes dryers include using cool down cycles, locating them in a heated space, and cleaning and proper maintenance. Also, simple timers, advanced temperature sensors and sophisticated moisture sensors in clothes dryers will reduce dryer energy use by 10% to 15%. o Electric ranges containing ceramic, halogen, or induction range elements are more efficient than the type containing electric coils. Electric ranges with solid disk elements are the most energy consuming.

Table A- 1 (Cont.)

DOE 2001b	Domestic hot water	Performance evaluation of the GFX in a typical residential application in Tennessee	o GFX saved about 40% of the total energy needed for the shower. o Actual savings in water heating energy depended on the specific installation, hot water consumption patterns, and whether the GFX is piped as balanced or unbalanced flow, however, 30-50% savings was a reasonable estimate of energy savings from GFX.
DOE 2004	Building energy use data	Residential building primary energy consumption and end-use splits for 2002, and aggregate residential building component loads for space heating and cooling	o Primary energy consumption of 20.9 quads of residential energy use was electricity: 67%, NG: 24%, oil: 7% and renewable: 2%. o End-use split was space heating and cooling: 32% and 12%, water heating: 13%, lighting: 12%, refrigeration 9%, electronics, cooking and wet clean: 5% each, computers 1%, other end uses 4%. o Heat loss through roofs, walls, infiltration, and conduction through window were 12%, 19%, 28% and 26% of the total space heating and 14%, 10% 16% and 1% of the total cooling load. Also, foundation caused 15% of heat loss, and solar gain through windows and internal gains caused 32% and 27% of the total heat gain.
Farrar-Nagy et al. 2000	Fenestration	Comparative analysis of effects of shading and glazing type on energy use and energy cost savings to optimize the interaction of various methods to reduce solar heat gain	o The results indicated 14% reduction in afternoon peak electricity demand and 12.4kWh (30%) reduction in daily total cooling load from combination of high performance shading and glazing in hot dry climates, 9.4kWh (22%) only from shading and 4.4kWh (11%) reduction from upgrading windows. o Spectrally selective glazing with shading performed the best for daily load of air conditioning electricity use. o Daily cooling energy savings were higher from architectural and site shading than from upgrading windows.
Fine and McElroy 1989	Insulation and fenestration	Energy conservation potential of passive and active fenestration and insulation systems with fixed and variable/switchable properties	o Annual energy use with the recommended passive insulation systems were 58, 62 and 90 MBtu/yr in Phoenix, Lexington and Minneapolis, respectively. o Active insulation systems generated smaller savings over passive super insulation systems. o Active fenestration systems performed better than the best passive systems by 12, 13 and 8 MBtu/yr, with slightly more savings from switching transmittance from 0.8 to 1.0. o Incorporating passive resistance systems with active fenestration systems showed higher saving potential (20, 20 and 25 MBtu/yr).
Friedman 2000	Building envelope	Guidelines for building layout and construction for achieving minimum energy requirements, and estimates for resultant energy savings	o Simple rectangular shape for buildings were recommended that results in energy savings both directly and indirectly due to reduced wall and window area, reduced heat gain or loss and reduced infiltration. o Simplifying floor plan from an L-shape to a rectangle showed up to 15% energy savings. Up to 21% and 43% savings were resulted in a 1200 ft^2 unit designed as a 14 ft. x36 ft. duplex and as a row house, respectively.
Geltz 1993	Lighting	Guidelines for energy-efficient lighting in home offices	o Energy-saving measures for lighting in home office included: considering task oriented lighting plan, small scale fixtures, multiple switching scheme, occupancy sensors, daylight with glare control, dimmers and proper installation of lighting and equipment (with proper circuit capacity to support the equipment, good power quality and code compliance)
Givoni 1998	Building envelope	Design guidelines for different climatic regions to improve comfort and energy conservation in that particular climate	o Discussed effects of architectural and structural design features including layout, window orientation, and shading and ventilation conditions on the indoor climate and energy use o A compact plan with smaller exposed surface area of the walls and roof reduces the energy demand, whereas a spread out plan has potential for natural ventilation and natural illumination. o Shading devices that intercept only the direct solar radiation would be less effective in hot and humid regions, where the diffused radiation from the sky comprises a significant portion of the total solar heat gain due to partly cloudy sky.
Hayden 1996	HVAC: Heating system	Advantages, disadvantages and typical seasonal efficiency of common heating equipment	o Duct leak can increase home’s heating cost by 20-30%. o The efficiency of furnace or boiler ranges from 60% for conventional natural gas furnace to 96% for a high-efficiency condensing gas furnace. o Furnaces with electric or electronic ignition have 3-9% fuel savings. o Electric resistance space heating equipment are typically 100% efficient. o Heat pumps can have efficiencies higher than 100%, since they transfer and upgrade heat from the outside air or ground, thereby increasing their heat output without losses. o The SEER of an air-source heat pump ranges from 9-16, and the HSPF ranges from 5.9-8.8. The SEER of a ground-source heat pump ranges from 11-17, and the HSPF ranges from 8.3-11.6.

Table A- 1 (Cont.)

<table>
<tr><td>Hedrick 2003a and b</td><td>HVAC (Ducts in conditioned space)</td><td>Estimated cost impacts and predicted energy savings of building homes with ducts in conditioned space</td><td>o The construction costs and the savings vary greatly by the size and type of the house, the tightness of the duct system, and the climate zone.
o For houses with typical duct construction (22% system airflow loss), the average annual cooling electricity savings range from 9% to 18% for single-family houses and 5% to 12% for townhouses.</td></tr>
<tr><td>ICFA 2004</td><td>Insulated concrete forms</td><td>Benefits, technology and application of insulated concrete forms</td><td>o ICF walls using polystyrene foam have insulating values of R-17 to R-26, compared to wood frame’s R-9 to R-15.
o ICF walls reduce conduction heat losses by 50%, are 50% more airtight and have thermal mass that contributes about 6% of the needed energy to the house for free.
o These result in heating and cooling energy savings of 30-40% compared to frame houses (with higher savings associated with bigger house), and allow the installation of smaller heating and cooling equipment.
o Cooling savings are higher in hot climates and heating savings are higher in heating climates.</td></tr>
<tr><td>Johnson and Wyatt 1997</td><td>DHW: GFX drain water heat recovery system</td><td>Discuses working of GFX drain water heat recovery system, its performance and energy-saving potential</td><td>o For houses with full basement or showers on the second floor, gravity-film heat exchanger (GFX) can increase the EF of the water heating system by about 34% and can triple first hour ratings- especially with an electric heater.
o A technical evaluation by Old Dominion University of Virginia showed 47% to 64% total energy savings (averaging 57%) by the GFX and 57-73% increase in the EF.</td></tr>
<tr><td>Kosny et al. 2001</td><td>Thermal mass walls</td><td>Discussed energy performance of sixteen light weight and massive wall systems for residential buildings in ten U.S. climates</td><td>o Thermal mass benefit depends on wall material configuration, climate, building size, and orientation.
o The most beneficial application was Phoenix, AZ and Bakersfield, CA (8% of the whole building energy savings in Minneapolis and 18% in Bakersfield, for high R-value walls).
o Most effective wall assembly is the wall with thermal mass in good contact with the interior.
o Walls with insulation concentrated on the interior side performed much worse.
o Wall with insulation on both sides of concrete wall core performed slightly better, but significantly worse than walls containing foam core and concrete shells on both sides.
o For ten U.S. locations, average whole building energy savings potential of R-15 and 20 ICF walls was between 6 and 8%.</td></tr>
<tr><td>Kosny et al. 1998</td><td>Thermal mass walls</td><td rowspan="2">Analyzed of the thermal performance of different massive wall configurations with insulation</td><td rowspan="2">o Most effective configurations were massive walls with thermal mass being in good contact with the interior.
o Dynamic thermal performance of massive walls depended on the climate.
o The most favorable climate for application of the massive walls systems was in Phoenix.
o The relatively worst location for these systems was in Minneapolis (especially for less insulating walls), where using a light-weight wall of the same steady-state R-value was more efficient.
o Massive walls with low R-value (below R-4) were found ineffective except in Phoenix.
o Up to 11% of heating and cooling energy savings were estimated in U.S. residential buildings containing massive walls by optimization of the mass and insulation distribution on the wall.</td></tr>
<tr><td>Kossecka and Kosny 1998</td><td>Thermal mass walls</td></tr>
<tr><td>DOE 1997</td><td>Fenestration</td><td>Guidelines for selecting fenestration properties for different climate regions</td><td>o In heating dominated climates, multiple pane, low-e and gas filled window configurations, or super windows that combine all the above advanced features are cost-effective and advisable.
o In hot climates, less expensive glazing with low-e coatings and gas fills with shading techniques are cost-effective and energy-saving option.
o In hot sunny climates, spectrally selective glazing with SHGC of 0.4 or less and visible transmittance of 0.6 or greater are recommended for maximum energy-efficiency, good light transmittance and visibility.
o Among the available frame and spacer options, wood, fiberglass, and vinyl frames are better insulators than metal. Aluminum frames with thermal break perform better than those without thermal break.
o Spacer thermal performance depends on its geometry and material composition. Well designed metal spacers insulate almost as well as foam.</td></tr>
</table>

Table A- 1 (Cont.)

Lechner 2001	Building envelope	Listed climatic design priorities; and design strategies for achieving them for schematic design of buildings in different climatic regions in the U.S.	o Natural ventilation is the highest priority measure for summer cooling and moisture removal in hot and humid climates, followed by that for protection from summer sun and exposure to winter sun. o For natural ventilation, orientation and planning the building for maximum contact to outdoors to capture the prevailing winds, open indoor plan, high ceiling, two storey spaces, open stairwell and elevated living spaces are recommended for maximized air flow and less humidity level indoors. o Compact designs, attached or clustered buildings and earth sheltering, are the common measures to protect from extreme hot and cold temperatures as well as undesired winds. o Orienting building along the east-west axis, maximizing exposure to south, southeast and southwest sides, providing clear solar access and sunspaces on the south, buffer spaces along the north, and temperature zoning inside the building, are additional measures to maximize solar gain and minimize heat loss in winter. o Building envelope shading could be added to these measures, to minimize heat gain in summer.
Marsh 1998	HVAC: Controls	Emphasized on HVAC controls as one of the potential energy-saving measures for HVAC systems	o Energy-saving measures for HVAC systems included: thermostat set backs, efficient motor and fan systems, and moving the ducts into the conditioned space. o The actual savings from thermostat setbacks depends on weather conditions, thermal efficiency of the building envelope and the thermal mass of the structure. However, a rule of thumb of 3% savings for every F of setback was given to estimate savings.
Mayfield 2000	Fenestration	Discussed different shading options and provided guidelines for their selection in different contexts	o Shading options for residences included: overhangs, decks and porches, awnings, low-e films and coatings, shade screens, solar screens and rolling shutters.
Miller et al. 2002	Roof emissivity	Introduces complex inorganic color pigments (CICPs) that could improve thermal performance of dark roof	o For climates predominated by heating loads, surfaces with moderate reflectance and low IR emittance will save in comfort heating. o CICPs make dark-color roofs behave similar to white-color roofs in the near-infrared portion of the solar energy spectrum and reflect much of the near-IR heat. This could improve energy thermal performance, durability and life expectancy, and reduce replacement and disposal cost for asphalt shingle roofing that has lower thermal performance, but is preferred due to their appearance, cost and durability.
Mitchell-Jackson and Meier 2001	Appliances: cooking options	Comparative analysis of cooking options in terms of energy use and efficiency	o Efficiencies of different cooking options are: 55% for a microwave oven (ranging from 49-57%, with largest microwaves-the least efficient), 70% for an electric stove, and 40% for a gas stove. o Microwave is the most convenient and the most energy-saving cooking option. It uses one-third as much energy as conventional ovens (about 110 kWh/yr of electricity, including approximately 24 kWh/yr in standby mode), and is recommended especially for heating smaller portions (no preheating required, time savings, less heat loss). o Electric stoves are more efficient and 25% less electricity consuming options than microwaves, they generate more heat loss for heating smaller portions. o Gas stoves require more energy than a microwave; however, they usually cost less to use due to the lower price of natural gas. o Recommended practices for using microwaves are heating consumable amount of food at a time, defrosting in refrigerator than in microwave, unplugging when not in use for long periods.
Mukhopadhyay 2005	Fenestration	Analyzed improved fenestration for code-compliant residential buildings in hot and humid climates	o The optimally-shaded, double-pane, low-E glazing option resulted in the lowest energy consumption for the north and east orientations. However, for the south orientation, optimally-shaded, double-pane, clear glazing resulted in the lowest energy consumption. o Using high performance options showed diminished impact of selection of glazing on different orientation. A maximum of 5% variation in overall energy consumption was seen when examining the performance of the options on each orientation. o House sizes and wall to window area ratios also impacted the performance of glazing options to a certain degree, with the impact of building envelope more clearly outlined for bigger house sizes. o For smaller houses, U-factors gained precedence, whereas for larger houses, SHGC gained precedence.

Table A- 1 (Cont.)

Nadel et al. 1998	Building envelope, Lighting, appliances, HVAC and DHW	Analyzed of energy-saving technologies in residential and commercial buildings sector	o Measures that have recently been or can be commercialized in recent future were prioritized according to their energy use and saving potential, cost information and likelihood of success. o High priority measures for residences included: efficient clothes washers, integrated space/water heating systems, dual source heat pumps, improved ducts and fittings, high-efficiency CFLs, and integrated new home design.
Nayarat R. 2003	Daylighting	Analyzed the effectiveness of three daylighting strategies and their energy performance using a scale model and DOE-2 simulations	o Daylighting strategies included: 6 ft. overhangs with vertical fins, 6 ft. overhangs, and 18-inch combined lightshelves. o Lighting electricity savings were 22%, 25%, and 18%, respectively. o Cooling energy savings were 10%, 8% and 6%, respectively. o Heating energy penalty were 4%, 4% and savings of 4%, respectively. o Annual electricity savings were 6%, 6% and 8%, respectively.
Olgyay 1963	Building envelope	Investigated the thermal impacts for different building shapes in different climates, and recommended optimum building shapes for each climate	o The optimum shape of a building in all climates was a form elongated somewhere along the east-west direction, with the amount of elongation depending upon the climate. o For hot and humid climate of Miami, Florida, length to width ratio of 1:1.7 was found the optimum for a 1000 ft^2 house with usual insulated frame construction (U=0.13) and 40% single pane glass on the south. o In all climates, attached units (such as row houses) with east and west common walls were most efficient.
ORNL 2002	Insulation	Provides guidelines for selecting type and level of insulation for different envelope components in residences in different U.S. climates	-
Parker and Barkaszi 1997	Roof reflectance	Impact of reflective roof coatings on cooling energy use in nine residential buildings in Florida, with different roofing systems, attic insulation levels, AC efficiencies	o Comparison between pre- and post-retrofit monitoring results showed that cooling energy use reduction averaged 7.4 kWh/day or 19%, ranging from 2-43% and peak electrical demand reduction averaged 427W or 22%, ranging from 12-38%. o The data suggested cooling energy-saving potential of up to 40%, with larger savings associated with poorly insulated roof assemblies or buildings with duct system in attic space and excessive attic air infiltration.
Parker and Schrum 1997	Lighting	Identified high use areas best for retrofitting; provided estimation of annual lighting energy use, variation with season and reduction in demand and energy savings due to CFL replacements	o Estimated annual use was 4050 kWh with 24% variation in lighting load between June and November. o The metering results showed 56% reduction (from 2.5 to 1.1 kWh) in lighting loads from replacement, 40% reduction in metered lighting and plug loads (61% in pure lighting load) i.e. approximately 2,500kWh (or $200) per year @ $0.08/kWh. o Most savings were identified between 7 a.m. and midnight, and highest between 6 p.m. to 10 p.m., with average 6.8 kWh savings per day change over the period. o Outdoor, kitchen & living room lamps, and those that are used for more than 3 hours, were found good candidates for CFL replacement.
Parker et al. 2000	Roof reflectance	Spectral data for reflectance of 37 roofing material samples based on laboratory testing	o Asphalt shingles showed poor reflectance (3-26%), improved white asphalt shingles had modest improvement (31%). o White elastomeric coatings showed high solar reflectance (65-78%). o Other white roofing system such as white concrete tile, metal roof, cement shingle and EPDM and Hypalon products showed 73%, 67%, 77% and 69-81% reflectance, respectively. o The desirable characteristic of high long-wave emittance was met by most of the tested samples, except unpainted aluminum, galvanized and Low-mit samples. o High total solar reflectance, but a lower ratio of visible to heat reflectance was considered as desirable properties for a reflective roof system, ensuring better thermal performance and lower level of glare. Conversely, the results showed higher visible reflectance than in the near IR region for most of the tested options.
Parker et al. 2002	Roof reflectance	Thermal performance of seven roofing systems with different materials, and different duct and attic configurations	o Measurements showed reduction of 18-26% in cooling energy consumption and 28-35% in peak demand with white reflective roofs, 3-9% with terra cotta tile roofs and 3-5% with white shingles (all having R-19 ceiling insulation). o The standard dark shingles with sealed attic construction and R-19 roof deck insulation produced 6-11% reductions, but no real peak reductions.

Table A- 1 (Cont.)

Pletzer et al. 1987	Fenestration	Provided estimation and comparative analysis of annual performance due to various shading devices	o Annual cooling energy savings were up to 32%, annual energy cost savings ranged from 5-15% of the total. o Interior shading strategies performed better than exterior ones, in terms of annual energy cost savings. o Graphs comparing the performance indicated correlation between heating and cooling energy savings, and shading options.
Proctor and Albright 1996 Proctor et al. 1995	HVAC: Air-conditioner	Discussed efficient operation for space conditioning equipment and importance of proper sizing for energy savings	o The heating or cooling requirements of a house over the annual heating or cooling season depends on the climate, size and type of the house, insulation level, air-tightness, solar gains, internal heat generation, thermostat setting, and other operational factors. Using energy-efficient strategies for these factors reduces building's thermal load and allows reduced system size. o Properly sized and energy-efficient systems and equipment achieve longest run time possible that optimizes their performance and minimizes energy use for space heating and cooling. o Properly sized air-conditioners also perform better in terms of moisture removal ability, noise and comfort.
RMI 1994	Lighting, windows, appliances, water heating and space conditioning.	Guidelines for selecting efficient models and following energy conserving practices, energy use and cost for different models, and savings from various strategies	o Heat loss reductions of 25-40% could be achieved from installing plastic barrier on single pane window, 40-50% from window shades and blinds, and 60-80% from insect screens or bamboo shades. o Clear solar access on south windows in winters can increase solar gain by 40%. o Space conditioning load can be reduced by up to 50 % from building envelope improvements such as sealing air leaks, adding adequate insulation, and upgrading window features.
Rosen and Meier 2000	Electronics	Usage, power and unit annual energy consumption of consumer electronics	o Specified over 10% of U.S. residential electricity consumption in U.S. homes from major consumer electronics, with television as the most energy consuming device. o Over 60% of electronics energy use was estimated to be consumed while the product was not in use.
Ross and Meier 2000	Electronics	Appliance standby loads, overall residential standby loads, and correlation between annual electricity consumption vs. standby power	o Estimated 14-169W total standby power consumption in ten homes in California, averaging 67 W, which corresponded to 5-26% of the homes' annual electricity use. o Televisions, set-top boxes and printers had the largest standby losses. o The large variation in the standby power of appliances providing the same service demonstrated that manufacturers are able to reduce standby losses without degrading performance. o Replacing existing units with appliances with 1W or less of standby power would reduce standby losses by 68%.
Simpson and McPherson 1997	Roof reflectivity	Effects of roof albedo on cooling loads using ¼ scale model buildings in Arizona	o Daily total and hourly peak air-conditioning load reductions due to white roofs were approximately 5% with insulation (compared to gray and silver roof), and 18-28% without insulation. o With R-30 ceiling insulation installed, 5% reduction in the daily total and hourly peak air-conditioning load with white colored roof, when compared to (compared to dark brown roofing). o White roofs were 20 to 30C cooler than silver or dark colored roofs on hot, sunny days, indicating higher emissivity as a desirable property. o Ceiling insulation was found to be more effective in reducing the daytime heat gain than increased roof albedo. o Increased surface albedo was expected to be more effective in climates with smaller temperature difference than found in Tucson.
SIPA 2004	Structural insulated panels (SIPs)	Benefits, technology and application of SIPs	o SIPs avoid thermal breaks or penetrations in the panels, thus, have higher insulating values and are 95% more airtight. o These allow reduced system size and save energy cost by 50%.
Sullivan 1995	Appliances	Explained ways to cut energy cost; gave guidelines for kitchen layout and design, choosing appliances, specifying lights, construction and usage etc.	Energy-saving considerations while selecting kitchen appliances included: o For refrigerators: optimum size, configuration, defrost type, proper refrigerator placement avoiding direct sunlight or close contact with hot appliances, adequate clearance to allow sufficient airflow, lower room temperature, adequate temperature setting, regular maintenance, and replacement of old refrigerators. Automatic ice makers, through-the-door dispensers and anti-sweat heaters increase the energy use. o For dishwashers: built-in water-heating booster and variable wash cycle, and air dry option. o For gas ranges: electronic or thermal igniters instead of standing pilot lights; electric convection ovens (30% less operating cost than conventional electric ovens, since they circulate air inside the oven to improve efficiency and reduce cooking time).

Table A- 1 (Cont.)

Ternes et al. 1994	Site fabricated wall insulation retrofit	Energy-saving potential of site fabricated insulation systems on eight single family masonry houses in Arizona, and extrapolation of the results to other U.S. climates	o The wall insulation retrofit from R-3 to R-13 reduced energy use by 9% (from 5499 kWh to 5008 kWh) and average peak demand by 15% (from 4.26 kW to 3.61kW). o Highest annual air conditioning energy savings estimation of 12-13% (between 450-700 kWh) and 8-12% (from 0.25 to 0.7 kW) peak-hour demand reductions in Phoenix and Las Vegas, in contrast to 50 kWh energy savings in Miami and Southern California, suggested much lower wall loads in southern climates (especially coastal regions), as compared to that for hot, dry climates. o In some locations, particularly in Miami, the addition of wall insulation actually increased the cooling load during the spring and fall.
Thorne 1998	Integrated space conditioning and water heating systems	Discussed available types of integrated systems, and provided an economic comparison between conventional and integrated systems	o Integrated space conditioning and water heating systems use one appliance or energy source. o They can result in 2-27% savings in annual energy costs for space conditioning and water heating, depending on household variables and regional climate conditions.
Tribwell 1997	Lighting	Identified best opportunities for lighting retrofits, analyzed factors affecting lighting energy use, and estimated energy savings from lamp replacements	o Average lighting energy use was 1800kWh/yr per household, 50% more use in darker months than in lighter months (6kWh in July-Feb, and 4kWh in Feb-Aug). o Living, kitchen, porches and outdoors were high energy use areas o Replacements of 50W-150W incandescent lamps with $15 CFL saved $5.60/yr @ $0.04/kWh with 2.7 yrs. Payback. o No correlation was found between energy use and floor area, number of occupants or hour of occupancy. o Conservation habits, behavior and other occupancy factors were found to affect energy use. o A rough estimate of lighting energy use was approximately 9% of the total energy use.
Turrell 2000	Fenestration: storm windows	Benefits of storm windows, effect of wind speed on heat loss and air leakage for window assemblies	o Benefits included: protection from storm damage, reduced conductive heat loss and air infiltration. o Adding storm windows was an energy-saving retrofit in older buildings, especially with single glazed windows. o Research results conducted in ORNL indicated higher reduction in heat loss and air leakage due to storm windows at higher wind speeds.
Vieira and Shienkopf 1992	Building design, envelope, doors and windows, systems and appliances	Recommendations for building energy-efficient residences in Florida, and energy savings and first cost estimates for all the strategies	Estimated energy savings of up to: o 50% for cooling and 70% for heating from building design, o 25% for heating and cooling each from foundations and floor, o 15% for cooling and 20% for heating from efficient walls, o 30% for heating and cooling each from efficient doors and windows, o 65% for heating and 60% for cooling from efficient space conditioning equipment, and o 30% energy cost savings from efficient appliances, in Florida o Combined energy savings can be calculated as: Total % savings = [100 - (100 -savings A) * (100 - savings B)]
Watson and Labs 1983	Building envelope	Control strategies for promoting or restricting heat gain or loss	The strategies included: o Wind breaks to minimize winter wind exposure, o Plants and water for shading and evaporative cooling, o Indoor/outdoor rooms for summer cooling and winter heating benefits, o Earth sheltering for insulation, winter wind protection and summer cooling, o Solar walls and windows for winter heating, o Thermal envelope isolating the interior space from the cold winter climate, and o Sun shading for overheated summer period and natural ventilation for summer cooling.
Weingarten and Weingarten 1996	DWH system	Guidelines for equipment sizing and selection, installation, operation, upgradation, replacement and maintenance for energy-efficiency	o Recommended proper maintenance, upgradation of components, providing exterior and piping insulation if needed, heat traps, flue dampers, and timers; upgrading relief valve drain line. o Recommended to provide manifold distribution system with 3/8-inch tubing, tempering tanks, solar heaters, recirculation systems and controls and supplemental heating, based on the context.

Table A- 2: Optimized Combination of Strategies for Energy-Efficient Residences

Source	Context	Special Importance	Summary
Chulsukon 2002	A typical house in Bangkok, Thailand	Analyzed strategies to reduce lifetime building energy use of the house	o Strategies included: insulated walls and roof, improved glass type, light-colored exterior surfaces, increased ground reflectance and variation in thermostat setting. o Maximum annual energy savings of up to 13% from improved glass type and from thermostat setting, followed by 3-4% savings from wall insulation, roof insulation and light-colored exterior wall surfaces, and 1-2% savings from increased ground reflectance and light-colored roof o Up to 30% annual energy savings from combining all these strategies.
Gamble et al. 2004	Achieving zero-energy in homes	Assessed opportunities to integrate energy-efficient and passive solar features with on-site generation	o Energy-efficiency packages included: upgraded building design, envelope, systems, lighting and appliances, and behavioral modifications o Demonstrated up to 75% energy savings in hot climates. o Demonstrated a net-zero energy use by coupling such upgrade packages with PV systems, with net overall costs close to that of standard code built homes.
Kootin-Sanwu 2004	A low-income housing in hot-humid climates of the U.S	Investigated energy-saving potential and cost-effectiveness of envelope, systems and landscape improvements	o Potential energy-efficient upgrades included: improved windows, CFL replacement, improved attic and wall insulation, efficient HVAC systems, equipment without pilots lights, and white roof. o The most economically favorable measures were: CFL replacement, equipment without pilot lights, and air-conditioner with a more efficient stainless system. o Improved insulation showed small annual electricity savings; however, a significant cooling energy savings in the summer.
Rasisuttha and Haberl 2004	A case study house in Bangkok, Thailand	Analyzed individual and combined effect of energy-efficient strategies for building components, systems and renewable energy systems	o Maximum total energy savings of 9.08% from light-weight concrete block walls with insulation on the inside compared to 4 inch brick walls. o 20% savings from combining this strategy with improved ceiling insulation, replacement of single-pane clear glass with double-pane low-e glazing, exterior shading, and efficient systems, lighting and refrigerator. o 72.58% savings from further addition of solar thermal and photovoltaic (PV) systems to the above combination.

Table A- 3: Case-Studies of High-Performance Homes

Source	Context	Special Importance	Summary
Building America 2004	Production homes in different climatic regions of the U.S.	Provided characteristics of the houses, key energy-efficient features, cost of efficiency upgrades, and energy performance summary	o Common energy-efficient features included: advanced framing, detailed air sealing and insulation, double-pane low-e vinyl-framed windows, un-vented attic, and efficient systems. o These features allowed downsizing air conditioner and a simplified duct layout, which reduced the added cost of incorporating these features. o REM/Design computer simulation program was used to evaluate energy cost and consumption, design loads and Energy Star scores.
Casebolt 1993	An off-grid solar house in Arizona.	Explained characteristics of the house, energy and water conserving practices, and average daily energy use and energy cost savings	o Energy-efficient features included: passive solar design, a PV system, efficient lighting, systems and appliances, and energy and water conserving features. o These features accompanied with energy and water conserving practices allowed the installation of a smaller, less expensive PV system. o The energy use was 855 kWh/year (2.34 kWh/day) as compared to 9,300 kWh/year in nearby homes.
Christian 2005	The four ORNL near net-zero energy homes in Tennessee	Described envelope and system characteristics, and energy performance of the houses	The common features included: o Airtight envelope with SIP, efficient windows, ducts inside the conditioned space, and metal roof, o Solar PV, mechanical ventilation, and HPWH; and o Efficient lighting, systems and appliances.
Christian et al. 2003	First ORNL zero energy home in Tennessee	Described energy-efficient features of the house and measured energy savings	o 35% heating and cooling energy savings from ducts in the conditioned space, o 10% less energy use from structural insulated panels, o 60% savings in DHW use (64kW/yr) from heat pump water heater, o 5% DHW savings from the heat recovery shower, and o 65% energy cost savings and 40% reductions in summer PM peaks from a grid-connected 2 kW PV system.
Kent 2003	A high efficiency house in Pennsylvania.	Described design, construction and monitoring of the test house to research, evaluate and test new systems, methods and practices	o Used standard construction practices to save time and construction cost. o Energy-efficient features included: improved building envelope, improved floor framing and duct design, efficient lighting, systems and appliances, and energy recovery ventilators (ERVs). o 5% increase in the construction cost due to energy-efficient upgrades. o 55% reduction in the energy use compared to 1993 MEC benchmark (HERS score: 91.4).
Smith 2001	A passive solar house in Colorado	Described building features, computer modeling and monitoring details	o Energy-efficient features included: air-tight concrete construction, natural ventilation with thermal mass, shading, solar heating, and efficient windows. o 56% energy savings as compared to the MEC base-case house. o The analysis indicated a potential energy savings of 70.4% with increased insulation.

Table A- 4: Simulation Software for Energy-Efficient Building Design

Source	Context	Special Importance	Summary
ACCA 2004	EnergyGauge USA	System sizing, which was analyzed by EnergyGauge	
Christensen et al. 2005	BEopt	Discussed interface components and capabilities of the software	BEopt, a software for identifying optimal building designs on the path to net zero energy, allows the user: o to select from many predefined options to be used for optimization (using the main input screen), o to display detailed results for many optimal and near-optimal building designs (using the output screen), and o to review and modify detailed information on all available option (using the option library spreadsheet).
DOE 1980	DOE-2	Reference manual	
EERE 2005	Tool directory	Provided information, technical contacts and links to download building software tools	-
Kim 2005	DOE-2	Discussed incapability of DOE-2 in simulating the attic with ducts in the attic; developed attic model for simulation with DOE-2	
LBNL 2005	Home Energy Saver	Calculates energy use for end uses in residential buildings	o Provides separate modules for heating/cooling, envelope, domestic hot water, appliances and lighting. o Provides estimate for energy savings by implementing energy-efficiency improvements. o Estimated annual energy cost to be $1706 for an average house in Houston, $962 for an efficient house, and $1785 for the basecase house to be used for this thesis.
Parker et al. 1999	EnergyGauge USA	Introduced the software and its capabilities	EnergyGauge USA uses DOE-2.1E with a number of enhancements that allows: o Energy use calculation and rating of residential buildings and cost-effectiveness of energy upgrades, o Simulation of duct air leakage and heat transfer, air infiltration, and mechanical ventilation systems, o Improved modeling of slab, crawlspace, basement, foundation types and thermal bridging in stud assemblies, and o Improved calculation of HVAC systems.
Reilly et al. 1995	Modeling windows in DOE-2	Demonstrates the use of Window-5 computer program in accurately modeling the windows in the DOE-2	For determining energy savings from the application of the selected optimum combination of fenestration properties, the Window-5 computer program gives DOE-2 the capability: o to account for the temperature effects on the U-value, o to update the incident angle corrections for the solar heat gain properties and visible transmittance, and o to account for the influence of framing elements on the heat transfer and solar heat gain through windows
UCLA 2005	HEED	Calculates and compares a user-defined building against a code compliant building and an energy-efficient building	o Allows the user to make various remodeling changes and assess their effect on building energy use. o Energy-efficient options include: building shape and orientation, envelope, windows, shading (fixed and operable), thermal mass, ventilation, daylighting, appliances, internal loads, and HVAC systems. o Estimated annual energy cost to be $1442 for the basecase house compliant with the 2000 IECC, $1821.75 for a similar building compliant with the California Energy Code, and $923 for the most energy-efficient building.

Table A- 5: Determination of Basecase House Characteristics

Source	Context	Special Importance	Summary
ASHRAE 2001b	Building Envelope	Air change rates for detached buildings	o ACH = normalized leakage (0.57) x weather factor o Weather factor for Houston = 0.81, that gave the estimated ACH per hour as 0.4617
ASHRAE 2003	Domestic water heating	Specified minimum water heater capacities that were adopted for the basecase	Minimum specifications for a tank-type gas-fired water heater in a 4 bedroom, 2.5 bath, single family living unit are: o 40 gallons storage with 72 gallons of 1 hour draw o 38 kBtu/hr input, and o 32 gph recovery
Energy Star 2002	Appliances	Specified energy use and wattage of conventional and Energy Star home appliances	
ICC 1999	Building envelope , HVAC and DHW systems	Specified envelope characteristics and minimum system performance for the standard house	o Wall U-factor: 0.085 Btu/ ft^2-hr-ºF, Roof insulation: R-30. o Window area: 18% of conditioned floor area, glazing U-factor: 0.47 Btu/ ft^2-hr-ºF, SHGC: 0.4. o Minimum system performance: 10 SEER for an air-conditioner, 78% AFUE for a gas-fired furnace, 0.54 EF for a 40 gallon tank-type gas-fired domestic water heater.
IESNA 2000	Lighting	Recommended illumination levels for general and task lighting in residences	o General lighting: 50 lux (horizontal illuminance). o Task lighting for critical seeing: 500 lux (horizontal illuminance), 100 lux (vertical illuminance). o Task lighting for non-critical seeing: 300 lux (horizontal illuminance), 50 lux (vertical illuminance).
NAHB 2003	Most common building and system characteristics	Provided survey data about the building and system characteristics in the east and the west Texas	The basecase characteristics that are adopted from the survey data included: o One-story configuration with 2,500 ft^2 floor area and 8 ft. floor height, o Wood frame construction with 2x4 studs @ 16" o. c., brick fascia on exterior walls, and slab-on-grade floor, and o Electric cooling, and natural gas space and water heating.
Stein and Reynolds 2002	Lighting	Provided relation between the lighting load and the illumination level for different types of lamps	The lighting load associated with 1 FC illumination level is: o 0.15 W/ ft^2 for incandescent lamps o 0.034 W/ ft^2 for fluorescent lamps
USCB 2002	Housing survey data	Provided statistics for number of bedrooms and floor area of the house	The data demonstrated that most of the units of 2,500 ft^2 conditioned floor area have 4 bedrooms.

Table A- 6: Product Details and Cost Information

Source	Context	Special Importance	Summary
ACEEE 2004 and Wilson et al. 2003	Appliances	Updated listing of the top-rated residential equipment on the U.S. market	o Products included: refrigerators, dishwashers, clothes washers, water heaters, central and room air conditioners, central heat pumps, and furnaces and boilers. o Provided efficiencies and annual energy use for the top rated models. o Facilitated selection of energy-efficient appliances.
AcDirect 2005	HVAC systems	Product details and price of Goodman air-conditioners	o Goodman SEER-15 air-conditioner o Price: $2637
Building Journal 2005	Construction cost	Quick online residential construction cost estimation	o The construction cost of a 2,500 ft^2 one-story house with no basement, standard construction and brick veneer exterior in Houston, Texas was estimated to be $220,653. o The estimate included 25% of the actual construction cost for the contractor's fee, 7% for the design fee and 5% for contingencies.
Cohen's 2005	Appliances	Product details and cost of appliances	o Wood's V10W 10 cu. ft. upright freezer with adjustable thermostat and magnetic door seal o Energy use: 353 kWh/yr o Price: $530
Consumer Guide 2005	Appliances	Product details and cost of appliances	o ASKO D3530 dishwasher o Energy use: 181 kWh (< 4 gal. water use) o Price: $1,149
House Needs 2005	Water heaters	Provided product details and cost of water heaters	o Bosch AquaStar 250 SX, tankless, electronic ignition , 0.85 EF o Energy use: 125 therms/yr o Price: $950
Lightbulbs-direct 2005	Lighting	Provided cost of different lamp types	o Incandescent lamps: $0.85 for 25W lamps, $0.45 for 40W and 100W lamps o Compact fluorescent lamps: $5.84 for 4W lamps, $ 6.04 for 14W lamps, $9.48 for 22W lamps
Liz Madison 2005	Appliances	Product details and cost of appliances	o Bosch WFMC3200 Nexxt, horizontal-axis clothes washer o Energy use: 186 kWh/yr (18.5 gal. water use) o Price: $940
Lowe's 2005	Windows	Cost of window products	o 3 ft. x5 ft. aluminum frame air-filled low-e: $106 o 3 ft. x5 ft. aluminum frame argon-filled low-e: $121.91 o 3 ft. x5 ft. vinyl frame air-filled low-e: $140 o 3 ft. x5 ft. vinyl frame argon-filled low-e: $150
Moloney 2005	Roofing	Cost of different roofing options	o Asphalt shingles: $50 to $100 per square (100 ft^2) o Fiber cement shingles: $200 per square (100 ft^2)
RONA 2005	Exterior siding products	Cost of different exterior wall finishes	o Brick masonry: $6.50 per ft^2 o Acrylic coatings: $5.50 per ft^2
Sears 2005	Appliances	Product details and cost of appliances	o Kenmore 18.8 cu. ft. top freezer refrigerator o Energy use: 392 kWh/yr o Price: $800
Thermapan 2005	SIP construction	Cost of SIP construction	o Building with SIP adds 1% to the project cost of a house built with conventional wood frame
Toolbase 2005	SIP construction	Costs of SIP construction	o Replacing conventionally-framed walls with SIPs increases production cost by $1/ ft^2
UltimateAir 2005	Energy recovery ventilator	Product description and cost of RecoupAerator 200DX ERV	o Application: Whole house ducted unit o Average power usage: 43 watts, (955 sensible effectiveness) o Suggested retail price: $1,099

Table A- 7: Resources for the Economic Analysis

Source	Context	Special Importance	Summary
ASHRAE 2003 and Haberl 1993	Economic analysis method	Provides methodology and equations for the annualized life-cycle cost analysis	-
Bankrate 2005	Economic factors	Current discount rate and mortgage rates	o Current discount rate: 4%, on June 23, 2005 o Current mortgage rate: 5.14% (30 years fixed), on June 23, 2005
Inflation Data 2005	Economic factors	Inflation rate	o Current inflation rate: 2.8%, on June 23, 2005
FAS 2005	Economic factors	Fuel Inflation rate	o Fuel inflation rate: 4.8%, on June 23, 2005

APPENDIX B

DETERMINATION OF LIGHTING LOAD AND REPLACEMENT COSTS

Determination of Lighting Load and Replacement Costs

This section of the appendix includes the assumptions and calculation for determining the lighting load, and the lighting replacement costs for the basecase scenario (with incandescent lamps) and for the energy-efficient lighting installations (with CFLs).

Table B- 1 lists the assumptions that were made regarding the daily activities of the occupants at different hours for weekdays, Saturdays and Sundays/Holidays.

Table B- 2 shows the lighting use at different hours, which was determined based on the assumptions listed in Table B- 1. The symbols used for lighting use correspond to the spaces where those lights are installed, for example, bedrooms (B1, B2, B3 and B4), dining room (Dn), dress (Dr), entrance (E), family room (F), hallway (H), kitchen (K), living room (L), pantry (P) and restrooms (T1, T2 and T3). Task lighting in kitchen and for reading in different spaces are denoted with an additional letter 't', for example, Kt, Ft, B1t, etc. For this study, exterior lighting and floor lighting at night were ignored. Lighting wattage in use for different hours was, then, determined from installed lighting wattage in different spaces; and average kW was calculated.

Table B- 3 calculates the number of hours used per year for each lamp, based on Table B-2, and determines the average replacement costs for incandescent lamps and CFLs.

Table B- 1: Activities of Occupants on Weekdays, Saturdays and Sundays/Holidays

Hour	Weekdays			Saturdays			Sundays/ Holidays		
	Mother	Father	Children	Mother	Father	Children	Mother	Father	Children
0:00									
0:30									
1:00									
1:30									
2:00									
2:30									
3:00									
3:30									
4:00									
4:30									
5:00									
5:30		Gets up, refershes							
6:00	Gets up, refreshes	Bath + Dress	Get up, refresh						
6:30	Breakfast prep.	Tea, Newspaper, TV	Bath + Dress						
7:00	Breakfast	Breakfast, leaves	Breakfast, leave						
7:30	Kitchen, utility								
8:00	Bath + Dress			Gets up, refreshes	Gets up, refreshes		Gets up, refreshes	Gets up, refreshes	
8:30	Bath + Dress			Tea	Tea		Tea, Laundry	Tea	
9:00	Reading			Breakfast prep.	Breakfast prep.	Get up, refresh	Breakfast prep.	Breakfast prep.	Get up, refresh
9:30	Reading			Breakfast prep.	Breakfast prep.	Get up, refresh	Breakfast prep.	Breakfast prep.	Bath + Dress
10:00	Computer			Breakfast	Breakfast	Breakfast	Breakfast	Breakfast	Breakfast
10:30	Computer			Breakfast	Breakfast	Breakfast	Breakfast	Breakfast	Breakfast
11:00	Shopping			Cleaning	Cleaning	Cleaning	Laundry	Laundry	Sports
11:30	Shopping			Cleaning	Cleaning	Cleaning	Laundry	Laundry	Sports
12:00	Shopping			Cleaning	Cleaning	Bathe	Computer	Laundry	Sports
12:30	Shopping			Cleaning	Cleaning	Bathe	Computer	Laundry	Sports
13:00	Cooking			Cooking	Cooking	Comp	Cooking	Computer	TV
13:30	Cooking			Cooking	Cooking	Comp	Cooking	Computer	TV
14:00	Lunch		Arrive,lunch	Lunch	Lunch	Lunch	Lunch	Lunch	Lunch
14:30	Lunch		lunch	Lunch	Lunch	Lunch	Lunch	Lunch	Lunch
15:00	Kitchen		Rest	Kitchen	Computer	TV	Kitchen	Rest, TV	Rest, TV
15:30	Kitchen		Rest	Kitchen	Computer	TV	Kitchen	Rest, TV	Rest, TV
16:00	TV		Study	Shopping	Shopping	Sports	TV	TV	Study
16:30	TV		Study	Shopping	Shopping	Sports	TV	TV	Study
17:00	TV		Study	Shopping	Shopping	Sports	TV	TV	Study
17:30	TV		Study	Shopping	Shopping	Sports	TV	TV	Study
18:00	TV, snacks	Arrives, TV, snacks	TV	Snacks, TV	Snacks, TV	Snacks, TV	Snacks, TV	Snacks, TV	Snacks, TV
18:30	TV, snacks	TV, snacks	TV	Snacks, TV	Snacks, TV	Snacks, TV	Snacks, TV	Snacks, TV	Snacks, TV
19:00	Cooking	TV	Study	Cooking	Cooking	TV	Getting Ready	Getting Ready	Getting Ready
19:30	Cooking	TV	Study	Cooking	Cooking	TV	Getting Ready	Getting Ready	Getting Ready
20:00	Dinner, TV	Dinner, TV	Dinner, TV	Dinner, TV	Dinner, TV	Dinner, TV	Eating out	Eating out	Eating out
20:30	Kitchen	TV	TV	Kitchen	TV	Study	Eating out	Eating out	Eating out
21:00	TV	TV	Study	TV	TV	Study	TV	TV	Study
21:30	TV	TV	Study	TV	TV	Study	TV	TV	Study
22:00	Reading	Reading		TV	TV	Study	Reading	Study	
22:30	Reading	Reading		TV	TV	Study	Reading	Study	
23:00				Reading	Reading				
23:30				Reading	Reading				

Table B- 2: Lighting Use on Weekdays, Saturdays and Sundays/Holidays

Hour	Weekdays			Saturdays			Sundays/ Holidays			Average Wh per 1/2 Hr.
	Lights in Use	Wattage in Use	Wh per 1/2 Hr.	Lights in Use	Wattage in Use	Wh per 1/2 Hr.	Lights in Use	Wattage in Use	Wh per 1/2 Hr.	
0:00		0	0		0	0		0	0	0
0:30		0	0		0	0		0	0	0
1:00		0	0		0	0		0	0	0
1:30		0	0		0	0		0	0	0
2:00		0	0		0	0		0	0	0
2:30		0	0		0	0		0	0	0
3:00		0	0		0	0		0	0	0
3:30		0	0		0	0		0	0	0
4:00		0	0		0	0		0	0	0
4:30		0	0		0	0		0	0	0
5:00		0	0		0	0		0	0	0
5:30	T1	80	80		0	0		0	0	57
6:00	(B1+Dr+T1)+(B2+ B3+T2+H)	(200+40+80)+(200 +200+40+40)	800		0	0		0	0	571
6:30	(K+Kt+P+Dn)+(B2 +B3+T2+H)	(120+32+40+200)+ (200+200+40+40)	872		0	0		0	0	623
7:00	K+Dn+E	32+200+40	272		0	0		0	0	194
7:30	K+U	32+40	72		0	0	T1+Dr	80+40	120	69
8:00	B1+T1	200+80	280	T1+Dr	80+40	120	Kt	120	120	234
8:30	B1+Dr	200+40	240	Kt	120	120	Kt+P+T2	120+40+40	200	217
9:00	Ft	25	25	Kt+P+T2	120+40+40	200	Kt	120	120	64
9:30	Ft	25	25	Kt	120	120		0	0	35
10:00		0	0		0	0		0	0	0
10:30		0	0		0	0	U	40	40	6
11:00		0	0	B1	200	200	U	40	40	34
11:30		0	0	B2	200	200	U	40	40	34
12:00		0	0	B3+T2	200+40	240	U	40	40	40
12:30		0	0	B4+T2	200+40	240	Kt	120	120	51
13:00	Kt+P	120+40	160	Kt	120	120	Kt	120	120	149
13:30	Kt+T2	120+40	160	Kt	120	120		0	0	131
14:00		0	0		0	0		0	0	0
14:30		0	0		0	0		0	0	0
15:00		0	0		0	0		0	0	0
15:30		0	0		0	0	B2t+B3t	25+25	50	7
16:00	B2t+B3t	25+25	50		0	0	B2t+B3t	25+25	50	43
16:30	B2t+B3t	25+25	50		0	0	B2t+B3t	25+25	50	43
17:00	B2t+B3t	25+25	50		0	0	B2t+B3t	25+25	50	43
17:30	B2t+B3t	25+25	50		0	0	(K+F+Dn)+T3	32+300+200+40	572	117
18:00	(K+F+Dn)+T1+E	32+300+200+80+4 0	652	(K+F+Dn)+T1+T 2+E	(32+300+200)+80 +40+40	692	(K+F+Dn)	32+300+200	532	641
18:30	(K+F+Dn)	32+300+200	532	(K+F+Dn)	32+300+200	532	B1+T1+Dr+B2+ B3+T2+H	200+80+40+200+ 200+40+40	800	570
19:00	(Kt+K+F+R)+(B2+ B3+B2t+B3t)	120+32+300+25)+(200+200+25+25)	927	Kt+K+F	120+32+300	452	B1+T1+Dr+B2+ B3+T2+H	200+80+40+200+ 200+40+41	800	841
19:30	(Kt+K+F+R)+(B2+ B3+B2t+B3t)	120+32+300+25)+(200+200+25+25)	927	Kt+K+F	120+32+300	452	L	200	200	755
20:00	(K+F+Dn)+L	(32+200+300)+200	732	(K+F+Dn)+L	(32+300+200)+20 0	732	L	200	200	656
20:30	(K+F+Dn)+L	(32+200+300)+201	732	(K+F+Dn)+L	(32+300+200)+20 1	732	F+Ft+(B2+B3+B 2t+B3t)+L	300+25+(200+200 +25+25)+200	975	767
21:00	F+Ft+(B2+B3+B2t +B3t)+L	300+25+(200+200 +25+25)+200	975	F+R+L	300+25+200	525	F+Ft+(B2+B3+B 2t+B3t)+L+T2	300+25+(200+200 +25+25)+200+40	1015	916
21:30	F+Ft+(B2+B3+B2t +B3t)+L+T2	300+25+(200+200 +25+25)+200+40	1015	F+R+L	300+25+201	525	B1+B1t+B1t	200+25+25	250	836
22:00	B1+B1t+B1t	200+25+25	250	F+(B2+B3+B2t+ B3t)	300+(200+200+2 5+25)	750	B1+B1t+B1t+T1	200+25+25+40	290	327
22:30	B1+B1t+B1t+T1	200+25+25+40	290	F+(B2+B3+B2t+ B3t)+T2	300+(200+200+2 5+25)+40	790		0	0	320
23:00		0	0	B1+B1t+B1t	200+25+25	250		0	0	36
23:30		0	0	B1+B1t+B1t+T1	200+25+25+40	290		0	0	41
		Total kWh/day	**5.11**			**4.20**			**3.40**	**4.73**
		Average kW	**0.21**			**0.18**			**0.14**	**0.20**

Table B- 3: Lighting Load and Replacement Costs for Incandescent Lamps and CFLs

Installed Lighting		Hours Used				Incandescent Lamps						Compact Fluorescent Lamps					
Description	Symbol Used	Weekdays	Saturdays	Sundays/ Holidays	Per Year	Installed Lamps[1]	Installed Wattage (W)	kWh Used per Year	Cost of Lamps[2] ($)	Replacement Year (Avg. Life: 1,000 hours.)	Average Annual Replacement Cost ($)	Installed Lamps[3]	Installed Wattage (W)	kWh Used per Year	Cost of Lamps[4] ($)	Replacement Year (Avg. Life: 10,000 hrs.)	Average Annual Replacement Cost ($)
Formal Living: General Lighting	Lv	2	2	2	730	2-100 W Incand	200	146.00	$0.90	0.73	$0.66	2-22 W CFL	44	32.12	$18.96	0.07	$1.38
Formal Living: Task Lighting	Lt	0	0	0	0	2-25 W Incand	50	0.00	$1.70	0.00	$0.00	2-4 W CFL	8	0.00	$11.68	0.00	$0.00
Family Room: General Lighting	F	4	5	2	1408	3-100 W Incand	300	422.36	$1.35	1.41	$1.90	3-22 W CFL	66	92.92	$28.44	0.14	$4.00
Family Room: Task Lighting	Ft	3	1	1	886	2-25 W Incand	50	44.32	$1.70	0.89	$1.51	2-4 W CFL	8	7.09	$11.68	0.09	$1.04
Dining Area: General Lighting	Dn	3	2	1	939	2-100 W Incand	200	187.71	$0.90	0.94	$0.84	2-22 W CFL	44	41.30	$18.96	0.09	$1.78
Kitchen: General Lighting	K	4.5	3	1	1382	1-32 W Fluor	32	44.22	$5.79	0.07	$0.40	1-32 W Fluor	32	44.22	$5.79	0.07	$0.40
Kitchen: Task Lighting	Kt	2.5	3.5	2.5	965	3-40 W Incand	120	115.76	$1.35	0.96	$1.30	3-14 W CFL	42	40.52	$18.12	0.10	$1.75
Pantry	P	1	0.5	0.5	313	1-40 W Incand	40	12.51	$0.45	0.31	$0.14	1-14 W CFL	14	4.38	$6.04	0.03	$0.19
Utility area	U	0.5	0	2	235	1-40 W Incand	40	9.39	$0.45	0.23	$0.11	1-14 W CFL	14	3.29	$6.04	0.02	$0.14
Bedroom 1: General Lighting	B1	2.5	2	2	860	2-100 W Incand	200	172.07	$0.90	0.86	$0.77	2-22 W CFL	44	37.86	$18.96	0.09	$1.63
Bedroom 2: General Lighting	B2	3	1.5	2	965	2-100 W Incand	200	192.93	$0.90	0.96	$0.87	2-22 W CFL	44	42.44	$18.96	0.10	$1.83
Bedroom 3: General Lighting	B3	3	1.5	2	965	2-100 W Incand	200	192.93	$0.90	0.96	$0.87	2-22 W CFL	44	42.44	$18.96	0.10	$1.83
Bedroom 4: General Lighting	B4	0	0.5	0	26	2-100 W Incand	200	5.21	$0.90	0.03	$0.02	2-22 W CFL	44	1.15	$18.96	0.00	$0.05
Bedroom 1: Task Lighting	B1t	2	2	2	730	2-25 W Incand	50	36.50	$1.70	0.73	$1.24	2-4 W CFL	8	5.84	$11.68	0.07	$0.85
Bedroom 2: Task Lighting	B2t	4	1	3	1251	1-25 W Incand	25	31.29	$0.85	1.25	$1.06	1-4 W CFL	4	5.01	$5.84	0.13	$0.73
Bedroom 3: Task Lighting	B3t	4	1	3	1251	1-25 W Incand	25	31.29	$0.85	1.25	$1.06	1-4 W CFL	4	5.01	$5.84	0.13	$0.73
Bedroom 4: Task Lighting	B4t	0	0	0	0	2-25 W Incand	50	0.00	$1.70	0.00	$0.00	2-4 W CFL	8	0.00	$11.68	0.00	$0.00
Dress	Dr	1	0.5	1.5	365	1-40 W Incand	40	14.60	$0.45	0.37	$0.16	1-14 W CFL	14	5.11	$6.04	0.04	$0.22
Toilet 1	T1	2.5	1.5	2	834	2-40 W Incand	80	66.74	$0.90	0.83	$0.75	2-14 W CFL	28	23.36	$12.08	0.08	$1.01
Toilet 2	T2	2	2.5	2	756	1-40 W Incand	40	30.24	$0.45	0.76	$0.34	1-14 W CFL	14	10.59	$6.04	0.08	$0.46
Toilet 3	T3	0	0	0.5	26	1-40 W Incand	40	1.04	$0.45	0.03	$0.01	1-14 W CFL	14	0.37	$6.04	0.00	$0.02
Hallway	H	1	0	1	313	1-40 W Incand	40	12.51	$0.45	0.31	$0.14	1-14 W CFL	14	4.38	$6.04	0.03	$0.19
Entrance	E	1	0.5	0	287	1-40 W Incand	40	11.47	$0.45	0.29	$0.13	1-14 W CFL	14	4.02	$6.04	0.03	$0.17
						Total	**2262.00**	**1781.10**	**$26.44**		**$14.30**		**570.00**	**453.38**	**$278.87**		**$20.40**
							Average kW	**0.20**					**Average kW**	**0.05**			

[1] 0.75 W/sq. ft. for General Lighting

[2] $0.85 for 25W, $0.45 for 40W and 100W Lamps

[3] 0.17 W/sq. ft. for General Lighting

[4] $5.84 for 4W, $6.04 for 14W, $9.48 for 22W Lamps

APPENDIX C

ADDITIONAL TASKS FOR THE DOE-2 SIMULATIONS

Additional Tasks for the DOE-2 Simulations

Appendix C provides details of the supplementary tasks performed for the DOE-2 simulations. Section C.1 lists the changes that were made to the DOE-2 input file SNGFAM2ST.INP v 1.14, developed by the Energy Systems Laboratory (ESL). Section C.2 shows the DOE-2 window library entries created by the WINDOW-5 program. Section C.3 presents the steps for using the BDI (Batch DOE-2 Input) and GAWK programs for performing the DOE-2 simulations in the batch mode, and extracting the required data from the DOE-2 output for the analysis.

C.1 Modifications to the SNGFAM2ST.INP v 1.14 (the DOE-2 Input File)

1) The original file simulates the house with collapsible zones for the second floor and the crawlspace, i.e. these zones always exist but their sizes are reduced to a minimum for a one story house and for a house with a slab-on-grade underground floor, respectively. For this study, these spaces were removed for the one-story and the slab-on-grade configurations of the house.
2) The original file simulates the overhangs only at the roof level. For this study, the overhangs were positioned at the lintel level of all the windows.
3) The original file uses 500 Btu/hr to account for the energy used by a standing pilot light. This study used 800 Btu/hr to represent the energy used by a pilot light in a typical house.
4) The original file simulates the house with a garage attached to the left wall of the house. For this study, a parameter b16 was added for the garage height to be able to simulate the house without a garage.
5) With the original file, only 2x4 wood-frame construction can be simulated. For this study, specifications for new materials and construction types, and a parameter c25 were added to account for different construction types.
6) With the original file, the windows areas can only be specified as percentages of the corresponding wall areas. For this study, a parameter c19 was added, and parameters c20 -

c24 were modified, to input window areas as a percentage of the conditioned floor area, also, distributed on all orientations in a specified ratio.

7) The original file simulates the window properties using the shading-coefficient method, only. For this study, parameters c18, and c29 - c32 were added for defining window properties using the WINDOW-5 method, also.

8) The original file simulates the house with a fixed value of infiltration, as specified by 2000 IECC for a given location. For this study, parameters b18 and b19 were added to account for an airtight construction.

9) The original file uses fixed values for lighting and equipment loads. For this study, parameters sp03 and sp04 were added to account for reduced loads due to energy-efficient lighting and equipment.

C.1.1 Modifications to the List of Parameters

Building Parameters

```
##def BLDG1[b01,b02,b03,b04,b05,b06,b07,b08,b09,b10,b11
           ,b12,b13,b14,b15,b16,b17,b18,b19,b20,b21
           ,b22,b23,b24,b25,b26,b27,b28,b29,b30,b31
           ,b32]
$
$b01     "T" THERMAL MASS MODE. USES CUSTOM WEIGHTING FACTORS
$        "Q" QUICK MODE. USE PRECALCULATED WEIGHTHING FACTORS
$
$b02     COUNTY AND WEATHER LOCATION (41 Counties)
$        NAME    CITY         LAT     LONG     ALT      AIR-CHANGE
$       HOU    HOUSTON     29.98     95.37   108.00    0.4617
$       BAS    BASTROP     29.90     97.21   454.00    0.456
$       BEX    BEXAR       29.31     98.22   798.75    0.4731
$       CAL    CALDWELL    29.48     97.35   433.00    0.4560
$       COM    COMAL       29.50     98.21  1065.17    0.4731
$       ELL    ELLIS       32.23     96.58   562.13    0.5073
$       GRE    GREGG       32.30     94.52   296.33    0.3648
$       GUA    GUADALUPE   29.40     97.69   555.67    0.4731
$       HAN    HARRISON    32.35     94.26   279.25    0.3648
$       HAY    HAYS        29.96     97.77   880.00    0.4560
$       JOH    JOHNSON     32.27     97.15   718.80    0.5073
$       KAU    KAUFMAN     32.36     96.21   429.00    0.5073
$       NUE    NUECES      27.46     97.32    47.67    0.4902
$       PAR    PARKER      32.50     97.38   846.80    0.5073
$       ROC    ROCKWALL    32.56     96.27   600.00    0.5073
$       RUS    RUSK        31.93     94.46   431.13    0.3648
$       SAP    SAN PATRICIO27.87     97.34    61.60    0.4902
$       SMI    SMITH       32.23     95.19   493.86    0.3648
$       TRA    TRAVIS      30.19     97.47   630.75    0.4560
$       UPS    UPSHUR      32.44     94.57   371.00    0.3648
$       VIC    VICTORIA    28.47     97.05   115.00    0.4902
$       WLL    WILLIAMSON  30.40     97.41   845.56    0.4560
$       WIL    WILSON      29.15     97.91   451.33    0.4731
$       BRA    BRAZORIA    28.98     95.27    23.13    0.4617
$       CHA    CHAMBERS    29.46     94.41    23.00    0.4503
$       COL    COLLIN      33.69     96.38   648.00    0.5073
$       DAL    DALLAS      32.47     96.39   548.86    0.5073
$       DEN    DENTON      33.11     96.94   638.57    0.5073
$       ELP    EL PASO     31.36    106.16  3648.20    0.4332
$       FOB    FORT BEND   29.34     95.41    89.00    0.4617
$       GAL    GALVESTON   29.25     94.78    15.00    0.4617
$       HAD    HARDIN      30.19     94.17    60.60    0.4503
$       HAR    HARRIS      29.47     95.03    68.00    0.4617
$       JEF    JEFFERSON   29.67     93.74    19.33    0.4503
$       LIB    LIBERTY     30.17     94.68    97.00    0.4503
$       MOG    MONTGOMERY  30.18     95.31   243.50    0.4617
$       ORA    ORANGE      30.04     93.45    10.00    0.4503
$       TAR    TARRANT     32.45     97.12   615.75    0.5073
$       WAL    WALLER      30.05     95.81   197.00    0.4617
$       HOD    HOOD        32.30     96.73   990.00    0.5073
$       HDS    HENDERSON   32.11     95.75   392.25    0.5073
$       HNT    HUNT        32.99     95.93   575.24    0.5073
$
$b03    The azimuth of building(0:SOUTH, 90:WEST, 180:NORTH, 270:EAST)
$
$b04    Width of building (ft), Refer to the following drawing
$
$b05     Depth of building (ft), Refer to the following drawing
$
$b06     Height of wall (ft), Refer to the following drawing
$
$b07     Door height (ft)
$
$b08     Door width (ft)
$
$b09    Run Year
$
$b10    Number of floor (1 or 2).
$       If 1, then one-story house, or if 2, then two-story house.
$
$b11    Activation/ Deactivation of crawl space (C or S).
$       If C, then activate crawl space, or if S, then Slab on Grade.
$
$b12    Height of crawlwall overground(ft)
$
```

```
$b13    Height of crawlwall underground(ft)
$
$b14    Pitch of Roof
$
$b15    Height of attic (ridge)
$
$b16    Height of garage (ft)
$
$b17    Switchable glazing: Y/N
$
$b18    Switch for airchange input
$       FX: fixed to b19,
$       FR: fraction of ACH/HR based on county,
$       CT: based on county
$
$b19    Fraction of ACH/HR based on county OR a fixed value in ACH/HR
$
$b20-b32      spare parameters
$
$
$                            |------------|------------|    ^
$                            |            |            |    |
$                            |            |            |    |
$                            |            |            |    |
$                            |            |            |    |
$  ^    |------------|       |            |            |   b05(ft)
$  |    |            |       |         House           |    |
$  |    |            |       |            |            |    |
$ 22ft  |   Garage   |       |            |            |    |
$  |    |   (FIXED)  |       |            |            |    |
$  |    |            |       |            |            |    |
$  v    |------------|       |------------|------------|    v
$
$       <----22ft----><-4ft-><---------b04(ft)-------->
$
$
$
$
$                            -------------|-------------
$                            |       -----------       |
$                            |      |   c21(%)  |      | (If second story is activated)
$                            |       -----------       |
$                            |-------------------------|   ^
$                            |       -----------       |   |
$       -------------- ^     |      |   c21(%)  |      |  b06(ft)
$       |   Garage   | |     |       -----------       |   |
$       |   (FIXED)  |b16(ft)|-------------------------|   v
$       |            | |     |          b12 (ft)       | (Heignt of crawlwall overground)
$  G.L ----------------v-----|------------------------------------------------------------- G.L
$                            |          b13 (ft)       | (Heignt of crawlwall underground)
$                            |-------------------------|
$
$
$
##def BLDG2[bb01,bb02,bb03,bb04,bb05,bb06,bb07,bb08,bb09,bb10
           ,bb11,bb12,bb13,bb14,bb15,bb16,bb17,bb18,bb19,bb20
           ,bb21,bb22,bb23,bb24,bb25,bb26,bb27,bb28,bb29,bb30
           ,bb31,bb32]

$bb01-b32      spare parameters

##enddef
```

Construction Parameters

```
##def CONS1[c01,c02,c03,c04,c05,c06,c07,c08,c09,c10,c11,c12,c13,c14,c15,c16
           ,c17,c18,c19,c20,c21,c22,c23,c24,c25,c26,c27
           ,c28,c29,c30,c31,c32]
$
$c01     Roof outside emissivity
$
$c02     Roof absorptance (from DOE2.1E BDL Summary, p.12)
$       Material                 Absorptance
$       Aluminum, ploished          0.12
$       reflector sheet
$       Asphalt pavement,           0.82
$       weather
$       Brick, buff, light          0.55
$       Brick, red                  0.88
$       Brick, Stafford blue        0.89
$       Brick, white glazed         0.25
$       Cement, uncolored asbestos  0.75
$       Cement, white asbestos      0.61
$       Concrete, black             0.91
$       Concrete, brown             0.85
$       Concrete, uncolored         0.65
$       Film Mylar aluminized       0.10
$       Felt, bituminous            0.88
$       Felt, bituminous,aluminized 0.40
$       Gravel                      0.29
$       Iron, white-on-galvanized   0.26
$       Lab vapor deposited coatings0.02
$       Marble, white               0.58
$       Roof, white built-up        0.50
$       Roofing, green              0.86
$       Slate, blue-gray            0.87
$       Tin surface                 0.05
$       Wood, smooth                0.78

$       Paint                  Absorptance
$       Aluminum paint              0.40
$       Black, flat                 0.95
$       Black, lacquer              0.92
$       Black, oil                  0.90
$       Black, optical flat         0.98
$       Blue, dark                  0.91
$       Blue, medium                0.51
$       Blue-gray, dark             0.88
$       Brown, dark brown           0.88
$       Brown, lacquer              0.79
$       Brown, medium               0.84
$       Brown, medium light         0.80
$       Gray, dark                  0.91
$       Gray, light oil             0.75
$       Green, lacquer              0.79
$       Green, lacquer, dark        0.88
$       Green, light                0.47
$       Green, medium dull          0.59
$       Green, medium Kelly         0.51
$       Olive, dark drab            0.89
$       Orange, medium              0.58
$       Red, oil                    0.74
$       Rust, medium                0.78
$       Silver                      0.25
$       White, gross                0.25
$       White, lacquer              0.21
$       White, semi-gloss           0.30
$       Yellow                      0.57
$
$c03     Roof roughness (from DOE2.1E BDL Summary, p.12)
$       Material               Code-number
$       Wood shingles or          1
$       Built-up roof w/stones
$       Asphalt shingles          3
$       Metal                     5
$
$c04     Roof R-value (hr-sq.ft-F/Btu)
$       According to IECC2000(p.81), if HDD is between 1500-1999 and
$       window area is 15 percent, R-26 is used for ceiling (U-value = 1/26 = 0.0385)
$
$c05     Wall absorptance (from DOE2.1E BDL Summary, p.12)
$       Refer to above absortance of roof
$
```

```
$c06     Wall roughness (from DOE2.1E BDL Summary, p.12)
$       Material               Code-number
$       Stucco                    1
$       Brick or Plaster          2
$       Concrete (poured)         3
$       Clear pine                4
$       Smooth plaster            5
$       Glass or Paint on pine    6
$
$c07     Wall outside emissivity
$
$c08     Wall R-value (hr-sq.ft-F/Btu)
$       According to IECC2000(p.81), if HDD is between 1500-1999 and
$       window area is 15 percent, R-13 is used for wall (U-value = 1/13 = 0.077)
$
$c09     Ground reflectance (from DOE2.1E BDL Summary, p.20)
$       Surface               Ground-Reflectance
$       Asphalt (Paved)           0.18
$       Concrete (Bituminous)     0.10
$       Concrete (Light-Colored)  0.32
$       Concrete (Old)            0.22
$       Field (Green)             0.12-0.25
$       Field (Wheat)             0.07
$       Grass (Dry)               0.24
$       Rock (Crushed) Surface    0.20
$       Soil (Dark)               0.08
$
$c10    Spare
$
$c11     U-Factor of glazing (Btu/hr-sq.ft-F)
$
$c12     Solar Heat Gain Coefficient(SHGC)
$
$c13     Spare
$
$c14     Frame absorptance of glazing
$
$c15    Frame type - A,B,C,D,E
$                 TYPE                 FRAME-CONDUCTANCE    WIDTH(FT)
$       A: ALUMINUM W/O THERMAL BREAK          3.037         0.125
$       B: ALUMINUM W/ THERMAL BREAK           1.245         0.125
$       C: EXTERNAL FLUSH GLAZED ALUMINUM      0.812         0.125
$       D: WOOD                                0.434         0.208
$       E: VINYL                               0.319         0.208
$
$c16   Spare Parameter
$
$c17    Floor weight (lb/sq-ft)
$
$c18    WINDOW INPUT METHOD
$       W5: WINDOW5 METHOD
$       SC: SHADING COEFFICIENT METHOD
$
$c19    OPTION: WW, WR, FW, FR
$       WW: Input gross window to wall %, distributed as percentage of wall area
$       WR: Input gross window to wall %, distributed as ratio of total window area
$       FW: Input gross window to floor area %, distributed as percentage of wall area
$       FR: Input gross window to floor area %, distributed as ratio of total window area
$
$c20     Gross window % (window to wall % OR window to floor area %)
$
$c21     Front window as a percentage of front wall area OR a ratio of total window area
$
$c22    Back window as a percentage of back wall area OR a ratio of total window area
$
$c23    Right window as a percentage of right wall area OR a ratio of total window area
$
$c24    Left window as a percentage of left wall area OR a ratio of total window area
$
$c25   Construction-type - A,B,C,D,E,F,P
$      A: WOOD-FRAME-4IN
$      B: WOOD-FRAME-4IN
$      C: SIP-WALLS
$      D: ICF
$      E: MWC_CF
$      F: MWC_PF
$      P: SIP-HOUSE
$
$c26     Interior Floor R-value (hr-sq.ft-F/Btu)
$
$c27     Crawl space wall R-value (hr-sq.ft-F/Btu)
```

```
$       According to IECC2000(p.81), if HDD is between 1500-1999 and
$       window area is 15 percent, R-5 is used for crawl space wall
$                 TYPE
$       A:   R-O
$       B:   R-1
$       C:   R-2
$       D:   R-3
$       E:   R-4
$       F:   R-5
$       G:   R-6
$       H:   R-7
$       I:   R-8
$       J:   R-9
$       K:   R-10
$       L:   R-11
$       M:   R-12
$       N:   R-13
$
$c28    Slab perimeter R-value and depth (Option: A, B, C, D, E, F, G, H, I, J, K)
$       According to IECC2000(p.81), if HDD is between 1500-1999 and
$       window area is 15 percent, R-0 is used for slab
$                 TYPE
$       A:   R-O, NO INSULATION
$       B:   R-1, 2FT
$       C:   R-2, 2FT
$       D:   R-3, 2FT
$       E:   R-4, 2FT
$       F:   R-5, 2FT
$       G:   R-6, 2FT
$       H:   R-7, 2FT
$       I:   R-8, 2FT
$       J:   R-9, 2FT
$       K:   R-10, 2FT
$
$c29   Glass-type-code for front window (>=1000)  FOR USING WINDOWS FROM WINDOW LIBRARY
$c30   Glass-type-code for back window (>=1000)  FOR USING WINDOWS FROM WINDOW LIBRARY
$c31   Glass-type-code for right window (>=1000)  FOR USING WINDOWS FROM WINDOW LIBRARY
$c32   Glass-type-code for left window (>=1000)  FOR USING WINDOWS FROM WINDOW LIBRARY
##enddef
```

Space Condition Parameters

```
##def SPCO1[sp01,sp02,sp03,sp04,sp05,sp06,sp07,sp08,sp09,sp10,sp11
           ,sp12,sp13,sp14,sp15,sp16,sp17,sp18,sp19,sp20,sp21
           ,sp22,sp23,sp24,sp25,sp26,sp27,sp28,sp29,sp30,sp31
           ,sp32]
$
$sp01    Occupancy(Number of people)
$
$sp02    The number of bedrooms (for hot water consumption calculation)
$       GAL/MIN=((30*a)+(10*b))/1440, a=living unit, b=# of bedroom
$
$sp03   Lighting-kW
$
$sp04   Equipment-kW
$
$sp05-sp32  spare parameters
##enddef
```

Shading Parameters

```
##def SHAD[s01,s02,s03,s04,s05,s06,s07,s08,s09,s10,s11,s12,s13
          ,s14,s15,s16,s17,s18,s19,s20,s21,s22,s23
          ,s24,s25,s26,s27,s28,s29,s30,s31,s32]
$
$s01   Shade projection(ft) on Front window
$
$s02   Shade projection(ft) on Back window
$
$s03   Shade projection(ft) on Left window
$
$s04   Shade projection(ft) on Right window
$
$s05-s32      Spare parameter
$
##enddef
```

System Parameters

```
##def SYST1[sy01,sy02,sy03,sy04,sy05,sy06,sy07,sy08,sy09,sy10
           ,sy11,sy12,sy13,sy14,sy15,sy16,sy17,sy18,sy19,sy20
           ,sy21,sy22,sy23,sy24,sy25,sy26,sy27,sy28,sy29,sy30
           ,sy31,sy32]
$
$sy01    Mode of System (OPTION: 1, 2, 3)
$       OPTION 1: 1)COOLING:ELECTRIC-A/C, 2)HEATING:GAS, 3)DHW:GAS
$       OPTION 2: 1)COOLING:ELECTRIC-A/C, 2)HEATING:ELECTRIC, 3)DHW:ELECTRIC
$       OPTION 3: 1)COOLING:ELECTRIC-A/C, 2)HEATING:HEAT-PUMP, 3)DHW:ELECTRIC
$
$sy02    Cooling Capacity of cooling system (0: Let DOE calculate)
$
$sy03    Heating Capacity of heating system (0: Let DOE calculate)
$
$sy04    SEASONAL ENERGY EFFICIENCY RATIO(SEER)
$       According to IECC2000(p.87), minimum performance of air-conditioner is 10 SEER
$       COOLING-EIR(DOE input) = 3.41/SEER = 3.41/10 = 0.341
$
$sy05    ANNUAL FUEL UTILIZATION EFFICIENCY(AFUE)
$       According to IECC2000(p.87), minimum performance of Gas-fired or oil furnace
$       is 0.8, FURNACE-HIR(DOE input) = 1/AFUE = 1/0.8 = 1.25
$
$sy06    HEATING SEASONAL PERFORMANCE FACTOR(HSPF)
$       According to IECC2000(p.87), minimum performance of heat-pump is 6.8 HSPF.
$       HEATING-EIR(DOE input) = 3.41/HSPF = 3.41/6.8 = 0.50
$
$sy07   The number of pilot light of Domestic Hot Water(From 0 to 10)
$
$sy08   The number of pilot light of Gas Furnace(From 0 to 10)
$
$sy09   The number of pilot light of others. (From 0 to 10)
$
$sy10   The option is "A" or "S".
$       If "A", then MACRO in DOE2 calculate EF(Energy Factor),
$       or if "S" then sy11 parameter is activated where a certain number is entered by the user,
$       If "A", MACRO uses fomula according to IEC2000(p.91) Table 504.2,
$       if fuel is Electric, EF(Energy Factor) is calculated by 0.93-0.00132*DHW-SIZE(Gallon)
$       if fuel is Gas, EF(Energy Factor) is calculated by 0.62-0.0019*DHW-SIZE(Gallon)
$       DHW-SIZE in Gallon = (30*a) + (10*b) (a: Number of living units, b: Number of bedrooms)
$       IECC2000(p.65) 402.1.3.7
$sy11   The user input for Energy Factor (0.01 to 1)
$
$sy12-sy32    Spare parameter
```

C.1.2 Addition of Macros

Macro for Changing ACH/hr:

```
##IF #[b18 EQS FX]
     ##SET1 ACHPERHOUR b19
##ELSEIF #[b18 EQS FR]
     ##SET1 ACHPERHOUR #[P-AIRCHANGE[] * b19]
##ELSEIF #[b18 EQS CT]
     ##SET1 ACHPERHOUR P-AIRCHANGE[]
##ENDIF
```

Macro for Window Input Method based on Window5 and Shading-Coefficient:

```
## SET1 WINDOWINPUT c18                               $ WINDOW INPUT METHOD (W5 OR SC)

##IF #[WINDOWINPUT[] EQS W5]
W-1 = GLASS-TYPE
          GLASS-TYPE-CODE = GLASSTYPECODE1[]     $SHOULD BE > OR = 1000
          FRAME-CONDUCTANCE = FRAME-CON[]        $DOE-2 DEFAULT = 0.434(BTU/HR.FT^2.F)
          FRAME-ABS = P-FRAMEABSORPTANCE[]       $DOE-2 DEFAULT = 0.7(0 TO 1)
          SPACER-TYPE-CODE = P-SPACERCODE[]      $0=SPACER TAKEN FROM THE LIBRARY,
                                                 $1=ALUMINUM
                                                 $2=GLASS
                                                 $3=BUTYL/METAL
                                                 $4=WOOD/FIBREGLASS
                                                 $5 = U-edge=U-center
                    ..                           $END OF GLASS-TYPE COMMAND

##ELSEIF #[WINDOWINPUT[] EQS SC]                $ADDED SC INPUT METHOD, M.MALHOTRA 07/02/2005
W-1 = GLASS-TYPE
          SHADING-COEF = SC1[]                   $(0 TO 1)
$          PANES = P-PANES[]                      MIN=1,MAX=3
          GLASS-CONDUCTANCE = GLASSCONDUCTANCE1[]  $(BTU/HR.FT^2.F)
$         VIS-TRANS = P-VISTRANSMITTENCE         DOE-2 DEFAULT = 0.9(0 TO 1)
          FRAME-CONDUCTANCE = FRAME-CON[]        $DOE-2 DEFAULT = 0.434(BTU/HR.FT^2.F)
          FRAME-ABS = P-FRAMEABSORPTANCE[]       $DOE-2 DEFAULT = 0.7(0 TO 1)
          SPACER-TYPE-CODE = P-SPACERCODE[]      $0=SPACER TAKEN FROM THE LIBRARY,
                                                 $1=ALUMINUM
                                                 $2=GLASS
                                                 $3=BUTYL/METAL
                                                 $4=WOOD/FIBREGLASS
                                                 $5 = U-edge=U-center
                    ..                           $END OF GLASS-TYPE COMMAND

##ENDIF
```

Macro for Window Area Input Option as Window-to-Floor Area and Window-to-Wall Area Ratio

```
##IF #[c19 EQS WW]                                    $ Input gross window to wall %
                                                      $ distributed as percentage of wall area
    ##SET1 PERCENTF #[c21 * 0.01]                     $ WINDOW PERCENTAGE OF WALL(FRONT)
    ##SET1 PERCENTB #[c22 * 0.01]                     $ WINDOW PERCENTAGE OF WALL(BACK)
    ##SET1 PERCENTR #[c23 * 0.01]                     $ WINDOW PERCENTAGE OF WALL(RIGHT)
    ##SET1 PERCENTL #[c24 * 0.01]                     $ WINDOW PERCENTAGE OF WALL(LEFT)
    ##SET1 TAOSW1 #[P-WALLAREA1F[] * PERCENTF[]]      $ WINDOW AREA(SQ.FT) OF FRONT WALL
    ##SET1 TAOSW2 #[P-WALLAREA2F[] * PERCENTB[]]      $ WINDOW AREA(SQ.FT) OF BACK WALL
    ##SET1 TAOSW3 #[P-WALLAREA3F[] * PERCENTR[]]      $ WINDOW AREA(SQ.FT) OF RIGHT WALL
    ##SET1 TAOSW4 #[P-WALLAREA4F[] * PERCENTL[]]      $ WINDOW AREA(SQ.FT) OF LEFT WALL

##ELSEIF #[c19 EQS WR]                                $ Input gross window to wall %,
                                                      $ distributed as ratio of total window
area
    ##SET1 PERCENTG #[c20 * 0.01]                     $ WINDOW PERCENTAGE OF WALL(GROSS)
    ##SET1 WINAREAG #[PERCENTG[] * TOTWALLAREA[]]      $ WINDOW AREA (GROSS)
    ##SET1 SUMOFRATIO #[c21 + #[c22 + #[c23 + c24]]]  $ SUM OF RATIO OF WINDOWS
    ##SET1 TAOSW1 #[WINAREAG[] * #[c21 / SUMOFRATIO[]]]  $ WINDOW AREA(SQ.FT) OF FRONT WALL
    ##SET1 TAOSW2 #[WINAREAG[] * #[c22 / SUMOFRATIO[]]]  $ WINDOW AREA(SQ.FT) OF BACK WALL
    ##SET1 TAOSW3 #[WINAREAG[] * #[c23 / SUMOFRATIO[]]]  $ WINDOW AREA(SQ.FT) OF RIGHT WALL
    ##SET1 TAOSW4 #[WINAREAG[] * #[c24 / SUMOFRATIO[]]]  $ WINDOW AREA(SQ.FT) OF LEFT WALL

##ELSEIF #[c19 EQS FW]                                $ Input gross window to floor area %,
                                                      $ distributed as percentage of wall area
    ##SET1 PERCENTG #[c20 * 0.01]                            $ WINDOW PERCENTAGE OF WALL(GROSS)
```

```
    ##SET1 WINAREAG #[PERCENTG[] * P-AREAF[]]                       $ WINDOW AREA (GROSS)
    ##SET1 TAOSW1 #[WINAREAG[] * #[P-WALLAREA1F[] / TOTWALLAREA[]]] $ WINDOW AREA(SQ.FT) OF FRONT WALL
    ##SET1 TAOSW2 #[WINAREAG[] * #[P-WALLAREA2F[] / TOTWALLAREA[]]] $ WINDOW AREA(SQ.FT) OF BACK WALL
    ##SET1 TAOSW3 #[WINAREAG[] * #[P-WALLAREA3F[] / TOTWALLAREA[]]] $ WINDOW AREA(SQ.FT) OF RIGHT WALL
    ##SET1 TAOSW4 #[WINAREAG[] * #[P-WALLAREA4F[] / TOTWALLAREA[]]] $ WINDOW AREA(SQ.FT) OF LEFT WALL

##ELSEIF #[c19 EQS FR]                                        $ Input gross window to wall %,
                                                              $ distributed as ratio of total window
area
    ##SET1 PERCENTG #[c20 * 0.01]                             $ WINDOW PERCENTAGE OF WALL(GROSS)
    ##SET1 WINAREAG #[PERCENTG[] * P-AREAF[]]                 $ WINDOW AREA (GROSS)
    ##SET1 SUMOFRATIO #[c21 + #[c22 + #[c23 + c24]]]          $ SUM OF RATIO OF WINDOWS
    ##SET1 TAOSW1 #[WINAREAG[] * #[c21 / SUMOFRATIO[]]]       $ WINDOW AREA(SQ.FT) OF FRONT WALL
    ##SET1 TAOSW2 #[WINAREAG[] * #[c22 / SUMOFRATIO[]]]       $ WINDOW AREA(SQ.FT) OF BACK WALL
    ##SET1 TAOSW3 #[WINAREAG[] * #[c23 / SUMOFRATIO[]]]       $ WINDOW AREA(SQ.FT) OF RIGHT WALL
    ##SET1 TAOSW4 #[WINAREAG[] * #[c24 / SUMOFRATIO[]]]       $ WINDOW AREA(SQ.FT) OF LEFT WALL

##ENDIF
```

Macro for Layering Different Construction Types

```
WALL-4IN_1 = LAYERS
       MATERIAL = (3IN-BRICK, AIR-GAP-VER, PLYWOOD-1/2,
                   INSULATION-R11, GYPSUM-BOARD)  ..

WALL-4IN_2 = LAYERS
       MATERIAL = (3IN-BRICK, AIR-GAP-VER, PLYWOOD-1/2,
                   STUD-4IN, GYPSUM-BOARD)  ..

WALL-6IN_1 = LAYERS
       MATERIAL = (3IN-BRICK, AIR-GAP-VER, PLYWOOD-1/2,
                   INSULATION-R20, GYPSUM-BOARD)  ..

WALL-6IN_2 = LAYERS
       MATERIAL = (3IN-BRICK, AIR-GAP-VER, PLYWOOD-1/2,
                   STUD-6IN, GYPSUM-BOARD)  ..

WALL-SIP = LAYERS
       MATERIAL = (3IN-BRICK, OSB-SIP, EPS5-SIP,
                   OSB-SIP, GYPSUM-BOARD)  ..

WALL-ICF = LAYERS
       MATERIAL = (3IN-BRICK, AIR-GAP-VER, EPS-ICF, CONC-4IN-ICF,
                   EPS-ICF, GYPSUM-BOARD)  ..

WALL-MWC_CF = LAYERS
       MATERIAL = (3IN-BRICK, INSULATION-CB, CONCBLK-MW-CF,
                   AIR-GAP-VER, GYPSUM-BOARD)  ..

WALL-MWC_PF = LAYERS
       MATERIAL = (3IN-BRICK, INSULATION-CB, CONCBLK-MW-PF,
                   AIR-GAP-VER, GYPSUM-BOARD)  ..

ROOF-4IN_1 = LAYERS
       MATERIAL = (ASPHALT-SHINGLE, PERMEABLE-FELT, PLYWOOD-3/4,
                   INSULATION-R30, GYPSUM-BOARD) ..

ROOF-4IN_2 = LAYERS
       MATERIAL = (ASPHALT-SHINGLE, PERMEABLE-FELT, PLYWOOD-3/4,
                   STUD-10IN, GYPSUM-BOARD) ..

ROOF-SIPH = LAYERS
       MATERIAL = (ASPHALT-SHINGLE, PERMEABLE-FELT, OSB-SIP, EPS9-SIP,
                   OSB-SIP, GYPSUM-BOARD)  ..

IW-4IN_1 = LAYERS
       MATERIAL = (CARPET&PADDING, PLYWOOD-3/4, AIR-GAP-HOR, GYPSUM-BOARD)  ..

IW-4IN_2 = LAYERS
       MATERIAL = (CARPET&PADDING, PLYWOOD-3/4, STUD-10IN, GYPSUM-BOARD)  ..
```

C.2 DOE-2 Window Library Entries Created by the WINDOW-5

For this study, the basecase house was simulated with double pane, air-filled, low-e windows (U-factor = 0.47, SHGC = 0.4). For the energy-efficient house, argon-filled, low-e windows (U-factor = 0.29, SHGC = 0.28) were simulated. These window types were specified by creating custom windows using the WINDOW-5 method, and were named as WINDOW ID: 8888 and WINDOW ID: 9999, respectively. The following window library entries for these windows were created by the WINDOW-5 program, which were included in the W4LIB.DAT for the DOE-2 simulation.

WINDOW ID: 8888 (Double Pane, Air-Filled, Low-e Window)

```
Window 5.2  v5.2.17  DOE-2 Data File : Multi Band Calculation

Unit System : SI
Name        : DOE-2 WINDOW LIB
Desc        : basecase
Window ID   : 8888
Tilt        : 90.0
Glazings    : 2
Frame       :  2 Al w/break             5.680
Spacer      :  1 Class1                 2.330  -0.010   0.138
Total Height: 1524.0 mm
Total Width :  914.4 mm
Glass Height: 1409.7 mm
Glass Width :  800.1 mm
Mullion     : None
Gap        Thick    Cond  dCond    Vis   dVis   Dens   dDens     Pr     dPr
1 Air       16.5 0.02407  7.760  1.722  4.940  1.292 -0.0046  0.720 -0.0002
2              0       0      0      0      0      0       0      0       0
3              0       0      0      0      0      0       0      0       0
4              0       0      0      0      0      0       0      0       0
5              0       0      0      0      0      0       0      0       0
Angle     0    10    20    30    40    50    60    70    80    90 Hemis
Tsol  0.403 0.405 0.399 0.391 0.381 0.360 0.316 0.231 0.108 0.000 0.336
Abs1  0.257 0.260 0.267 0.272 0.273 0.277 0.290 0.303 0.254 0.001 0.274
Abs2  0.031 0.031 0.031 0.032 0.033 0.033 0.032 0.028 0.021 0.000 0.031
Abs3      0     0     0     0     0     0     0     0     0     0     0
Abs4      0     0     0     0     0     0     0     0     0     0     0
Abs5      0     0     0     0     0     0     0     0     0     0     0
Abs6      0     0     0     0     0     0     0     0     0     0     0
Rfsol 0.310 0.304 0.302 0.305 0.313 0.330 0.361 0.437 0.617 0.999 0.349
Rbsol 0.307 0.303 0.301 0.301 0.307 0.323 0.360 0.452 0.641 1.000 0.349
Tvis  0.664 0.668 0.659 0.647 0.631 0.598 0.524 0.382 0.179 0.000 0.555
Rfvis 0.202 0.196 0.193 0.196 0.207 0.228 0.270 0.365 0.573 0.999 0.254
Rbvis 0.154 0.148 0.147 0.151 0.164 0.193 0.255 0.395 0.657 1.000 0.231
SHGC  0.446 0.449 0.444 0.437 0.427 0.407 0.363 0.276 0.144 0.000 0.381
SC: 0.47

Layer ID#          930      102        0        0        0        0
Tir              0.000    0.000        0        0        0        0
Emis F           0.840    0.840        0        0        0        0
Emis B           0.062    0.840        0        0        0        0
Thickness(mm)      4.7      3.0        0        0        0        0
Cond(W/m2-K     )212.8    328.1        0        0        0        0
Spectral File CMFTRT_5.AFG  CLEAR_3.DAT         None         None         None
None
```

```
Overall and Center of Glass Ig U-values (W/m2-K)
Outdoor Temperature                 -17.8 C      15.6 C      26.7 C      37.8 C
Solar      WdSpd  hcout hrout  hin
(W/m2)     (m/s)     (W/m2-K)
   0        0.00   4.00  3.32  2.21  1.43 1.43  1.23 1.23  1.26 1.26  1.33 1.33
   0        6.71  30.84  3.21  2.32  1.77 1.77  1.38 1.38  1.41 1.41  1.49 1.49
 783        0.00   4.00  3.75  1.16  1.43 1.43  1.23 1.23  1.26 1.26  1.33 1.33
 783        6.71  30.84  3.32  2.01  1.77 1.77  1.38 1.38  1.41 1.41  1.49 1.49
```

WINDOW ID: 9999 (Double Pane, Argon-Filled, Low-e Window)

```
Window 5.2  v5.2.17  DOE-2 Data File : Multi Band Calculation

Unit System : SI
Name        : DOE-2 WINDOW LIB
Desc        : bestcase
Window ID   : 9999
Tilt        : 90.0
Glazings    : 2
Frame       :  5 Vinyl                 1.700
Spacer      :  1 Class1                2.330  -0.010   0.138
Total Height: 1524.0 mm
Total Width :  914.4 mm
Glass Height: 1384.3 mm
Glass Width :  774.7 mm
Mullion     : None
Gap        Thick    Cond  dCond    Vis   dVis   Dens   dDens     Pr     dPr
1 Argon     16.5 0.01635  5.149  2.100  6.451  1.782 -0.0063  0.670 -0.0001
2              0       0      0      0      0      0       0      0       0
3              0       0      0      0      0      0       0      0       0
4              0       0      0      0      0      0       0      0       0
5              0       0      0      0      0      0       0      0       0
Angle     0    10    20    30    40    50    60    70    80    90 Hemis
Tsol  0.273 0.275 0.270 0.264 0.256 0.241 0.210 0.153 0.070 0.000 0.225
Abs1  0.263 0.268 0.274 0.277 0.277 0.278 0.285 0.287 0.231 0.001 0.273
Abs2  0.069 0.066 0.067 0.067 0.068 0.068 0.065 0.056 0.038 0.000 0.063
Abs3      0     0     0     0     0     0     0     0     0     0     0
Abs4      0     0     0     0     0     0     0     0     0     0     0
Abs5      0     0     0     0     0     0     0     0     0     0     0
Abs6      0     0     0     0     0     0     0     0     0     0     0
Rfsol 0.395 0.391 0.390 0.392 0.399 0.413 0.439 0.504 0.660 0.999 0.428
Rbsol 0.250 0.265 0.262 0.260 0.261 0.268 0.294 0.369 0.547 1.000 0.294
Tvis  0.605 0.608 0.599 0.587 0.571 0.541 0.473 0.345 0.160 0.000 0.503
Rfvis 0.248 0.242 0.239 0.242 0.252 0.272 0.311 0.399 0.596 0.999 0.295
Rbvis 0.211 0.206 0.204 0.207 0.217 0.239 0.288 0.403 0.628 1.000 0.271
SHGC  0.346 0.345 0.341 0.336 0.328 0.313 0.281 0.216 0.115 0.000 0.293
SC: 0.33

Layer ID#          772     2208        0        0        0        0
Tir              0.000    0.000        0        0        0        0
Emis F           0.840    0.840        0        0        0        0
Emis B           0.030    0.840        0        0        0        0
Thickness(mm)      5.6     11.8        0        0        0        0
Cond(W/m2-K     )178.1     48.1        0        0        0        0
Spectral File     ESB1.AFG  clcl716.pgt         None         None         None
None

Overall and Center of Glass Ig U-values (W/m2-K)
Outdoor Temperature                 -17.8 C      15.6 C      26.7 C      37.8 C
Solar      WdSpd  hcout hrout  hin
(W/m2)     (m/s)     (W/m2-K)
   0        0.00   4.00  3.29  2.09  1.15 1.15  0.89 0.89  0.91 0.91  0.97 0.97
   0        6.71  30.84  3.20  2.18  1.37 1.37  0.97 0.97  0.98 0.98  1.05 1.05
 783        0.00   4.00  3.76  1.94  1.15 1.15  0.89 0.89  0.91 0.91  0.97 0.97
 783        6.71  30.84  3.32  0.92  1.37 1.37  0.97 0.97  0.98 0.98  1.05 1.05
```

C.3 Working with the BDI (Batch DOE-2 Input) and GAWK Programs

For this study, the DOE-2 simulations were performed in the batch mode using the BDI (Batch DOE-2 Input) program, and the required data from the DOE-2 output was extracted using the GAWK program (Figure C- 1). For using the BDI program for one batch of input, a spreadsheet A_SNGFAM2ST.XML was prepared to assign values to all the parameters that were specified in the input file. Using this spreadsheet, different values were assigned to the parameters for different runs, simultaneously, each run corresponding to each row of the spreadsheet (Figure C- 2). The BDI used this spreadsheet to develop a number of include files (for example, N_SNGFAM2ST.INC corresponding to the N^{th} row of the BDI spreadsheet) to be used with the input file SNGFAM2ST.INP (Figure C- 4), called the DOE-2 simulation in the batch mode using those include files (Figure C- 3), and generated output files, for example, N_SNGFAM2ST.OUT corresponding to the include file N_SNGFAM2ST.INC (Figure C- 5). By using the GAWK program (Figure C- 6 and Figure C- 7), the annual energy use for different end-uses was extracted from the Building Energy Performance Summary (BEPS) of all the output files to SUMMARY.OUT (Figure C- 8). The extracted data was, then, sorted to perform the analysis (Figure C- 9).

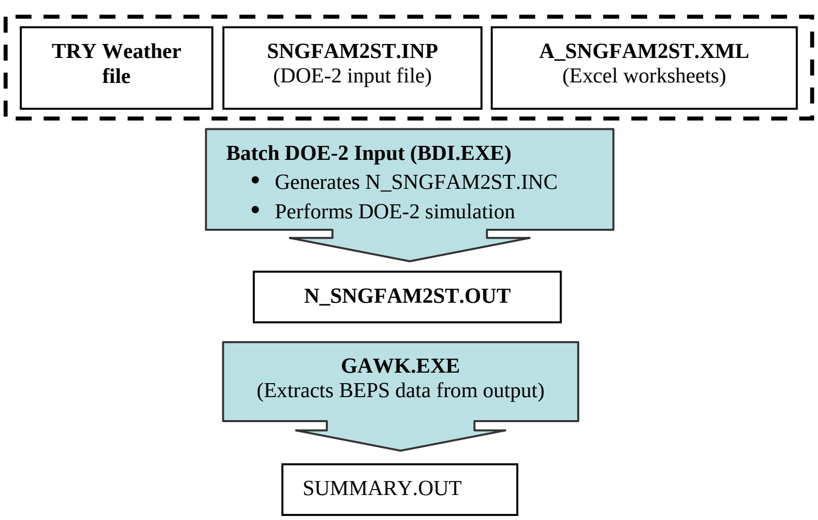


Figure C- 1: Steps for Using the BDI and GAWK Programs

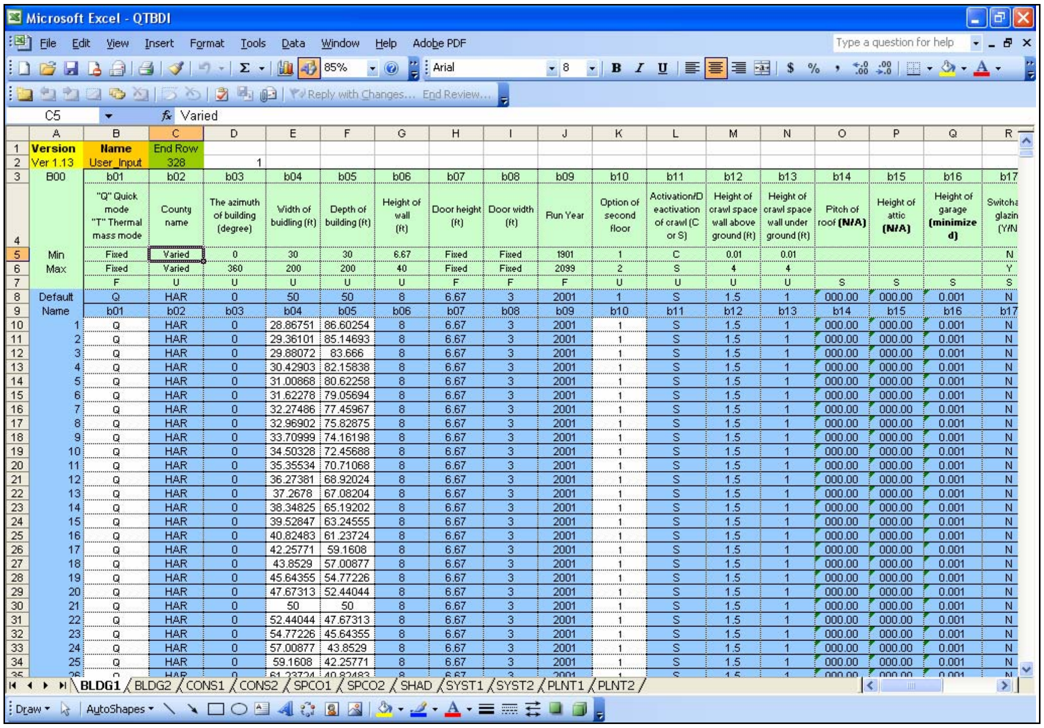


Figure C- 2: BDI Spreadsheet (A_SNGFAM2ST.XLS)

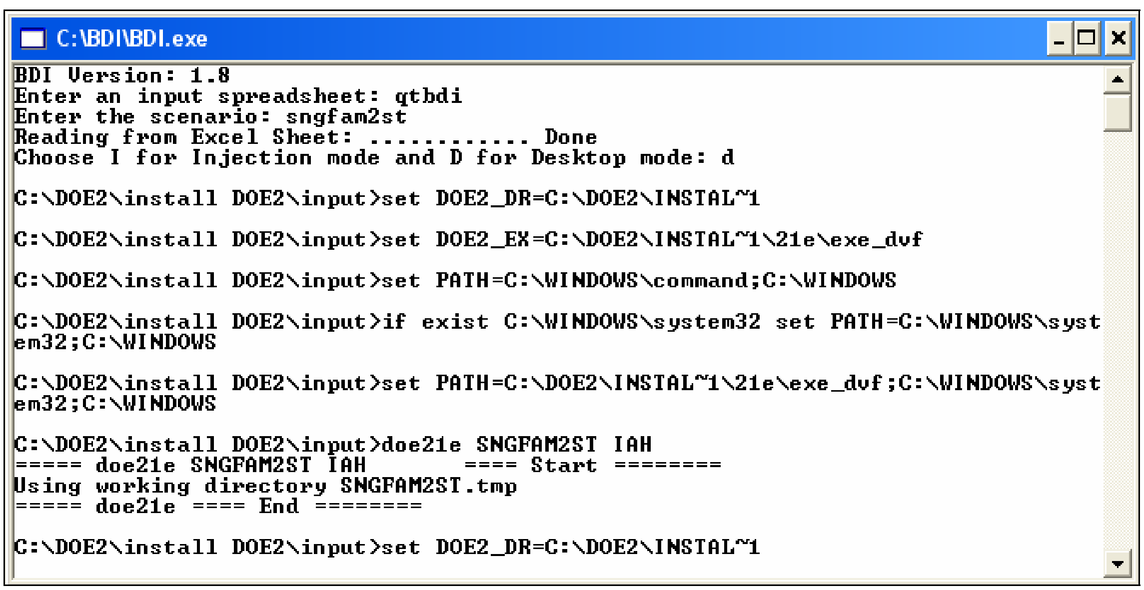
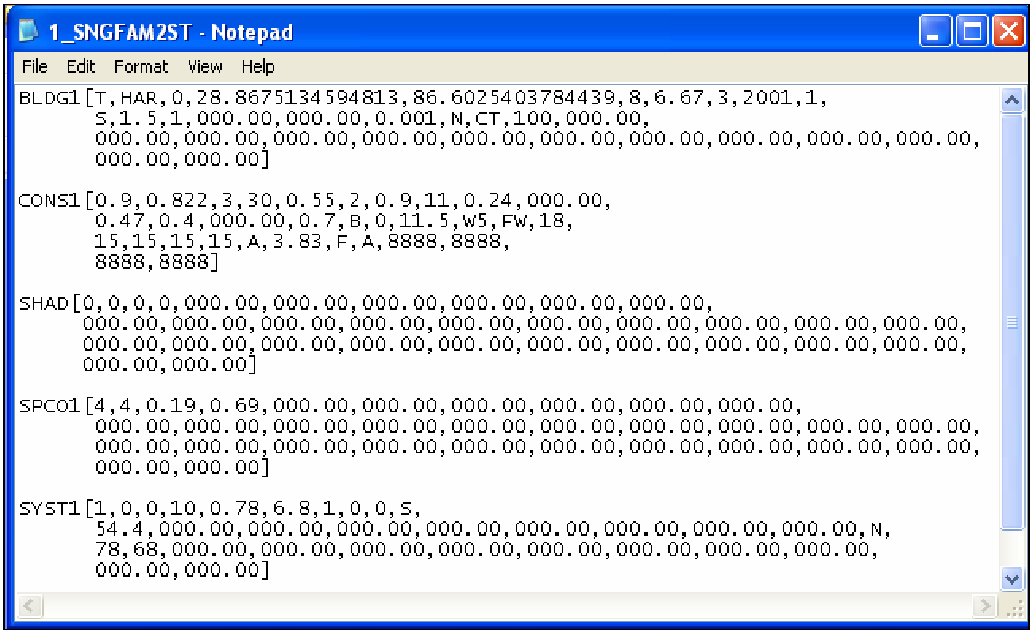


Figure C- 3: DOE-2 Simulation in the Batch Mode Performed by the BDI Program


1_SNGFAM2ST - Notepad

File Edit Format View Help

```
BLDG1[T,HAR,0,28.8675134594813,86.6025403784439,8,6.67,3,2001,1,
      S,1.5,1,000.00,000.00,0.001,N,CT,100,000.00,
      000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
      000.00,000.00]

CONS1[0.9,0.822,3,30,0.55,2,0.9,11,0.24,000.00,
      0.47,0.4,000.00,0.7,B,0,11.5,W5,FW,18,
      15,15,15,15,A,3.83,F,A,8888,8888,
      8888,8888]

SHAD[0,0,0,0,000.00,000.00,000.00,000.00,000.00,000.00,
     000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
     000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
     000.00,000.00]

SPCO1[4,4,0.19,0.69,000.00,000.00,000.00,000.00,000.00,000.00,
      000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
      000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
      000.00,000.00]

SYST1[1,0,0,10,0.78,6.8,1,0,0,S,
      54.4,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,N,
      78,68,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
      000.00,000.00]
```

Figure C- 4: Include File (N_SNGFAM2ST.TXT) Generated by the BDI Program

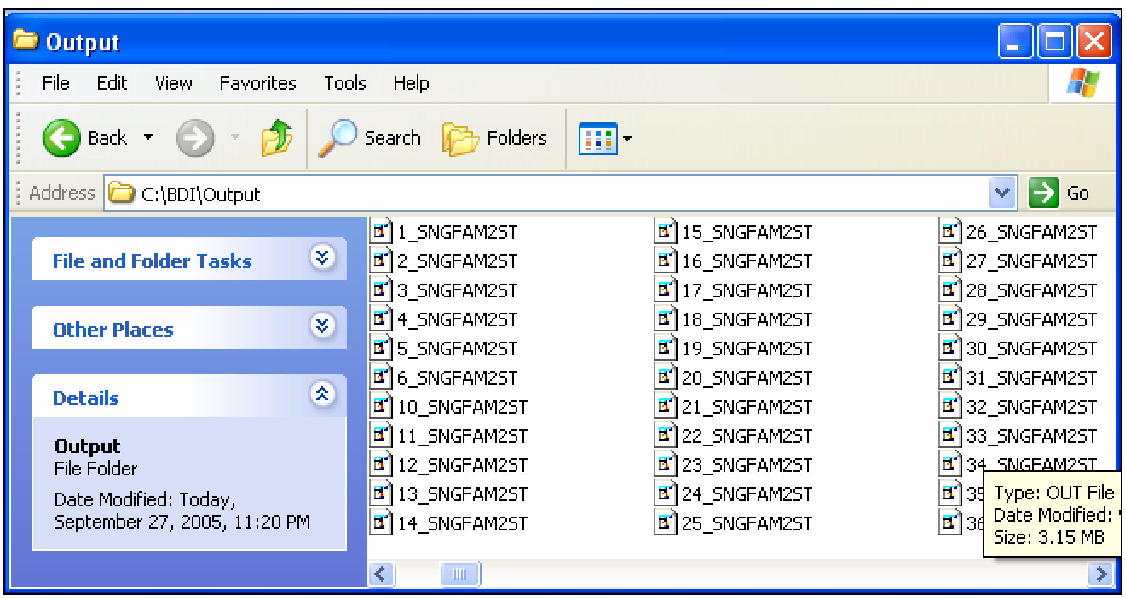


Figure C- 5: Output Files (N_SNGFAM2ST.OUT) Generated by the BDI Program

```
BEGIN {
 }
 {
  lgt[NR] = $3;
  eqp[NR] = $3;
  sph[NR] = $4;
  spc[NR] = $3;
  pmp[NR] = $4;
  vfn[NR] = $3;
  dhw[NR] = $4;
  site[NR] = $4;
  sqft[NR] = $9
  src[NR] = $4;
  kwh[NR] = $3;
  therm[NR] = $3

  if (($1 == "REPORT-") && ($2 == "BEPU"))
     {a= NR-30; b= NR-28; c= NR-26; d= NR-24; e= NR-22; f= NR-20; g=
NR-18; h = NR-11; i = NR-11; j= NR-10; k= NR+30; l= NR+31}
 }

 END {
     print lgt[a], eqp[b], sph[c], spc[d], pmp[e], vfn[f], dhw[g],
site[h], sqft[i], src[j], kwh[k], therm[l] >> "summary.out"
}
```

Figure C- 6: Commands in GAWK to Extract the Specified Data to SUMMARY.OUT

```
C:\BDI\Output>gawk -f test_S.awk 1_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f test_S.awk 2_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f test_S.awk 3_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f test_S.awk 4_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f test_S.awk 5_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f test_S.awk 6_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f test_S.awk 7_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f test_S.awk 8_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f test_S.awk 9_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f test_S.awk 10_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f test_S.awk 11_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f test_S.awk 12_SNGFAM2ST.OUT
```

Figure C- 7: MS-DOS Batch File Extracting Data from the DOE-2 Output Files (N_SNGFAM2ST.OUT)

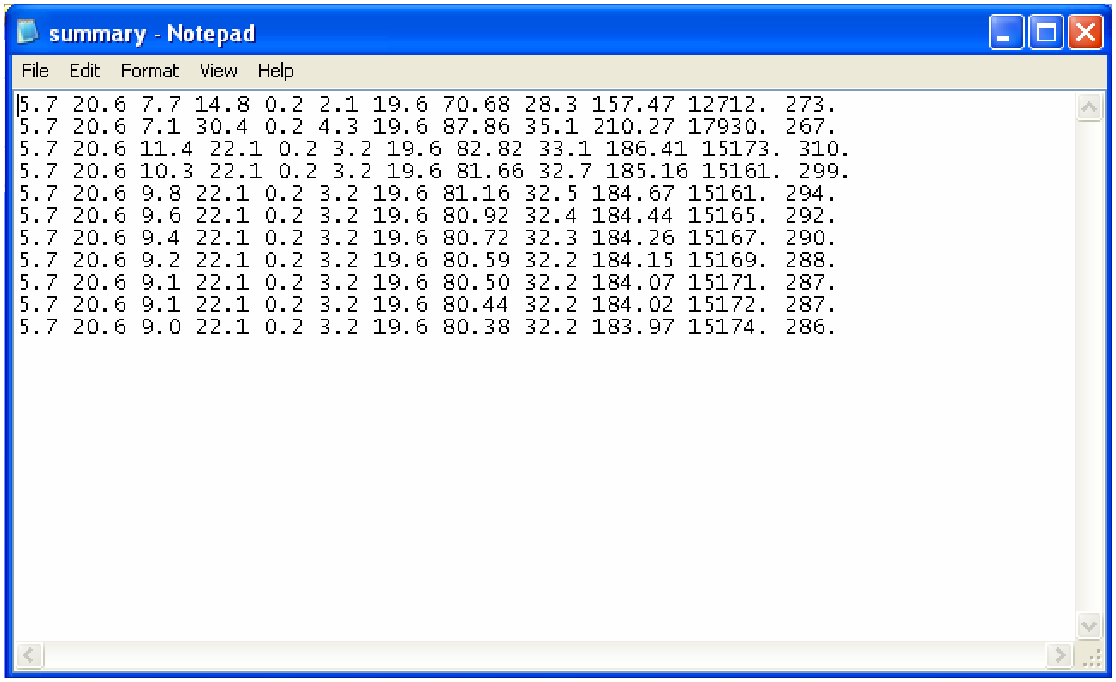


Figure C- 8: SUMMARY.OUT Showing Data Extracted by the GAWK Program

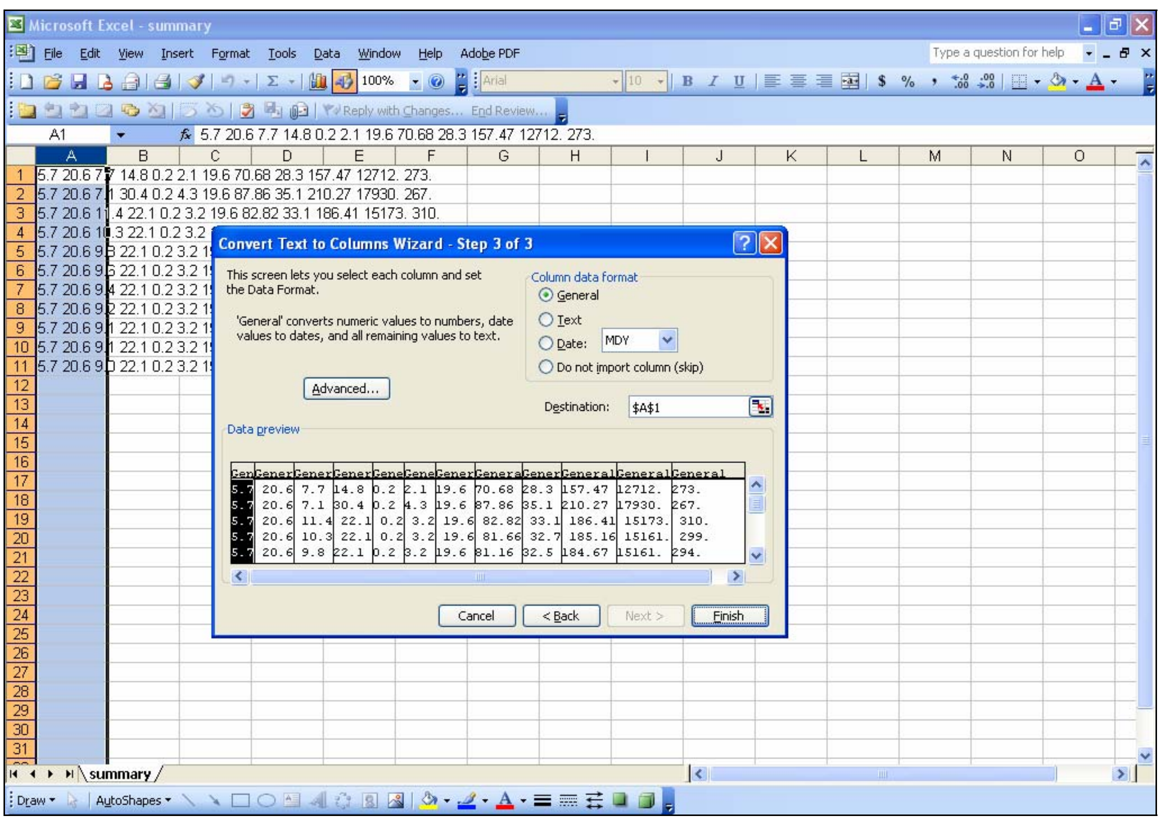


Figure C- 9: Sorting Data in SUMMARY.OUT for the Analysis

APPENDIX D

SUMMARY OF RESULTS OF THE SIMULATIONS

Summary of Results of the Simulations

This section of the appendix presents a summary of the results of the DOE-2 simulations performed for this study. The tables present the annual energy use (MBtu/yr) obtained from the BEPS report of the selected DOE-2 output files. The first column and the row header represent intermediate values of the two building parameters whose effect on annual energy use was analyzed. The annual energy use for the basecase scenario is highlighted, and the percent energy savings are calculated with reference to the basecase scenario.

Table D- 1: Effect of Quick and Delayed Construction Mode on Energy Use

Gross Window Area	18% Window-to-Floor Area					28% Window-to-Wall Area				
Building Configuration	Quick Mode		Delayed Mode		Quick vs. Delayed Mode	Quick Mode		Delayed Mode		Quick vs. Delayed Mode
	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	Difference (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	Difference (%)
Total Energy Use										
1 : 3, 1-story	83.6	(2.49)	74.77	(1.74)	11.81	86.24	(5.73)	76.35	(3.89)	12.95
1 : 2.5, 1-story	83.19	(1.99)	74.59	(1.50)	11.53	84.97	(4.17)	75.67	(2.97)	12.29
1 : 2, 1-story	82.7	(1.39)	74.38	(1.21)	11.19	83.72	(2.64)	74.97	(2.01)	11.67
1 : 1.5, 1-story	82.17	(0.74)	74.04	(0.75)	10.98	82.5	(1.14)	74.23	(1.01)	11.14
1 : 1, 1-story	**81.57**	0.00	**73.49**	0.00	10.99	**81.57**	0.00	**73.49**	0.00	10.99
1.5 : 1, 1-story	81.17	0.49	72.95	0.73	11.27	81.5	0.09	73.12	0.50	11.46
2 : 1, 1-story	81.06	0.63	72.62	1.18	11.62	81.96	(0.48)	73.09	0.54	12.14
2.5 : 1, 1-story	81.05	0.64	72.4	1.48	11.95	82.64	(1.31)	73.19	0.41	12.91
3 : 1, 1-story	81.11	0.56	72.21	1.74	12.33	83.42	(2.27)	73.32	0.23	13.78
1 : 3, 2-story	81.36	0.26	74.25	(1.03)	9.58	91.53	(12.21)	80.68	(9.78)	13.45
1 : 2.5, 2-story	80.84	0.89	73.99	(0.68)	9.26	89.75	(10.03)	79.67	(8.41)	12.65
1 : 2, 2-story	80.26	1.61	73.71	(0.30)	8.89	87.97	(7.85)	78.61	(6.97)	11.91
1 : 1.5, 2-story	79.59	2.43	73.32	0.23	8.55	86.25	(5.74)	77.51	(5.47)	11.28
1 : 1, 2-story	78.86	3.32	72.77	0.98	8.37	84.88	(4.06)	76.46	(4.04)	11.01
1.5 : 1, 2-story	78.39	3.90	72.24	1.70	8.51	84.71	(3.85)	75.99	(3.40)	11.48
2 : 1, 2-story	78.28	4.03	71.9	2.16	8.87	85.35	(4.63)	76.01	(3.43)	12.29
2.5 : 1, 2-story	78.3	4.01	71.68	2.46	9.24	86.31	(5.81)	76.25	(3.76)	13.19
3 : 1, 2-story	78.42	3.86	71.5	2.71	9.68	87.45	(7.21)	76.58	(4.20)	14.19
Space Cooling Energy Use										
1 : 3, 1-story	23.3	(4.95)	18.2	(5.20)	28.02	25.4	(14.41)	19.6	(13.29)	29.59
1 : 2.5, 1-story	23.2	(4.50)	18.1	(4.62)	28.18	24.6	(10.81)	19.1	(10.40)	28.80
1 : 2, 1-story	23	(3.60)	18	(4.05)	27.78	23.8	(7.21)	18.5	(6.94)	28.65
1 : 1.5, 1-story	22.7	(2.25)	17.8	(2.89)	27.53	22.9	(3.15)	17.9	(3.47)	27.93
1 : 1, 1-story	**22.2**	0.00	**17.3**	0.00	28.32	**22.2**	0.00	**17.3**	0.00	28.32
1.5 : 1, 1-story	21.7	2.25	16.8	2.89	29.17	22	0.90	17	1.73	29.41
2 : 1, 1-story	21.4	3.60	16.5	4.62	29.70	22.1	0.45	16.9	2.31	30.77
2.5 : 1, 1-story	21.1	4.95	16.3	5.78	29.45	22.4	(0.90)	16.9	2.31	32.54
3 : 1, 1-story	20.9	5.86	16	7.51	30.63	22.7	(2.25)	17	1.73	33.53
1 : 3, 2-story	21.7	2.25	17.4	(0.58)	24.71	30	(35.14)	22.8	(31.79)	31.58
1 : 2.5, 2-story	21.5	3.15	17.3	0.00	24.28	28.8	(29.73)	22.1	(27.75)	30.32
1 : 2, 2-story	21.3	4.05	17.1	1.16	24.56	27.5	(23.87)	21.3	(23.12)	29.11
1 : 1.5, 2-story	20.9	5.86	16.9	2.31	23.67	26.3	(18.47)	20.4	(17.92)	28.92
1 : 1, 2-story	20.3	8.56	16.4	5.20	23.78	25.2	(13.51)	19.5	(12.72)	29.23
1.5 : 1, 2-story	19.8	10.81	15.9	8.09	24.53	24.8	(11.71)	19.1	(10.40)	29.84
2 : 1, 2-story	19.5	12.16	15.6	9.83	25.00	25.1	(13.06)	19	(9.83)	32.11
2.5 : 1, 2-story	19.2	13.51	15.3	11.56	25.49	25.5	(14.86)	19.1	(10.40)	33.51
3 : 1, 2-story	19.1	13.96	15.1	12.72	26.49	26.1	(17.57)	19.3	(11.56)	35.23
Space Heating Energy Use										
1 : 3, 1-story	3.8	(22.58)	0.9	(50.00)	322.22	4	(29.03)	0.9	(50.00)	344.44
1 : 2.5, 1-story	3.6	(16.13)	0.8	(33.33)	350.00	3.7	(19.35)	0.8	(33.33)	362.50
1 : 2, 1-story	3.4	(9.68)	0.7	(16.67)	385.71	3.4	(9.68)	0.7	(16.67)	385.71
1 : 1.5, 1-story	3.2	(3.23)	0.6	0.00	433.33	3.2	(3.23)	0.7	(16.67)	357.14
1 : 1, 1-story	**3.1**	0.00	**0.6**	0.00	416.67	**3.1**	0.00	**0.6**	0.00	416.67
1.5 : 1, 1-story	3.2	(3.23)	0.6	0.00	433.33	3.3	(6.45)	0.6	0.00	450.00
2 : 1, 1-story	3.5	(12.90)	0.7	(16.67)	400.00	3.6	(16.13)	0.7	(16.67)	414.29
2.5 : 1, 1-story	3.8	(22.58)	0.7	(16.67)	442.86	3.9	(25.81)	0.8	(33.33)	387.50
3 : 1, 1-story	4.1	(32.26)	0.8	(33.33)	412.50	4.3	(38.71)	0.8	(33.33)	437.50
1 : 3, 2-story	3.4	(9.68)	1.3	(116.67)	161.54	4.1	(32.26)	1.5	(150.00)	173.33
1 : 2.5, 2-story	3.1	0.00	1.2	(100.00)	158.33	3.7	(19.35)	1.3	(116.67)	184.62
1 : 2, 2-story	2.9	6.45	1.1	(83.33)	163.64	3.4	(9.68)	1.2	(100.00)	183.33
1 : 1.5, 2-story	2.6	16.13	1	(66.67)	160.00	3.1	0.00	1.1	(83.33)	181.82
1 : 1, 2-story	2.5	19.35	1	(66.67)	150.00	3	3.23	1.1	(83.33)	172.73
1.5 : 1, 2-story	2.7	12.90	1	(66.67)	170.00	3.2	(3.23)	1.1	(83.33)	190.91
2 : 1, 2-story	2.9	6.45	1	(66.67)	190.00	3.5	(12.90)	1.2	(100.00)	191.67
2.5 : 1, 2-story	3.2	(3.23)	1.1	(83.33)	190.91	4	(29.03)	1.3	(116.67)	207.69
3 : 1, 2-story	3.5	(12.90)	1.2	(100.00)	191.67	4.4	(41.94)	1.4	(133.33)	214.29

Table D- 2: Effect of Building Configuration on Energy Savings from Roof Insulation

Building Configuration	1 : 1, 1-story		3 : 1, 1-story		1 : 1, 2-story		3 : 1, 2-story	
Roof Insulation	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use								
R-10	94.81	(16.03)	94.79	(16.66)	80.92	(2.57)	80.72	(2.91)
R-15	87.84	(7.50)	87.7	(7.94)	79.94	(1.33)	79.57	(1.44)
R-20	84.7	(3.66)	84.35	(3.82)	79.43	(0.68)	79	(0.71)
R-25	82.88	(1.43)	82.48	(1.51)	79.09	(0.25)	78.67	(0.29)
R-30	**81.71**	0.00	**81.25**	0.00	**78.89**	0.00	**78.44**	0.00
R-35	80.95	0.93	80.37	1.08	78.74	0.19	78.26	0.23
R-40	80.39	1.62	79.71	1.90	78.64	0.32	78.15	0.37
R-45	79.95	2.15	79.19	2.54	78.54	0.44	78.05	0.50
R-50	79.61	2.57	78.84	2.97	78.47	0.53	77.97	0.60
R-55	79.33	2.91	78.53	3.35	78.42	0.60	77.9	0.69
Space Cooling Energy Use								
R-10	27.8	(24.66)	26.7	(26.54)	21	(3.45)	80.72	(2.91)
R-15	25	(12.11)	23.8	(12.80)	20.7	(1.97)	79.57	(1.44)
R-20	23.7	(6.28)	22.4	(6.16)	20.5	(0.99)	79	(0.71)
R-25	22.9	(2.69)	21.6	(2.37)	20.4	(0.49)	78.67	(0.29)
R-30	**22.3**	0.00	**21.1**	0.00	**20.3**	0.00	**78.44**	0.00
R-35	22	1.35	20.7	1.90	20.3	0.00	78.26	0.23
R-40	21.7	2.69	20.4	3.32	20.3	0.00	78.15	0.37
R-45	21.4	4.04	20.2	4.27	20.2	0.49	78.05	0.50
R-50	21.3	4.48	20	5.21	20.2	0.49	77.97	0.60
R-55	21.1	5.38	19.8	6.16	20.2	0.49	77.9	0.69
Space Heating Energy Use								
R-10	9.8	(216.13)	26.7	(26.54)	21	(3.45)	19.8	(3.66)
R-15	6.1	(96.77)	23.8	(12.80)	20.7	(1.97)	19.5	(2.09)
R-20	4.5	(45.16)	22.4	(6.16)	20.5	(0.99)	19.3	(1.05)
R-25	3.6	(16.13)	21.6	(2.37)	20.4	(0.49)	19.2	(0.52)
R-30	**3.1**	0.00	**21.1**	0.00	**20.3**	0.00	**19.1**	0.00
R-35	2.7	12.90	20.7	1.90	20.3	0.00	19.1	0.00
R-40	2.5	19.35	20.4	3.32	20.3	0.00	19	0.52
R-45	2.3	25.81	20.2	4.27	20.2	0.49	19	0.52
R-50	2.1	32.26	20	5.21	20.2	0.49	19	0.52
R-55	2	35.48	19.8	6.16	20.2	0.49	18.9	1.05

Table D- 3: Effect of Building Configuration on Energy Savings from Roof Absorptance

Building Configuration	1 : 1, 1-story		3 : 1, 1-story		1 : 1, 2-story		3 : 1, 2-story	
Roof Absorptance	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use								
a-0.25	78.66	3.73	78.22	3.73	78.28	0.77	77.86	0.74
a-0.4	79.47	2.74	79	2.77	78.44	0.57	78.02	0.54
a-0.55	80.23	1.81	79.77	1.82	78.6	0.37	78.16	0.36
a-0.7	80.96	0.92	80.51	0.91	78.74	0.19	78.3	0.18
a-0.85	**81.71**	0.00	**81.25**	0.00	**78.89**	0.00	**78.44**	0.00
Space Cooling Energy Use								
a-0.25	19.4	13.00	18.1	14.22	19.6	3.45	18.4	3.66
a-0.4	20.2	9.42	18.9	10.43	19.8	2.46	18.6	2.62
a-0.55	20.9	6.28	19.6	7.11	20	1.48	18.8	1.57
a-0.7	21.6	3.14	20.4	3.32	20.2	0.49	18.9	1.05
a-0.85	**22.3**	0.00	**21.1**	0.00	**20.3**	0.00	**19.1**	0.00
Space Heating Energy Use								
a-0.25	3.4	(9.68)	4.4	(7.32)	2.7	(8.00)	3.7	(5.71)
a-0.4	3.3	(6.45)	4.3	(4.88)	2.7	(8.00)	3.6	(2.86)
a-0.55	3.2	(3.23)	4.2	(2.44)	2.6	(4.00)	3.6	(2.86)
a-0.7	3.1	0.00	4.1	0.00	2.6	(4.00)	3.5	0.00
a-0.85	**3.1**	0.00	**4.1**	0.00	**2.5**	0.00	**3.5**	0.00

Table D- 4: Effect of Building Configuration on Energy Savings from Roof Emissivity

Building Configuration	1 : 1, 1-story		3 : 1, 1-story		1 : 1, 2-story		3 : 1, 2-story	
Roof Emissivity	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use								
e-0.1	84.83	(3.82)	84.01	(3.40)	79.52	(0.80)	79.02	(0.74)
e-0.3	83.69	(2.42)	82.99	(2.14)	79.29	(0.51)	78.8	(0.46)
e-0.5	82.85	(1.40)	82.3	(1.29)	79.11	(0.28)	78.64	(0.25)
e-0.7	82.22	(0.62)	81.71	(0.57)	78.98	(0.11)	78.53	(0.11)
e-0.9	**81.71**	0.00	**81.25**	0.00	**78.89**	0.00	**78.44**	0.00
Space Cooling Energy Use								
e-0.1	25.7	(15.25)	24.4	(15.64)	21.2	(4.43)	19.9	(4.19)
e-0.3	24.5	(9.87)	23.1	(9.48)	20.9	(2.96)	19.6	(2.62)
e-0.5	23.6	(5.83)	22.3	(5.69)	20.7	(1.97)	19.4	(1.57)
e-0.7	22.9	(2.69)	21.6	(2.37)	20.5	(0.99)	19.2	(0.52)
e-0.9	**22.3**	0.00	**21.1**	0.00	**20.3**	0.00	**19.1**	0.00
Space Heating Energy Use								
e-0.1	2.3	25.81	3.1	24.39	2.3	8.00	3.2	8.57
e-0.3	2.6	16.13	3.4	17.07	2.4	4.00	3.3	5.71
e-0.5	2.8	9.68	3.7	9.76	2.4	4.00	3.4	2.86
e-0.7	3	3.23	3.9	4.88	2.5	0.00	3.4	2.86
e-0.9	**3.1**	0.00	**4.1**	0.00	**2.5**	0.00	**3.5**	0.00

Table D- 5: Effect of Roof Insulation on Energy Savings from Building Configuration

Roof Insulation	R-10		R-30		R-50	
Building Configuration	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use						
1 : 1, 1-story	**94.81**	0.00	**81.71**	0.00	**79.61**	0.00
1.5 : 1, 1-story	94.53	0.30	81.3	0.50	79.15	0.58
2 : 1, 1-story	94.52	0.31	81.19	0.64	78.92	0.87
2.5 : 1, 1-story	94.63	0.19	81.17	0.66	78.84	0.97
3 : 1, 1-story	94.79	0.02	81.25	0.56	78.84	0.97
1 : 1, 2-story	80.92	14.65	78.89	3.45	78.47	1.43
1.5 : 1, 2-story	80.47	15.12	78.42	4.03	77.98	2.05
2 : 1, 2-story	80.4	15.20	78.31	4.16	77.88	2.17
2.5 : 1, 2-story	80.53	15.06	78.32	4.15	77.89	2.16
3 : 1, 2-story	80.72	14.86	78.44	4.00	77.97	2.06
Space Cooling Energy Use						
1 : 1, 1-story	**27.8**	0.00	**22.3**	0.00	**21.3**	0.00
1.5 : 1, 1-story	27.4	1.44	21.8	2.24	20.8	2.35
2 : 1, 1-story	27.1	2.52	21.5	3.59	20.5	3.76
2.5 : 1, 1-story	26.9	3.24	21.3	4.48	20.2	5.16
3 : 1, 1-story	26.7	3.96	21.1	5.38	20	6.10
1 : 1, 2-story	21	24.46	20.3	8.97	20.2	5.16
1.5 : 1, 2-story	20.5	26.26	19.8	11.21	19.7	7.51
2 : 1, 2-story	20.2	27.34	19.5	12.56	19.4	8.92
2.5 : 1, 2-story	20	28.06	19.3	13.45	19.1	10.33
3 : 1, 2-story	19.8	28.78	19.1	14.35	19	10.80
Space Heating Energy Use						
1 : 1, 1-story	**9.8**	0.00	**3.1**	0.00	**2.1**	0.00
1.5 : 1, 1-story	10.1	(3.06)	3.2	(3.23)	2.3	(9.52)
2 : 1, 1-story	10.4	(6.12)	3.5	(12.90)	2.4	(14.29)
2.5 : 1, 1-story	10.7	(9.18)	3.8	(22.58)	2.7	(28.57)
3 : 1, 1-story	11	(12.24)	4.1	(32.26)	2.9	(38.10)
1 : 1, 2-story	3.9	60.20	2.5	19.35	2.3	(9.52)
1.5 : 1, 2-story	4	59.18	2.7	12.90	2.4	(14.29)
2 : 1, 2-story	4.3	56.12	2.9	6.45	2.6	(23.81)
2.5 : 1, 2-story	4.6	53.06	3.2	(3.23)	2.9	(38.10)
3 : 1, 2-story	5	48.98	3.5	(12.90)	3.2	(52.38)

Table D- 6: Effect of Roof Insulation on Energy Savings from Roof Absorptance

Roof Insulation	R-10		R-30		R-50	
Roof Absorptance	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use						
a-0.25	86.75	8.50	78.66	3.73	77.68	2.42
a-0.4	88.68	6.47	79.47	2.74	78.19	1.78
a-0.55	90.73	4.30	80.23	1.81	78.68	1.17
a-0.7	92.78	2.14	80.96	0.92	79.14	0.59
a-0.85	**94.81**	0.00	**81.71**	0.00	**79.61**	0.00
Space Cooling Energy Use						
a-0.25	19.5	29.86	19.4	13.00	19.5	8.45
a-0.4	21.7	21.94	20.2	9.42	20	6.10
a-0.55	23.7	14.75	20.9	6.28	20.5	3.76
a-0.7	25.8	7.19	21.6	3.14	20.9	1.88
a-0.85	**27.8**	0.00	**22.3**	0.00	**21.3**	0.00
Space Heating Energy Use						
a-0.25	11.3	(15.31)	3.4	(9.68)	2.3	(9.52)
a-0.4	10.8	(10.20)	3.3	(6.45)	2.2	(4.76)
a-0.55	10.4	(6.12)	3.2	(3.23)	2.2	(4.76)
a-0.7	10.1	(3.06)	3.1	0.00	2.2	(4.76)
a-0.85	**9.8**	0.00	**3.1**	0.00	**2.1**	0.00

Table D- 7: Effect of Roof Insulation on Energy Savings from Roof Emissivity

Roof Insulation	R-10		R-30		R-50	
Roof Emissivity	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use						
e-0.1	101.56	(7.12)	84.83	(3.82)	81.54	(2.42)
e-0.3	98.95	(4.37)	83.69	(2.42)	80.82	(1.52)
e-0.5	97.1	(2.42)	82.85	(1.40)	80.32	(0.89)
e-0.7	95.81	(1.05)	82.22	(0.62)	79.93	(0.40)
e-0.9	**94.81**	0.00	**81.71**	0.00	**79.61**	0.00
Space Cooling Energy Use						
e-0.1	101.56	(7.12)	84.83	(3.82)	81.54	(2.42)
e-0.3	98.95	(4.37)	83.69	(2.42)	80.82	(1.52)
e-0.5	97.1	(2.42)	82.85	(1.40)	80.32	(0.89)
e-0.7	95.81	(1.05)	82.22	(0.62)	79.93	(0.40)
e-0.9	**94.81**	0.00	**81.71**	0.00	**79.61**	0.00
Space Heating Energy Use						
e-0.1	5.8	40.82	2.3	25.81	1.7	19.05
e-0.3	7.2	26.53	2.6	16.13	1.9	9.52
e-0.5	8.2	16.33	2.8	9.68	2	4.76
e-0.7	9.1	7.14	3	3.23	2.1	0.00
e-0.9	**9.8**	0.00	**3.1**	0.00	**2.1**	0.00

Table D- 8: Effect of Roof Absorptance on Energy Savings from Building Configuration

Roof Absorptance	a-0.25		a-0.55		a-0.85	
Building Configuration	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use						
1 : 1, 1-story	**78.66**	0.00	**80.23**	0.00	**81.71**	0.00
1.5 : 1, 1-story	78.26	0.51	79.84	0.49	81.3	0.50
2 : 1, 1-story	78.12	0.69	79.7	0.66	81.19	0.64
2.5 : 1, 1-story	78.11	0.70	79.69	0.67	81.17	0.66
3 : 1, 1-story	78.22	0.56	79.77	0.57	81.25	0.56
1 : 1, 2-story	78.28	0.48	78.6	2.03	78.89	3.45
1.5 : 1, 2-story	77.82	1.07	78.12	2.63	78.42	4.03
2 : 1, 2-story	77.7	1.22	78.01	2.77	78.31	4.16
2.5 : 1, 2-story	77.73	1.18	78.03	2.74	78.32	4.15
3 : 1, 2-story	77.86	1.02	78.16	2.58	78.44	4.00
Space Cooling Energy Use						
1 : 1, 1-story	**19.4**	0.00	**20.9**	0.00	**22.3**	0.00
1.5 : 1, 1-story	18.9	2.58	20.4	2.39	21.8	2.24
2 : 1, 1-story	18.6	4.12	20.1	3.83	21.5	3.59
2.5 : 1, 1-story	18.3	5.67	19.8	5.26	21.3	4.48
3 : 1, 1-story	18.1	6.70	19.6	6.22	21.1	5.38
1 : 1, 2-story	19.6	(1.03)	20	4.31	20.3	8.97
1.5 : 1, 2-story	19.1	1.55	19.5	6.70	19.8	11.21
2 : 1, 2-story	18.8	3.09	19.2	8.13	19.5	12.56
2.5 : 1, 2-story	18.6	4.12	18.9	9.57	19.3	13.45
3 : 1, 2-story	18.4	5.15	18.8	10.05	19.1	14.35
Space Heating Energy Use						
1 : 1, 1-story	**3.4**	0.00	**3.2**	0.00	**3.1**	0.00
1.5 : 1, 1-story	3.5	(2.94)	3.4	(6.25)	3.2	(3.23)
2 : 1, 1-story	3.8	(11.76)	3.6	(12.50)	3.5	(12.90)
2.5 : 1, 1-story	4.1	(20.59)	3.9	(21.88)	3.8	(22.58)
3 : 1, 1-story	4.4	(29.41)	4.2	(31.25)	4.1	(32.26)
1 : 1, 2-story	2.7	20.59	2.6	18.75	2.5	19.35
1.5 : 1, 2-story	2.9	14.71	2.7	15.63	2.7	12.90
2 : 1, 2-story	3.1	8.82	3	6.25	2.9	6.45
2.5 : 1, 2-story	3.4	0.00	3.3	(3.13)	3.2	(3.23)
3 : 1, 2-story	3.7	(8.82)	3.6	(12.50)	3.5	(12.90)

Table D- 9: Effect of Roof Absorptance on Energy Savings from Roof Insulation

Roof Absorptance	a-0.25		a-0.55		a-0.85	
Roof Insulation	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use						
R-10	86.75	(10.28)	90.73	(13.09)	94.81	(16.03)
R-15	82.19	(4.49)	85.03	(5.98)	87.84	(7.50)
R-20	80.28	(2.06)	82.52	(2.85)	84.7	(3.66)
R-25	79.25	(0.75)	81.1	(1.08)	82.88	(1.43)
R-30	**78.66**	0.00	**80.23**	0.00	**81.71**	0.00
R-35	78.26	0.51	79.66	0.71	80.95	0.93
R-40	78.04	0.79	79.27	1.20	80.39	1.62
R-45	77.83	1.06	78.93	1.62	79.95	2.15
R-50	77.68	1.25	78.68	1.93	79.61	2.57
R-55	77.58	1.37	78.49	2.17	79.33	2.91
Space Cooling Energy Use						
R-10	19.5	(0.52)	23.7	(13.40)	27.8	(24.66)
R-15	19.3	0.52	22.3	(6.70)	25	(12.11)
R-20	19.3	0.52	21.6	(3.35)	23.7	(6.28)
R-25	19.3	0.52	21.2	(1.44)	22.9	(2.69)
R-30	**19.4**	0.00	**20.9**	0.00	**22.3**	0.00
R-35	19.4	0.00	20.7	0.96	22	1.35
R-40	19.5	(0.52)	20.6	1.44	21.7	2.69
R-45	19.5	(0.52)	20.5	1.91	21.4	4.04
R-50	19.5	(0.52)	20.5	1.91	21.3	4.48
R-55	19.5	(0.52)	20.4	2.39	21.1	5.38
Space Heating Energy Use						
R-10	11.3	(232.35)	10.4	(225.00)	9.8	(216.13)
R-15	7	(105.88)	6.5	(103.13)	6.1	(96.77)
R-20	5.1	(50.00)	4.8	(50.00)	4.5	(45.16)
R-25	4	(17.65)	3.8	(18.75)	3.6	(16.13)
R-30	**3.4**	0.00	**3.2**	0.00	**3.1**	0.00
R-35	2.9	14.71	2.8	12.50	2.7	12.90
R-40	2.7	20.59	2.6	18.75	2.5	19.35
R-45	2.4	29.41	2.4	25.00	2.3	25.81
R-50	2.3	32.35	2.2	31.25	2.1	32.26
R-55	2.1	38.24	2.1	34.38	2	35.48

Table D- 10: Effect of Roof Absorptance on Energy Savings from Roof Emissivity

Roof Absorptance	a-0.25		a-0.55		a-0.85	
Roof Emissivity	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use						
e-0.1	80.07	(1.79)	82.54	(2.88)	84.83	(3.82)
e-0.3	79.53	(1.11)	81.66	(1.78)	83.69	(2.42)
e-0.5	79.15	(0.62)	81.06	(1.03)	82.85	(1.40)
e-0.7	78.88	(0.28)	80.58	(0.44)	82.22	(0.62)
e-0.9	**78.66**	0.00	**80.23**	0.00	**81.71**	0.00
Space Cooling Energy Use						
e-0.1	21.3	(9.79)	23.6	(12.92)	25.7	(15.25)
e-0.3	20.6	(6.19)	22.6	(8.13)	24.5	(9.87)
e-0.5	20.1	(3.61)	21.9	(4.78)	23.6	(5.83)
e-0.7	19.7	(1.55)	21.4	(2.39)	22.9	(2.69)
e-0.9	**19.4**	0.00	**20.9**	0.00	**22.3**	0.00
Space Heating Energy Use						
e-0.1	2.6	23.53	2.5	21.88	2.3	25.81
e-0.3	2.9	14.71	2.8	12.50	2.6	16.13
e-0.5	3.1	8.82	2.9	9.37	2.8	9.68
e-0.7	3.3	2.94	3.1	3.12	3	3.23
e-0.9	**3.4**	0.00	**3.2**	0.00	**3.1**	0.00

Table D- 11: Effect of Roof Emissivity on Energy Savings from Building Configuration

Roof Emissivity	e-0.1		e-0.5		e-0.9	
Building Configuration	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use						
1 : 1, 1-story	**84.83**	0.00	**82.85**	0.00	**81.71**	0.00
1.5 : 1, 1-story	84.39	0.52	82.39	0.56	81.3	0.50
2 : 1, 1-story	84.13	0.83	82.23	0.75	81.19	0.64
2.5 : 1, 1-story	84.04	0.93	82.22	0.76	81.17	0.66
3 : 1, 1-story	84.01	0.97	82.3	0.66	81.25	0.56
1 : 1, 2-story	79.52	6.26	79.11	4.51	78.89	3.45
1.5 : 1, 2-story	79.03	6.84	78.66	5.06	78.42	4.03
2 : 1, 2-story	78.91	6.98	78.53	5.21	78.31	4.16
2.5 : 1, 2-story	78.91	6.98	78.55	5.19	78.32	4.15
3 : 1, 2-story	79.02	6.85	78.64	5.08	78.44	4.00
Space Cooling Energy Use						
1 : 1, 1-story	**25.7**	0.00	**23.6**	0.00	**23.1**	0.00
1.5 : 1, 1-story	25.2	1.95	23.1	2.12	22.7	1.73
2 : 1, 1-story	24.8	3.50	22.7	3.81	22.5	2.60
2.5 : 1, 1-story	24.6	4.28	22.5	4.66	22.3	3.46
3 : 1, 1-story	24.4	5.06	22.3	5.51	20.7	10.39
1 : 1, 2-story	21.2	17.51	20.7	12.29	20.1	12.99
1.5 : 1, 2-story	20.7	19.46	20.1	14.83	19.8	14.29
2 : 1, 2-story	20.4	20.62	19.8	16.10	19.6	15.15
2.5 : 1, 2-story	20.2	21.40	19.6	16.95	19.4	16.02
3 : 1, 2-story	19.9	22.57	19.4	17.80	24.5	(6.06)
Space Heating Energy Use						
1 : 1, 1-story	**2.3**	0.00	**2.8**	0.00	**3.1**	0.00
1.5 : 1, 1-story	2.5	(8.70)	2.9	(3.57)	3.2	(3.23)
2 : 1, 1-story	2.6	(13.04)	3.1	(10.71)	3.5	(12.90)
2.5 : 1, 1-story	2.8	(21.74)	3.4	(21.43)	3.8	(22.58)
3 : 1, 1-story	3.1	(34.78)	3.7	(32.14)	4.1	(32.26)
1 : 1, 2-story	2.3	0.00	2.4	14.29	2.5	19.35
1.5 : 1, 2-story	2.4	(4.35)	2.6	7.14	2.7	12.90
2 : 1, 2-story	2.6	(13.04)	2.8	0.00	2.9	6.45
2.5 : 1, 2-story	2.9	(26.09)	3.1	(10.71)	3.2	(3.23)
3 : 1, 2-story	3.2	(39.13)	3.4	(21.43)	3.5	(12.90)

Table D- 12: Effect of Roof Emissivity on Energy Savings from Roof Insulation

Roof Emissivity	**e-0.1**		**e-0.5**		**e-0.9**	
Roof Insulation	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use						
R-10	97.1	(17.20)	95.81	(16.53)	94.81	(16.03)
R-15	89.78	(8.36)	88.69	(7.87)	87.84	(7.50)
R-20	86.24	(4.09)	85.37	(3.83)	84.7	(3.66)
R-25	84.16	(1.58)	83.48	(1.53)	82.88	(1.43)
R-30	**82.85**	0.00	**82.22**	0.00	**81.71**	0.00
R-35	81.95	1.09	81.4	1.00	80.95	0.93
R-40	81.27	1.91	80.77	1.76	80.39	1.62
R-45	80.74	2.55	80.29	2.35	79.95	2.15
R-50	80.32	3.05	79.93	2.79	79.61	2.57
R-55	79.99	3.45	79.64	3.14	79.33	2.91
Space Cooling Energy Use						
R-10	31.2	(32.20)	29.3	(27.95)	27.8	(24.66)
R-15	27.4	(16.10)	26.1	(13.97)	25	(12.11)
R-20	25.5	(8.05)	24.5	(6.99)	23.7	(6.28)
R-25	24.3	(2.97)	23.5	(2.62)	22.9	(2.69)
R-30	**23.6**	0.00	**22.9**	0.00	**22.3**	0.00
R-35	23.1	2.12	22.5	1.75	22	1.35
R-40	22.7	3.81	22.1	3.49	21.7	2.69
R-45	22.3	5.51	21.9	4.37	21.4	4.04
R-50	22.1	6.36	21.6	5.68	21.3	4.48
R-55	21.8	7.63	21.5	6.11	21.1	5.38
Space Heating Energy Use						
R-10	8.2	(192.86)	9.1	(203.33)	9.8	(216.13)
R-15	5.3	(89.29)	5.7	(90.00)	6.1	(96.77)
R-20	4	(42.86)	4.3	(43.33)	4.5	(45.16)
R-25	3.2	(14.29)	3.5	(16.67)	3.6	(16.13)
R-30	**2.8**	0.00	**3**	0.00	**3.1**	0.00
R-35	2.5	10.71	2.6	13.33	2.7	12.90
R-40	2.3	17.86	2.4	20.00	2.5	19.35
R-45	2.1	25.00	2.2	26.67	2.3	25.81
R-50	2	28.57	2.1	30.00	2.1	32.26
R-55	1.9	32.14	2	33.33	2	35.48

Table D- 13: Effect of Roof Emissivity on Energy Savings from Roof Absorptance

Roof Emissivity	**e-0.1**		**e-0.5**		**e-0.9**	
Roof Absorptance	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use						
a-0.25	80.07	5.61	79.15	4.47	78.66	3.73
a-0.4	81.32	4.14	80.1	3.32	79.47	2.74
a-0.55	82.54	2.70	81.06	2.16	80.23	1.81
a-0.7	83.69	1.34	81.97	1.06	80.96	0.92
a-0.85	**84.83**	0.00	**82.85**	0.00	**81.71**	0.00
Space Cooling Energy Use						
a-0.25	21.3	17.12	20.1	14.83	19.4	13.00
a-0.4	22.4	12.84	21	11.02	20.2	9.42
a-0.55	23.6	8.17	21.9	7.20	20.9	6.28
a-0.7	24.6	4.28	22.8	3.39	21.6	3.14
a-0.85	**25.7**	0.00	**23.6**	0.00	**22.3**	0.00
Space Heating Energy Use						
a-0.25	2.6	(13.04)	3.1	(10.71)	3.4	(9.68)
a-0.4	2.6	(13.04)	3	(7.14)	3.3	(6.45)
a-0.55	2.5	(8.70)	2.9	(3.57)	3.2	(3.23)
a-0.7	2.4	(4.35)	2.9	(3.57)	3.1	0.00
a-0.85	**2.3**	0.00	**2.8**	0.00	**3.1**	0.00

Table D- 14: Effect of Building Configuration on Energy Savings from Wall Insulation

Building Configuration	1 : 1, 1-story		3 : 1, 1-story		1 : 1, 2-story		3 : 1, 2-story	
Wall Insulation	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use								
R-10	**81.96**	0.00	**81.61**	0.00	**79.39**	0.00	**79.09**	0.00
R-15	80.65	1.60	79.8	2.22	77.66	2.18	76.76	2.95
R-20	80.02	2.37	78.98	3.22	76.99	3.02	75.8	4.16
R-25	79.7	2.76	78.5	3.81	76.65	3.45	75.34	4.74
R-30	79.47	3.04	78.22	4.15	76.46	3.69	75.08	5.07
R-35	79.3	3.25	78	4.42	76.36	3.82	74.92	5.27
R-40	79.18	3.39	77.85	4.61	76.27	3.93	74.82	5.40
R-45	79.1	3.49	77.76	4.72	76.21	4.01	74.74	5.50
R-50	79.02	3.59	77.66	4.84	76.18	4.04	74.69	5.56
R-55	78.98	3.64	77.59	4.93	76.16	4.07	74.64	5.63
Space Cooling Energy Use								
R-10	**22.3**	0.00	**21**	0.00	**20.4**	0.00	**79.09**	0.00
R-15	22	1.35	20.6	1.90	20	1.96	76.76	2.95
R-20	21.8	2.24	20.4	2.86	19.9	2.45	75.8	4.16
R-25	21.7	2.69	20.3	3.33	19.8	2.94	75.34	4.74
R-30	21.6	3.14	20.2	3.81	19.8	2.94	75.08	5.07
R-35	21.6	3.14	20.2	3.81	19.7	3.43	74.92	5.27
R-40	21.6	3.14	20.1	4.29	19.7	3.43	74.82	5.40
R-45	21.6	3.14	20.1	4.29	19.7	3.43	74.74	5.50
R-50	21.5	3.59	20.1	4.29	19.7	3.43	74.69	5.56
R-55	21.5	3.59	20.1	4.29	19.7	3.43	74.64	5.63
Space Heating Energy Use								
R-10	**3.4**	0.00	**21**	0.00	**20.4**	0.00	**19.2**	0.00
R-15	2.5	26.47	20.6	1.90	20	1.96	18.7	2.60
R-20	2	41.18	20.4	2.86	19.9	2.45	18.5	3.65
R-25	1.8	47.06	20.3	3.33	19.8	2.94	18.4	4.17
R-30	1.6	52.94	20.2	3.81	19.8	2.94	18.4	4.17
R-35	1.5	55.88	20.2	3.81	19.7	3.43	18.4	4.17
R-40	1.4	58.82	20.1	4.29	19.7	3.43	18.3	4.69
R-45	1.4	58.82	20.1	4.29	19.7	3.43	18.3	4.69
R-50	1.3	61.76	20.1	4.29	19.7	3.43	18.3	4.69
R-55	1.3	61.76	20.1	4.29	19.7	3.43	18.3	4.69

Table D- 15: Effect of Building Configuration on Energy Savings from Wall Absorptance

Building Configuration	1 : 1, 1-story		3 : 1, 1-story		1 : 1, 2-story		3 : 1, 2-story	
Wall Absorptance	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use								
a-0.25	80.88	1.32	80.39	1.49	77.87	1.91	77.41	2.12
a-0.4	81.41	0.67	81	0.75	78.65	0.93	78.25	1.06
a-0.55	**81.96**	0.00	**81.61**	0.00	**79.39**	0.00	**79.09**	0.00
a-0.7	82.49	(0.65)	82.22	(0.75)	80.13	(0.93)	79.96	(1.10)
a-0.85	83.02	(1.29)	82.82	(1.48)	80.91	(1.91)	80.83	(2.20)
Space Cooling Energy Use								
a-0.25	21.2	4.93	19.8	5.71	18.9	7.35	17.4	9.38
a-0.4	21.8	2.24	20.4	2.86	19.6	3.92	18.3	4.69
a-0.55	**22.3**	0.00	**21**	0.00	**20.4**	0.00	**19.2**	0.00
a-0.7	22.8	(2.24)	21.7	(3.33)	21.2	(3.92)	20.1	(4.69)
a-0.85	23.4	(4.93)	22.2	(5.71)	22	(7.84)	21	(9.38)
Space Heating Energy Use								
a-0.25	3.5	(2.94)	4.6	(4.55)	3.2	(10.34)	4.3	(7.50)
a-0.4	3.4	0.00	4.5	(2.27)	3.1	(6.90)	4.2	(5.00)
a-0.55	**3.4**	0.00	**4.4**	0.00	**2.9**	0.00	**4**	0.00
a-0.7	3.3	2.94	4.3	2.27	2.8	3.45	3.9	2.50
a-0.85	3.2	5.88	4.3	2.27	2.7	6.90	3.7	7.50

Table D- 16: Effect of Building Configuration on Energy Savings from Wall Emissivity

Building Configuration	1 : 1, 1-story		3 : 1, 1-story		1 : 1, 2-story		3 : 1, 2-story	
Wall Emissivity	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use								
e-0.1	83	(1.27)	82.87	(1.54)	80.96	(1.98)	81.13	(2.58)
e-0.3	82.59	(0.77)	82.38	(0.94)	80.32	(1.17)	80.33	(1.57)
e-0.5	82.32	(0.44)	82.09	(0.59)	79.92	(0.67)	79.8	(0.90)
e-0.7	82.12	(0.20)	81.83	(0.27)	79.63	(0.30)	79.4	(0.39)
e-0.9	**81.96**	0.00	**81.61**	0.00	**79.39**	0.00	**79.09**	0.00
Space Cooling Energy Use								
e-0.1	23.6	(5.83)	22.8	(8.57)	22.4	(9.80)	21.8	(13.54)
e-0.3	23.1	(3.59)	22.1	(5.24)	21.7	(6.37)	20.8	(8.33)
e-0.5	22.8	(2.24)	21.7	(3.33)	21.2	(3.92)	20.2	(5.21)
e-0.7	22.5	(0.90)	21.3	(1.43)	20.7	(1.47)	19.7	(2.60)
e-0.9	**22.3**	0.00	**21**	0.00	**20.4**	0.00	**19.2**	0.00
Space Heating Energy Use								
e-0.1	2.9	14.71	3.6	18.18	2.3	20.69	3	25.00
e-0.3	3.1	8.82	3.9	11.36	2.5	13.79	3.3	17.50
e-0.5	3.2	5.88	4.2	4.55	2.7	6.90	3.6	10.00
e-0.7	3.3	2.94	4.3	2.27	2.8	3.45	3.8	5.00
e-0.9	**3.4**	0.00	**4.4**	0.00	**2.9**	0.00	**4**	0.00

Table D- 17: Effect of Wall Insulation on Energy Savings from Building Configuration

Wall Insulation	R-10		R-30		R-50	
Building Configuration	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use						
1 : 1, 1-story	**81.96**	0.00	**79.47**	0.00	**79.02**	0.00
1.5 : 1, 1-story	81.59	0.45	78.98	0.62	78.5	0.66
2 : 1, 1-story	81.48	0.59	78.62	1.07	78.14	1.11
2.5 : 1, 1-story	81.51	0.55	78.37	1.38	77.87	1.46
3 : 1, 1-story	81.61	0.43	78.22	1.57	77.66	1.72
1 : 1, 2-story	79.39	3.14	76.46	3.79	76.18	3.59
1.5 : 1, 2-story	78.96	3.66	75.91	4.48	75.61	4.32
2 : 1, 2-story	78.84	3.81	75.55	4.93	75.23	4.80
2.5 : 1, 2-story	78.91	3.72	75.3	5.25	74.94	5.16
3 : 1, 2-story	79.09	3.50	75.08	5.52	74.69	5.48
Space Cooling Energy Use						
1 : 1, 1-story	**22.3**	0.00	**21.6**	0.00	**21.5**	0.00
1.5 : 1, 1-story	21.8	2.24	21.2	1.85	21	2.33
2 : 1, 1-story	21.5	3.59	20.8	3.70	20.7	3.72
2.5 : 1, 1-story	21.2	4.93	20.5	5.09	20.4	5.12
3 : 1, 1-story	21	5.83	20.2	6.48	20.1	6.51
1 : 1, 2-story	20.4	8.52	19.8	8.33	19.7	8.37
1.5 : 1, 2-story	19.9	10.76	19.3	10.65	19.2	10.70
2 : 1, 2-story	19.6	12.11	18.9	12.50	18.8	12.56
2.5 : 1, 2-story	19.4	13.00	18.6	13.89	18.6	13.49
3 : 1, 2-story	19.2	13.90	18.4	14.81	18.3	14.88
Space Heating Energy Use						
1 : 1, 1-story	**3.4**	0.00	**1.6**	0.00	**1.3**	0.00
1.5 : 1, 1-story	3.5	(2.94)	1.7	(6.25)	1.3	0.00
2 : 1, 1-story	3.8	(11.76)	1.8	(12.50)	1.4	(7.69)
2.5 : 1, 1-story	4.1	(20.59)	1.9	(18.75)	1.5	(15.38)
3 : 1, 1-story	4.4	(29.41)	2	(25.00)	1.6	(23.08)
1 : 1, 2-story	2.9	14.71	0.8	50.00	0.6	53.85
1.5 : 1, 2-story	3.1	8.82	0.8	50.00	0.6	53.85
2 : 1, 2-story	3.3	2.94	0.9	43.75	0.6	53.85
2.5 : 1, 2-story	3.6	(5.88)	0.9	43.75	0.6	53.85
3 : 1, 2-story	4	(17.65)	1	37.50	0.7	46.15

Table D- 18: Effect of Wall Insulation on Energy Savings from Wall Absorptance

Wall Insulation	R-10		R-30		R-50	
Wall Absorptance	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use						
a-0.25	80.88	1.32	79.08	0.49	78.78	0.30
a-0.4	81.41	0.67	79.27	0.25	78.91	0.14
a-0.55	**81.96**	0.00	**79.47**	0.00	**79.02**	0.00
a-0.7	82.49	(0.65)	79.67	(0.25)	79.14	(0.15)
a-0.85	83.02	(1.29)	79.83	(0.45)	79.26	(0.30)
Space Cooling Energy Use						
a-0.25	21.2	4.93	21.3	1.39	21.3	0.93
a-0.4	21.8	2.24	21.5	0.46	21.4	0.47
a-0.55	**22.3**	0.00	**21.6**	0.00	**21.5**	0.00
a-0.7	22.8	(2.24)	21.8	(0.93)	21.7	(0.93)
a-0.85	23.4	(4.93)	22	(1.85)	21.8	(1.40)
Space Heating Energy Use						
a-0.25	3.5	(2.94)	1.7	(6.25)	1.3	0.00
a-0.4	3.4	0.00	1.6	0.00	1.3	0.00
a-0.55	**3.4**	0.00	**1.6**	0.00	**1.3**	0.00
a-0.7	3.3	2.94	1.6	0.00	1.3	0.00
a-0.85	3.2	5.88	1.6	0.00	1.3	0.00

Table D- 19: Effect of Wall Insulation on Energy Savings from Wall Emissivity

Wall Insulation	R-10		R-30		R-50	
Wall Emissivity	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use						
e-0.1	83	(1.27)	79.96	(0.62)	79.41	(0.49)
e-0.3	82.59	(0.77)	79.77	(0.38)	79.27	(0.32)
e-0.5	82.32	(0.44)	79.66	(0.24)	79.16	(0.18)
e-0.7	82.12	(0.20)	79.55	(0.10)	79.08	(0.08)
e-0.9	**81.96**	0.00	**79.47**	0.00	**79.02**	0.00
Space Cooling Energy Use						
e-0.1	83	(1.27)	79.96	(0.62)	79.41	(0.49)
e-0.3	82.59	(0.77)	79.77	(0.38)	79.27	(0.32)
e-0.5	82.32	(0.44)	79.66	(0.24)	79.16	(0.18)
e-0.7	82.12	(0.20)	79.55	(0.10)	79.08	(0.08)
e-0.9	**81.96**	0.00	**79.47**	0.00	**79.02**	0.00
Space Heating Energy Use						
e-0.1	2.9	14.71	1.5	6.25	1.2	7.69
e-0.3	3.1	8.82	1.5	6.25	1.3	0.00
e-0.5	3.2	5.88	1.6	0.00	1.3	0.00
e-0.7	3.3	2.94	1.6	0.00	1.3	0.00
e-0.9	**3.4**	0.00	**1.6**	0.00	**1.3**	0.00

Table D- 20: Effect of Wall Absorptance on Energy Savings from Building Configuration

Wall Absorptance	a-0.25		a-0.55		a-0.85	
Building Configuration	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use						
1 : 1, 1-story	**80.88**	0.00	**81.96**	0.00	**83.02**	0.00
1.5 : 1, 1-story	80.49	0.48	81.59	0.45	82.64	0.46
2 : 1, 1-story	80.32	0.69	81.48	0.59	82.56	0.55
2.5 : 1, 1-story	80.31	0.70	81.51	0.55	82.67	0.42
3 : 1, 1-story	80.39	0.61	81.61	0.43	82.82	0.24
1 : 1, 2-story	77.87	3.72	79.39	3.14	80.91	2.54
1.5 : 1, 2-story	77.42	4.28	78.96	3.66	80.49	3.05
2 : 1, 2-story	77.28	4.45	78.84	3.81	80.44	3.11
2.5 : 1, 2-story	77.28	4.45	78.91	3.72	80.59	2.93
3 : 1, 2-story	77.41	4.29	79.09	3.50	80.83	2.64
Space Cooling Energy Use						
1 : 1, 1-story	**21.2**	0.00	**22.3**	0.00	**23.4**	0.00
1.5 : 1, 1-story	20.7	2.36	21.8	2.24	22.9	2.14
2 : 1, 1-story	20.3	4.25	21.5	3.59	22.6	3.42
2.5 : 1, 1-story	20	5.66	21.2	4.93	22.4	4.27
3 : 1, 1-story	19.8	6.60	21	5.83	22.2	5.13
1 : 1, 2-story	18.9	10.85	20.4	8.52	22	5.98
1.5 : 1, 2-story	18.3	13.68	19.9	10.76	21.5	8.12
2 : 1, 2-story	18	15.09	19.6	12.11	21.2	9.40
2.5 : 1, 2-story	17.7	16.51	19.4	13.00	21	10.26
3 : 1, 2-story	17.4	17.92	19.2	13.90	21	10.26
Space Heating Energy Use						
1 : 1, 1-story	**3.5**	0.00	**3.4**	0.00	**3.2**	0.00
1.5 : 1, 1-story	3.7	(5.71)	3.5	(2.94)	3.4	(6.25)
2 : 1, 1-story	3.9	(11.43)	3.8	(11.76)	3.6	(12.50)
2.5 : 1, 1-story	4.3	(22.86)	4.1	(20.59)	4	(25.00)
3 : 1, 1-story	4.6	(31.43)	4.4	(29.41)	4.3	(34.38)
1 : 1, 2-story	3.2	8.57	2.9	14.71	2.7	15.63
1.5 : 1, 2-story	3.4	2.86	3.1	8.82	2.9	9.37
2 : 1, 2-story	3.6	(2.86)	3.3	2.94	3.1	3.12
2.5 : 1, 2-story	4	(14.29)	3.6	(5.88)	3.4	(6.25)
3 : 1, 2-story	4.3	(22.86)	4	(17.65)	3.7	(15.63)

Table D- 21: Effect of Wall Absorptance on Energy Savings from Wall Insulation

Wall Absorptance	a-0.25		a-0.55		a-0.85	
Wall Insulation	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use						
R-10	**80.88**	0.00	**81.96**	0.00	**83.02**	0.00
R-15	79.91	1.20	80.65	1.60	81.4	1.95
R-20	79.45	1.77	80.02	2.37	80.59	2.93
R-25	79.21	2.06	79.7	2.76	80.12	3.49
R-30	79.08	2.23	79.47	3.04	79.83	3.84
R-35	78.95	2.39	79.3	3.25	79.61	4.11
R-40	78.88	2.47	79.18	3.39	79.48	4.26
R-45	78.82	2.55	79.1	3.49	79.35	4.42
R-50	78.78	2.60	79.02	3.59	79.26	4.53
R-55	78.75	2.63	78.98	3.64	79.2	4.60
Space Cooling Energy Use						
R-10	**21.2**	0.00	**22.3**	0.00	**23.4**	0.00
R-15	21.2	0.00	22	1.35	22.7	2.99
R-20	21.2	0.00	21.8	2.24	22.3	4.70
R-25	21.3	(0.47)	21.7	2.69	22.2	5.13
R-30	21.3	(0.47)	21.6	3.14	22	5.98
R-35	21.3	(0.47)	21.6	3.14	21.9	6.41
R-40	21.3	(0.47)	21.6	3.14	21.9	6.41
R-45	21.3	(0.47)	21.6	3.14	21.8	6.84
R-50	21.3	(0.47)	21.5	3.59	21.8	6.84
R-55	21.3	(0.47)	21.5	3.59	21.7	7.26
Space Heating Energy Use						
R-10	**3.5**	0.00	**3.4**	0.00	**3.2**	0.00
R-15	2.5	28.57	2.5	26.47	2.4	25.00
R-20	2.1	40.00	2	41.18	2	37.50
R-25	1.8	48.57	1.8	47.06	1.7	46.88
R-30	1.7	51.43	1.6	52.94	1.6	50.00
R-35	1.5	57.14	1.5	55.88	1.5	53.13
R-40	1.5	57.14	1.4	58.82	1.4	56.25
R-45	1.4	60.00	1.4	58.82	1.3	59.38
R-50	1.3	62.86	1.3	61.76	1.3	59.38
R-55	1.3	62.86	1.3	61.76	1.3	59.38

Table D- 22: Effect of Wall Absorptance on Energy Savings from Wall Emissivity

Wall Absorptance	a-0.25		a-0.55		a-0.85	
Wall Emissivity	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use						
e-0.1	81.44	(0.69)	83	(1.27)	84.49	(1.77)
e-0.3	81.2	(0.40)	82.59	(0.77)	83.93	(1.10)
e-0.5	81.08	(0.25)	82.32	(0.44)	83.55	(0.64)
e-0.7	80.96	(0.10)	82.12	(0.20)	83.26	(0.29)
e-0.9	**80.88**	0.00	**81.96**	0.00	**83.02**	0.00
Space Cooling Energy Use						
e-0.1	22.1	(4.25)	23.6	(5.83)	25	(6.84)
e-0.3	21.8	(2.83)	23.1	(3.59)	24.4	(4.27)
e-0.5	21.5	(1.42)	22.8	(2.24)	24	(2.56)
e-0.7	21.4	(0.94)	22.5	(0.90)	23.6	(0.85)
e-0.9	**21.2**	0.00	**22.3**	0.00	**23.4**	0.00
Space Heating Energy Use						
e-0.1	3	14.29	2.9	14.71	2.8	12.50
e-0.3	3.2	8.57	3.1	8.82	2.9	9.37
e-0.5	3.3	5.71	3.2	5.88	3.1	3.12
e-0.7	3.4	2.86	3.3	2.94	3.1	3.12
e-0.9	**3.5**	0.00	**3.4**	0.00	**3.2**	0.00

Table D- 23: Effect of Wall Emissivity on Energy Savings from Building Configuration

Wall Emissivity	e-0.1		e-0.5		e-0.9	
Building Configuration	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use						
1 : 1, 1-story	**83**	0.00	**82.32**	0.00	**81.96**	0.00
1.5 : 1, 1-story	82.64	0.43	81.97	0.43	81.59	0.45
2 : 1, 1-story	82.58	0.51	81.9	0.51	81.48	0.59
2.5 : 1, 1-story	82.69	0.37	81.96	0.44	81.51	0.55
3 : 1, 1-story	82.87	0.16	82.09	0.28	81.61	0.43
1 : 1, 2-story	80.96	2.46	79.92	2.92	79.39	3.14
1.5 : 1, 2-story	80.64	2.84	79.53	3.39	78.96	3.66
2 : 1, 2-story	80.7	2.77	79.51	3.41	78.84	3.81
2.5 : 1, 2-story	80.88	2.55	79.61	3.29	78.91	3.72
3 : 1, 2-story	81.13	2.25	79.8	3.06	79.09	3.50
Space Cooling Energy Use						
1 : 1, 1-story	**23.6**	0.00	**22.8**	0.00	**22.3**	0.00
1.5 : 1, 1-story	23.2	1.69	22.3	2.19	22.1	0.90
2 : 1, 1-story	23	2.54	22.1	3.07	21.9	1.79
2.5 : 1, 1-story	22.9	2.97	21.9	3.95	21.7	2.69
3 : 1, 1-story	22.8	3.39	21.7	4.82	21.2	4.93
1 : 1, 2-story	22.4	5.08	21.2	7.02	20.7	7.17
1.5 : 1, 2-story	22	6.78	20.7	9.21	20.4	8.52
2 : 1, 2-story	21.9	7.20	20.4	10.53	20.3	8.97
2.5 : 1, 2-story	21.9	7.20	20.3	10.96	20.2	9.42
3 : 1, 2-story	21.8	7.63	20.2	11.40	23.1	(3.59)
Space Heating Energy Use						
1 : 1, 1-story	**2.9**	0.00	**3.2**	0.00	**3.4**	0.00
1.5 : 1, 1-story	3	(3.45)	3.3	(3.13)	3.5	(2.94)
2 : 1, 1-story	3.2	(10.34)	3.6	(12.50)	3.8	(11.76)
2.5 : 1, 1-story	3.4	(17.24)	3.8	(18.75)	4.1	(20.59)
3 : 1, 1-story	3.6	(24.14)	4.2	(31.25)	4.4	(29.41)
1 : 1, 2-story	2.3	20.69	2.7	15.63	2.9	14.71
1.5 : 1, 2-story	2.3	20.69	2.8	12.50	3.1	8.82
2 : 1, 2-story	2.5	13.79	3	6.25	3.3	2.94
2.5 : 1, 2-story	2.8	3.45	3.3	(3.13)	3.6	(5.88)
3 : 1, 2-story	3	(3.45)	3.6	(12.50)	4	(17.65)

Table D- 24: Effect of Wall Emissivity on Energy Savings from Wall Insulation

Wall Emissivity	**e-0.1**		**e-0.5**		**e-0.9**	
Wall Insulation	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use						
R-10	**82.32**	0.00	**82.12**	0.00	**81.96**	0.00
R-15	80.95	1.66	80.78	1.63	80.65	1.60
R-20	80.27	2.49	80.13	2.42	80.02	2.37
R-25	79.88	2.96	79.75	2.89	79.7	2.76
R-30	79.66	3.23	79.55	3.13	79.47	3.04
R-35	79.47	3.46	79.38	3.34	79.3	3.25
R-40	79.34	3.62	79.26	3.48	79.18	3.39
R-45	79.23	3.75	79.15	3.62	79.1	3.49
R-50	79.16	3.84	79.08	3.70	79.02	3.59
R-55	79.11	3.90	79.03	3.76	78.98	3.64
Space Cooling Energy Use						
R-10	**22.8**	0.00	**22.5**	0.00	**22.3**	0.00
R-15	22.3	2.19	22.1	1.78	22	1.35
R-20	22.1	3.07	21.9	2.67	21.8	2.24
R-25	21.9	3.95	21.8	3.11	21.7	2.69
R-30	21.9	3.95	21.7	3.56	21.6	3.14
R-35	21.8	4.39	21.7	3.56	21.6	3.14
R-40	21.7	4.82	21.7	3.56	21.6	3.14
R-45	21.7	4.82	21.6	4.00	21.6	3.14
R-50	21.7	4.82	21.6	4.00	21.5	3.59
R-55	21.7	4.82	21.6	4.00	21.5	3.59
Space Heating Energy Use						
R-10	**3.2**	0.00	**3.3**	0.00	**3.4**	0.00
R-15	2.4	25.00	2.4	27.27	2.5	26.47
R-20	2	37.50	2	39.39	2	41.18
R-25	1.7	46.88	1.7	48.48	1.8	47.06
R-30	1.6	50.00	1.6	51.52	1.6	52.94
R-35	1.5	53.13	1.5	54.55	1.5	55.88
R-40	1.4	56.25	1.4	57.58	1.4	58.82
R-45	1.3	59.38	1.3	60.61	1.4	58.82
R-50	1.3	59.38	1.3	60.61	1.3	61.76
R-55	1.3	59.38	1.3	60.61	1.3	61.76

Table D- 25: Effect of Wall Emissivity on Energy Savings from Wall Absorptance

Wall Emissivity	**e-0.1**		**e-0.5**		**e-0.9**	
Wall Absorptance	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use						
a-0.25	81.44	1.88	81.08	1.51	80.88	1.32
a-0.4	82.22	0.94	81.69	0.77	81.41	0.67
a-0.55	**83**	0.00	**82.32**	0.00	**81.96**	0.00
a-0.7	83.73	(0.88)	82.92	(0.73)	82.49	(0.65)
a-0.85	84.49	(1.80)	83.55	(1.49)	83.02	(1.29)
Space Cooling Energy Use						
a-0.25	22.1	6.36	21.5	5.70	21.2	4.93
a-0.4	22.9	2.97	22.2	2.63	21.8	2.24
a-0.55	**23.6**	0.00	**22.8**	0.00	**22.3**	0.00
a-0.7	24.3	(2.97)	23.4	(2.63)	22.8	(2.24)
a-0.85	25	(5.93)	24	(5.26)	23.4	(4.93)
Space Heating Energy Use						
a-0.25	3	(3.45)	3.3	(3.13)	3.5	(2.94)
a-0.4	3	(3.45)	3.2	0.00	3.4	0.00
a-0.55	**2.9**	0.00	**3.2**	0.00	**3.4**	0.00
a-0.7	2.8	3.45	3.1	3.12	3.3	2.94
a-0.85	2.8	3.45	3.1	3.12	3.2	5.88

Table D- 26: Effect of Construction Type on Annual Energy Use

Building configuration	1:1, 1-story		1:1, 2-story		2:1, 1-story		2:1, 2-story		3:1, 1-story		3:1, 2-story	
Construction Type	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use												
WD24	**73.49**	0.00	**72.77**	0.00	**72.62**	0.00	**71.9**	0.00	**72.21**	0.00	**71.5**	0.00
WD26	73.23	0.35	72.25	0.71	72.31	0.43	71.34	0.78	71.9	0.43	70.83	0.94
SIP	73.23	0.35	72.28	0.67	72.33	0.40	71.38	0.72	71.81	0.55	70.85	0.91
ICF	73.06	0.59	71.98	1.09	72.12	0.69	71.06	1.17	71.55	0.91	70.5	1.40
CFCB	72.95	0.73	71.87	1.24	72.01	0.84	70.87	1.43	71.5	0.98	72.67	(1.64)
PFCB	73.01	0.65	71.94	1.14	72.07	0.76	70.98	1.28	71.54	0.93	70.43	1.50
SIPH (85% Airtight)	72.05	1.96	71.44	1.83	71.11	2.08	70.52	1.92	70.43	2.47	69.93	2.20
WD24 (85% Airtight)	72.28	1.65	71.45	1.81	71.35	1.75	70.54	1.89	70.85	1.88	70.06	2.01
ICF (50% Airtight)	72.56	1.27	71.52	1.72	71.63	1.36	70.6	1.81	71.01	1.66	70.01	2.08
WD24 (50% Airtight)	72.7	1.07	71.95	1.13	71.78	1.16	71.05	1.18	71.35	1.19	70.63	1.22
Space Cooling Energy Use												
WD24	**17.3**	0.00	**16.4**	0.00	**16.5**	0.00	**15.6**	0.00	**16**	0.00	**15.1**	0.00
WD26	17.4	(0.58)	16.4	0.00	16.5	0.00	15.5	0.64	16.2	(1.25)	15	0.66
SIP	17.4	(0.58)	16.4	0.00	16.6	(0.61)	15.6	0.00	16.1	(0.63)	15.1	0.00
ICF	17.4	(0.58)	16.3	0.61	16.5	0.00	15.5	0.64	16	0.00	15	0.66
CFCB	17.2	0.58	16.1	1.83	16.3	1.21	15.3	1.92	15.8	1.25	17.1	(13.25)
PFCB	17.3	0.00	16.3	0.61	16.5	0.00	15.4	1.28	15.9	0.62	14.9	1.32
SIPH (85% Airtight)	16.6	4.05	16	2.44	15.7	4.85	15.2	2.56	15.2	5.00	14.7	2.65
WD24 (85% Airtight)	16.7	3.47	15.8	3.66	15.8	4.24	15	3.85	15.4	3.75	14.4	4.64
ICF (50% Airtight)	17	1.73	16.1	1.83	16.2	1.82	15.3	1.92	15.6	2.50	14.7	2.65
WD24 (50% Airtight)	16.9	2.31	16	2.44	16.1	2.42	15.2	2.56	15.6	2.50	14.7	2.65
Space Heating Energy Use												
WD24	**0.6**	0.00	**1**	0.00	**0.7**	0.00	**1**	0.00	**0.8**	0.00	**1.2**	0.00
WD26	0.3	50.00	0.5	50.00	0.3	57.14	0.5	50.00	0.3	62.50	0.6	50.00
SIP	0.2	66.67	0.4	60.00	0.3	57.14	0.4	60.00	0.4	50.00	0.5	58.33
ICF	0.2	66.67	0.2	80.00	0.2	71.43	0.2	80.00	0.2	75.00	0.3	75.00
CFCB	0.2	66.67	0.4	60.00	0.3	57.14	0.3	70.00	0.4	50.00	0	100.00
PFCB	0.2	66.67	0.3	70.00	0.2	71.43	0.3	70.00	0.3	62.50	0.3	75.00
SIPH (85% Airtight)	0	100.00	0	100.00	0	100.00	0	100.00	0	100.00	0.1	91.67
WD24 (85% Airtight)	0.1	83.33	0.3	70.00	0.1	85.71	0.3	70.00	0.2	75.00	0.5	58.33
ICF (50% Airtight)	0	100.00	0.1	90.00	0	100.00	0.1	90.00	0.1	87.50	0.1	91.67
WD24 (50% Airtight)	0.3	50.00	0.5	50.00	0.3	57.14	0.6	40.00	0.4	50.00	0.7	41.67

Table D- 27: Effect of Overhang Depth on Energy Savings from Window Redistribution

Overhang Depth (ft.)	0		2		4		6	
Window Distribution (S,N,E,W)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use								
25,25,25,25	**74.39**	0.00	**71.45**	0.00	**70.43**	0.00	**70.2**	0.00
35,25,20,20	74.02	0.50	71.04	0.57	70.12	0.44	70.05	0.21
45,25,15,15	73.86	0.71	70.72	1.02	69.8	0.89	69.91	0.41
55,25,10,10	73.76	0.85	70.41	1.46	69.49	1.33	69.78	0.60
65,25,5,5	73.68	0.95	70.14	1.83	69.18	1.77	69.65	0.78
35,55,5,5	72.1	3.08	70.15	1.82	69.8	0.89	69.92	0.40
45,45,5,5	72.49	2.55	70.05	1.96	69.6	1.18	69.84	0.51
55,35,5,5	73.03	1.83	70.07	1.93	69.36	1.52	69.75	0.64
65,25,5,5	73.68	0.95	70.14	1.83	69.18	1.77	69.65	0.78
75,15,5,5	74.44	(0.07)	70.25	1.68	69.06	1.95	69.57	0.90
Space Cooling Energy Use								
25,25,25,25	**17.9**	0.00	**14.9**	0.00	**13.4**	0.00	**12.8**	0.00
35,25,20,20	17.6	1.68	14.7	1.34	13.3	0.75	12.7	0.78
45,25,15,15	17.6	1.68	14.5	2.68	13.1	2.24	12.6	1.56
55,25,10,10	17.6	1.68	14.3	4.03	13	2.99	12.5	2.34
65,25,5,5	17.7	1.12	14.2	4.70	12.8	4.48	12.4	3.13
35,55,5,5	15.7	12.29	13.6	8.72	12.7	5.22	12.4	3.13
45,45,5,5	16.3	8.94	13.7	8.05	12.7	5.22	12.4	3.13
55,35,5,5	16.9	5.59	13.9	6.71	12.8	4.48	12.4	3.13
65,25,5,5	17.7	1.12	14.2	4.70	12.8	4.48	12.4	3.13
75,15,5,5	18.4	(2.79)	14.4	3.36	12.8	4.48	12.4	3.13
Space Heating Energy Use								
25,25,25,25	**0.9**	0.00	**1.4**	0.00	**2**	0.00	**2.5**	0.00
35,25,20,20	0.8	11.11	1.2	14.29	1.8	10.00	2.4	4.00
45,25,15,15	0.6	33.33	1.1	21.43	1.7	15.00	2.4	4.00
55,25,10,10	0.5	44.44	1	28.57	1.6	20.00	2.4	4.00
65,25,5,5	0.4	55.56	0.9	35.71	1.5	25.00	2.4	4.00
35,55,5,5	1.1	(22.22)	1.5	(7.14)	2.2	(10.00)	2.7	(8.00)
45,45,5,5	0.8	11.11	1.3	7.14	2	0.00	2.6	(4.00)
55,35,5,5	0.6	33.33	1.1	21.43	1.7	15.00	2.5	0.00
65,25,5,5	0.4	55.56	0.9	35.71	1.5	25.00	2.4	4.00
75,15,5,5	0.3	66.67	0.8	42.86	1.3	35.00	2.3	8.00

Table D- 28: Effect of Overhang Depth on Energy Savings from Window U-factor

Overhang Depth (ft.)	0		2		4		6	
U-value	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use								
0.29	74.68	(0.39)	71.17	0.39	69.62	1.15	69.12	1.54
0.47	**74.39**	0.00	**71.45**	0.00	**70.43**	0.00	**70.2**	0.00
0.65	74.66	(0.36)	72.26	(1.13)	71.51	(1.53)	71.47	(1.81)
0.83	75.26	(1.17)	73.18	(2.42)	72.68	(3.19)	72.79	(3.69)
1.1	76.43	(2.74)	74.84	(4.74)	74.59	(5.91)	74.87	(6.65)
Space Cooling Energy Use								
0.29	18.7	(4.47)	15.4	(3.36)	13.8	(2.99)	13.1	(2.34)
0.47	**17.9**	0.00	**14.9**	0.00	**13.4**	0.00	**12.8**	0.00
0.65	17.3	3.35	14.6	2.01	13.3	0.75	12.7	0.78
0.83	16.9	5.59	14.3	4.03	13.1	2.24	12.6	1.56
1.1	16.5	7.82	14.1	5.37	13.1	2.24	12.6	1.56
Space Heating Energy Use								
0.29	0.2	77.78	0.5	64.29	0.8	60.00	1.1	56.00
0.47	**0.9**	0.00	**1.4**	0.00	**2**	0.00	**2.5**	0.00
0.65	1.8	(100.00)	2.5	(78.57)	3.3	(65.00)	3.9	(56.00)
0.83	2.8	(211.11)	3.7	(164.29)	4.6	(130.00)	5.3	(112.00)
1.1	4.5	(400.00)	5.5	(292.86)	6.5	(225.00)	7.4	(196.00)

Table D- 29: Effect of Overhang Depth on Energy Savings from SHGC

Overhang Depth (ft.)	0		2		4		6	
SHGC	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use								
0.25	71.18	4.32	69.77	2.35	69.32	1.58	69.31	1.27
0.4	**74.39**	0.00	**71.45**	0.00	**70.43**	0.00	**70.2**	0.00
0.55	78.48	(5.50)	73.86	(3.37)	71.86	(2.03)	71.33	(1.61)
0.7	83.06	(11.65)	76.64	(7.26)	73.71	(4.66)	72.69	(3.55)
0.85	87.86	(18.11)	79.74	(11.60)	75.82	(7.65)	74.29	(5.83)
Space Cooling Energy Use								
0.25	14.2	20.67	12.5	16.11	11.7	12.69	11.3	11.72
0.4	**17.9**	0.00	**14.9**	0.00	**13.4**	0.00	**12.8**	0.00
0.55	21.9	(22.35)	17.5	(17.45)	15.3	(14.18)	14.4	(12.50)
0.7	26	(45.25)	20.2	(35.57)	17.3	(29.10)	16	(25.00)
0.85	30.4	(69.83)	23.1	(55.03)	19.4	(44.78)	17.7	(38.28)
Space Heating Energy Use								
0.25	1.8	(100.00)	2.4	(71.43)	2.9	(45.00)	3.3	(32.00)
0.4	**0.9**	0.00	**1.4**	0.00	**2**	0.00	**2.5**	0.00
0.55	0.4	55.56	0.8	42.86	1.3	35.00	1.8	28.00
0.7	0.2	77.78	0.5	64.29	0.8	60.00	1.3	48.00
0.85	0.1	88.89	0.2	85.71	0.5	75.00	0.9	64.00

Table D- 30: Effect of Window Redistribution on Energy Savings from Overhangs

Window Distribution (S,N,E,W)	65,25,5,5		25,25,25,25		75,15,5,5		35,55,5,5	
Overhang Depth (ft.)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use								
0	**73.68**	0.00	**74.39**	0.00	**74.44**	0.00	**72.1**	0.00
1	71.49	2.97	72.64	2.35	72.29	2.89	70.87	1.71
2	70.14	4.80	71.45	3.95	70.25	5.63	70.15	2.70
3	69.36	5.86	70.76	4.88	69.34	6.85	69.85	3.12
4	69.18	6.11	70.43	5.32	69.06	7.23	69.8	3.19
5	69.42	5.78	70.28	5.52	69.29	6.92	69.86	3.11
6	69.65	5.47	70.2	5.63	69.57	6.54	69.92	3.02
Space Cooling Energy Use								
0	**17.7**	0.00	**17.9**	0.00	**18.4**	0.00	**15.7**	0.00
1	15.6	11.86	16.1	10.06	16.4	10.87	14.4	8.28
2	14.2	19.77	14.9	16.76	14.4	21.74	13.6	13.38
3	13.3	24.86	14	21.79	13.4	27.17	13.1	16.56
4	12.8	27.68	13.4	25.14	12.8	30.43	12.7	19.11
5	12.5	29.38	13.1	26.82	12.5	32.07	12.5	20.38
6	12.4	29.94	12.8	28.49	12.4	32.61	12.4	21.02
Space Heating Energy Use								
0	**0.4**	0.00	**0.9**	0.00	**0.3**	0.00	**1.1**	0.00
1	0.6	(50.00)	1.1	(22.22)	0.5	(66.67)	1.3	(18.18)
2	0.9	(125.00)	1.4	(55.56)	0.8	(166.67)	1.5	(36.36)
3	1.1	(175.00)	1.7	(88.89)	1	(233.33)	1.9	(72.73)
4	1.5	(275.00)	2	(122.22)	1.3	(333.33)	2.2	(100.00)
5	2	(400.00)	2.3	(155.56)	1.9	(533.33)	2.4	(118.18)
6	2.4	(500.00)	2.5	(177.78)	2.3	(666.67)	2.7	(145.45)

Table D- 31: Effect of Window Redistribution on Energy Savings from Window U-factor

Window Distribution (S,N,E,W)	65,25,5,5		25,25,25,25		75,15,5,5		35,55,5,5	
U-value	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use								
0.29	74.5	(1.11)	74.68	(0.39)	75.4	(1.29)	72.16	(0.08)
0.47	**73.68**	0.00	**74.39**	0.00	**74.44**	0.00	**72.1**	0.00
0.65	73.51	0.23	74.66	(0.36)	74.07	0.50	72.65	(0.76)
0.83	73.71	(0.04)	75.26	(1.17)	74.08	0.48	73.37	(1.76)
1.1	74.43	(1.02)	76.43	(2.74)	74.61	(0.23)	74.88	(3.86)
Space Cooling Energy Use								
0.29	18.7	(5.65)	18.7	(4.47)	19.5	(5.98)	16.4	(4.46)
0.47	**17.7**	0.00	**17.9**	0.00	**18.4**	0.00	**15.7**	0.00
0.65	17	3.95	17.3	3.35	17.6	4.35	15.2	3.18
0.83	16.5	6.78	16.9	5.59	17.1	7.07	14.9	5.10
1.1	16	9.60	16.5	7.82	16.5	10.33	14.6	7.01
Space Heating Energy Use								
0.29	0.1	75.00	0.2	77.78	0	100.00	0.3	72.73
0.47	**0.4**	0.00	**0.9**	0.00	**0.3**	0.00	**1.1**	0.00
0.65	1	(150.00)	1.8	(100.00)	0.8	(166.67)	2.2	(100.00)
0.83	1.8	(350.00)	2.8	(211.11)	1.5	(400.00)	3.3	(200.00)
1.1	3.1	(675.00)	4.5	(400.00)	2.6	(766.67)	5.1	(363.64)

Table D- 32: Effect of Window Redistribution on Energy Savings from SHGC

Window Distribution (S,N,E,W)	65,25,5,5		25,25,25,25		75,15,5,5		35,55,5,5	
SHGC	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use								
0.25	70.07	4.90	71.18	4.32	70.32	5.53	69.97	2.95
0.4	**73.68**	0.00	**74.39**	0.00	**74.44**	0.00	**72.1**	0.00
0.55	78.23	(6.18)	78.48	(5.50)	79.35	(6.60)	75.08	(4.13)
0.7	83.03	(12.69)	83.06	(11.65)	84.64	(13.70)	78.58	(8.99)
0.85	88.08	(19.54)	87.86	(18.11)	90.1	(21.04)	82.4	(14.29)
Space Cooling Energy Use								
0.25	13.9	21.47	14.2	20.67	14.2	22.83	12.9	17.83
0.4	**17.7**	0.00	**17.9**	0.00	**18.4**	0.00	**15.7**	0.00
0.55	21.8	(23.16)	21.9	(22.35)	23	(25.00)	18.8	(19.75)
0.7	26.2	(48.02)	26	(45.25)	27.7	(50.54)	22.1	(40.76)
0.85	30.7	(73.45)	30.4	(69.83)	32.5	(76.63)	25.5	(62.42)
Space Heating Energy Use								
0.25	1.2	(200.00)	1.8	(100.00)	1	(233.33)	2.1	(90.91)
0.4	**0.4**	0.00	**0.9**	0.00	**0.3**	0.00	**1.1**	0.00
0.55	0.2	50.00	0.4	55.56	0.1	66.67	0.5	54.55
0.7	0.1	75.00	0.2	77.78	0	100.00	0.2	81.82
0.85	0	100.00	0.1	88.89	0	100.00	0.1	90.91

Table D- 33: Effect of Window U-factor on Energy Savings from Overhangs

U-Value	0.47		0.65		0.83	
Overhang Depth (ft.)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use						
0	**74.39**	0.00	**74.66**	0.00	**75.26**	0.00
1	72.64	2.35	73.23	1.92	73.95	1.74
2	71.45	3.95	72.26	3.21	73.18	2.76
3	70.76	4.88	71.72	3.94	72.78	3.30
4	70.43	5.32	71.51	4.22	72.68	3.43
5	70.28	5.52	71.47	4.27	72.73	3.36
6	70.2	5.63	71.47	4.27	72.79	3.28
Space Cooling Energy Use						
0	**17.9**	0.00	**17.3**	0.00	**16.9**	0.00
1	16.1	10.06	15.7	9.25	15.4	8.88
2	14.9	16.76	14.6	15.61	14.3	15.38
3	14	21.79	13.8	20.23	13.6	19.53
4	13.4	25.14	13.3	23.12	13.1	22.49
5	13.1	26.82	12.9	25.43	12.8	24.26
6	12.8	28.49	12.7	26.59	12.6	25.44
Space Heating Energy Use						
0	**0.9**	0.00	**1.8**	0.00	**2.8**	0.00
1	1.1	(22.22)	2.2	(22.22)	3.2	(14.29)
2	1.4	(55.56)	2.5	(38.89)	3.7	(32.14)
3	1.7	(88.89)	2.9	(61.11)	4.1	(46.43)
4	2	(122.22)	3.3	(83.33)	4.6	(64.29)
5	2.3	(155.56)	3.6	(100.00)	5	(78.57)
6	2.5	(177.78)	3.9	(116.67)	5.3	(89.29)

Table D- 34: Effect of Window U-factor on Energy Savings from Window Redistribution

U-Value	0.47		0.65		0.83	
Window Distribution (S,N,E,W)	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use						
25,25,25,25	**74.39**	0.00	**74.66**	0.00	**75.26**	0.00
35,25,20,20	74.02	0.50	74.15	0.68	74.7	0.74
45,25,15,15	73.86	0.71	73.86	1.07	74.29	1.29
55,25,10,10	73.76	0.85	73.65	1.35	73.98	1.70
65,25,5,5	73.68	0.95	73.51	1.54	73.71	2.06
35,55,5,5	72.1	3.08	72.65	2.69	73.37	2.51
45,45,5,5	72.49	2.55	72.68	2.65	73.32	2.58
55,35,5,5	73.03	1.83	73.03	2.18	73.44	2.42
65,25,5,5	73.68	0.95	73.51	1.54	73.71	2.06
75,15,5,5	74.44	(0.07)	74.07	0.79	74.08	1.57
Space Cooling Energy Use						
25,25,25,25	**17.9**	0.00	**17.3**	0.00	**16.9**	0.00
35,25,20,20	17.6	1.68	17.1	1.16	16.7	1.18
45,25,15,15	17.6	1.68	17	1.73	16.6	1.78
55,25,10,10	17.6	1.68	17	1.73	16.5	2.37
65,25,5,5	17.7	1.12	17	1.73	16.5	2.37
35,55,5,5	15.7	12.29	15.2	12.14	14.9	11.83
45,45,5,5	16.3	8.94	15.7	9.25	15.3	9.47
55,35,5,5	16.9	5.59	16.3	5.78	15.9	5.92
65,25,5,5	17.7	1.12	17	1.73	16.5	2.37
75,15,5,5	18.4	(2.79)	17.6	(1.73)	17.1	(1.18)
Space Heating Energy Use						
25,25,25,25	**0.9**	0.00	**1.8**	0.00	**2.8**	0.00
35,25,20,20	0.8	11.11	1.6	11.11	2.6	7.14
45,25,15,15	0.6	33.33	1.3	27.78	2.3	17.86
55,25,10,10	0.5	44.44	1.2	33.33	2	28.57
65,25,5,5	0.4	55.56	1	44.44	1.8	35.71
35,55,5,5	1.1	(22.22)	2.2	(22.22)	3.3	(17.86)
45,45,5,5	0.8	11.11	1.6	11.11	2.7	3.57
55,35,5,5	0.6	33.33	1.3	27.78	2.2	21.43
65,25,5,5	0.4	55.56	1	44.44	1.8	35.71
75,15,5,5	0.3	66.67	0.8	55.56	1.5	46.43

Table D- 35: Effect of Window U-factor on Energy Savings from SHGC

U-Value	0.47		0.65		0.83	
SHGC	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**	**MBtu/yr**	**Savings (%)**
Total Energy Use						
0.25	71.18	4.32	72.11	3.42	73.25	2.67
0.4	**74.39**	0.00	**74.66**	0.00	**75.26**	0.00
0.55	78.48	(5.50)	78.16	(4.69)	78.29	(4.03)
0.7	83.06	(11.65)	82.35	(10.30)	82.02	(8.98)
0.85	87.86	(18.11)	86.88	(16.37)	86.27	(14.63)
Space Cooling Energy Use						
0.25	14.2	20.67	13.8	20.23	13.6	19.53
0.4	**17.9**	0.00	**17.3**	0.00	**16.9**	0.00
0.55	21.9	(22.35)	21.1	(21.97)	20.5	(21.30)
0.7	26	(45.25)	25.1	(45.09)	24.4	(44.38)
0.85	30.4	(69.83)	29.3	(69.36)	28.4	(68.05)
Space Heating Energy Use						
0.25	1.8	(100.00)	3.2	(77.78)	4.6	(64.29)
0.4	**0.9**	0.00	**1.8**	0.00	**2.8**	0.00
0.55	0.4	55.56	1	44.44	1.7	39.29
0.7	0.2	77.78	0.6	66.67	1.1	60.71
0.85	0.1	88.89	0.3	83.33	0.7	75.00

Table D- 36: Effect of SHGC on Energy Savings from Overhangs

SHGC	0.4		0.55		0.7	
Overhang Depth (ft.)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use						
0	**74.39**	0.00	**78.48**	0.00	**83.06**	0.00
1	72.64	2.35	75.74	3.49	79.27	4.56
2	71.45	3.95	73.86	5.89	76.64	7.73
3	70.76	4.88	72.62	7.47	74.84	9.90
4	70.43	5.32	71.86	8.44	73.71	11.26
5	70.28	5.52	71.51	8.88	73.07	12.03
6	70.2	5.63	71.33	9.11	72.69	12.48
Space Cooling Energy Use						
0	**17.9**	0.00	**21.9**	0.00	**26**	0.00
1	16.1	10.06	19.3	11.87	22.7	12.69
2	14.9	16.76	17.5	20.09	20.2	22.31
3	14	21.79	16.2	26.03	18.5	28.85
4	13.4	25.14	15.3	30.14	17.3	33.46
5	13.1	26.82	14.8	32.42	16.6	36.15
6	12.8	28.49	14.4	34.25	16	38.46
Space Heating Energy Use						
0	**1**	0.00	**0.4**	0.00	**0.2**	0.00
1	1.1	(10.00)	0.6	(50.00)	0.3	(50.00)
2	1.4	(40.00)	0.8	(100.00)	0.5	(150.00)
3	1.7	(70.00)	1	(150.00)	0.6	(200.00)
4	2	(100.00)	1.3	(225.00)	0.8	(300.00)
5	2.3	(130.00)	1.5	(275.00)	1.1	(450.00)
6	2.5	(150.00)	1.8	(350.00)	1.3	(550.00)

Table D- 37: Effect of SHGC on Energy Savings from Window Redistribution

SHGC	0.4		0.55		0.7	
Window Distribution (S,N,E,W)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use						
25,25,25,25	**74.39**	0.00	**78.48**	0.00	**83.06**	0.00
35,25,20,20	74.02	0.50	78.1	0.48	82.72	0.41
45,25,15,15	73.86	0.71	78.07	0.52	82.79	0.33
55,25,10,10	73.76	0.85	78.14	0.43	82.94	0.14
65,25,5,5	73.68	0.95	78.23	0.32	83.03	0.04
35,55,5,5	72.1	3.08	75.08	4.33	78.58	5.39
45,45,5,5	72.49	2.55	75.96	3.21	79.99	3.70
55,35,5,5	73.03	1.83	77.04	1.83	81.51	1.87
65,25,5,5	73.68	0.95	78.23	0.32	83.03	0.04
75,15,5,5	74.44	(0.07)	79.35	(1.11)	84.64	(1.90)
Space Cooling Energy Use						
25,25,25,25	**18**	0.00	**21.9**	0.00	**26**	0.00
35,25,20,20	17.6	2.22	21.6	1.37	25.8	0.77
45,25,15,15	17.6	2.22	21.6	1.37	25.9	0.38
55,25,10,10	17.6	2.22	21.7	0.91	26	0.00
65,25,5,5	17.7	1.67	21.8	0.46	26.2	(0.77)
35,55,5,5	15.7	12.78	18.8	14.16	22.1	15.00
45,45,5,5	16.3	9.44	19.7	10.05	23.4	10.00
55,35,5,5	16.9	6.11	20.7	5.48	24.8	4.62
65,25,5,5	17.7	1.67	21.8	0.46	26.2	(0.77)
75,15,5,5	18.4	(2.22)	23	(5.02)	27.7	(6.54)
Space Heating Energy Use						
25,25,25,25	**0.9**	0.00	**0.4**	0.00	**0.2**	0.00
35,25,20,20	0.8	11.11	0.3	25.00	0.2	0.00
45,25,15,15	0.6	33.33	0.3	25.00	0.1	50.00
55,25,10,10	0.5	44.44	0.2	50.00	0.1	50.00
65,25,5,5	0.4	55.56	0.2	50.00	0.1	50.00
35,55,5,5	1.1	(22.22)	0.5	(25.00)	0.2	0.00
45,45,5,5	0.8	11.11	0.4	0.00	0.2	0.00
55,35,5,5	0.6	33.33	0.3	25.00	0.1	50.00
65,25,5,5	0.4	55.56	0.2	50.00	0.1	50.00
75,15,5,5	0.3	66.67	0.1	75.00	0	100.00

Table D- 38: Effect of SHGC on Energy Savings from Window U-factor

SHGC	0.4		0.55		0.7	
U-Value	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Total Energy Use						
0.29	74.68	(0.39)	79.38	(1.15)	84.35	(1.55)
0.47	**74.39**	0.00	**78.48**	0.00	**83.06**	0.00
0.65	74.66	(0.36)	78.16	0.41	82.35	0.85
0.83	75.26	(1.17)	78.29	0.24	82.02	1.25
1.1	76.43	(2.74)	78.87	(0.50)	82.15	1.10
Space Cooling Energy Use						
0.29	18.7	(4.47)	23	(5.02)	27.4	(5.38)
0.47	**17.9**	0.00	**21.9**	0.00	**26**	0.00
0.65	17.3	3.35	21.1	3.65	25.1	3.46
0.83	16.9	5.59	20.5	6.39	24.4	6.15
1.1	16.5	7.82	19.9	9.13	23.6	9.23
Space Heating Energy Use						
0.29	0.2	77.78	0	100.00	0	100.00
0.47	**0.9**	0.00	**0.4**	0.00	**0.2**	0.00
0.65	1.8	(100.00)	1	(150.00)	0.6	(200.00)
0.83	2.8	(211.11)	1.7	(325.00)	1.1	(450.00)
1.1	4.5	(400.00)	3	(650.00)	2	(900.00)

Table D- 39: Effect of Air-conditioner Efficiency on Annual Energy Use

SEER	1 : 1, 1-story		1 : 1, 2-story		3 : 1, 1-story		3 : 1, 2-story	
	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Space Cooling Energy Use								
10	**17.3**	0.00	**16.4**	0.00	**16**	0.00	**15.1**	0.00
11	15.8	8.67	14.9	9.15	14.6	8.75	13.7	9.27
12	14.4	16.76	13.7	16.46	13.4	16.25	12.6	16.56
13	13.3	23.12	12.6	23.17	12.3	23.13	11.6	23.18
14	12.4	28.32	11.7	28.66	11.5	28.13	10.8	28.48
15	11.6	32.95	10.9	33.54	10.7	33.13	10.1	33.11
16	10.8	37.57	10.2	37.80	10	37.50	9.4	37.75
17	10.2	41.04	9.6	41.46	9.4	41.25	8.9	41.06
18	9.6	44.51	9.1	44.51	8.9	44.38	8.4	44.37
19	9.1	47.40	8.6	47.56	8.4	47.50	7.9	47.68
Total Energy Use								
10	**73.49**	0.00	**72.77**	0.00	**72.21**	0.00	**71.5**	0.00
11	71.91	2.15	71.28	2.05	70.75	2.02	70.13	1.92
12	70.6	3.93	70.04	3.75	69.53	3.71	68.99	3.51
13	69.49	5.44	68.99	5.19	68.5	5.14	68.02	4.87
14	68.54	6.74	68.09	6.43	67.62	6.36	67.19	6.03
15	67.71	7.87	67.31	7.50	66.86	7.41	66.48	7.02
16	66.99	8.84	66.62	8.45	66.19	8.34	65.85	7.90
17	66.35	9.72	66.02	9.28	65.6	9.15	65.29	8.69
18	65.78	10.49	65.48	10.02	65.08	9.87	64.8	9.37
19	65.28	11.17	65	10.68	64.61	10.52	64.36	9.99

Table D- 40: Effect of Water Heater Efficiency on Annual Energy Use

DHW EF	1 : 1, 1-story		1 : 1, 2-story		3 : 1, 1-story		3 : 1, 2-story	
	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
Water Heating Energy Use								
0.45	30.7	(17.34)	30.7	(17.34)	30.7	(17.34)	30.7	(17.34)
0.5	28.3	(7.66)	28.3	(7.66)	28.3	(7.66)	28.3	(7.66)
0.55	**26.4**	0.00	**26.4**	0.00	**26.4**	0.00	**26.4**	0.00
0.6	24.8	6.45	24.8	6.45	24.8	6.45	24.8	6.45
0.65	23.4	12.10	23.4	12.10	23.4	12.10	23.4	12.10
0.7	22.2	16.94	22.2	16.94	22.2	16.94	22.2	16.94
0.75	21.2	20.97	21.2	20.97	21.2	20.97	21.2	20.97
0.8	20.3	24.60	20.3	24.60	20.3	24.60	20.3	24.60
0.85	19.5	27.82	19.5	27.82	19.5	27.82	19.5	27.82
0.9	18.8	30.65	18.8	30.65	18.8	30.65	18.8	30.65
Total Energy Use								
0.45	77.58	(5.87)	76.86	(5.93)	76.3	(5.99)	75.6	(6.05)
0.5	75.22	(2.65)	74.5	(2.67)	73.93	(2.69)	73.23	(2.72)
0.55	**73.28**	0.00	**72.56**	0.00	**71.99**	0.00	**71.29**	0.00
0.6	71.66	2.21	70.94	2.23	70.38	2.24	69.67	2.27
0.65	70.3	4.07	69.58	4.11	69.01	4.14	**68.31**	4.18
0.7	69.12	5.68	68.4	5.73	67.84	5.76	67.14	5.82
0.75	68.11	7.06	67.39	7.13	66.82	7.18	66.12	7.25
0.8	67.22	8.27	66.5	8.35	65.94	8.40	65.23	8.50
0.85	66.44	9.33	65.72	9.43	65.15	9.50	64.45	9.59
0.9	65.74	10.29	65.02	10.39	64.45	10.47	63.75	10.58

Table D- 41: Energy Savings from Individual Application of Energy-Efficient Measures

Item No.	Energy-Efficient Measures	Space Heating		Space Cooling		DHW		Others		Total Site Energy	
		MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)
1	Basecase House	0.6		17.3		26.6		29		73.49	
2a	SIP Construction	0.1	83.33%	17.1	1.16%	26.6	0.00%	28.9	0.34%	72.72	1.05%
2b	+ Energy Recovery Ventilator	0	100.00%	16.6	4.05%	26.6	0.00%	28.9	0.34%	72.05	1.96%
3	High-Albedo Roofing	0.8	-33.33%	15	13.29%	26.6	0.00%	28.6	1.38%	71.11	3.24%
4	High-Albedo Exterior Walls	0.7	-16.67%	16.6	4.05%	26.6	0.00%	28.9	0.34%	72.76	0.99%
5	Argon-Filled Low-e Windows	0.6	0.00%	15.6	9.83%	26.6	0.00%	28.7	1.03%	71.56	2.63%
6	Vinyl Window Frames	0.5	16.67%	16.3	5.78%	26.6	0.00%	28.8	0.69%	72.19	1.77%
7a	Overhangs	1.4	-133.33%	13.1	24.28%	26.6	0.00%	28.4	2.07%	69.46	5.48%
7b	+ 75% Windows on the South	1	-66.67%	12.5	27.75%	26.6	0.00%	28.3	2.41%	68.31	7.05%
8	Efficient Lighting	0.8	-33.33%	16.4	5.20%	26.6	0.00%	24.5	15.52%	68.45	6.86%
9	Efficient Refrigerator	0.6	0.00%	17.1	1.16%	26.6	0.00%	28.1	3.10%	72.42	1.46%
10	Efficient Freezer	0.7	-16.67%	17	1.73%	26.6	0.00%	27.1	6.55%	71.36	2.90%
11	Efficient Dishwasher	0.7	-16.67%	17	1.73%	26.6	0.00%	27.1	6.55%	71.36	2.90%
12	Efficient Clothes Washer	0.7	-16.67%	16.9	2.31%	26.6	0.00%	26.8	7.59%	71.01	3.37%
13a	Tankless Water Heater (a) With	0.6	0.00%	17.3	0.00%	19.5	26.69%	29	0.00%	66.44	9.59%
13b	and (b) Without Electric Ignition	0.6	0.00%	17.3	0.00%	12.5	53.01%	29	0.00%	59.43	19.13%
14	SEER-15 AC	0.6	0.00%	11.6	32.95%	26.6	0.00%	29	0.00%	67.71	7.87%

Table D- 42: Energy Savings from Combined Application of Energy-Efficient Measures

Item No.	Energy-Efficient Measures	Space Heating		Space Cooling		DHW		Others		Total Site Energy		
		MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	MBtu/yr	Savings (%)	Incremental Savings (%)
1	Basecase House	0.6		17.3		26.6		29		73.49		
2a	+ SIP Construction	0.1	83.33%	17.1	1.16%	26.6	0.00%	28.9	0.34%	72.72	1.05%	
2b	+ Energy Recovery Ventilator	0	100.00%	16.6	4.05%	26.6	0.00%	28.9	0.34%	72.05	1.96%	0.91%
3	+ High-Albedo Roofing	0	100.00%	14.7	15.03%	26.6	0.00%	28.6	1.38%	69.95	4.82%	2.86%
4	+ High-Albedo Exterior Walls	0	100.00%	14.3	17.34%	26.6	0.00%	28.6	1.38%	69.51	5.42%	0.60%
5	+ Argon-Filled Low-e Windows	0	100.00%	12.5	27.75%	26.6	0.00%	28.3	2.41%	67.35	8.35%	2.94%
6	+ Vinyl Window Frames	0	100.00%	11.5	33.53%	26.6	0.00%	28.2	2.76%	66.26	9.84%	1.48%
7a	+ Overhangs	0	100.00%	8.2	52.60%	26.6	0.00%	27.7	4.48%	62.55	14.89%	5.05%
7b	+ 75% Windows on the South	0	100.00%	7.8	54.91%	26.6	0.00%	27.6	4.83%	62.01	15.62%	0.73%
8	+ Efficient Lighting	0.1	83.33%	7	59.54%	26.6	0.00%	23.2	20.00%	56.88	22.60%	6.98%
9	+ Efficient Refrigerator	0.1	83.33%	6.8	60.69%	26.6	0.00%	22.3	23.10%	55.83	24.03%	1.43%
10	+ Efficient Freezer	0.3	50.00%	6.4	63.01%	26.6	0.00%	20.1	30.69%	53.43	27.30%	3.27%
11	+ Efficient Dishwasher	0.3	50.00%	6.2	64.16%	26.6	0.00%	18.6	35.86%	51.71	29.64%	2.34%
12	+ Efficient Clothes Washer	0.6	0.00%	5.7	67.05%	26.6	0.00%	16.2	44.14%	49.05	33.26%	3.62%
13a	+ Tankless Water Heater (a) With	0.5	16.67%	5.7	67.05%	19.5	26.69%	16.3	43.79%	42.11	42.70%	9.44%
13b	and (b) Without Electric Ignition	0.5	16.67%	5.7	67.05%	12.5	53.01%	16.3	43.79%	35.1	52.24%	9.54%
14	+ SEER-15 AC	0.5	16.67%	3.8	78.03%	12.5	53.01%	16.3	43.79%	33.18	54.85%	2.61%

APPENDIX E

CALCULATIONS FOR THE ECONOMIC ANALYSIS

Calculations for the Economic Analysis

Section E.1 presents the economic analysis techniques used in this study. Section E.2 presents the input data and results of the analysis, using these techniques, for the basecase house with individual and combined application of energy-efficient measures.

E.1 Explanation of Terms and Equations for the Economic Analysis

This study used the annualized life-cycle cost analysis techniques described in ASHRAE (2003) and Haberl (1993). The explanation of terms and equations are given below. Table E- 1 presents the spreadsheet used for the calculations, which was originally developed by Haberl (1993) (based on up to 10-year life of the system to be analyzed), and was later modified by Kootin-Sanwu (2004) to account for up to 25-year life of the building. Table E- 2 presents the formulae used in this spreadsheet.

Definitions of Terms

C_e = cost of energy to operate the system for one period

$CRF(i,n)$ = capital recovery factor, defined by $i/\left[1-(1+i)^{-n}\right]$

$C_{s,assess}$ = initial assessed system value

$C_{s,salv}$ = system salvage value at the end of its useful life in constant dollars

$C_{s,init}$ = initial system cost

C_y = annualized system cost in constant dollars

$D_{k,SL}$ or $D_{k,SD}$ = amount of depreciation at the end of period k depending on the type of depreciation schedule used, *where*

$D_{k,SL} = (C_{s,init} - C_{s,salv})/n$, for the straight line depreciation method, and

$D_{k,SD} = (C_{s,init} - C_{s,salv})[2(n-k+1)]/n(n+1)$, for the sum-of-digits depreciation method in constant dollars

F	=	future value of a sum of money, defined by $P(1+i')^n$
i_d	=	discount rate
i_m	=	market mortgage rate (real rate + general inflation rate)
$i_m P_k$	=	interest charge at the end of period k
i'	=	$(i_d - j)/(1+j)$ = effective discount rate adjusted for energy inflation j, sometimes called the real discount rate
i''	=	$(i_d - j_e)/(1+j_e)$ = effective discount rate adjusted for energy inflation j_e
I	=	annual insurance costs
ITC	=	investment tax credit for energy efficiency improvements, if applicable
j	=	general inflation rate per period
j_e	=	general energy rate per period
k	=	end if period(s) in which replacement(s), repair(s), depreciation, or interest is calculated
M	=	periodic maintenance cost
n	=	number of period(s) under consideration
P	=	a sum of money at the present time, *i.e.*, its present value
P_k	=	$(C_{s,init} - ITC)\left[(1+i_m)^{k-1} + \frac{(1+i_m)^{k-1} - 1}{(1+i_m)^{-n} - 1}\right]$ = outstanding principle of the loan for $C_{s,init}$ at the end of period k in current dollars
$PWF(i,n)$	=	present worth factor, defined by $1/(1+i)^n$
R_k	=	net replacement(s), repair cost(s), or disposals at the end of period k in constant dollars

T_{inc} = (state tax rate + federal tax rate) – (state tax rate X federal tax rate) where tax rates are based on the last dollar earned, i.e., the marginal rates

T_{prop} = property tax rate

T_{salv} = tax rate applicable to salvage value of the system

Annualized Costs

C_y = – capital and interest + salvage value – replacements (or disposals) – operating energy – property tax – maintenance – insurance + interest tax deduction + depreciation (for commercial systems)

where

$(C_{s,init} - ITC)CRF(i',n)$ = capital and interest

$C_{s,salv}PWF(i',n)CRF(i',n)(1-T_{salv})$ = salvage value

$\sum_{k-1}^{n}[R_k PWF(i',k)]CRF(i',n)(1-T_{inc})$ = replacements for disposals

$C_e[CRF(i',n)/CRF(i'',n)](1-T_{inc})$ = operating energy

$C_{s,assess}T_{prop}(1-T_{inc})$ = property tax

$M(1-T_{inc})$ = maintenance

$I(1-T_{inc})$ = insurance

$T_{inc}\sum_{k-1}^{n}[i_m P_{k-1} PWF(i_d,k)]CRF(i',n)$ = interest tax deduction

$T_{inc}\sum_{k-1}^{n}[D_k PWF(i_d,k)]CRF(i',n)$ = depreciation (for commercial systems)

Working with Spreadsheet

The spreadsheet that was used for this analysis is shown in Table E- 1 Inputs to the spread sheet are entered into cell C3 to C29. Calculations then start from C32 to C98, proceed through the table F4 to L28 by column, E34, E 38, table F44 to H68, and are summarized in L44 to L54. The cell formulas are provided in Table E- 2.

Table E- 1: Spreadsheet for Calculating the Annualized Life-Cycle Cost

Row No. / Col. No.	A	B	C	D	E	F	G	H	I	J	K	L
1	ECONOMICS				Year	Payment	Interest	Princ	Outstand	PWF(id,k)	Disc	Disc
2	VALUES -------------------					Amount	Payment	Payment	Princ		Inter	Payment
3	Total 1st Year Cost =		$224,598		0				$224,598			
4	Investment Tax Credit =		$0		1	$16,160	$11,544	$4,616	$219,982	0.9615	$11,100	$15,539
5	Life =		25		2	$16,160	$11,307	$4,853	$215,129	0.9246	$10,454	$14,941
6	Salvage Value =		$0		3	$16,160	$11,058	$5,102	$210,027	0.8890	$9,830	$14,366
7	Salvage Year =		25		4	$16,160	$10,795	$5,365	$204,662	0.8548	$9,228	$13,814
8	Replacement/Disposal =		$72		5	$16,160	$10,520	$5,640	$199,021	0.8219	$8,646	$13,282
9	Replace/Disposal Yr =		5		6	$16,160	$10,230	$5,930	$193,091	0.7903	$8,085	$12,772
10	Replacement/Disposal =		$622		7	$16,160	$9,925	$6,235	$186,856	0.7599	$7,542	$12,280
11	Replace/Disposal Yr =		10		8	$16,160	$9,604	$6,556	$180,300	0.7307	$7,018	$11,808
12	Replacement/Disposal =		$2,620		9	$16,160	$9,267	$6,893	$173,407	0.7026	$6,511	$11,354
13	Replace/Disposal Yr =		15		10	$16,160	$8,913	$7,247	$166,160	0.6756	$6,021	$10,917
14	Replacement/Disposal =		$1,472		11	$16,160	$8,541	$7,619	$158,541	0.6496	$5,548	$10,497
15	Replace/Disposal Yr =		20		12	$16,160	$8,149	$8,011	$150,530	0.6246	$5,090	$10,094
16	Replacement/Disposal =		$72		13	$16,160	$7,737	$8,423	$142,107	0.6006	$4,647	$9,705
17	Replace/Disposal Yr =		25		14	$16,160	$7,304	$8,856	$133,251	0.5775	$4,218	$9,332
18	Discount Rate (id) =		4%		15	$16,160	$6,849	$9,311	$123,940	0.5553	$3,803	$8,973
19	Inflation Rate (j) =		3%		16	$16,160	$6,371	$9,790	$114,151	0.5339	$3,401	$8,628
20	Fuel Inflation Rate (je) =		5%		17	$16,160	$5,867	$10,293	$103,858	0.5134	$3,012	$8,296
21	Mortgage Rate (im) =		5%		18	$16,160	$5,338	$10,822	$93,036	0.4936	$2,635	$7,977
22	Annual Energy Costs =		$1,438		19	$16,160	$4,782	$11,378	$81,658	0.4746	$2,270	$7,670
23	Annual Maintenance =		$100		20	$16,160	$4,197	$11,963	$69,695	0.4564	$1,916	$7,375
24	Annual Insurance =		$50		21	$16,160	$3,582	$12,578	$57,117	0.4388	$1,572	$7,092
25	Depreciation =	S.L.	7%		22	$16,160	$2,936	$13,224	$43,893	0.4220	$1,239	$6,819
26	Income Tax =		5%		23	$16,160	$2,256	$13,904	$29,989	0.4057	$915	$6,557
27	Property Tax =		1%		24	$16,160	$1,541	$14,619	$15,370	0.3901	$601	$6,304
28	% of System Cost =		100%		25	$16,160	$790	$15,370	$0	0.3751	$296	$6,062
29	Salvage Tax =		0%				--------	--------			--------	--------
30					TOTAL		$103,164	$58,438			$84,436	$131,073
31	CALCULATIONS-------------------											
32	Effective int.(i')=		0.0117		Next apply the capital recovery factor & tax rate to total discounted int.sum.							
33	Effective int.(i")=		-0.0076									
34	CRF(i',n) =		0.0464		$196							
35	CRF(i",n) =		0.0362									
36	CRF(im,n) =		0.0720		Calculate the depreciation...first calculate depreciation							
37	PWF(id,1) =		0.9615									
38	PWF(id,2) =		0.9246		$8,984							
39	PWF(id,3) =		0.8890									
40	PWF(id,4) =		0.8548		Next, discount the depreciation and sum...							
41	PWF(id,5) =		0.8219									
42	PWF(id,6) =		0.7903		Year	Dk,SL	PWF(id,k)	Disc.Depr	Summarize the terms...			
43	PWF(id,7) =		0.7599									
44	PWF(id,8) =		0.7307		1	$8,984	0.9615	$8,638	Capital & Interest =			($10,410)
45	PWF(id,9) =		0.7026		2	$8,984	0.9246	$8,306	Salvage Value =			$0
46	PWF(id,10) =		0.6756		3	$8,984	0.8890	$7,987	Replacements			($178)
47	PWF(id,11) =		0.6496		4	$8,984	0.8548	$7,679	Operating Costs =			($1,752)
48	PWF(id,12) =		0.6246		5	$8,984	0.8219	$7,384	Property Tax =			($2,134)
49	PWF(id,13) =		0.6006		6	$8,984	0.7903	$7,100	Maintenance =			($95)
50	PWF(id,14) =		0.5775		7	$8,984	0.7599	$6,827	Insurance =			($48)
51	PWF(id,15) =		0.5553		8	$8,984	0.7307	$6,564	Interest Deduction =			$196
52	PWF(id,16) =		0.5339		9	$8,984	0.7026	$6,312	Depreciation Deduction =			$169
53	PWF(id,17) =		0.5134		10	$8,984	0.6756	$6,069				--------
54	PWF(id,18) =		0.4936		11	$8,984	0.6496	$5,836	TOTAL			($14,252)
55	PWF(id,19) =		0.4746		12	$8,984	0.6246	$5,611				
56	PWF(id,20) =		0.4564		13	$8,984	0.6006	$5,396				
57	PWF(id,21) =		0.4388		14	$8,984	0.5775	$5,188				

Table E- 1 (Cont.)

Row No. Col. No.	A	B	C	D	E	F	G	H	I	J	K	L
58	PWF(id,22) =		0.4220	|	15	$8,984	0.5553	$4,988				
59	PWF(id,23) =		0.4057	|	16	$8,984	0.5339	$4,797				
60	PWF(id,24) =		0.3901	|	17	$8,984	0.5134	$4,612				
61	PWF(id,25) =		0.3751	|	18	$8,984	0.4936	$4,435				
62	PWF(i',1) =		0.9885	|	19	$8,984	0.4746	$4,264				
63	PWF(i',2) =		0.9771	|	20	$8,984	0.4564	$4,100				
64	PWF(i',3) =		0.9658	|	21	$8,984	0.4388	$3,942				
65	PWF(i',4) =		0.9546	|	22	$8,984	0.4220	$3,791				
66	PWF(i',5) =		0.9436	|	23	$8,984	0.4057	$3,645				
67	PWF(i',6) =		0.9327	|	24	$8,984	0.3901	$3,505				
68	PWF(i',7) =		0.9220	|	25	$8,984	0.3751	$3,370				
69	PWF(i',8) =		0.9113	|				--------				
70	PWF(i',9) =		0.9008	|	TOTAL			$72,868				
71	PWF(i',10) =		0.8904	|								
72	PWF(i',11) =		0.8802	|	Now apply the capital recovery factor and tax...							
73	PWF(i',12) =		0.8700	|								
74	PWF(i',13) =		0.8600	|	$169							
75	PWF(i',14) =		0.8500	|								
76	PWF(i',15) =		0.8402	|								
77	PWF(i',16) =		0.8305	|								
78	PWF(i',17) =		0.8209	|								
79	PWF(i',18) =		0.8115	|								
80	PWF(i',19) =		0.8021	|								
81	PWF(i',20) =		0.7929	|								
82	PWF(i',21) =		0.7837	|								
83	PWF(i',22) =		0.7747	|								
84	PWF(i',23) =		0.7657	|								
85	PWF(i',24) =		1.2019	|								
86	PWF(i',25) =		0.3222	|								
87	Capitol & interest =		$10,410	|								
88	Salvage Value =		$0	|								
89	Replacement Costs (5th Yr) =		$2.97	|								
90	Replacement Costs (10th Yr) =		$24.37	|								
91	Replacement Costs (15th Yr) =		$96.92	|								
92	Replacement Costs (20th Yr) =		$51.37	|								
93	Replacement Costs (25th Yr) =		$2.36	|								
94	Replacement Costs =		$177.99	|								
95	Operating Energy =		$1,752	|								
96	Property Tax =		$2,134	|								
97	Maintenance =		$95	|								
98	Insurance =		$48	|								

Table E- 2: Formulae Used in the Spreadsheet for Calculating the Annualized Life-Cycle Cost

Row No. / Col. No.	A	B	C
31	CALCULATIONS-------------------		
32	Effective int.(i')=		=($C$18-$C$19)/(1+$C$19)
33	Effective int.(i")=		=($C$18-$C$20)/(1+$C$20)
34	CRF(i',n) =		=$C$32/(1-(1+$C$32)^(-$C$5))
35	CRF(i",n) =		=$C$33/(1-(1+$C$33)^(-$C$5))
36	CRF(im,n) =		=$C$21/(1-(1+$C$21)^(-$C$5))
37	PWF(id,1) =		=1/(1+$C$18)^1
38	PWF(id,2) =		=1/(1+$C$18)^2
39	PWF(id,3) =		=1/(1+$C$18)^3
40	PWF(id,4) =		=1/(1+$C$18)^4
41	PWF(id,5) =		=1/(1+$C$18)^5
42	PWF(id,6) =		=1/(1+$C$18)^6
43	PWF(id,7) =		=1/(1+$C$18)^7
44	PWF(id,8) =		=1/(1+$C$18)^8
45	PWF(id,9) =		=1/(1+$C$18)^9
46	PWF(id,10) =		=1/(1+$C$18)^10
47	PWF(id,11) =		=1/(1+$C$18)^11
48	PWF(id,12) =		=1/(1+$C$18)^12
49	PWF(id,13) =		=1/(1+$C$18)^13
50	PWF(id,14) =		=1/(1+$C$18)^14
51	PWF(id,15) =		=1/(1+$C$18)^15
52	PWF(id,16) =		=1/(1+$C$18)^16
53	PWF(id,17) =		=1/(1+$C$18)^17
54	PWF(id,18) =		=1/(1+$C$18)^18
55	PWF(id,19) =		=1/(1+$C$18)^19
56	PWF(id,20) =		=1/(1+$C$18)^20
57	PWF(id,21) =		=1/(1+$C$18)^21
58	PWF(id,22) =		=1/(1+$C$18)^22
59	PWF(id,23) =		=1/(1+$C$18)^23
60	PWF(id,24) =		=1/(1+$C$18)^24
61	PWF(id,25) =		=1/(1+$C$18)^25
62	PWF(i',1) =		=1/(1+$C$32)^1
63	PWF(i',2) =		=1/(1+$C$32)^2
64	PWF(i',3) =		=1/(1+$C$32)^3
65	PWF(i',4) =		=1/(1+$C$32)^4
66	PWF(i',5) =		=1/(1+$C$32)^5
67	PWF(i',6) =		=1/(1+$C$32)^6
68	PWF(i',7) =		=1/(1+$C$32)^7
69	PWF(i',8) =		=1/(1+$C$32)^8
70	PWF(i',9) =		=1/(1+$C$32)^9
71	PWF(i',10) =		=1/(1+$C$32)^10
72	PWF(i',11) =		=1/(1+$C$32)^11
73	PWF(i',12) =		=1/(1+$C$32)^12
74	PWF(i',13) =		=1/(1+$C$32)^13
75	PWF(i',14) =		=1/(1+$C$32)^14
76	PWF(i',15) =		=1/(1+$C$32)^15
77	PWF(i',16) =		=1/(1+$C$32)^16
78	PWF(i',17) =		=1/(1+$C$32)^17
79	PWF(i',18) =		=1/(1+$C$32)^18
80	PWF(i',19) =		=1/(1+$C$32)^19
81	PWF(i',20) =		=1/(1+$C$32)^20
82	PWF(i',21) =		=1/(1+$C$32)^21
83	PWF(i',22) =		=1/(1+$C$32)^22
84	PWF(i',23) =		=1/(1+$C$32)^23
85	PWF(i',24) =		=1/(1+$C$33)^24
86	PWF(i',25) =		=1/(1+$C$34)^25
87	Capitol & interest =		=($C$3-$C$4)*$C$34
88	Salvage Value =		=$C$6*(1/(1+$C$32)^$C$7)*$C$34*(1-$C$29)
89	Replacement Costs (5th Yr) =		=($C$8*(1/(1+$C$32)^$C$9)*$C$34*(1-$C$26))
90	Replacement Costs (10th Yr) =		=($C$10*(1/(1+$C$32)^$C$11)*$C$34*(1-$C$26))
91	Replacement Costs (15th Yr) =		=($C$12*(1/(1+$C$32)^$C$13)*$C$34*(1-$C$26))
92	Replacement Costs (20th Yr) =		=($C$14*(1/(1+$C$32)^$C$15)*$C$34*(1-$C$26))
93	Replacement Costs (25th Yr) =		=($C$16*(1/(1+$C$32)^$C$17)*$C$34*(1-$C$26))
94	Replacement Costs =		=SUM(C89:C93)
95	Operating Energy =		=$C$22*($C$34/$C$35)*(1-$C$26)
96	Property Tax =		=$C$3*$C$28*$C$27*(1-$C$26)
97	Maintenance =		=$C$23*(1-$C$26)
98	Insurance =		=$C$24*(1-$C$26)

Table E- 2 (Cont.)

Row No. / Col. No.	E	F	G	H	I	J	K	L
1 / 2	Year	Payment Amount	Interest Payment	Princ Payment	Outstand Princ	PWF(id,k)	Disc Inter	Disc Payment
3	0				$0			
4	1	=IF(E4<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E4<'=$C$5,+$C$21*$I3,0)	=F4-G4	=IF(E4<'=$C$5,+I3-H4,0)	=IF(E4<'=$C$5,+1/(1+$C$18)^E4,0)	=G4*J4	=F4*J4
5	2	=IF(E5<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E5<'=$C$5,+$C$21*$I4,0)	=F5-G5	=IF(E5<'=$C$5,+I4-H5,0)	=IF(E5<'=$C$5,+1/(1+$C$18)^E5,0)	=G5*J5	=F5*J5
6	3	=IF(E6<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E6<'=$C$5,+$C$21*$I5,0)	=F6-G6	=IF(E6<'=$C$5,+I5-H6,0)	=IF(E6<'=$C$5,+1/(1+$C$18)^E6,0)	=G6*J6	=F6*J6
7	4	=IF(E7<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E7<'=$C$5,+$C$21*$I6,0)	=F7-G7	=IF(E7<'=$C$5,+I6-H7,0)	=IF(E7<'=$C$5,+1/(1+$C$18)^E7,0)	=G7*J7	=F7*J7
8	5	=IF(E8<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E8<'=$C$5,+$C$21*$I7,0)	=F8-G8	=IF(E8<'=$C$5,+I7-H8,0)	=IF(E8<'=$C$5,+1/(1+$C$18)^E8,0)	=G8*J8	=F8*J8
9	6	=IF(E9<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E9<'=$C$5,+$C$21*$I8,0)	=F9-G9	=IF(E9<'=$C$5,+I8-H9,0)	=IF(E9<'=$C$5,+1/(1+$C$18)^E9,0)	=G9*J9	=F9*J9
10	7	=IF(E10<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E10<'=$C$5,+$C$21*$I9,0)	=F10-G10	=IF(E10<'=$C$5,+I9-H10,0)	=IF(E10<'=$C$5,+1/(1+$C$18)^E10,0)	=G10*J10	=F10*J10
11	8	=IF(E11<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E11<'=$C$5,+$C$21*$I10,0)	=F11-G11	=IF(E11<'=$C$5,+I10-H11,0)	=IF(E11<'=$C$5,+1/(1+$C$18)^E11,0)	=G11*J11	=F11*J11
12	9	=IF(E12<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E12<'=$C$5,+$C$21*$I11,0)	=F12-G12	=IF(E12<'=$C$5,+I11-H12,0)	=IF(E12<'=$C$5,+1/(1+$C$18)^E12,0)	=G12*J12	=F12*J12
13	10	=IF(E13<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E13<'=$C$5,+$C$21*$I12,0)	=F13-G13	=IF(E13<'=$C$5,+I12-H13,0)	=IF(E13<'=$C$5,+1/(1+$C$18)^E13,0)	=G13*J13	=F13*J13
14	11	=IF(E14<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E14<'=$C$5,+$C$21*$I13,0)	=F14-G14	=IF(E14<'=$C$5,+I13-H14,0)	=IF(E14<'=$C$5,+1/(1+$C$18)^E14,0)	=G14*J14	=F14*J14
15	12	=IF(E15<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E15<'=$C$5,+$C$21*$I14,0)	=F15-G15	=IF(E15<'=$C$5,+I14-H15,0)	=IF(E15<'=$C$5,+1/(1+$C$18)^E15,0)	=G15*J15	=F15*J15
16	13	=IF(E16<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E16<'=$C$5,+$C$21*$I15,0)	=F16-G16	=IF(E16<'=$C$5,+I15-H16,0)	=IF(E16<'=$C$5,+1/(1+$C$18)^E16,0)	=G16*J16	=F16*J16
17	14	=IF(E17<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E17<'=$C$5,+$C$21*$I16,0)	=F17-G17	=IF(E17<'=$C$5,+I16-H17,0)	=IF(E17<'=$C$5,+1/(1+$C$18)^E17,0)	=G17*J17	=F17*J17
18	15	=IF(E18<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E18<'=$C$5,+$C$21*$I17,0)	=F18-G18	=IF(E18<'=$C$5,+I17-H18,0)	=IF(E18<'=$C$5,+1/(1+$C$18)^E18,0)	=G18*J18	=F18*J18
19	16	=IF(E19<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E19<'=$C$5,+$C$21*$I18,0)	=F19-G19	=IF(E19<'=$C$5,+I18-H19,0)	=IF(E19<'=$C$5,+1/(1+$C$18)^E19,0)	=G19*J19	=F19*J19
20	17	=IF(E20<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E20<'=$C$5,+$C$21*$I19,0)	=F20-G20	=IF(E20<'=$C$5,+I19-H20,0)	=IF(E20<'=$C$5,+1/(1+$C$18)^E20,0)	=G20*J20	=F20*J20
21	18	=IF(E21<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E21<'=$C$5,+$C$21*$I20,0)	=F21-G21	=IF(E21<'=$C$5,+I20-H21,0)	=IF(E21<'=$C$5,+1/(1+$C$18)^E21,0)	=G21*J21	=F21*J21
22	19	=IF(E22<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E22<'=$C$5,+$C$21*$I21,0)	=F22-G22	=IF(E22<'=$C$5,+I21-H22,0)	=IF(E22<'=$C$5,+1/(1+$C$18)^E22,0)	=G22*J22	=F22*J22
23	20	=IF(E23<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E23<'=$C$5,+$C$21*$I22,0)	=F23-G23	=IF(E23<'=$C$5,+I22-H23,0)	=IF(E23<'=$C$5,+1/(1+$C$18)^E23,0)	=G23*J23	=F23*J23
24	21	=IF(E24<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E24<'=$C$5,+$C$21*$I23,0)	=F24-G24	=IF(E24<'=$C$5,+I23-H24,0)	=IF(E24<'=$C$5,+1/(1+$C$18)^E24,0)	=G24*J24	=F24*J24
25	22	=IF(E25<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E25<'=$C$5,+$C$21*$I24,0)	=F25-G25	=IF(E25<'=$C$5,+I24-H25,0)	=IF(E25<'=$C$5,+1/(1+$C$18)^E25,0)	=G25*J25	=F25*J25
26	23	=IF(E26<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E26<'=$C$5,+$C$21*$I25,0)	=F26-G26	=IF(E26<'=$C$5,+I25-H26,0)	=IF(E26<'=$C$5,+1/(1+$C$18)^E26,0)	=G26*J26	=F26*J26
27	24	=IF(E27<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E27<'=$C$5,+$C$21*$I26,0)	=F27-G27	=IF(E27<'=$C$5,+I26-H27,0)	=IF(E27<'=$C$5,+1/(1+$C$18)^E27,0)	=G27*J27	=F27*J27
28	25	=IF(E28<'=$C$5,($C$21/(1-(1+$C$21)^(-$C$5)))*$C$3,0)	=IF(E28<'=$C$5,+$C$21*$I27,0)	=F28-G28	=IF(E28<'=$C$5,+I27-H28,0)	=IF(E28<'=$C$5,+1/(1+$C$18)^E28,0)	=G28*J28	=F28*J28
29			--------	--------			--------	--------
30	TOTAL		=SUM(G4:G13)	=SUM(H4:H13)			=SUM(K4:K13)	=SUM(L4:L13)
31								
32	Next apply the capital recovery factor & tax rate to total discounted int.sum.							
33								
34	=$K$30*$C$34*$C$26							
35								
36	Calculate the depreciation...first calculate depreciation							
37								
38	=($C$3-$C$6)/$C$5							

Table E- 2 (Cont.)

Row No. / Col. No.	E	F	G	H
40	Next, discount the depreciation and sum...			
41				
42	Year	Dk,SL	PWF(id,k)	Disc.Depr
43				
44	1	=IF(E44<'=$C$5,+$E$38,0)	=IF(E44<'=$C$5,+1/(1+$C$18)^$E44,0)	=F44*G44
45	2	=IF(E45<'=$C$5,+$E$38,0)	=IF(E45<'=$C$5,+1/(1+$C$18)^$E45,0)	=F45*G45
46	3	=IF(E46<'=$C$5,+$E$38,0)	=IF(E46<'=$C$5,+1/(1+$C$18)^$E46,0)	=F46*G46
47	4	=IF(E47<'=$C$5,+$E$38,0)	=IF(E47<'=$C$5,+1/(1+$C$18)^$E47,0)	=F47*G47
48	5	=IF(E48<'=$C$5,+$E$38,0)	=IF(E48<'=$C$5,+1/(1+$C$18)^$E48,0)	=F48*G48
49	6	=IF(E49<'=$C$5,+$E$38,0)	=IF(E49<'=$C$5,+1/(1+$C$18)^$E49,0)	=F49*G49
50	7	=IF(E50<'=$C$5,+$E$38,0)	=IF(E50<'=$C$5,+1/(1+$C$18)^$E50,0)	=F50*G50
51	8	=IF(E51<'=$C$5,+$E$38,0)	=IF(E51<'=$C$5,+1/(1+$C$18)^$E51,0)	=F51*G51
52	9	=IF(E52<'=$C$5,+$E$38,0)	=IF(E52<'=$C$5,+1/(1+$C$18)^$E52,0)	=F52*G52
53	10	=IF(E53<'=$C$5,+$E$38,0)	=IF(E53<'=$C$5,+1/(1+$C$18)^$E53,0)	=F53*G53
54	11	=IF(E54<'=$C$5,+$E$38,0)	=IF(E54<'=$C$5,+1/(1+$C$18)^$E54,0)	=F54*G54
55	12	=IF(E55<'=$C$5,+$E$38,0)	=IF(E55<'=$C$5,+1/(1+$C$18)^$E55,0)	=F55*G55
56	13	=IF(E56<'=$C$5,+$E$38,0)	=IF(E56<'=$C$5,+1/(1+$C$18)^$E56,0)	=F56*G56
57	14	=IF(E57<'=$C$5,+$E$38,0)	=IF(E57<'=$C$5,+1/(1+$C$18)^$E57,0)	=F57*G57
58	15	=IF(E58<'=$C$5,+$E$38,0)	=IF(E58<'=$C$5,+1/(1+$C$18)^$E58,0)	=F58*G58
59	16	=IF(E59<'=$C$5,+$E$38,0)	=IF(E59<'=$C$5,+1/(1+$C$18)^$E59,0)	=F59*G59
60	17	=IF(E60<'=$C$5,+$E$38,0)	=IF(E60<'=$C$5,+1/(1+$C$18)^$E60,0)	=F60*G60
61	18	=IF(E61<'=$C$5,+$E$38,0)	=IF(E61<'=$C$5,+1/(1+$C$18)^$E61,0)	=F61*G61
62	19	=IF(E62<'=$C$5,+$E$38,0)	=IF(E62<'=$C$5,+1/(1+$C$18)^$E62,0)	=F62*G62
63	20	=IF(E63<'=$C$5,+$E$38,0)	=IF(E63<'=$C$5,+1/(1+$C$18)^$E63,0)	=F63*G63
64	21	=IF(E64<'=$C$5,+$E$38,0)	=IF(E64<'=$C$5,+1/(1+$C$18)^$E64,0)	=F64*G64
65	22	=IF(E65<'=$C$5,+$E$38,0)	=IF(E65<'=$C$5,+1/(1+$C$18)^$E65,0)	=F65*G65
66	23	=IF(E66<'=$C$5,+$E$38,0)	=IF(E66<'=$C$5,+1/(1+$C$18)^$E66,0)	=F66*G66
67	24	=IF(E67<'=$C$5,+$E$38,0)	=IF(E67<'=$C$5,+1/(1+$C$18)^$E67,0)	=F67*G67
68	25	=IF(E68<'=$C$5,+$E$38,0)	=IF(E68<'=$C$5,+1/(1+$C$18)^$E68,0)	=F68*G68
69				--------
70	TOTAL			=SUM(H44:H53)
71				
72	Now apply the capital recovery factor and tax...			
73				
74	=$H$70*$C$34*$C$26			

Row No. / Col. No.	I	J	K	L
42	Summarize the terms...			
43				
44	Capital & Interest =			=-$C$87
45	Salvage Value =			=$C$88
46	Replacements			=-$C$94
47	Operating Costs =			=-$C$95
48	Property Tax =			=-$C$96
49	Maintenance =			=-$C$97
50	Insurance =			=-$C$98
51	Interest Deduction =			=$E$34
52	Depreciation Deduction =			=$E$74
53				--------
54	TOTAL			=SUM(L44:L52)

E.2 Input Data and the Results

Table E- 3 and Table E- 4 present the input data and results of the annualized life-cycle cost analysis of the house with individual and combined application of energy-efficient measures, respectively. The total first year costs, annual energy costs and the resulting annualized energy costs are highlighted.

Table E- 3: Input Data and Results for the Individual Application of Energy-Efficient Measures

	Basecase	SIP Const.	SIP + ERV	High-Albedo Roof	High-Albedo Walls	Ar-Filled Low-e Glazing	Vinyl Window Frames	Over-hangs	+ 75% Glaz. on South	CFL	Efficient Refri-gerator	Efficient Freezer	Efficient Dish-washer	Efficient Clothes Washer	Tankless DWH	SEER-15 AC
Input Data																
Total 1st Year Cost	**$224,598**	**$226,805**	**$227,904**	**$227,098**	**$223,448**	**$225,394**	**$226,003**	**$227,118**	**$227,118**	**$224,850**	**$224,848**	**$224,828**	**$225,247**	**$224,948**	**$224,998**	**$225,787**
Investment Tax Credit	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Life	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
Salvage Value	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Salvage Year	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
Replacement/Disposal	$72	$72	$72	$72	$72	$72	$72	$72	$72	$102	$72	$72	$72	$72	$72	$72
Replace/Disposal Yr	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Replacement/Disposal	$622	$622	$622	$622	$2,122	$622	$622	$622	$622	$652	$622	$622	$622	$622	$1,022	$622
Replace/Disposal Yr	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Replacement/Disposal	$2,620	$2,620	$2,620	$2,620	$2,620	$2,620	$2,620	$2,620	$2,620	$2,650	$2,620	$2,620	$3,269	$2,970	$2,620	$3,809
Replace/Disposal Yr	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Replacement/Disposal	$1,472	$1,472	$1,472	$1,472	$2,972	$1,472	$1,472	$1,472	$1,472	$1,502	$1,722	$1,702	$1,472	$1,472	$1,872	$1,472
Replace/Disposal Yr	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Replacement/Disposal	$72	$72	$72	$72	$72	$72	$72	$72	$72	$102	$72	$72	$72	$72	$72	$72
Replace/Disposal Yr	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
Discount Rate (id)	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%
Inflation Rate (j)	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Fuel Inflation Rate (je)	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Martgage Rate (im)	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Annual Energy Costs	**$1,438**	**$1,426**	**$1,411**	**$1,371**	**$1,417**	**$1,386**	**$1,406**	**$1,317**	**$1,295**	**$1,301**	**$1,409**	**$1,380**	**$1,380**	**$1,371**	**$1,326**	**$1,286**
Annual Maintenance	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100
Annual Insurance	$50	$50	$50	$50	$50	$50	$50	$50	$50	$50	$50	$50	$50	$50	$50	$50
Depreciation	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%
IncomeTax	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
PropertyTax	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
% of System Cost	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Salvage Tax	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Results																
Capital & Interest	($10,410)	($10,513)	($10,564)	($10,526)	($10,357)	($10,447)	($10,476)	($10,527)	($10,527)	($10,422)	($10,422)	($10,421)	($10,441)	($10,427)	($10,429)	($10,466)
Salvage Value	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Replacements	($178)	($178)	($178)	($178)	($289)	($178)	($178)	($178)	($178)	($184)	($187)	($186)	($202)	($191)	($208)	($222)
Operating Costs	($1,752)	($1,737)	($1,719)	($1,669)	($1,726)	($1,689)	($1,713)	($1,604)	($1,578)	($1,584)	($1,716)	($1,681)	($1,681)	($1,669)	($1,615)	($1,566)
Property Tax	($2,134)	($2,155)	($2,165)	($2,157)	($2,123)	($2,141)	($2,147)	($2,158)	($2,158)	($2,136)	($2,136)	($2,136)	($2,140)	($2,137)	($2,137)	($2,145)
Maintenance	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)
Insurance	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)
Interest Deduction	$196	$198	$199	$198	$195	$196	$197	$198	$198	$196	$196	$196	$196	$196	$196	$197
Depreciation Deduction	$169	$171	$171	$171	$168	$169	$170	$171	$171	$169	$169	$169	$169	$169	$169	$170
TOTAL	**($14,252)**	**($14,357)**	**($14,398)**	**($14,305)**	**($14,275)**	**($14,232)**	**($14,289)**	**($14,241)**	**($14,214)**	**($14,104)**	**($14,238)**	**($14,202)**	**($14,240)**	**($14,201)**	**($14,166)**	**($14,175)**
Percent Increase	0.00%	0.73%	1.03%	0.37%	0.16%	-0.14%	0.26%	-0.08%	-0.26%	-1.04%	-0.10%	-0.35%	-0.08%	-0.36%	-0.60%	-0.54%

Table E- 4: Input Data and Results for the Combined Application of Energy-Efficient Measures

	Basecase	+ SIP Const.	+ ERV	+ High-Albedo Roof	+ High-Albedo Walls	+ Ar-Filled Low-e	+ Vinyl Window Frames	+ Over-hangs	+ 75% Glaz. on South	+ CFL	+ Eff. Refri-gerator	+ Eff. Freezer	+ Eff. Dish-washer	+ Eff. Clothes Washer	+ Tank-less DWH	+ SEER-15 AC
Input Data																
Total 1st Year Cost	**$224,598**	**$226,805**	**$227,904**	**$230,404**	**$229,254**	**$230,049**	**$231,454**	**$233,974**	**$233,974**	**$234,226**	**$234,476**	**$234,706**	**$235,355**	**$235,705**	**$236,105**	**$237,294**
Investment Tax Credit	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Life	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
Salvage Value	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Salvage Year	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
Replacement/Disposal	$72	$72	$72	$72	$72	$72	$72	$72	$72	$102	$102	$102	$102	$102	$102	$102
Replace/Disposal Yr	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Replacement/Disposal	$622	$622	$622	$622	$2,122	$2,122	$2,122	$2,122	$2,122	$2,152	$2,152	$2,152	$2,152	$2,152	$2,552	$2,552
Replace/Disposal Yr	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Replacement/Disposal	$2,620	$2,620	$2,620	$2,620	$2,620	$2,620	$2,620	$2,620	$2,620	$2,650	$2,650	$2,650	$3,299	$3,649	$3,649	$4,838
Replace/Disposal Yr	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Replacement/Disposal	$1,472	$1,472	$1,472	$1,472	$2,972	$2,972	$2,972	$2,972	$2,972	$3,002	$3,252	$3,482	$3,482	$3,482	$3,882	$3,882
Replace/Disposal Yr	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Replacement/Disposal	$72	$72	$72	$72	$72	$72	$72	$72	$72	$102	$102	$102	$102	$102	$102	$102
Replace/Disposal Yr	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
Discount Rate (id)	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%
Inflation Rate (j)	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Fuel Inflation Rate (je)	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Martgage Rate (im)	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Annual Energy Costs	**$1,438**	**$1,426**	**$1,411**	**$1,356**	**$1,344**	**$1,287**	**$1,259**	**$1,160**	**$1,146**	**$1,010**	**$981**	**$915**	**$869**	**$794**	**$686**	**$635**
Annual Maintenance	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100	$100
Annual Insurance	$50	$50	$50	$50	$50	$50	$50	$50	$50	$50	$50	$50	$50	$50	$50	$50
Depreciation	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%
IncomeTax	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
PropertyTax	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
% of System Cost	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Salvage Tax	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Results																
Capital & Interest	($10,410)	($10,513)	($10,564)	($10,680)	($10,626)	($10,663)	($10,728)	($10,845)	($10,845)	($10,857)	($10,868)	($10,879)	($10,909)	($10,925)	($10,944)	($10,999)
Salvage Value	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Replacements	($178)	($178)	($178)	($178)	($289)	($289)	($289)	($289)	($289)	($295)	($304)	($312)	($336)	($349)	($378)	($422)
Operating Costs	($1,752)	($1,737)	($1,719)	($1,651)	($1,637)	($1,568)	($1,533)	($1,413)	($1,396)	($1,230)	($1,195)	($1,115)	($1,058)	($968)	($835)	($774)
Property Tax	($2,134)	($2,155)	($2,165)	($2,189)	($2,178)	($2,185)	($2,199)	($2,223)	($2,223)	($2,225)	($2,228)	($2,230)	($2,236)	($2,239)	($2,243)	($2,254)
Maintenance	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)	($95)
Insurance	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)	($48)
Interest Deduction	$196	$198	$199	$201	$200	$200	$202	$204	$204	$204	$204	$204	$205	$205	$206	$207
Depreciation Deduction	$169	$171	$171	$173	$172	$173	$174	$176	$176	$176	$176	$176	$177	$177	$178	$178
TOTAL	**($14,252)**	**($14,357)**	**($14,398)**	**($14,466)**	**($14,501)**	**($14,474)**	**($14,516)**	**($14,532)**	**($14,515)**	**($14,369)**	**($14,357)**	**($14,297)**	**($14,299)**	**($14,240)**	**($14,160)**	**($14,206)**
Incremental % Increase	0.00%	0.73%	0.29%	0.47%	0.24%	-0.18%	0.29%	0.11%	-0.12%	-1.01%	-0.09%	-0.42%	0.02%	-0.41%	-0.57%	0.33%
Cumulative % Increase	0.00%	0.73%	1.03%	1.50%	1.74%	1.56%	1.85%	1.97%	1.85%	0.82%	0.73%	0.31%	0.33%	-0.08%	-0.65%	-0.32%

VITA

Mini Malhotra
4/375 Modern Colony, Shukla Ganj
Unnao, India – 209861
Email: minimalhotra@tamu.edu

Education

Master of Science in Architecture, December 2005
Texas A&M University, College Station, Texas

Bachelor of Architecture, May 1999
Birla Institute of Technology, Mesra, Ranchi, India

Professional Experience

Graduate Assistant - Research, June 2004 - December 2005
Energy Systems Laboratory, Texas A&M University

Graduate Assistant - Teaching, September 2003 – May 2004
Department of Architecture, Texas A&M University

Graduate Assistant – Non-teaching, June 2003 – August 2003
Women's Center, Texas A&M University

Architect, April 2002 – December 2002
Private Practice, Unnao, India

Assistant Architect, August 1999 – March 2002
Ar. Dhirendra K. Mishra, Kanpur, India

Scholarships and Awards

Academic Year 2005-2006
- AEE Scholarship, Association of Energy Engineers
- International Education Study Grant, Texas A&M University
- SBSE Retreat Scholarship, Society of Building Science Educators

Academic Year 2004-2005
- ASHRAE Student Scholarship, Houston Chapter of ASHRAE
- R. Joseph Reeves Endowed Memorial Scholarship, Texas A&M University

Academic Year 2003-2004
- Charles F. Dean Memorial Scholarship, Texas A&M University
- AUF Architect Graduate Tuition Fellowship, Texas A&M University