ANALYSIS OF IMPROVED FENESTRATION FOR CODE-COMPLIANT RESIDENTIAL BUILDINGS IN HOT AND HUMID CLIMATES

A Thesis

by

JAYA MUKHOPADHYAY

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

August 2005

Major Subject: Architecture

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Approved by:

Chair of Committee,	Jeff S. Haberl
Committee Members,	Charles H. Culp
	Liliana Beltran
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ABSTRACT

Analysis of Improved Fenestration for Code-Compliant Residential Buildings in Hot and Humid Climates.

(August 2005)

Jaya Mukhopadhyay, Dip Arch., Tulsi Vidya Bharati School of Habitat Studies

Chair of Advisory Committee: Dr. Jeff S. Haberl

This thesis presents an analysis of energy efficient residential windows in hot and humid climates. To accomplish this analysis, the use of accurate simulation tools such as DOE-2.1e is required, which incorporates the results from the WINDOW-5.2 simulation program to assess accurate fenestration performance. The thesis also investigates the use of optimal glazing types, which, for future applications, could be specified in the code to reduce annual net energy consumption to zero.

Results show that combinations of low-E and double pane, clear-glazed windows, which are optimally shaded according to orientation are the best solution for lowering both annual energy consumption and peak electricity loads. The study also concludes that the method used to model fenestration in the simulation program plays an important role in accurately determining the effectiveness of the glazing option used. In this particular study, the use of the WINDOW-5.2 program is highly recommended especially for high performance windows (i.e., low-E glazing). Finally, a discussion on the incorporation of super high performance windows (i.e., super low-E, ultra low-E and dynamic / switchable glazing) into the IECC code concludes that these types of glazing strategies can reduce annual net energy use of the window to zero.

Future work identified by this thesis includes a more extensive examination of the passive solar potential of high performance fenestration, and an examination of the appropriate methods for specifying these properties in future versions of the IECC code. This implies that future specifications for fenestration in the IECC code could aim for zero net annual energy consumption levels from residential fenestration.

DEDICATION

To my father and mother, who have always stood by my side.

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I take this opportunity to thank the chair of my advisory committee, Dr. Jeff Haberl, for his time and invaluable advice. I would also like to express my gratitude to Dr. Liliana Beltran and Dr. Charles Culp, members of the advisory committee, for their time and advice.

My special thanks to my friend and colleague Mushtaq Ahmad for helping me and bearing with me. I would also like to thank Rhonda Holley for painstakingly editing and proof-reading my thesis.

Finally and most importantly, I am deeply grateful to my family for their good cheer, support, and unconditional love which has helped me through difficult times.

Thank you.

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CHAPTER I

INTRODUCTION

1.1 Brief overview

In 1994, it was estimated that 19 billion square feet of residential windows in the United States were responsible for 1.7 Quads (1 quad = 1,000,000,000,000,000 Btu) per year of energy use – 1.3 Quads for heating and 0.4 Quads for cooling energy – or about 2% of the national energy consumption. Although this represents a small amount of the total U.S. consumption (97.1 Quads), this energy consumption could be reduced by 25% by the year 2010 if appropriate fenestration technology was adopted (Frost et al., 1996). As part of the nation's drive to reduce energy consumption, building energy codes have been enacted and enforced by most states, which include specifications for efficient fenestration. In May 2001, Texas adopted the 2000 International Energy Conservation Code (IECC 2000), including the 2001 Supplement (IECC 2001) as its official energy code for buildings. On examining the code, it was found that a schematic approach was most often used in laying out specifications for energy efficient fenestration, which had the potential for improvement. Moreover, the potential for shading as an energy saving strategy was not directly addressed in the 2000 IECC. Thus, this study investigates the specifications for fenestration with shading options, which have the potential of yielding higher energy savings than those currently contained in the 2000 IECC.

This study is not the first attempt to reinterpret the 2000 IECC specifications for fenestration. In this regard several counties in Texas have proposed shaded, double-pane, clear glazing to be used instead of the low-E glazing prescribed by the 2000 IECC. Therefore, this study also examines the viability of this proposal along with other alternatives which can be integrated into a residence to meet code requirements. The analysis is carried out by making use of a sophisticated hourly building simulation to establish accurate results and draw conclusions.

This thesis follows the format of *ASHRAE Transactions*.

1.2 Hypothesis/problem statement

In hot and humid climates such as Texas, shading in combination with a less efficient glazing (i.e., double-pane, clear glazing) is comparable to using higher efficiency glazing (i.e., double pane, low-E glazing) as specified by the 2000 IECC and the 2001 supplement. To justify this assertion, the use of accurate simulation tools such as the DOE-2.1e program with Custom Weighting Factors (CWFs) is required, which incorporates results from the WINDOW-5 simulation program to assess fenestration performance.

1.3 Objectives of the study

The primary objective of this study is to determine whether the use of overhangs with less efficient glazing provides an annual energy consumption performance equivalent to that specified by the 2000 IECC, which mandates the use of double-pane low-E glazing (SHGC =< 0.4), for those areas of Texas with 3500 Heating Degree Days or less. The long-term goal of this work would be to develop a set of design guidelines which can be used in the selection of code-compliant fenestration. These guidelines will take into consideration the selection of glazing and shading on each orientation, as well as the percentage of opening possible for an optimum configuration for energy-efficient fenestration for selected locations.

To properly accomplish the first objective it is necessary to investigate the sensitivity of using the WINDOW-5 (i.e., W5 method) program in combination with the DOE-2.1e simulation program versus the more traditional shading coefficient (i.e., SC method) method of analysis with the DOE-2.1e program, to assess fenestration performance. This investigation will also assess the impact of using the more accurate Custom Weighting Factor method (i.e., thermal mass mode) versus the pre-calculated ASHRAE weighting factors (i.e., quick mode) in the DOE-2.1e program, which has been used by researchers to calculate the heat transfer through building components in code-compliant construction.

Finally, the third objective is to investigate the performance of selected hypothetical glazing types. This study speculates that these new windows could set more efficient trends for fenestration specifications in future versions of the IECC.

1.4 Organization of the thesis

This chapter discusses the background of the proposed research as its purpose and objectives. Chapter II reviews the previous research conducted in this area, which provides a basis for the development of this study. The discussion includes an assessment of the options for residential fenestration systems, an assessment of the methods used for calculating heat gain through fenestration, and the modeling windows in simulation software. Specifications for describing window properties in building codes are also discussed.

Chapter III discusses the significance of the study and the potential contributions from this research. The scope and limitations of the research as well as the development of procedures used in this research are also discussed in this chapter.

Chapter IV discusses the methodology used in this research. It describes the basis for the selection of the simulation model, and outlines the detailed simulation scheme adopted by the study for analysis.

Discussions of the analysis and results can be found in Chapter V and Appendices A and B. This includes results that can be assimilated into future revisions of the IECC as well as alternative interpretations of a shading concept, which could be incorporated in a future code. Appendices C through G provide data to help support this study.

Finally, Chapter VI summarizes the current research work and provides conclusions about the study.

CHAPTER II

LITERATURE REVIEW

This literature review includes an overview of the role played by fenestration in residential envelope loads, an assessment of the previous research that tested the various properties of windows, as well as the previous research that has tested the different options to reduce energy consumption in various residential buildings, different methods of calculating window heat transfer and the available window simulation software, and the basis for fenestration specifications in residential building energy codes. The prime sources of information for this study are articles published by The Daylighting Group at Lawrence Berkeley National Laboratories (LBNL), and the ASHRAE Transactions which are compiled by the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE). Also of significance are national Renewable Energy Laboratory (NREL) publications, proceedings from conferences on the Thermal Performance of the Exterior Envelopes of Buildings sponsored by ASHRAE, the International Building Performance Simulation Association (IBPSA), the American Council for an Energy Efficient Economy (ACEEE), and the American Solar Energy Society (ASES).

2.1 Overview of the role played by fenestration in residential envelope loads

In the 1960's not much emphasis was given to window design other than traditional concepts such as increasing the number of panes in heating-dominated climates, and tinted or shaded glazing in cooling-dominated climates. With the rising energy costs in the 1970's, extensive research was performed to reduce heat transfer through windows as part of an effort to reduce building energy use. Research to determine the relative influence of different building envelope components on heating and cooling loads indicated that windows play a major role in contributing to energy loads (Rudoy and Duran 1975), especially in residences, where energy consumption loads, in most cases, are dominated by the building envelope (Sullivan and Selkowitz 1986). From the 1970's onwards, new glazing technologies were developed, tested and subsequently adopted by the building industry. The underlying goal that has been carried through to present day research has been to develop the potential of windows as net energy suppliers (Arasteh 1994;

Apte et. al., 2003; Selkowitz 1981); although it can be argued that this potential has only been demonstrated for heating-dominated climates.

Technological advancements in fenestration technology have delivered many energy-efficient fenestration products for residential buildings in both heating and cooling climates. Prominent among these options is the emergence of low-E coatings which are usually ultra-thin, heat-reflecting, metalized optical coatings applied to one or more surfaces of a window that drastically alters the windows heat transfer properties (Johnson 1991). More information on the range of options available can be found in the following references: Arasteh (1994); Baumeister (2004); Carmody et al. (2000, 2003); Johnson (1991); and Wasley and Utzinger (1996). Recent efforts have focused on incorporating energy-efficient windows for heating and cooling climates into energy codes, but it is argued that these specifications fall short of maximizing the potential of using energy-efficient fenestration in residential building design because the simulation support work for the code officials may not have used the most accurate simulation models.

2.2 Basic concepts of heat transfer through fenestration

Basic information about window heat transfer processes is contained in the *ASHRAE Handbook of Fundamentals* (2001c). Other references of significance include the textbook *Solar Engineering of Thermal Processes* by Duffie and Beckman (1991); and the e-book *Vital Signs–Glazing Performance* by Wasley and Utzinger (1996).

2.3 Assessing options for residential fenestration systems

Over the years, many studies have been performed that document the effect of windows on residential energy use. In general, the objective of these studies has been to better understand the performance of window systems and their contribution to the building envelope loads. In order to establish a basis for the hypothesis assumed in this study, this thesis restricts itself to the review of only a narrow segment of this extensive research. This includes a better understanding of glazing characteristics, analyzing the performance of various glazing strategies and the impact of various parameters such as orientation and window size on energy consumption. Of major significance to this review is the assessment of various shading strategies, which are the traditional methods of reducing solar heat gain. The review also touches upon the recent research performed on windows for zero-energy homes, which includes monitoring the performance of high performance glazing as well as hypothetical super glazing with dynamic properties (i.e., glazing that has the ability to reduce solar heat gain in the summer without the decrease of useful solar heat gain in the winter).

2.3.1 Glazing characteristics: U-value and SHGC

Research performed by Arasteh et al. (1985), Reilly and Hawthorne (1998), Rubin (1982a, 1982b), Rubin and Selkowitz (1981), Selkowitz (1981), Selkowitz and Bazjanac (1981), and Sullivan et al. (1993) are some examples of the work published by the LBNL that investigates the impact of glazing characteristics on heat transfer through the building envelope when subjected to different parametric conditions (i.e., orientation, climate, window size, building thermal properties, etc). Of particular interest is research performed by Sullivan et al. (1993) that assesses the impact of window U-values on residential cooling loads. In addition, to obtain a complete understanding of the impact of glazing characteristics on overall energy consumption, studies of glazing performance in heating-dominated climates were also considered. Of these studies, Dubois (1998) at The University of Lund in Sweden carried out an analysis on the performance of solar protective glazing in heating dominated climates and research published by Hunn et al. (1993) at The University of Texas, which is based in part on the work by Pletzer et al. (1993) on shading devices, includes an analysis of low-E glazing performance in heating-dominated climates.

From the above work it can be concluded that, for controlling heating energy consumption, both U-values and the solar heat gain play an important role (Hunn et al. 1993; Reilly and Hawthorne 1998). Low U-values are preferred to mitigate the heat loss occurring due to high temperature difference between warm interiors and cold exteriors – a phenomenon specific to the heating seasons. In heating-dominated climates, high winter-time solar heat gain optimization properties are also preferred, which helps reduce heating energy consumption (Reilly and Hawthorne 1998; Rubin and Selkowitz 1981). Conversely, in cooling-dominated climates, reducing solar heat gain plays a decisive role in controlling cooling energy consumption. Lower solar gains reduce cooling energy loads, while varying the conductance properties of glazing only marginally affects the overall cooling loads (Reilly and Hawthorne 1998; Sullivan et al. 1993; Sullivan and Selkowitz 1984; 1987).

A study on the effects of window U-values on residential cooling loads (Sullivan et al. 1993) observed that large U-values can yield to lower annual cooling loads; however, smaller U-values can yield lower peak cooling loads. This is because a larger U-value permits higher conductance from the interiors to exteriors during morning and evening hours when outside air temperatures are often lower than inside air temperatures. While a lower U-value conducts less heat at peak cooling hours, usually occurring in the afternoon. These studies also concluded that the magnitude of the difference in results for overall loads is small and hence can be ignored. However, both reduced solar heat gain and reduced U-values are effective in reducing peak cooling loads. The previous literature provided an understanding of the performance of fenestration properties in terms of both annual as well as peak load energy consumption. Hence, these studies were useful to this research in selecting the appropriate alternate glazing options which will be compared with the specifications laid out by the IECC code.

When examining methods to control and regulate solar heat gain, it was found that glazing with low-absorptance and high transmittance properties were used as options to increase solar heat gain, while glazing with high-absorptance properties was used to control solar heat gain. Shading was found to alter the SHGC significantly (McCluney and Mills 1993).

The use of low-E coated glazing immensely alters glazing properties. Low-E coatings applied to the outer surface of the inner pane of double pane fenestration help to retain heat trapped within the envelope, and hence is preferred for heating dominated climates (Johnson 1991); low-E coatings applied to the inner surface of the outer pane of double-pane fenestration helps to keep out solar heat gain. Low conductance gases such as argon and krypton are often used to fill the gap between the panes in low-E fenestration to reduce the U-value and enhance the effectiveness of the low-E coating (Johnson, 1991).

Houston is a cooling-dominated climate but still experiences a significant number of heating degree days (1,548 HDD), which makes it difficult to prescribe one glazing option to reduce both heating and cooling loads. Therefore, an ideal glazing for this climate should have low solar heat gain properties in the summer and high solar gain in the winter. Furthermore, the window should have a low U-value to counteract the heating energy losses, and peak cooling energy loads, and a switchable high U-value during transition from daytime to nighttime hours of the cooling season to allow for heat loss to the ambient temperature. While such dynamic windows are still a theoretical concept, it is hypothesized that some portion of these properties could be achieved by an appropriate combination of shading attachments and high-performance glazing.

2.3.2 Implementation of shading devices

Effective shading can be achieved using a number of techniques. Louvered blinds, draperies and curtains, and hanging shades and shutters are popular examples of interior shading devices. Architectural features (i.e., roof eaves, window overhangs and side fins), solar screens, outside shutters as well as shading from adjacent objects like trees and neighboring buildings are considered exterior shading (Pletzer et al. 1993). An important fact to be considered is that the selection of shading strategies must be orientation dependent to achieve the maximum benefit. This aspect will be discussed in the next section.

Implementation of shading devices and strategies has been one of the traditional options to reduce unwanted summertime heat gain through windows. Research on shading can be traced to the 1950s with work performed by Olgyay and Olgyay (1957). In the 1960s – 1970s, studies conducted by Pennington (1968), Yellott (1972), and Ewing and Yellott (1976) provided details of the effectiveness of various outside shading devices. More recently studies include those conducted by McCluney and Chandra (1984), McCluney and Mills (1993) at the Florida Solar Energy Center (FSEC), Pletzer et al. (1993), Hunn et al. (1993), and Dubois (1998, 1999, 2000). Farrar-Nagy et al. (2000) at the National Renewable Energy Laboratory (NREL) have also studied the viability of using various shading strategies to optimize energy consumption in residential buildings in combination with low-E glazing. These studies unanimously agree that shading remains an effective strategy for reducing summertime heat gain without decreasing useful wintertime heat gain if used judiciously on the proper orientation.

The implementation of shading strategies reduces the solar heat gain properties of fenestration systems (Hunn et al. 1993; McCluney and Mills 1993; Pletzer et al. 1993), which makes them ideal for use in cooling-dominated climates for reducing cooling loads, especially peak cooling loads. This was demonstrated in Pletzer et al.'s research for the cooling-dominated climate of Austin, Texas which compared the effectiveness of various shading strategies. Pletzer concluded that movable/seasonal shading strategies were preferred because they can be withdrawn during the heating season to admit useful solar gain and pulled back over the window during the brief cooling periods. Similar results were reported for heating-dominated climates (Hunn et al. 1993), although in this case the additional insulating properties of shading screens gain importance and hence have to be taken into consideration. It was also concluded that improperly designed, fixed, exterior devices have reduced the beneficial wintertime solar gains, which resulted in increased annual heating energy usage (Dubois 1998; Pletzer et al. 1993).

From these studies it can be concluded that shading plays a crucial role in optimizing energy consumption for Houston, both for overall as well as peak load reduction. As it is a cooling dominated climate, the heat transfer through the fenestration is primarily solar gain driven. Fenestration systems can reduce solar gain by using an appropriate shading device, which is orientation dependent. The next section examines the impact of orientation on choice of glazing and shading.

2.3.3 Orientation and amount of glazing

Victor Olgyay in his seminal book *Design with Climate* (1963) looked at orientation as one of the key components to be considered for energy efficient design. This study stated that shading needs to be orientation dependent in order to achieve the maximum potential benefit. Later, studies by Farrar et al. (1998), McCluney (1987), McCluney and Chandra (1984), Pletzer et al. (1993), and Rubin and Selkowitz (1981) confirmed Olgyay's work, especially for achieving a reduction in peak cooling loads. All these studies also emphasized the importance of orientation in the selection of glazing types and optimum size of window openings.

Sullivan and Selkowitz (1984) stated that window orientation had a minor effect on cooling energy consumption when compared to the impact of altering the shading-coefficient (SC) and U-values of the window. Along similar lines, Dubois (1998) also investigated the impact of window orientation on heating and cooling energy consumption. She pointed out that heating energy consumption was more affected by a change in orientation than cooling energy consumption, in which case the choice of glazing was a more significant factor affecting cooling energy use.

Rubin and Sullivan (1981) examined the performance of glazing properties in heating-dominated climates and noted that the U-value was the prime determinant of window performance in the heating season for north orientations (or shaded orientations receiving minimum solar gain). While in the case of south, east and west orientations, which receive significant amounts of solar radiation, the shading coefficient played a significant role in regulating heating energy use. For the case of low-E glazing, several studies have shown that the use of low-E glazing greatly diminishes the impact of orientation on energy consumption both for heating as well as cooling dominated climates (Carmody and Crooks 1996; Dubois 1998; Farrar et al. 1998).

Investigating the impact of orientation on the choice of shading devices to be implemented in heating dominated climates, Dubois (1998) concluded that seasonal/movable shading outperformed the fixed exterior shading especially on the south façade. In a study of the window shading strategies in predominantly hot and humid climatic zones of Florida, McCluney and Chandra (1984) demonstrated that shading measures were, on average, almost equally effective for all compass directions including the north due to the high diffuse radiation component in Florida climatic conditions. This high diffuse radiation factor along with the relative unimportance of wintertime direct solar heat gain implies that the shading effectiveness in Florida is not orientation-dependent.

Examining the impact of orientation on window area, Selkowitz and Sullivan (1984) noted that it is possible to reduce heating energy by increasing the window size, provided the resistance and solar heat gain are appropriately chosen. Similarly, analyzing the impact of varying the Glazing-to-Wall Area Ratio (GWAR) in a heating dominated climate, Dubois measured the solar aperture (Shading Coefficient x GWAR) to carry out her analysis. She noted that varying the solar aperture for different orientations increased the solar radiation through the window, which subsequently increased the cooling loads. The opposite trend was observed for heating loads. In general, Dubois observed that a southern orientation was the most affected by a change in the solar aperture. Also, annual energy consumption was minimized at lower GWAR or SC on east or west facades than on the south façade.

Therefore, since Houston is predominantly a cooling dominated climate, the orientation should not play an important role in optimizing annual energy loads, although it will have an impact on optimizing peak cooling loads. In this case, orientation-dependent shading strategies might be used to counter peak cooling loads associated with direct solar heat gain.

2.3.4 Other building characteristics

Also of importance are building characteristics like thermal mass, color and type of shading surfaces, and internal loads. When properly combined together these characteristics make fenestration performance results more effective. Several studies previously cited have reported on the combined effects of these characteristics, including Rubin and Selkowitz (1981) and Kapur (2003). In their research on fenestration with high solar transmittance, Rubin and Selkowitz noted that a variation in the thermal mass properties of the house will introduce very large changes in the apparent performance of window characteristics especially on the southern exposures. This is because of the high amount of solar energy absorbed from that orientation during the winter. Kapur's (2003) study assessed the impact of the qualities of the overhang color and material on solar heat gain, which required the use of sophisticated building simulation programs that calculated the radiant heat transfer of the external shade. These studies are important in accounting for the performance of fenestration strategies. However, these issues lie beyond the scope of this study.

2.3.5 Assessment of recent trends and developments in fenestration technologies

Several technologies have been developed to improve heat transfer through windows. These include multi-layered windows with evacuated or low-conductance, gas-filled gaps (Carmody et al. 2004), and aerogel windows to reduce the heat loss (U-factor) of windows (Hartman et al. 1987). Technologies to reduce solar heat gain include improvements to existing low-E coatings, light redirecting layers, and self-shading windows (Carmody et al. 2000; Apte et al. 2003). More recent developments include investigating advanced façade systems which are designed to manage energy flows, view and comfort (Carmody et al., 2004). These technologies are slowly being incorporated into commercial buildings, but have yet to be implemented on a large scale in the residential building industry. Limited attempts have been made to incorporate these technologies into residential building code specifications.

A relatively recent concept – zero energy homes – are becoming popular for residential construction. Zero Energy Homes (ZEH) are homes designed to use zero net annual energy from the utility grid. The aim of a ZEH is to combine solar energy technology with energy-efficient construction techniques to help create a new generation of cost-effective buildings that have zero net annual non-renewable energy use. Interesting to note is the role of windows in zero energy homes. A study recently conducted at LBNL by Apte et al. (2003) found that even today's highest performing commercially available window products did not meet the requirements of a zero-energy home. In this study it was suggested that one way to improve climatic-specific glazing was to develop the concept of dynamic fenestration systems that can alter their solar heat gain properties according to seasonal/temperature variations. Technologies that enable windows to have dynamic properties include electrochromic glazing, operable shading systems, and light redirecting devices (Apte et al. 2003). These technologies change their properties in response to the ambient temperature and solar radiation using different methods. In the study, typical residential windows and use of traditional shading strategies were compared to the most effective residential windows, as well as several advanced window technologies, which include products with fixed and dynamic properties. Products with dynamic heat gain properties were found to offer significant potential in reducing energy use and peak demand technologies in northern climates while windows with low solar gain properties offered the most potential in southern climates. While investigating options for using shading strategies, Apte et al. concluded that in cooling-dominated climates, although the potential of overhangs was maximized, the strategies needed to be coupled with future window technologies to bring the window energy consumption to “zero” levels. The shading/overhangs contributed more towards the peak reductions while implementation of advanced window technologies contributed more towards improving the overall/annual energy consumption reductions.

In summary, it is felt that the introduction of low-E coatings and the resultant improved performance of low-E glazing gives designers a greater control in the sizing and placement of windows. The combination of low-E glazing and orientation-specific shading has previously been shown to be a highly effective strategy to curb both the overall as well as peak loads. When appropriately used, this strategy has been shown to be an effective tool to optimize energy consumption through windows. Unfortunately, many of the previous studies have used various versions of different simulation programs to draw their conclusions. Therefore an assessment of energy simulation programs is needed to evaluate the accuracy of previously reported results.

2.4 Assessing heat gain though windows: methods of calculations and modeling

Advances in glazing technology have necessitated more flexible and accurate methods to assess the heat transfer through fenestration. The resultant algorithms have been used in various building energy simulation programs with varying degrees of complexity. Unfortunately, with the rapid development of high-performance fenestration technologies, simulation programs need periodic updates to their algorithms to assure accuracy in reported results. Furthermore, these programs need to be validated either experimentally or by comparing against other standard programs in order to make them appropriate for use as an accurate energy assessment tool. Some of these simulation programs have been used in the performance path option in building codes to achieve compliance. The IECC provides a performance path option that requires the use of a certified building simulation program in order to achieve compliance (2000 IECC). However, it gives limited advice on how to model the complex properties of multi-glazed windows.

2.4.1 Assessment of algorithms for calculating heat gain through fenestration

There are four characteristics of a window that quantify its energy performance: conductance, solar heat gain, transmittance, and infiltration. Of these properties, indices reporting the conductance and solar heat gain properties are directly specified in the 2000 IECC, and therefore are considered by this study. Extensive research has been performed at the LBNL to analyze these properties. Window analysis can be traced back to the 1970s and early 1980s where work by Arasteh et al. (1985), Rubin (1980), Rubin and Selkowitz (1981), Selkowitz and Bazjanak (1981), Selkowitz and Winkelmann (1982), and Selkowitz et al. (1979) examined and assessed the thermal characteristics of fenestration. Subsequent research focused on establishing calculation procedures to accurately model advanced window systems. Research by Rubin (1982a, 1982b) and later Arasteh et al. (1989) played a key role in establishing calculation procedures used in LBNL's WINDOW-5 program, which is a sophisticated program for calculating the thermal properties of complex fenestration products.

Experimental verification of the simulation models has also been performed. A series of experiments conducted by Klems examined the thermal performance of fenestration systems under realistic conditions and compared the results with those obtained from LBNL's simulation models (Klems 1988, 1989; Klems and Kelley 1995). An analysis was also performed on complex fenestration systems to characterize the most advanced commercially available fenestration products (Klems and Kelley 1995; Klems et al. 1996). Also of significance is research performed at the Florida Solar Energy Center by McCluney (1987, 1991, 1993, 1994, 1996, 2002); McCluney and Chandra (1984); McCluney and Mills (1993), that focused on assessing the solar heat gain through fenestration. Empirical testing at the LBNL, included the Infrared Thermography Laboratory (Griffith et al. 1995, 1996; Türler et al. 1997), the Mobile Window Thermal Test Facility (MoWITT) (Klems 1989), Bidirectional Radiometric Scanner (Klems et al. 1995), and a Glazing Optics Laboratory. Algorithms for calculating the indices responsible for heat gain through fenestration systems are published in the ASHRAE Handbook of Fundamentals (2001) and ISO-15099 (2004).

2.4.2 Fenestration analysis software

For the purpose of calculating heat transfer through fenestration, laboratory testing is too expensive for an exhaustive analysis of all possible combinations of products and conditions. This fact has established the need for computer modeling of fenestration performance. In the 1960s and 1970s there were only a few algorithms for analyzing building energy consumption performance by means of computer modeling (Ayres and Stamper 1995) that included an analysis of fenestration. In the 1970s and 1980s emerging high-performance glazing technology pushed researchers at LBNL to develop new algorithms for fenestration simulation software (Arasteh et al. 1998). The current simulation software for fenestration analysis utilizes these sophisticated techniques for analyzing complete, spectrally-dependent glazing systems. The programs WINDOW-5 and VISION are good examples of such software (Wright 1995).

Solar heat gain through windows is calculated in WINDOW-5 by a Solar Heat Gain Coefficient (SHGC). An LBNL report by Finlayson et al. (1993), research work by Arasteh et al. (1989), Rubin (1982b), and Appendix A in the WINDOW-5.0 (LBNL 2003) manual provides a description of the model used by this program to calculate the solar heat gain properties of glazing. The first step of the two step process involves an optical analysis of the glazing that requires detailed inputs of the angular-dependent properties of spectral reflectance, transmittance and absorptance properties of the glass. A spectral calculation option is also provided that enables an accurate analysis of two or more spectrally-selective panes used together. Also considered is the dependence of solar radiation on the incidence angle (Furler 1991).

The second step involves a heat transfer analysis that includes both the radiative and convective heat transfer models. Accurate correlations for the inside and the outside convective heat transfer coefficients are used, which play a significant role in varying the SHGC of windows with high absorption properties (Wright 1995). It is important to note that glazing with high solar transmittance relies more heavily on the solar optical model, while the low solar transmittance glazing relies more on the heat transfer model (Wright 1995). The optimal selection of glazing for cooling-dominated climates should ideally be the low solar transmittance option; hence examining the heat transfer model in WINDOW-5 becomes important. However, high solar transmittance coincides with high visible transmittance – a glazing property preferred in residential construction – in which case the optical model gains priority.

Calculating Solar Heat Gain also takes into account the wind speed that the glazing is exposed to on the exterior side of the window. Not surprisingly, it has been found that single-pane glazing, with high absorptance properties, are the most sensitive to variations in wind-speed, while multi-pane glazing is not as sensitive (Reilly et al. 1992).

Temperature-driven heat transfer is accounted for by the U-value of the glazing. This is calculated once the temperature profile across the glazing is known. The U-value of the window is also influenced by the various film coefficients (i.e., convective and radiative effects which depend on temperature and air movement). Thus the U-value can vary widely depending on surrounding conditions. Updated algorithms for accurate calculation of U-values can be obtained from numerous sources which include publications by Curcija and Goss (1994, 1995a, 1995b).

Finally, a number of programs work in conjunction with WINDOW-5 to accurately assess heat transfer through fenestration systems. These include THERM (2003) – a program that analyses two-dimensional heat transfer through building components, which is used to analyze the opaque components of the fenestration system (i.e., frames and window sashes); and OPTICS – a data base of glazing data, that is utilized in WINDOW-5 calculations.

2.4.3 Modeling fenestration by use of whole-building simulation computer programs

Whole-building simulations have to accurately calculate the complex interrelation between building components and processes. As a result, fenestration modeling is usually simplified to a great extent. DOE-2.1e and BLAST were the two predominant building simulation programs used in the United States whose development and maintenance are funded by various government agencies. A relatively new program, ENERGYPLUS, which is based on a combination of DOE-2.1e and BLAST simulation capabilities, is reported to give more accurate results (Crawley and Pederson., 2001).

Prior to the introduction of ENERGYPLUS, DOE-2.1e was considered to be the most advanced simulation program sponsored by the U.S. Department of Energy where it served as the technical basis for setting energy codes and standards in the United States. DOE-2.1e gives three options for calculating heat gain through windows. The first, the two-digit glass code method, uses pre-calculated, angular dependent, transmittance and absorptance coefficients, which are listed in the DOE-2.1e manual, to determine solar gain through windows as a function of the angle of incidence of solar radiation. In the second method, the Shading Coefficient (SC) method, the program first calculates the angle-dependent solar heat gain using transmission coefficients for clear, 1/8” glass using the angle-dependent polynomial developed by ASHRAE Task Group on Energy Requirements-TGER (1975). The solar heat gain is then calculated by multiplying this result with the Shading Coefficient value input by the user. In the third method, the user uses a four digit code to reference a window in the input file from a user-defined library file (i.e., WIN.DAT). This library contains a list of WINDOW-5 generated output files arranged by four digit code numbers. The user can make additions to this file by adding new WINDOW-5 output files customized in accordance with the choice of glazing, size, frame and type. The DOE-2.1e program references these files for incident angle dependent SHGC values which are used by the DOE-2.1e program. Details of the fenestration modeling in the DOE-2.1e input code are provided in Appendix C.

A number of studies have shown that the SHGC more accurately accounts for the angle-dependent transmittance properties than the SC method of assessing solar heat gain through windows (McCluney 1991; Reilly et al. 1995). Therefore, of the three methods used in DOE-2.1e, use of the WINDOW-5 library gives the most accurate window heat transfer calculations because the angular dependence of transmission and adsorption of solar radiation is more precisely modeled and the temperature dependence of the window U-value is more accurately calculated.

2.4.4 Validation of simulation software

Differences in the results obtained from the outputs of different simulation programs may be caused by algorithmic differences, modeling limitations, or coding errors in simulation software models. Therefore, in order to identify and diagnose differences in predictions, it is essential to have a validation methodology. Standard 140-2001 developed by ASHRAE (2001) is a method of test for the evaluation of building energy analysis computer programs and has been accepted as the standard test in the U.S. It lays out three methods: comparative tests, analytical tests and empirical tests for evaluating the technical capabilities and range of applicability of computer programs that calculate the thermal performance of buildings and their HVAC systems. Standard 140-2001 uses the DOE-2 and BLAST programs as one standard to evaluate the accuracy of other programs.

From the above discussion on simulation programs, it can be concluded that the advancement in glazing properties has led to the development of accurate simulation models used to assess the resultant energy consumption. These simulation models, in turn, are incorporated into advanced fenestration simulation programs and whole-building simulation programs. Unfortunately, the advanced features of these simulation programs may not be incorporated into the analysis that supports code revisions. The next section attempts to answer these questions.

2.5 Building codes, standards, and model codes

Building energy codes, standards and model codes have been developed and used in many countries to provide a minimum standard for building design and to encourage awareness and innovation of energy conscious design in buildings (Janda and Busch 1994). This policy has been adopted by many governments to assume minimum energy efficiency in the building sector, which typically accounts for 30 to 50% of the primary energy demand and half of the total electricity consumption in general (Hui 2002). In fact, a properly applied energy code is considered one of the easiest and most cost-effective ways to help consumers reduce energy costs by mandating efficiency in the building construction.

Typically, a building energy code provides regulatory, prescriptive and performance design requirements. Regulatory requirements include referenced test methods and standards as well as any certification and labeling requirements. Prescriptive requirements include the minimum performance criteria that building components must meet, which typically vary depending on climate zones. In addition, some energy codes provide trade-offs that allow building components to exceed specifications laid out by the code when using other more energy efficient products that compensate for the component that was less stringent than the code specifications. Such performance methods are typically computational approaches that allow for customization of building designs and more flexible product selection.

In the case of fenestration, the use of large window areas, skylights, and other glazed products is allowed provided that improvements in lighting, HVAC systems, and other parts of the building envelope compensate for the added losses (NFRC 2002a, 2002b). In recent years, there has been strong interest to develop or revise building energy codes using such a performance-based approach, with the aim to improve flexibility, clarity and effectiveness of the codes. Of interest to Texas, the 2000 IECC contains such provisions for the performance-based approach in Chapter 4 of the code. In drawing specifications for residential cooling loads, glazing plays a critical role because windows increase air-conditioning loads. Conversely, window performance in heating climates where solar heat gain through the windows can be harnessed to reduce heating, credit can be given for increased window areas on southern exposures. In this way, optimally designed windows would allow users greater window areas to allow more daylight and heat gain in the winter, while at the same time to reduce heat gain in the summer. Energy codes thus have the task to set the balance between user needs and minimizing energy consumption (Halverson 2001). The IECC makes certain provisions in both prescriptive as well as performance-based approaches to optimize the energy consumption through windows. However, are these provisions flexible enough to incorporate the energy efficiency potential of advanced windows? The following sections discuss the issues involved.

2.5.1 Standardizing fenestration rating system

To ensure a certain consistency for the effective implementation of codes on a nation-wide basis, a standardized rating system is required. The Energy Policy Act of 1992 (Geller et al. 1992) specified the NFRC as a preferred developer of a consistent rating system for fenestration to be implemented on a nationwide basis. Supported by LBNL, the NFRC uses the WINDOW-5 program as the technical foundation for its specifications. However, although the NFRC gives a uniform assessment of the performance indices, it does not give the relative performance of glazing properties depending on site and building specific conditions. Nevertheless, the specifications are extensively referenced as regulatory requirements by building energy codes for specifying fenestration performance.

2.5.2 Energy codes implemented in the United States of America

The following paragraphs describe different energy codes implemented across the United States with a focus on fenestration system specifications adopted by each energy code.

2.5.2.1 Title-24 of the California Energy Code

This code is a part of the California building code. It consists of 12 sections which deal with different aspects of building design, construction and maintenance. Established in 1978 in response to state legislation to reduce California's energy consumption, the code was one of the first energy codes to be adopted on a state-wide basis. It is probably the most stringent energy code implemented in the U.S.

The NFRC's three key rating components, U-value, SHGC, and infiltration, are the basis for the glazing standards included in Title-24. Under the version in effect since 1999, all manufactured glazing products sold in California must carry a NFRC certified label. Although Title-24 defines 16 climate zones in California, in the specifications for windows, its "not-to-exceed" requirements for U-value and SHGC are allocated among two sets of zones. For cooling load dominated zones, implementation of shading strategies is encouraged to achieve a SHGC requirement of 0.4 or less. For shading specifications, Title-24 specifies the effective SHGC, which can be computed by multiplying a glazing system's SHGC by a factor that varies by the size of an exterior overhang relative to glazed area. No credit is given for interior shading devices, only for permanent exterior overhangs. Prescriptive tables of options for compliance in the manual are given in Appendix D.

The other method for providing compliance in Title-24 is the performance approach in which the designers are allowed to model their buildings using software approved by the California Energy Commission. These programs include CALRES2 (CEC 2004), Energy Pro (CEC 2004), Micropas 6 (CEC 2004), and Perform 2001 (CEC 2004). To comply with the code, the simulated energy use of the proposed design cannot exceed the annual energy usage of a standard design (CEC 2004).

2.5.2.2 ASHRAE 90.2-2001 energy efficient design for new low-rise residential buildings (ASHRAE 2001)

This code was developed by ASHRAE and the IES to provide minimum requirements for the energy-efficient design of residential buildings. Prescriptive paths and an annual energy cost budget method, which is a performance-based method are the two paths provided for compliance. The prescriptive paths can be used when a rapid and easy compliance check is desired. The annual energy cost method should be used when the proposed design does not meet the prescriptive requirements or when more innovated design concepts are proposed. Calculation procedures listed in the ASHRAE Handbook of Fundamentals are used to establish compliance with the code. The NFRC 100 (2002a) is used to determine the thermal properties of fenestration.

In Standard 90.2-2001 the U-value is the variable used to set the requirements for the thermal properties of the windows while the Shading Coefficient is the variable used to set the requirements for solar gains. The prescriptive data for the U-values for fenestration is based on Figure 5-15A/B (ASHRAE

2001, p. 20), which establishes the required U-value for a given location, based on that locations average heating and cooling load. The heating degree days are measured from a base of 65°F and the cooling degree hours are measured from a base of 74°F. The U-values dictated for each area of the chart roughly correspond to the following types of fenestration: U=1.31 – single pane glazing with aluminum sash, U=0.87 – single pane glazing with a storm window, U = 0.49 – double pane glazing, and U = 0.36 – double pane glazing with low-E coating or triple glazing. The nearly vertical cutoff lines in the U-value chart indicate the severity of the winter climate as the primary determinant of the U-value requirement. However, summer, too, can be a factor as can be seen in the example of a window in a 5000 HDD65 climate with 0 hours of cooling only requires a U-value of 0.87, but at a location with the same winter value and a summer value of 45,000 cooling degree hours or more, the U value requirement is raised to 0.49 – insulating glass (Wasley and Utzinger 1996).

Similarly, for the case of the Shading Coefficient, a chart can be found in Figure 5-16-A/B (ASHRAE 2002, p. 21). The SC-values dictated for each area of the chart roughly correspond to the following types of fenestration. A nearly horizontal cutoff indicates the role of the cooling climate in determining optimum SC requirements. Furthermore, there is no direct reference to choice of optimum shading strategies, and their implementation is left to individual interpretation. A SC of 0.7 is achieved by standard window treatment of draperies, blinds, etc. A Shading Coefficient of 0.5 is achieved by treatments applied to or in the glass in addition to standard window treatments. U-value and SC specifications are given in Appendix D of this report. Notwithstanding the requirements provided in the figure, other specifications for SC and U-factors may be used if the envelope meets the requirement provided in Section 5.9 of the standard, which presents an envelope tradeoff calculation procedure.

In the case of Houston with 1548HDD_{65} and 30474CDH_{74}, ASHRAE Standard 90.2-2001 specifications are as follows: U = 0.87, SC = 0.7. This implies the use of optimum shading strategies for double-pane glazing.

2.5.2.3 The Model Energy Code (MEC)

This code was developed jointly by the Building Officials and Code Administrators International (BOCA), the International Conference of Building Officials (ICBO), the National Conference of States on Building Codes and Standards (NCSBCS) and the Southern Building Code Conference International (SBCCI). It was the first official building energy code applicable to the entire United States (ICC 1999). The Council of American Building Officials (CABO) assigned all rights and responsibilities of the Model Energy Code to the International Code Council (ICC).

NFRC 100(2002a) and NFRC 200(2002b) are referenced by the MEC for rating, certifying and labeling U-factors and Solar Heat Gain Coefficients. In the absence of NFRC ratings, procedures for determining the default ratings for different window types with a limited number of options are provided. As part of the prescriptive requirements, all three versions of the CABO-MEC established fenestration performance requirements based on fenestration area expressed as a percentage of the gross wall area and climate zone. The 1992 and 1993 versions set the U-factor requirements from no requirements to 0.35. While the 1995 version sets the SHGC requirements ranging from no requirements to 0.4. Credit is given to overhangs that provide shading to windows. An alternative path, called the software approach, is established for alternative compliance. REScheck (USDOE 2003) is a computer program was developed by the Pacific Northwest National Laboratories (PNNL) to provide an automated approach for tradeoffs and incorporate additional features to make CABO-MEC more flexible.

2.5.2.4 International Energy Conservation Code 2000 (IECC 2000)

As the successor to the ICC Model Energy Code (MEC) and the 1998 IECC, the 2000 IECC is similar to the previous codes but includes several new requirements. In Chapter 4 of this code, the simulated analysis of annual energy usage are allowed in order to achieve compliance. According to section 402.1 .1 of the code, in order to achieve compliance, the annual energy consumption of the building in question needs to be less than or equal to the energy consumption of a similar building with 18% window-to-floor area whose specifications are prescribed in the code. Section 402.1.3.1 lists specifications of fenestration in the standard design against which other designs are to be compared. Chapter 5 specifies a component performance compliance approach, in which individual envelope components are required to demonstrate compliance and provides prescriptive tables. Chapter 6 lists a series of simplified prescriptive requirements for residential buildings that have 15% or less window to wall area ratio in order to achieve compliance. The code assumes equal window area on all orientations for all the specifications. Tabular prescriptions of window U-values and SHGC are presented in Appendix D.

For fenestration specifications, the NFRC plays a key role in determining the U-value and SHGC of fenestration products in the 2000 IECC (NFRC-100 and NFRC-200). Products not meeting these requirements are assigned product values based on default values which typically do not give full credit to energy efficient performance. The 2000 IECC has 17 climate zones for the U.S. based on Heating Degree Days with minimum fenestration performance U-factors and maximum SHGC requirements, which take into account exterior shading effects via a Chapter 4 analysis. While the simplified Prescriptive Requirements in Chapter 6 require that glazing area cannot exceed 15% of the gross wall area for one and two family units, the component approach for code compliance (Chapters 4 and 5) utilizes the same 17 climate zones but do not restrict fenestration area to 15% of the gross wall area; rather it provides tables for 8%, 12%, 15%, 18%, 20% and 25% fenestration area. Furthermore, the IECC has a requirement for a SHGC <= 0.4 for all climate zones with HDD below 3500. In general, the U-factor requirements become more restrictive as fenestration area increases.

In conclusion it can be seen that specifications for fenestration products provided in the codes are most often given in terms of U-values and SC or SHGC values. In most cases the prescribed values imply the use of low-E or tinted glazing for SHGC less than 0.4. In almost all cases specifications for shading as an option are not clearly stated or defined although certain propriety codes allow this analysis through simulation. The most elaborate shading specifications are provided by the California Title-24 Energy code that has performance-based specifications which use certified compliance tools. Nationally, however, there is no direct provision in any of the reviewed residential codes for credit from shaded fenestration.

2.5.3 Methods and software used for code compliance

For an effective implementation of the performance-based approach in codes, compliance would have to be achieved with reliable and certified compliance tools. The following paragraphs describe existing code compliance certification agencies and tools.

RESNET is a national organization providing certification to residential code checking software. RESNET validates the Home Energy Rating Systems (HERS) which was included in the 1992 Energy

Policy Act in order to gauge the energy consumption of residential buildings. Rating software programs accredited by RESNET include CHEERS – Calfornia Home Energy Efficiency Rating System (CEC 2001), E-Star Colorado, EnergyCheckup Server, Energygauge®USA, Micropas, REM/Rate and TREAT. On parallel lines HERS BESTEST (Judkoff and Neymark, 1995) developed by NREL is a comparative validation method for evaluating the credibility of building energy software used by Home Energy Rating Systems. Also, the U.S Department of Energy provides the Building Energy Codes Program for supporting the MEC and the IECC codes by developing compliance materials that simplify its use. These include REScheck and COMcheck code (USDOE 2003) compliance software. In the sections that follow, software used in Texas to demonstrate compliance with building energy codes is discussed.

ENERGYGAUGE®USA: Developed by the Florida Solar Energy Center, ENERGYGAUGE®*USA* (Fairey and Wichers, 2004) allows assessing Model Energy code compliance along with the evaluation of economic improvement. DOE-2.1e is used as the simulation engine, along with a number of enhancements. ENERGY GAUGE is RESNET as well as HERS BESTEST certified.

REMRATE: Developed by Architectural Energy Corporation, REM/Rate (AEC, 2005) is considered one of the easiest residential energy analysis and rating tools to use. It is one of the only tools that allows side-by-side comparison of two homes, making analysis of energy upgrades easy. Also, the software performs design optimization, improvement analysis, compliance analysis and equipment sizing. REMRATE uses the solar heat gain coefficient and U-value of a window assembly as input by the user to determine its impact on the heating/cooling loads.

REScheck: REScheck (USDOE 2003) is sponsored by the Department of Energy's Building Energy Codes Program to provide compliance support to the Model Energy Code, 1992, 1993, and 1995 editions and to the 1998 and 2000 editions of the International Energy Conservation Code. It has been developed by the PNNL. The software is appropriate for thermal shell trade-off calculations in typical single family and multifamily residential buildings. It allows for quick comparison of different insulation levels. It also determines compliance by comparing the total heat loss UA through the building envelope to the UA value of a building defined by the code. Windows are assessed using the UA calculation method in REScheck. Unfortunately, important parameters of Solar Heat Gain Coefficient, Shading Coefficient, thermal mass or orientation are not taken into consideration by the software to assess windows.

From the above review it has been shown that most of the compliance software programs do not have accurate methods such as the WINDOW-5 program, for assessing fenestration performance, implying that the full potential of energy saving of high performance windows may not be realized in energy codes in use in the U.S.

2.6 Summary and conclusions

Summarizing the literature review, it can be concluded that the combination of low-E glazing along with double-pane clear glazing and orientation specific shading has been shown to be an effective strategy to curb both overall as well as peak heating and cooling loads. In cooling-dominated climates the use of shading along with double-pane clear windows exclusively has been shown to give comparable results to un-shaded code compliant low-E windows. However, with the exception of the Title-24 California Energy Code, none of the surveyed energy codes have a direct provision to give credit for orientation-specific, shaded fenestration. Also considered were the advanced glazing products, which have been shown to be capable of driving the energy consumption loads down to levels where the window has no net loss over the year (Apte et al. 2003). Furthermore, more accurate simulation techniques need to be implemented to verify the above mentioned results. Subsequently, these methods must be incorporated in the whole-building energy simulation programs in order to assess the impact of fenestration strategies on overall building energy loads.

Specifications for fenestration products defined in the energy codes, almost in all cases, refer to the use of unshaded low-E glazing. Therefore, shading as an energy optimization strategy is given little or no credit without the use of performance simulations. Moreover, the available performance approach methods rely on proprietary software which may not give an accurate assessment of the options implemented, especially when evaluating high performance fenestration. This includes the use of high performance fenestration to achieve compliance. Also, by only specifying compliance with annual energy consumption loads, the codes are severely restricted in controlling peak cooling loads, and hence NO_X emission reductions which are affected by peak electricity supply demands during the cooling season.

CHAPTER III

STUDY SIGNIFICANCE AND LIMITATIONS

3.1 Significance of the study

The first objective of this study is to establish an accurate simulation model which can be used for code compliance. Therefore, this study focuses on defining an accurate input for fenestration. The literature review identified research performed by Reilly et al. (1992) as the key reference for this issue. Therefore, this study focuses on comparing two options of specifying fenestration input in DOE2.1e input files. However, in order to focus on the performance of these options, this study reports results in terms of solar heat gain. For the more accurate WINDOW-5 method to be practically incorporated in the IECC code, its implication on heating and cooling loads needs to be assessed. Therefore, this study assesses the fenestration input options by analyzing hourly as well as annual reports for energy consumption.

The second objective of this study is to analyze the use of thermal mass in the code-compliant simulations. Most of the research work cited in the literature review does not account for the thermal capacity of building envelope components. Therefore, the resultant heat peak gain or losses may be grossly overestimated and the passive solar heat potential of the building components may not be adequately addressed. Currently it is acceptable to use pre-calculated Custom Weighting Factors in the DOE-2 model for code compliance. Therefore, this study proposes to incorporate DOE-2's custom weighting factors (CWF's) in its building simulation model. By doing so, the study takes a step towards addressing a more accurate assessment of the passive solar potential of the windows through the combined use of the WINDOW-5 program and Custom Weighting Factors.

Third, it is also noted that implications of using the IECC specifications for code compliant building simulation modelling are not appropriately addressed in many of the previous studies. Key features in the 2000 version of the code specifications include a square building aspect ratio, equal window-to-wall area ratios for all orientations, fixed internal energy specifications and mandatory building component U-values. These specifications also have an impact on the selection of windows. By analyzing these loads properly, the study takes into consideration the impact of these specifications on the selection of windows. This study also investigates the sensitivity of the above mentioned specifications to various house size options and window-to-wall area ratios.

Finally, the literature review cites a number of studies that have investigated the use of high-performance glazing in achieving a 'zero-energy' window concept that fully utilizes the passive solar potential of windows. However, the previous papers stopped short of making practical recommendations to allow for such an advanced concept to become part of the IECC. Therefore, by using an IECC-specified building simulation model and analysis of overall loads this study seeks to develop a list of specifications needed to effectively define these advanced windows in the IECC.

3.2 Scope and limitations

Due to time constraints and limitations in software capabilities the following issues are not taken into consideration:

- The variation in the exterior convection coefficient that accounts for the presence of shading or screens which creates a microclimate at the exterior surface of the window, (Sullivan and Selkowitz 1984).
- The radiant heat transfer from exterior shades that is not currently accounted for in the DOE-2 program (Kapur 2003).
- The impact of varying combinations of parameters such as thermal mass, internal loads, air-conditioner efficiency, varying thermostat settings, etc. (Rubin 1991).

The investigation of shading devices is also limited to horizontal, exterior, fixed shading only.

CHAPTER IV

METHODOLOGY

4.1 Overview

Three primary tasks are identified to carry out the objectives of the thesis: Examining the methods of evaluating fenestration in the simulation program; examining the specifications for shaded and un-shaded fenestration in the 2000 IECC; and examining a wider set of options for fenestration and shading, which are currently not specified in the code.

4.2 Brief description of the methodology implemented by this study

Figure 4.1 presents a schematic layout of the methodology implemented by this study. The original file considered is the IECC1105.inp (Haberl et al. 2003a) which has been developed by the Energy Systems Laboratory at Texas A&M University. The input is based on specifications outlined in Chapter 4 of the IECC. The characteristics of this file include the use of Pre-calculated Weighting Factors to describe the building envelope and the Shading Coefficient method of modeling fenestration.

In the first section of analysis, two methods of modeling fenestration are examined using this file. The traditionally used Shading Coefficient method is compared with the more accurate WINDOW-5 method. To examine the options of input for building envelope components, the performance of the building model using traditional Pre-calculated Weighting Factors is compared with the performance of the building model in which Custom Weighting Factors are activated. TMY2 weather tape for Houston is used to provide the weather data for this simulation. The results are obtained from output reports of the DOE-2.1e simulation program. The resultant input file used for the next steps of analysis incorporates the WINDOW-5 method to model fenestration and activated Custom weighting Factors to model building envelope components.

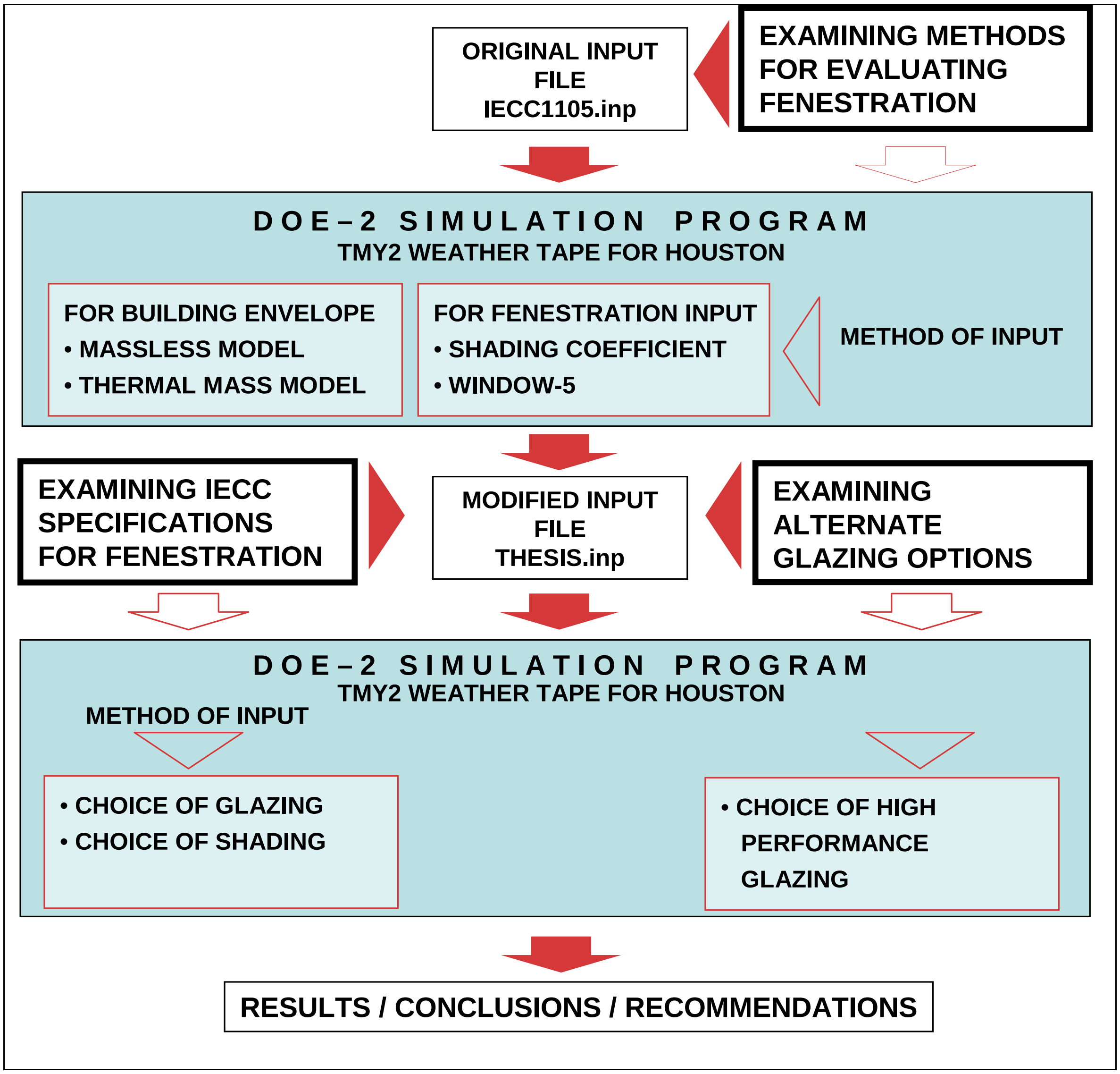


Figure 4.1 Schematic layout of the methodology to be implemented

The final step of analysis involves the assessment of high-performance glazing with the updated IECC building simulation model. The underlying objective is to achieve zero-energy consumption levels from the fenestration options installed in the IECC specified residential model. The properties of high-performance glazing are simulated in the DOE-2.1e program.

Final conclusions and recommendations are drawn which are based on the output reports obtained from the above mentioned simulation runs.

4.3 Selecting the basic test conditions

Various conditions were identified under which the tests were carried out. These included: selecting an appropriate simulation program, developing an appropriate building model, and selecting the appropriate weather data to be used in the simulations.

4.3.1 Selecting a simulation program

The DOE-2.1e (Version 119) program was selected as the simulation program to be used for obtaining the results. A customized input file was created to facilitate the numerous simulations that needed to be run by this study.

4.3.2 Selecting an appropriate building model

The building model used for the DOE-2.1e input file is based on the IECC specifications for a single family building. The version of the model used for this study is 'IECC1105.inp'. This model has been developed by the Energy Systems Laboratory, Texas A&M University (Haberl et al., 2003a) on the basis of specifications provided by the 2000 IECC.

4.3.3 Selecting building locations

Houston was chosen as the building location for this analysis. Houston was considered a good climate location since it represents a sizable percentage of population living in the non-attainment areas identified by the Environmental Protection Agency for failing to meet the required NOx emission standards. The TMY2 weather file (NREL, 1995) for Houston is used to carry out simulations.

4.3.4 Selecting peak load conditions

In order to select the appropriate days for peak conditions weather data for peak cooling and peak heating periods were examined. Subsequently, three clear days are selected: August 9th represents the peak cooling conditions for summer, January 14th represents the peak conditions in winter, and March 20th represents the peak conditions for interim season.

4.4 Defining the building model as per IECC specifications

Figure 4.2 presents views of the building model constructed in the DOE-2.1e input file using the DrawBDL program. Section 402.1.3.1.1 of the 2000 IECC requires an equal percentage of windows on all the orientations. Although the input file provides options to incorporate a second story, flexible house size and different window-to-wall area ratios on each orientation, the building modeled in this thesis assumes the dimensions of a square with equal percentage of window-to-wall area on each orientation. These assumptions were made to simplify the analysis of the effect of glazing for all the orientations.

The model is a single storied structure with a garage attached on the west side of the building. Three house sizes – 1500ft^2, 2500 ft^2, and 5000 ft^2 – and three WWARs – 15%, 20%, and 25% – were analyzed to make it compatible to the IECC model. Also, this version of the input file uses electricity for space cooling while heating energy and heating for domestic hot water is provided by natural gas.

4.4.1 Building location specifications

The latitude and the longitude also need to be specified in the DOE-2.1e model in order to overwrite the generic building location specifications provided in the assigned TMY2 weather tape.
Table 4.1 describes the latitude and the longitude for Houston.

Table 4.1 Details for the BUILDING-LOCATION command for Houston

BUILDING-LOCATION specifications	Houston
Latitude	30.6
Longitude	96.4

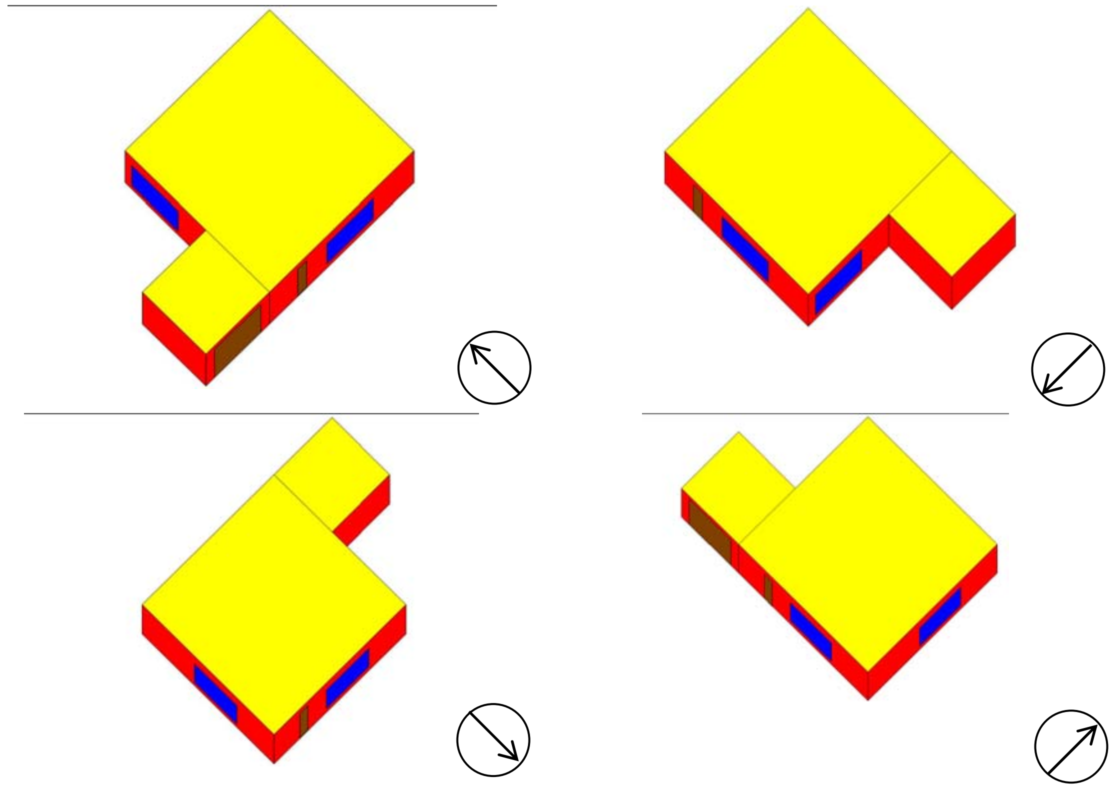


Figure 4.2 DrawBDL views of the building model

4.4.2 Envelope components options

Table 4.2 presents excerpts of the prescriptive tables for the building envelope specifications in the 2000 IECC (Chapter 5). Specifications provided for envelope components correspond to a range of heating degree days (HDDs) identified by the 2000 IECC for Texas. Texas is divided into eight such ranges or climate zones. Houston lies in climate zone 4, specifications of which are mentioned in the above table. Since the focus of this study was on performance of fenestration, all other specifications for building components other than fenestration were fixed.

Table 4.2 Table of building envelope requirements for climate zones 4 (Houston) as specified by IECC (Source: IECC 2001)

Climate Zone	**Path**	**Glazing and Insulation**					**Foundation Type**			
		Area %	U-Factor	SHGC	Ceiling	Wall	Floor	Basement	Slab Perimeter	Crawl Space
4 (Houston)	1	15	.75	.40	R-26	R-13	R-11	R-5	R-0	R-5
	2	20	.60	.40	R-30	R-13	R-13	R-5	R-0	R-5
	3	25	.52	.4	R-30	R-13	R-13	R-6	R-0	R-6

4.4.3 Space conditions

Table 4.3 presents the specifications of space conditions used by the IECC.inp file. Most of the mentioned values were taken from the 2000 IECC specifications as modified by the 2001 IECC supplement (IECC 2001) for single family residences. Information regarding the PEOPLE-HEAT-GAIN-SENSIBLE and PEOPLE-HEAT-GAIN-LATENT are taken from the *ASHRAE Handbook of Fundamentals* (ASHRAE2001b). Table 3, Chapter 26, of the *ASHRAE Handbook of Fundamentals* (ASHRAE 2001b) describes nominal heat gain values from occupants. In this table typical activities are listed along with their heat gain values. Values for 'Seated, light office work' activity are assumed for the input file.

4.4.4 Systems

The RESYS option is implemented to simulate the system portion of the input file. Table 4.3 and Table 4.4 presents specifications used in the SYSTEMS sub-section of the IECC1105.inp file. Specifications are taken from the 2001 IECC. In the absence of information in the IECC, several of the specifications required by this option were set at default values. For the calculation of energy consumption by the domestic hot water heater, a customized curve fit had to be introduced.

Table 4.3 Specifications for SPACE-CONDITION of IECC.inp

SPACE-CONDITIONS DOE-2 Sub-Command	**Specifications**	**Source**
TEMPERATURE	73	(ºF) Average value of winter and summer conditions which are taken from Table 402.1.3.5 of 2000IECC
NUMBER-OF-PEOPLE	2	(No. of people) As there is no specification given in the 2000 IECC, 2 people are assumed to occupy the space.
PEOPLE-HEAT-GAIN-SENSIBLE	200	(Btu/hr) ASHRAE Handbook of Fundamentals 2001 Chapter 29
PEOPLE-HEAT-GAIN-LATENT	200	(Btu/hr) ASHRAE Handbook of Fundamentals 2001 Chapter 29
LIGHTING-TYPE	INCAND	(KEYWORD LIST) Assumption based on typical residence.
LIGHTING-KW	0.44	(%) Fraction of the 879 Watts constant internal heat gain of a Type A1 house as per IECC2000, section 402.1.3.6.
EQUIPMENT-KW	0.44	(%) Fraction of the 879 Watts constant internal heat gain of a Type A1 house as per IECC2000, section 402.1.3.6.
INF-METHOD	AIR-CHANGE	(KEYWORD LIST) Section 402.1.3.10, 2000 IECC
AIR-CHANGES/HR	0.46	(ACH) As per section 402.1.3.10, 2000 IECC, annual average air changes per hour for the standard design shall be determined using the following equation: ACH = Normalized leakage X Weather factor Where: Normalized leakage = 0.57 And Weather factor is determined in accordance with weather factors given b ASHRAE 136, as taken from the weather station nearest to the building site.
FLOOR-WEIGHT	11.5	(Lb/sqft) 2000 IECC, section 402.1.3.3
ZONE-TYPE	Conditioned	(KEYWORD LIST)

Table 4.4 Specifications for SYSTEM in IECC.inp

Zone Control		**Source**
DESIGN-HEAT-T	68	(ºF) From Table 402.1.3.5, Pg 64, 2000 IECC
DESIGN-COOL-T	78	(ºF)
SET-BACK/ SET-UP DURATION	6	Hours per day
THERMOSTAT-TYPE	PROPORTIONAL	(KEYWORD LIST) Default for residential building
THROTTLING-RANGE	5	(ºF) Value from Pg.88 IECC2000
System Fans		
SUPPLY-STATIC	2	(INCHES W.G.) Typical values for residence
SUPPLY-EFF	0.75	(%) Typical values for residence
Domestic Hot water		
DHW-TYPE	Gas	Options given in the IECC: Electric, Gas
DHW-SUPPLY-T	120	(°F) From Section 402.1.3.7, Pg 65, 2000 IECC.
DHW-GAL/MIN	0.027	Calculated by using equation specified in Section 402.1.3.7, Pg 65, 2000 IECC. For DHW-GAL/MIN: (Gallons/min) =[(30 x a) + (10 x b)]/1440 For DHW-SIZE (Gallons) =[(30 x a) + (10 x b)] Where: a = Number of living units b = Number of bedrooms in each living unit
DHW-SIZE	40	
DHW-EIR	1.83	DHW-EIR = 1/EF EF(Energy Factor) is calculated by formula from Table 504.2, Pg. 91, IEC2000. If fuel is Electric, EF = 0.93-0.00132*DHW-SIZE(Gallon) If fuel is Gas, EF = 0.62-0.0019*DHW-SIZE(Gallon)
DHW-EIR-FPLR	NEWDHW	Use of customized curve fit specified by S.Kim 2004 on the basis of specs given in NREL report Pg 34, "Building America House Performance Analysis Procedures" NREL/TP-550-27754.
System Equipment		
COOLING-EIR	0.341	(Btu/Btu) EIR = 3.41/SEER (Seasonal Energy EFFICIENCY Ratio) SEER values given in Table 503.2, Pg 87 , 2000 IECC.
FURNACE-HIR	1.25	(Btu/Btu) HIR = 1/AFUE AFUE values are given in Table 503.2, Pg 87, 2000 IECC.

The method using the Energy Factor for DHW in DOE-2 is from NREL report (NREL/TP-550-27754) "Building America House Performance Analysis Procedures" (NREL, 2001). To use this method, the DOE-2 part-load performance curve for DHW equipment must be overridden with a curve that eliminates any efficiency dependency on partial loads, and tank losses must be set to zero. Therefore, a new curve-fit (NEWDHW) was used for DHW-EIR-FPLR and DHW-LOSS set to zero from 0.03.

4.5 Developing a test matrix

An analysis procedure in the form of a test matrix was developed to systematically analyze the three tasks identified in the opening section of this chapter. Table 4.5 presents a broad outline of this analysis procedure. This matrix was divided into three sections, each section focusing on one of the three tasks listed. To provide a method of analysis for each section, the matrix lists the objective, the procedure to be adopted to carry out the analysis, and the reports to be obtained from simulation runs to be used. The test matrix for each section is further divided into two parts – Part A and Part B. Part A of the simulation scheme briefly states the objective of the procedure, conditions of the simulation model and the options for the method of im\nput used in the DOE-2 program. While Part B presents a list of tests used by the analysis scheme. A list of corresponding output reports from the DOE-2 program are also included.

Table 4.5 Overview of test matrix

SECTION	Objective	Procedure to perform the analysis	Reports
I	Examining the methods for evaluating fenestration	- SC method vs. WINDOW-5 method - Quick method vs. Thermal mass method	Reports examined from LOADS and /or SYSTEMS: - Hourly reports - Peak reports - Annual reports
II	Examining specifications for fenestration laid out by the IECC	- Specifications provided by the code vs. alternate specifications which include shading.	Reports examined from LOADS and /or SYSTEMS: - Hourly reports - Peak reports - Annual reports
III	Examining alternative glazing/shading options	- Specifications provided by the code vs. Alternate specifications which include high performance glazing both practical and hypothetical.	Reports examined from LOADS and /or SYSTEMS: - Hourly reports - Peak reports - Annual reports

4.5.1 Sensitivity analysis and resultant selection of base-cases

In order to assess the performance of the glazing and shading options in the three sections of the analysis, it was found necessary to conduct a series of sensitivity simulations. The purpose of the sensitivity analysis was to:

1. Determine the sensitivity of the prototypical model's energy use to changes in the methods used to simulate the various glazing options.
2. Bound the problem by determining the maximum/minimum benefit derivable for the simulation model, in hopes it will show whether the glazing/shading strategy would produce any significant annual energy savings as well as provide an absolute performance limit by which specific strategies can be judged.

3. Determine the significance of prototype fenestration characteristics such as orientation in determining the energy use predicted by these models. In this case the optimum shade length is to be investigated.

Resultant base-case prototypes are listed in Table 4.6.

Table 4.6 Table of base-case options

Base-case options	Base -case description
Base-case I	Building prototype model as currently defined in the IECC. (Predefined floor weight factors to determine construction type).
Base-case II Base-case II variable	Building prototype model modified as per results from simulation part I (Custom weighting factors and WINDOW-5 library). Variant of building prototype model modified as per results from simulation part I (Custom weighting factors and WINDOW-5 library. Glazing on one orientation only).
Base-case III	Code compliant house with 18% Window-to-Floor Area Ratio (WFAR)
Base-case IV	Building Prototype Model: (Windowless)

4.5.2 Examining the methods for evaluating fenestration

4.5.2.1 Objective

The objective of this section is to investigate the impact of using various options in the DOE-2.1e input file which give a more accurate assessment of performance of building envelope components including windows. The options taken into consideration are:

1. The Custom Weighting Factor option (i.e., Thermal mass option) vs. currently implemented pre-calculated ASHRAE weighting factor option (i.e., Quick option) for specifying building envelope components in the input file.
2. WINDOW 5.2 vs. the Shading Coefficient (SC) method for input specifications for fenestration.

The results of this analysis will provide an appropriate combination of options to be used in the remaining sections of the analysis.

4.5.2.2 Thermal mass vs. Quick option – detailed description of the input options

When using the Quick mode option, pre-calculated ASHRAE weighting factors are used to calculate heat transfer through the building components in a space. These weighting factors summarize the combined effect of the weight of floors, walls and furniture in a single input value: the floor weight.

Table 4.7 gives a summary of the floor-weight factors available in DOE-2.1e. Currently the IECC uses a floor weight of 11.3 to define typical construction as specified in Chapter 4 section 402.1.3.3 (p. 64).

Table 4.7 Floor weight specifications for different building types
(Source: DOE-2.1A manual, p. III.51)

Pre-calculated Floor Weight factor (lb/ft²)	Type of Construction
30	Light construction
70	Medium construction
130	Heavy construction

Another method of calculating the heat transfer through building components in an input file is by activating the Custom Weighting Factors (CWFs). This method requires a more detailed description of the building components in terms of their conductivity, R-value and thickness. Tables 4.8 – 4.10 present the properties of the building components which are used on activation of CWFs in this study. Further information on the method of input and verification of materials used in this study can be found in Appendix E. This study includes a comparison of the impact of using the DOE-2.1e Custom Weighting Factors (i.e., the Thermal mass method) versus ASHRAE pre-calculated weighting factors (i.e., the Quick method).

Table 4.8 Thermal properties of wall construction (Source: Kim and Haberl 2003)

No.	Name	Conductivity	R	Thickness	DOE code
		Btu-ft/Hr-ft2-F	Ft2.hr.F/Btu	Ft	
1	Asbestos-Vinyl Tile		0.05		AV01
2	Plywood ½”	0.0667	0.63	0.0417	PW03
3	Mineral wool / fiber Insulation	0.027	15	0.405	
4	2*4” stud	0.0667	4.37	0.3333	WD05
5	Gypsum board ½”	0.0926	0.45	0.0417	GP01

Table 4.9 Thermal properties of roof construction (Source: Kim and Haberl 2003)

No.	Name	Conductivity	R	Thickness	DOE code
		Btu-ft/Hr-ft2-F	Ft2.hr.F/Btu	Ft	
1	Asphalt shingle		0.44		AR02
2	Plywood ½”	0.0667	0.63	0.0417	PW03
3	Air gap 24"		0.92		AL33
4	2*6 Stud	0.0667	7.5	0.5	
5	Mineral wool / fiber Insulation	.027	27	Variable	
6	Gypsum board ½”	0.0926	0.45	0.0417	GP01

Table 4.10 Thermal properties of slab construction (Source: Kim and Haberl 2003)

No	Name	Conductivity	R	Thickness	DOE code
		Btu-ft/Hr-ft2-F	Ft2.hr.F/Btu	Ft	
1	Concrete Slab	1.0417	0.32	0.3333	CC14
2	Ground Beam	1.0417	2.08	2.17	CC14

4.5.2.3 WINDOW-5 vs. SC method of definition–detailed description of input options

When using the SC method to define fenestration, DOE-2.1e first calculates solar gain and loads using algorithms developed for single pane clear glass (ASHRAE 1975). Subsequently the values get multiplied by the SC of the glazing taken into consideration.

When using the WINDOW-5 method to define fenestration, DOE-2.1e refers to the required WIN-5 out file from WIN.DAT library in DOE program, which can be modified by the user. Further details on the two methods of input can be found in Appendix C. The study intends to test the accuracy of using the WINDOW-5 (W5) option against the Shading Coefficient (SC) option.

4.5.2.4 Analysis matrix for Section I

A detailed simulation scheme for Section I which is briefly described in Table 4.5, is presented in Table 4.11 and Table 4.12. The objective of this matrix is to test the accuracy of using Custom Weighting Factors against the use of Pre-calculated Weighting Factors to define the building envelope components, as well as using the W-5 option against the SC option for modeling windows in the DOE-2 input file. To carry out this analysis, two base-line cases are used. The first base-line case is a residential building prototype as currently defined in the IECC with pre-defined floor weight factors to determine the construction type and shading coefficient method for specifying fenestration. The second case is similar to the first, but uses Custom-Weighting-Factors and WINDOW-5 library to specify the building components. The house size is fixed at 1500 ft^2 and has a 25% Window-to-Wall Area Ratio. Three glazing types – Single Pane Clear (SPC), Double Pane Clear (DPC) and Double Pane low-E (DPlowE) are used to carry out the analysis. This information is summarized and tabulated in Part A of the matrix which is presented in Table 4.11.

In Part B of the simulation matrix which is presented in Table 4.12, Run Set A describes the steps adopted by the analysis to assess the impact of using the SC and W5 methods of modeling fenestration in

DOE-2. Results from the hourly output reports obtained from the LOADS subsection in the DOE-2 output file were analyzed. Run Set B examines the impact of activating the Custom Weighting Factors in the input file on solar loads, conduction loads, cooling electric and zone temperature. Results from the hourly output reports from the LOADS and the SYSTEMS subsections in the DOE-2 file were analyzed. In Run Set C, the impact of using combinations of SC, W5, Quick, and CWF methods in the IECC input file on the entire building energy consumption is assessed. Results from BEPS and peak heating and cooling loads reports were considered. To execute the three run sets discussed above, the two base-line cases described in Part A were used as simulation models. The three glazing options described in Part A of the simulation matrix were used as variables to perform the simulations.

4.5.3 Examining the specifications for shaded and un-shaded fenestration in the IECC2001

4.5.3.1 Objective

The objective of this section is to compare the performance of optimally shaded glazing options with glazing specified by the code where no specific mention is made for the choice of shading.

4.5.3.2 Details of glazing and shading specified in the code and the simulation model

For prescriptive option of the code, specifications for glazing listed in the IECC are given in Table 502.2.4 Series (1-9). These values correspond to the properties of low-E glazing. Excerpts from these tables for conditions which include specifications for Houston are given in Appendix D.

For the performance based option, the Proposed design is compared to a Standard design option sanctioned by the code which provides for 18% window-to-floor area ratio (2001 IECC, Section 402.1.1). Also, the Proposed design is permitted to have exterior shading, while the Standard design is not provided with any kind of shading. For interior shading, fractions are provided in Section 402.1.3.1.5 of the code, which are multiplied for both Standard and Proposed designs. This study does not consider the option of interior shading. Different values are assigned by the code to building envelope components which vary according to window-to-wall percentage and heating degree days. But for the purpose of an unbiased comparison of window performance, these building envelope components are assigned the same values for all the iterations in the simulation model.

Table 4.11 Detailed analysis scheme for Section I of the simulation matrix - Part A

SECTION I	
OBJECTIVE Examining the methods used for evaluating fenestration and building envelope components	
PROCEDURE SC method vs. WINDOW-5 method Quick method vs. Thermal mass method	
Part A	
Base-case options used	Base case I (Ref Table 4.6): Building prototype model as currently defined in the IECC using Pre-defined Floor Weight Factors to determine construction type & shading coefficient method for specifying fenestration. Base case II (Ref Table 4.6): Building prototype model as currently defined in the IECC but modified to include Custom weighting factors & results from WINDOW-5 library.
Conditions	FIXED CONDITIONS: House size – 1500sqft. WWAR – 25% Orientation – Front facing South VARIABLE CONDITIONS: 3 glazing types: o Single pane clear (SPC) o Double pane clear (DPC) o Double pane low-E (DPlow-E)
Options for the method of input	INPUT FOR CONSTRUCTION MATERIALS FOR BUILDING ENVELOPE o 11.3 For pre-calculated custom weighting factors – Quick option. o 0 to activate custom weighting factors – Thermal mass option. INPUT FOR FENESTRATION 2 methods: o Shading Coefficient Method o WINDOW-5 Method

Table 4.12 Detailed analysis scheme for Section I of the simulation matrix - Part B

Part B					
PROCEDURE				**CONCLUSIONS**	
Run set	**Building models**	**Primary conditions**	**Method of input used**	**Figures**	**Reports**
A Measuring hourly solar heat gain due to transmittance, absorptance and conductance components of the selected glazing types. This is done in order to assess the difference in results obtained from using Shading Coefficient method vs. WINDOW5 method of input for fenestration.	Base-case I Base-case II	3 glazing types selected - SPC - DPC - DPlow-E	Shading Coefficient vs. WINDOW-5	**Figure 5.1.1:** Incident solar radiation for 14th Jan, 20th Mar and 9th Aug. **Figure 5.1.2:** Transmittance properties of selected glazing. **Figure 5.1.3:** Transmittance for 14th Jan, 20th Mar and 9th Aug. **Figure 5.1.4:** Solar absorptance for 14th Jan, 20th Mar and 9th Aug. **Figure 5.1.5:** Conductance for 14th Jan, 20th Mar and 9th Aug. **Table 5.1.1:** Transmittance, Conductance and Absorptance properties of the selected glazing types.	Hourly reports from LOADS: ○ Global - Dry bulb temp - Wind speed - Direct normal solar radiation - Global solar radiation ○ Window - Direct solar - Diffuse solar - Transmittance - Absorptance - Conduction
B Measuring the loads in space due to solar heat gain and conduction thru windows. Measuring corresponding zone temperature and cooling electric load results. This is done in order to assess the impact of thermal mass option on solar loads, conduction loads, cooling electric, zone temperature.			Shading Coefficient vs. WINDOW-5 Thermal mass option vs. Quick option	**Figure 5.1.6 - 8:** Cooling loads from LOADS and SYSTEMS for Aug 6th -12th for SPC,DPC & DPlow-E **Figure 5.1.9-11:** Heating loads from LOADS and SYSTEMS for January 10th -16th for SPC, DPC & DPlow-E	Hourly report from LOADS: ○ Space - Conduction loads - Glass solar loads Hourly report from SYSTEMS: ○ Zone - Zone Temperature - Cooling Electric
C Examining annual and peak energy performance from implementing combinations of the 4 options available in the building model. This comparison is carried out to assess the impact of using combinations of the 4 options mentioned previously on the resultant overall energy consumption and peak loads.			Shading Coefficient vs. WINDOW-5 Thermal mass option vs. Quick option	**Figure 5.1.12:** Annual building energy performance (BEPS) report **Figure 5.1.13:** Peak heating and cooling loads **Figure 5.1.14:** **Figure 5.1.11:** **Table 5.1.2:** Percentage difference in energy consumption: a) Quick to Thermal mass mode b) SC to W5 option	Building energy performance synopsis - BEPS. Report for peak heating and cooling - LS-B.

4.5.3.3 Analysis matrix for Section II

Articles by Dubois (1998, 1999, 2000), Rubin et al. (1981), Farrar-Nagy et al. (2000), and Carmody et al. (2000, 2003), cited by the literature review of this study, proved to be instrumental in the development of the simulation matrix and analysis of this section.

A detailed simulation scheme for Section 2 which is briefly described in Table 4.5 is presented in Tables 4.13– 4.15. The objective of this matrix is to examine the specifications laid out for fenestration in the IECC input file. For this purpose, alternate methods, which include the specification for shading, were compared with the existing methods of specifying fenestration. To carry out this analysis, three base-line cases were used. The first case is a residential building prototype, as currently defined in the IECC, but uses Custom-Weighting-Factors and WINDOW-5 library to specify the building components. The second case used in this section of analysis is similar to the first case, but has provision for glazing on one orientation only. The third case is similar to the first case in its specifications, with the exception of having an 18% Window-to-Floor Area Ratio.

Three house sizes (i.e., 1500 ft^2, 2500 ft^2, and 5000 ft^2), three Window-to-Wall Area Ratios (15%, 20%, and 25%), two glazing types (Double Pane Clear [DPC] and Double Pane low-E [DPlowE]), and a range of 0 – 4ft of horizontal shading were used as variables to carry out this section of analysis. The analysis was conducted for North, South, and East orientation. This information is summarized and tabulated in Part A of the matrix which is presented in Table 4.13.

Table 4.13 Detailed analysis scheme for Section II of the simulation matrix, Part I

SECTION II	
OBJECTIVE Examining specifications for fenestration laid out by the IECC	
PROCEDURE Specifications provided by the code vs. alternate specifications which include shading	
Part A	
Base-case options used	Base case II (Ref Table 4.6): Building prototype model as currently defined in the IECC using Pre-defined Floor Weight Factors to determine construction type & shading coefficient method for specifying fenestration. Base case II variant (Ref Table 4.6): Variant of Building prototype model as currently defined in the IECC using Pre-defined Floor Weight Factors to determine construction type & shading coefficient method for specifying fenestration.. Provision for glazing on one orientation only. Base case III (Ref Table 4.6): Code compliant house with 18% Window to Floor Area Ratio (WFAR)
Conditions	VARIABLE CONDITIONS: 3 House sizes: o 1500sqft o 2500sqft o 5000sqft 3 GWARs: o 15% o 20% o 25% 3 Orientation: o North o South o East Shade width range: o Range 0 - 8ft 2 Glazing types: o Double pane low-E o Double pane clear
Options for method input	INPUT FOR CONSTRUCTION MATERIALS CONSIDERING THERMAL MASS PROPERTIES: o Floor weight set at zero to activate custom weighting factors. INPUT FOR FENESTRATION: o Window-5 method used for fenestration input.

Table 4.14 Detailed analysis scheme for Section II of the simulation matrix, Part II

Part B					
PROCEDURE				**CONCLUSIONS**	
Run set	**Building models**	**Primary conditions**	**Method of input used**	**Figures**	**Reports**
A Determining optimum size of horizontal shading length for each orientation for the two glazing types selected for this simulation set.	Base case II variant (3 orientations considered)	Orientation Shade width Glazing type	WINDOW-5 Thermal mass option	**Figure A.1:** Schematic representation on horizontal shading implemented in the building simulation model. **Figure A.2:** Schematic representation on horizontal shading implemented in the building simulation model. **Table A.1:** Optimum horizontal shading on each orientation for DPC and DPlow-E options. **Figure A.3:** Selecting optimum shading for south, north & east orientation.	BEPS
B Reiterating the impact of shading on solar heat gain incident on each of the vertical surfaces of the building model, by comparing the solar radiation incident on un-shaded as well as optimally shaded vertical surface. Compare the above mentioned variations in solar heat gain with corresponding BEPS report examples.	Base case II including result from run set A	Orientation Optimum shade-width Glazing type	WINDOW-5 Thermal mass option	**Figure A.3:** Diffuse and direct components for annual solar radiation incident on vertical surface for north, south and east with corresponding BEPS reports for DPC glazing option. **Table A.2:** Percentage decrease of solar radiation incident on a window and corresponding BEPS report for DPC glazing option due to optimum shading.	Hourly report from LOADS for solar radiation incident on window for north, south and east. BEPS
C Determining optimum choice of glazing, shading and WWAR for a single orientation					
C-1 Varying the orientation and glazing options	Base case II variant including result from run set A	Orientation, Glazing options	WINDOW-5 Thermal mass option	**Figure A.4:** Annual energy consumption trends: A comparison by varying glazing type & orientation **Figure A.5:** Peak heating & cooling energy consumption trends: A comparison by varying glazing type & orientation	BEPS Peak heating and cooling loads: LS-B Report
C-2 Varying the orientation, glazing option and house size		Orientation, House-size, Glazing options		**Figure A.6:** Annual energy consumption trends: A comparison by varying glazing type, orientation & house size **Figure A.7:** Peak heating & cooling energy consumption trends: A comparison by varying glazing type, orientation & house size	
C-3 Varying the orientation, glazing option, house size and WWAR		Orientation, House-size, WWAR, glazing options		**Figure A.8:** Annual energy consumption trends: A comparison by varying glazing type, orientation, house size & WWAR **Figure A.9:** Peak load energy consumption trends: A comparison by varying glazing type, orientation, house size & WWAR	

Table 4.15 Detailed analysis scheme for Section II of the simulation matrix, Part II contd….

PROCEDURE				CONCLUSIONS	
Run set	**Building models**	**Primary conditions**	**Method of input used**	**Figures**	**Reports**
D Determining the optimum WWAR and horizontal shading combination for South.	Base case II variant including results from Run Set A	WWAR- range 5% - 65% Shade width-range 0-8ft Glazing types - un-shaded DPC - optimally shaded DPC - un-shaded DPlow-e - optimally shaded DPlowe	WINDOW-5 Thermal mass option	**Table A.3:** Optimum WWAR at south for DPC and low-E glazing options for different house sizes	BEPS
E Determining optimum choice of glazing , optimum length of horizontal shading and WWAR for fenestration on all orientations. Comparing results which are based on Window to Floor Area Ratio to the code compliant standard design model prescribed by the code which has 18% window to floor area ratio.	Base case II including results from Run Set B Base case III	House Size GWAR Glazing type Glazing/shading combination	WINDOW-5 Thermal mass option	**Figure A.10:** Annual energy consumption trends for overall performance: A comparison to results obtained from code run of 18% WFAR	Annual Energy Consumption: BEPS Peak Loads: LS-B Report

In Part B of the simulation matrix, which is presented in Tables 4.14 – 4.15, Run Set A was performed to determine the optimum horizontal shading size for south orientation, while horizontal shading projections for east and west were fixed at 4 ft. Case II was used as the simulation model. Results for the overall building energy performance from the PLANTS subsection in the DOE-2 output file were considered. Run Set B examines the impact of shading on solar radiation incident on each of the vertical surfaces and the resultant impact on the overall building energy performance. Case II was used as the simulation model. Results from the hourly output reports for solar radiation from the LOADS and BEPS report from the PLANTS subsections in the DOE-2 file were analyzed. In Run Set C, combinations of lower performance windows (i.e., Double Pane Clear), along with horizontal shading, were compared with windows specified by the IECC code (i.e., Double Pane low-E). Run Set C was further subdivided to test the impact of variations in glazing options, house-sizes, and WWARs. The orientation and glazing type were changed in Run Set C-1. In Run Set C-2, variation in house-size was considered, in addition to changing the orientation and glazing options. While in Run Set C-3, all the four variables (i.e., orientation, glazing option, house-size, and WWAR) were altered. Case II variant is used as a simulation model. Results from peak heating and cooling loads reports from the LOADS sub-program and BEPS from the PLANTS subprogram of the DOE-2 are considered. Run Set D was performed to determine the optimum WWAR and horizontal shading for the south orientation. Case II variant was used as the simulation model. Results were obtained by analyzing the BEPS reports obtained from the simulations. In Run Set E, optimum glazing and shading strategies for each orientation were tested together on a single simulation model. Case II is used as a simulation model. Results from this set of simulations were compared to results from Case III, which specifies an 18% Window-to-Floor Area ratio. Peak load reports from LOADS and BEPS from PLANTS sub-section of the DOE-2 program were used for analysis.

4.5.4 Analysis of alternative options

4.5.4.1 Objective

The objective in this section is to investigate whether the energy consumption due to windows can be further reduced by utilizing alternate shading strategies. This includes examining the options of movable awnings and utilizing both practical and theoretical options of high performance windows which could subsequently be incorporated in the code. The analysis also looks at various possibilities of re-interpreting the code wherein the specifications for assigning window ratios are reassessed and refined.

4.5.4.2 Criteria for selection of glazing

The criteria for the selection of the glazing are based on research work conducted by Apte et al. (2003) mentioned earlier in the literature review. The study listed several practical and hypothetical high performance windows, taking into account their U-value and SHGC properties. The first set of options – low-E, low-solar/low-E, high-solar glazing represented mid-range glazing products. The second set of options – Super low-solar/Super high-solar glazing represented the most efficient glazing products available in the market today. The next three products represented a range of next generation products. The Ultra low-solar/Ultra high-solar glazing options represented a future improvement of high performance glazing products currently available in the market. While Dynamic glazing options, DYSULS and DYULLD, are assumed to have the cooling season performance of low solar gain windows, SULS and ULLS respectively, and heating season performance properties which correspond to high solar gain windows.

However, Apte et al.'s study used a highly insulated building envelope and high efficiency HVAC system, which minimize the impact of windows on the energy consumption of the building prototype, and the impact of thermal mass properties of the building envelope components was not taken into consideration. Also the impact of the choice of glazing on the house size and window to wall area ratio was not taken into account.

As the current study focuses on hot and humid climates, only the low solar options are considered. The above mentioned shortcomings were addressed by using a code specified building simulation model, which is a more practical option for the building being simulated. Also, the thermal mass option for building envelope component was activated in this study which yields to more accurate and realistic results.

4.5.4.3 Methods implemented by DOE-2.1e to model dynamic glazing

In order to simulate the properties of glazing that change according to environmental conditions, DOE-2.1e lists two options to model dynamic glazing.

a) Model for switchable glazing.

b) Schedule option:

Details of the two methods are provided in Appendix F. The model for switchable glazing proved to be more accurate than the shading schedule method, and hence was used by this study. A table describing the high-performance glazing options used by the detailed review of the selection procedure for dynamic glazing are given in Appendix B.

4.5.4.4 Analysis matrix for Section III

A detailed simulation scheme for Section III, which is briefly described in Table 4.5, is presented in Tables 4.16 – 4.18. The objective of this matrix is to test the performance of various high-performance glazing options. To carry out this analysis, four base-line cases were used. Case II is a residential building prototype as currently defined in the IECC but uses Custom-Weighting-Factors and WINDOW-5 library to specify the building components. Case II variant is similar to base-case III, but has provision for glazing in one orientation only. Case III is the code complaint base-line case with an 18% Window-to-Floor Area Ratio. Case IV is a windowless building model.

Six glazing types consisting of commercially available as well as hypothetical examples are selected to perform the simulations. Apart from the glazing options, three house sizes (i.e., 1500 ft^2, 2500 ft^2, and 5000 ft^2), three Window to Wall Area Ratios (15%, 20%, and 25%) and provision for glazing on the North, South, East, and on all orientations were also considered. This information is summarized and tabulated in Part A of the matrix which is presented in Table 4.16.

Table 4.16 Detailed analysis scheme for Section III of the simulation matrix: Part I

SECTION III	
OBJECTIVE To assess the potential of windows as net energy providers	
PROCEDURE Analyzing the performance of high-performance glazing High performance glazing vs. glazing specified by the IECC code vs. windowless base-case	
Part A	
Base-case options used	Base case II (Ref Table 4.6): Building prototype model modified as per results from simulation part I using custom weighting factors & WINDOW-5 library. Base case II variant (Ref Table 4.6): Variant of Building prototype model modified as per results from simulation part I using custom weighting factors & WINDOW-5 library. Glazing on one orientation only. Base case III (Ref Table 4.6): Code compliant house with 18% Window to Floor Area Ratio (WFAR) Base case IV (Ref Table 4.6): Windowless building prototype model
Conditions	VARIABLE CONDITIONS: 3 House sizes: o 1500sqft o 2500sqft o 5000sqft 3 GWARs: o 15% o 20% o 25% 3 Orientation: o North o South o East o Fenestration on all the orientations 6 Glazing types: o Double pane low-E o Low-E low solar- 8004 o Super low solar - 8002 o Dynamic super low solar – 8002-03 o Ultra low solar - 8000 o Dynamic ultra low solar - 8000-01
Options for the method of input	INPUT FOR CONSTRUCTION MATERIALS CONSIDERING THERMAL MASS PROPERTIES: o Floor weight set at zero to activate custom weighting factors. INPUT FOR FENESTRATION: o Window-5 method used for fenestration input.

Table 4.17 Detailed analysis scheme for Section III of the simulation matrix: Part II

Part B				
PROCEDURE			**CONCLUSIONS**	
Run set	**Building models**	**Primary conditions**	**Figures**	**Reports**
A Selection procedure and analysis of high performance glazing				
A-1 Choosing high performance glazing options	Base case II	Various switching temperature used	**Figure 5.3.1:** Sample DOE-2.1e input code for switchable glazing **Figure 5.3.2:** Optimizing the switching temperature **Figure 5.3.3:** Resultant DOE-2.1e input code as used in the simulation runs **Table 5.3.1:** List of options for switching schedule **Table 5.3.2:** Optimum switching temperature for the three house sizes selected **Table 5.3.3:** Optimizing the switching schedule **Table 5.3.4:** U-factor multipliers for switchable glazing **Table 5.3.5:** Description of glazing alternates used in the simulation	BEPS
A-2 Observing the performance of selected high performance glazing			**Figure 5.3.4:** Annual performance of selected code specified low-E glazing option **Figure 5.3.5:** Annual performance of low-E low-solar (LELS) glazing option **Figure 5.3.6:** Annual performance of super low-E low-solar (SULLS) glazing option **Figure 5.3.7:** Annual performance of dynamic super low-E low-solar (DySULS) glazing option **Figure 5.3.8:** Annual performance of ultra low-E low-solar (ULLS) glazing option **Figure 5.3.9:** Annual performance of dynamic ultra low-E low-solar (DyULLS) glazing option **Figure 5.3.10:** Weekly conduction + solar gain performance of selected glazing types (Jan 10^{th} – 16^{th}) **Figure 5.3.11:** Weekly conduction + solar gain performance of selected glazing types (Aug 6^{th} – 12^{th}) **Table 5.3.6:** Results from BEPU and BEPS reports for the selected high-performance glazing options	Hourly reports from LOADS Hourly reports from SYSTEMS

Table 4.18 Detailed analysis scheme for Section III of the simulation matrix: Part II contd….

Part B contd…				
PROCEDURE contd…			**CONCLUSIONS contd…**	
Run set	**Building models**	**Primary conditions**	**Figures**	**Reports**
B Assessing the impact on energy consumption of building model which has provisions for windows in one orientation only	Base case II variant			BEPS report
B-1 Varying the orientation and glazing options		House size Glazing options	**Figure 5.3.12:** Annual energy consumption trends: A comparison by varying the glazing type and orientation	
B-2 Varying the orientation, glazing option and house size		House size Glazing options Orientation	**Figure 5.3.13:** Annual energy consumption trends: A comparison by varying the glazing type orientation and house size	
B-3 Varying the orientation, glazing option, house size and WWAR		House size Glazing options WWAR Orientation	**Figure 5.3.14:** Annual energy consumption trends: A comparison by varying the glazing type orientation WWAR and house size	
C Assessing the overall performance of high-performance windows				BEPS report
C-1 Comparing the performance of high-performance windows to the performance of windows specified by the code	Base case II	House size WWAR	**Figure 5.3.15:** Percentage difference between CODE glazing option and high –performance glazing options: Annual energy consumption **Figure 5.3.16:** Percentage difference between CODE glazing option and high –performance glazing options: Annual space heating **Figure 5.3.17:** Percentage difference between CODE glazing option and high –performance glazing options: Annual space cooling	
C-2 Comparing the performance of high-performance windows to windowless building model	Base case IV	House size WWAR	**Figure 5.3.18:** Percentage difference between windowless base-case and high –performance glazing options: Annual energy consumption **Figure 5.3.19:** Percentage difference between windowless base-case and high –performance glazing options: Annual space heating **Figure 5.3.20:** Percentage difference between windowless base-case and high –performance glazing options: Annual space cooling	

In Part B of the simulation matrix, which is presented in Tables 4.17 – 4.18, Run Set A describes the selection procedure and the analysis of high-performance glazing. Run Set A is further divided into two parts. Run Set A-1 describes the selection procedure of high-performance glazing (dynamic option) from the options available in the DOE-2 program. Results were obtained from analyzing the BEPS report from the PLANTS sub-section of the DOE-2 program. Subsequently, the performance of all the glazing types selected by this section was observed in Run Set A-2. Results were obtained from examining the hourly reports from both LOADS and SYSTEMS. Case II is used as a simulation model for both the simulation sets. Run Set B assesses the impact on energy consumption of the building model, which has provision for windows in one orientation only. This set was further categorized into three categories. Results were obtained examining the BEPS report. Case II variant was used as the simulation model in this set of simulations. In Run Set C, an assessment of the overall performance of the selected glazing was performed. The set was further divided into two parts. Run Set C-1 compared the performance of the selected glazing to the performance of code compliant glazing. Case II was used as a simulation model for this set of simulations. Run Set C-2 compared the performance of the selected glazing to the windowless building model. Cases II and IV were used in this simulation set. Results were obtained analyzing the BEPS reports, which are obtained from the PLANTS sub-section of the DOE-2 output files.

CHAPTER V

DATA ANALYSIS AND RESULTS

5.1 Comparison of methods of input for fenestration in the DOE-2 building simulation program

This section presents results of tests performed to examine the accuracy of building energy simulations for code compliance. The focus of these tests is on the fenestration input method to the DOE-2.1e building simulation model. To perform these tests two options for the input of fenestration characteristics in the building model were compared. The Shading Coefficient method (SC), which has been the traditional method of defining fenestration in the DOE-2.1e (Ver.119) building simulation model, is compared to the WINDOW-5 (W5) method. The previous research by Reilly et al. (1992) was the primary motivation for this work. The testing also included an analysis of the interaction with DOE-2's Custom Weighting Factors (CWFs) in the simulation model versus the use of ASHRAE Pre-calculated Weighting Factors (i.e., the Quick method), which have not been previously reported in the literature.

Three glazing options, Single Pane Clear (SPC), Double Pane Clear (DPC) and Double Pane Low-E (DPlow-E), were selected for the purpose of the analysis. Results from both the LOADS and SYSTEMS section of the DOE-2's simulation output were analyzed and are presented in terms of hourly / daily reports, annual reports and peak load reports.

To compare the SC and the W5 methods, a two-step test procedure was adopted. The first step looked at the properties of glazing, which determines the amount of solar radiation entering the space. The second step examined the impact of using each of these options on the annual and peak energy consumption reports. The CWFs were also analyzed in the test procedure versus DOE-2's Pre-calculated Weighting Factor calculation mode. The impact of their activation/deactivation was simultaneously tested with the SC and W5 methods.

5.1.1 Comparing the performance of glazing properties: transmittance, absorbtance and reflectance for the SC and W5 methods

Three properties of glazing determine the amount of solar radiation entering the conditioned space. They are - transmittance, absorptance and reflectance. At any instant of time, total solar radiation I falling on a window must be equal to the sum of radiation which is transmitted, reflected and absorbed:

$$\tau + \acute{\alpha} + \rho = 1$$

Table 5.1 presents these properties for the glazing options selected for this analysis at normal angle of incidence of solar radiation on the glazing. It is important to note that the properties of transmittance, absorptance and reflectance vary considerably for the three options chosen by this study. The numbers are extracted from the WINDOW-5 output files which can be found in Appendix G. For comparison purposes, the specifications for the Single Pane Clear adopted by Lokmahekim (ASHRAE 1975) to prepare the algorithms used by the Shading Coefficient (SC method) for calculating heat gain through fenestration in DOE-2.

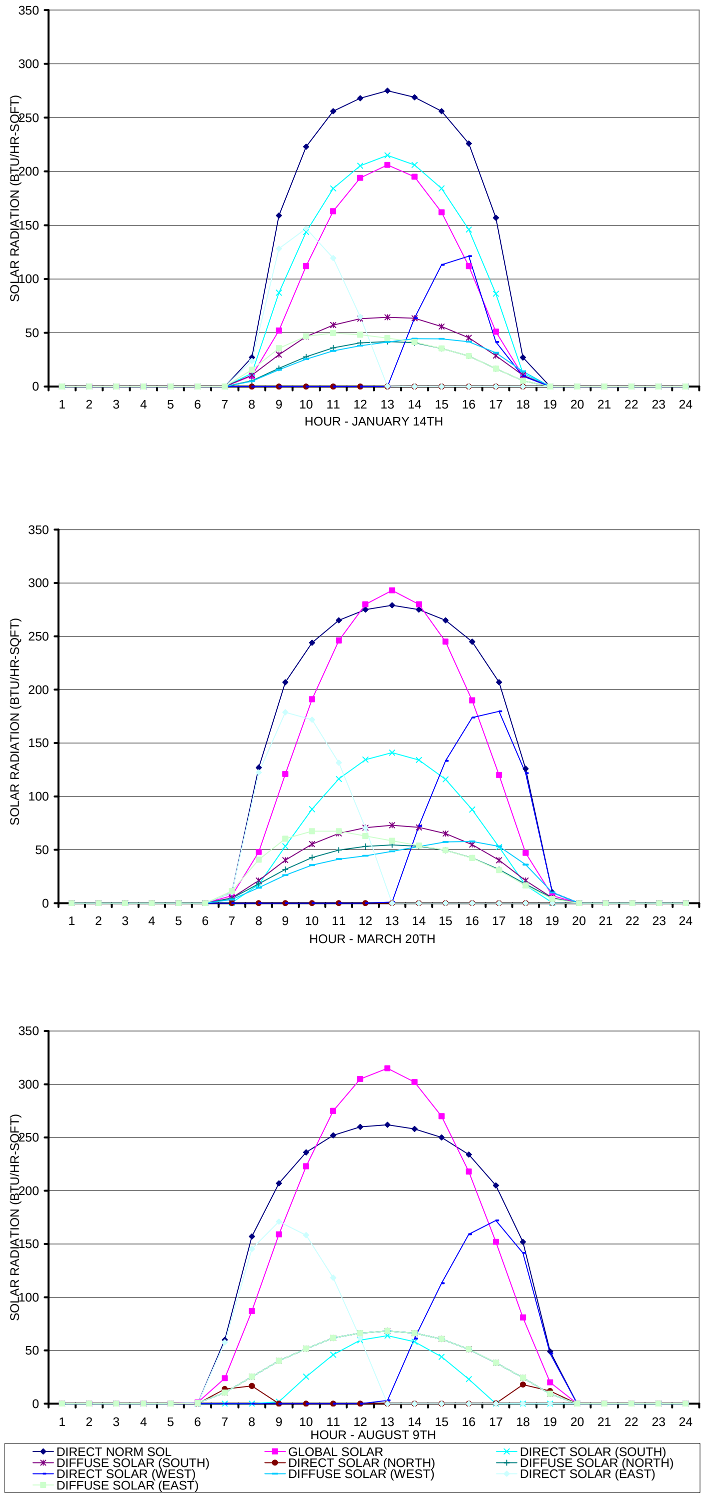
Table 5.1 Transmittance, absorptance and reflectance properties of the selected glazing (Source: WINDOW-5 output files, Appendix G)

Type of Glazing (Lokmanhekim 1975)	Properties		
	% Transmittance	% Absorptance	% Reflectance
Single Pane Clear (Lokmanhekim 1975)	86	8	6
Single Pane Clear (1000)	83.7	8.8	7.5
Double Pane Clear (2000)	70.5	16.8	12.8
Double Pane Low-E (2661)	35.8	28.7	35.5

The glazing properties are examined in terms of their hourly performance for the three days which are selected to represent different ambient temperature conditions for three different periods of the year. All of these days – January 14, March 20, and August 9 – represent peak heating and cooling conditions for clear days in the winter, spring, and summer respectively. Figure 5.1 shows the incident solar radiation for the three selected days. In this figure it can be observed that the diffuse radiation for all four orientations is the same for August, while for January and March diffuse radiation for the four orientations is different. As expected, the global horizontal solar radiation is highest in August and lowest in January. The direct solar radiation is about the same for all months, varying only by length of the day.

Taking a cue from the research performed by Reilly et al. (1992), the study examined the transmittance properties of the three glazing options by examining the pattern of transmittance for the different angles of incidence of solar radiation on the glazing surface. Figure 5.2a shows the transmittance properties of the three selected glazing options, when subjected to solar radiation at different angles of incidence. Figure 5.2b presents the normalized transmittance of the selected glazing, which is obtained by dividing the transmittance at any given angle by the transmittance values obtained at the normal angle of incidence. Figure 5.2a and b help to better understand the discrepancy in the results from the DPC and the DPlow-E glazing options at higher incidence angles when compared to the SPC option. It should be noted that the properties of SPC are used as reference properties by the SC method to predict the transmittance of other glazing options. Although the SC method gives satisfactory results for all the glazing options at low-incidence angles, the results vary significantly at higher incidence angles, where this method tends to overstate the solar transmittance.

Figure 5.3–5.5 show the hourly heat gain for the solar transmittance through the south facing glazing for the three window types - SPC, DPC and DPlow-E as calculated by the SC method and W5 method. For the month of January (Figure 5.3), in the case of the SPC glazing option, the W5 method results over-predict the SC method results by up to 5% at mid-day. Conversely, for the case of the DPC and the DPlow-E glazing options, the SC method shows slightly higher transmittance than the W5 method. For the DPC glazing option, the SC method over-predicts the W5 method by up to 10.65%.



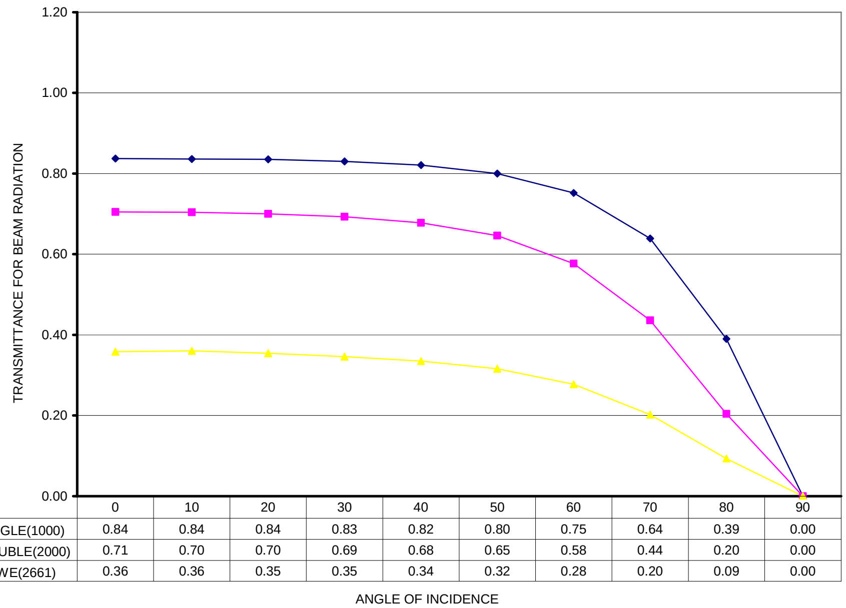
a) Plot for January 14

b) Plot for March 20

c) Plot for August 9

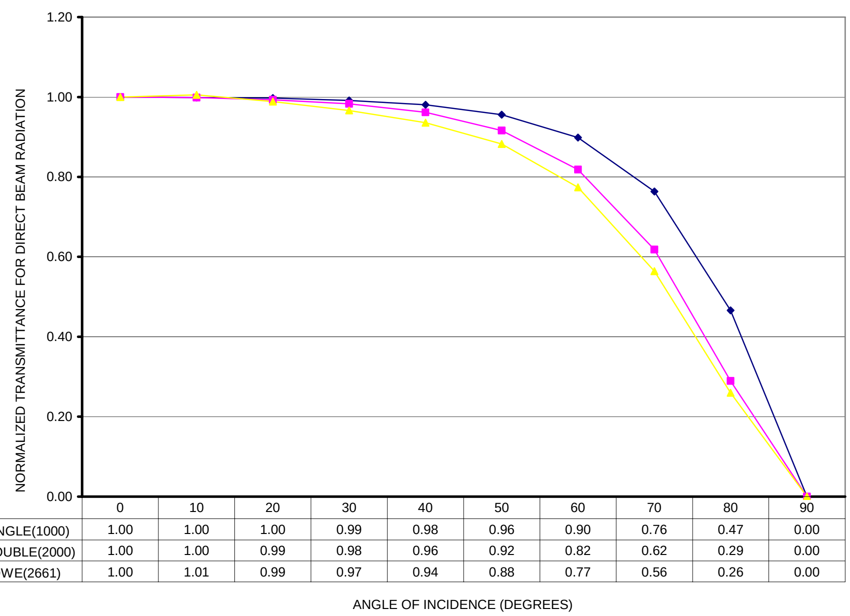
Figure 5.1 Solar radiation incident on vertical surface for January 14, March 20 and August 9

5.1.1.1 Solar Transmittance



	0	10	20	30	40	50	60	70	80	90
SINGLE(1000)	0.84	0.84	0.84	0.83	0.82	0.80	0.75	0.64	0.39	0.00
DOUBLE(2000)	0.71	0.70	0.70	0.69	0.68	0.65	0.58	0.44	0.20	0.00
LOWE(2661)	0.36	0.36	0.35	0.35	0.34	0.32	0.28	0.20	0.09	0.00

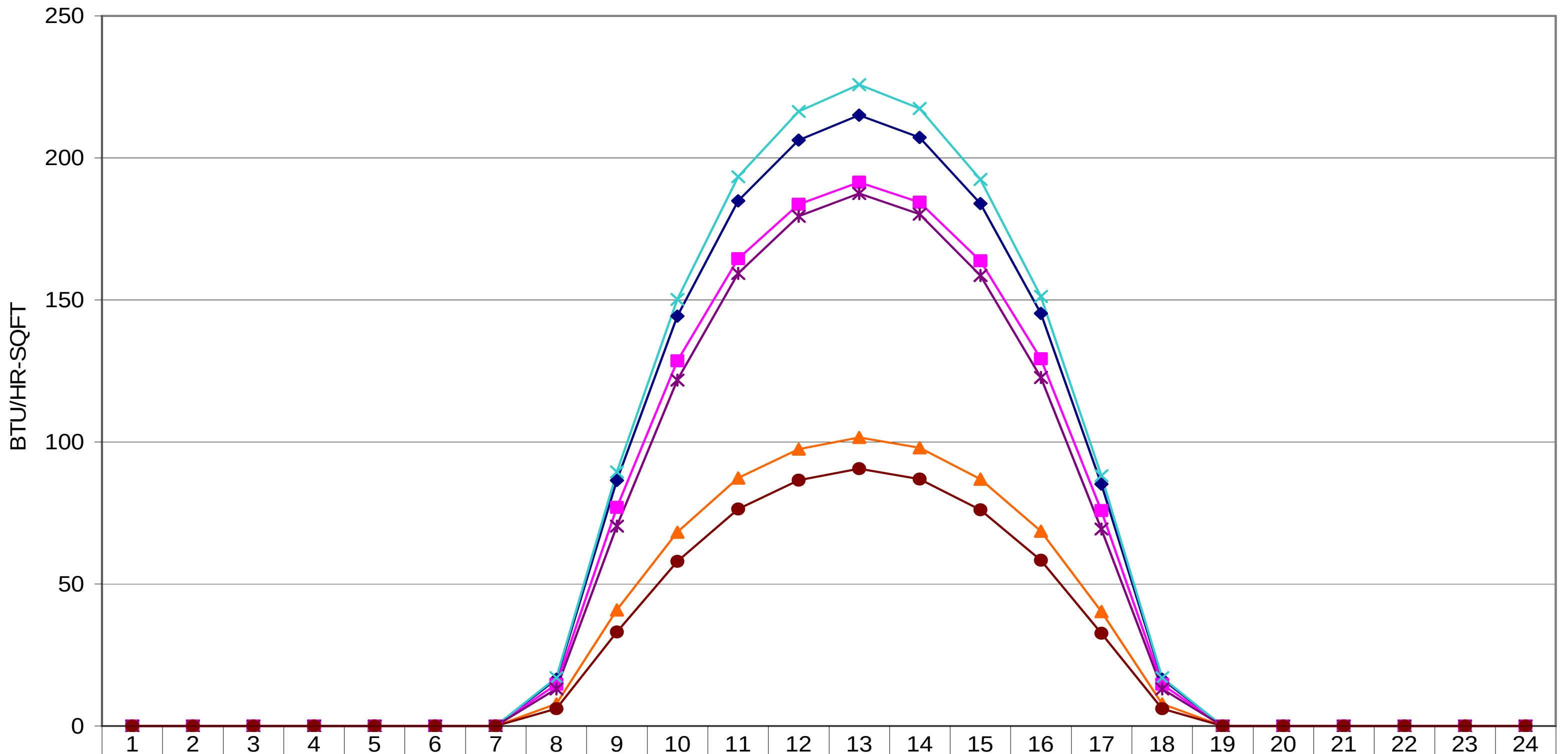
a) Solar transmittance curves for the three glazing options depending on the angle of incidence



	0	10	20	30	40	50	60	70	80	90
SINGLE(1000)	1.00	1.00	1.00	0.99	0.98	0.96	0.90	0.76	0.47	0.00
DOUBLE(2000)	1.00	1.00	0.99	0.98	0.96	0.92	0.82	0.62	0.29	0.00
LOWE(2661)	1.00	1.01	0.99	0.97	0.94	0.88	0.77	0.56	0.26	0.00

b) Normalized solar transmittance curves for the glazing options depending on the angle of incidence

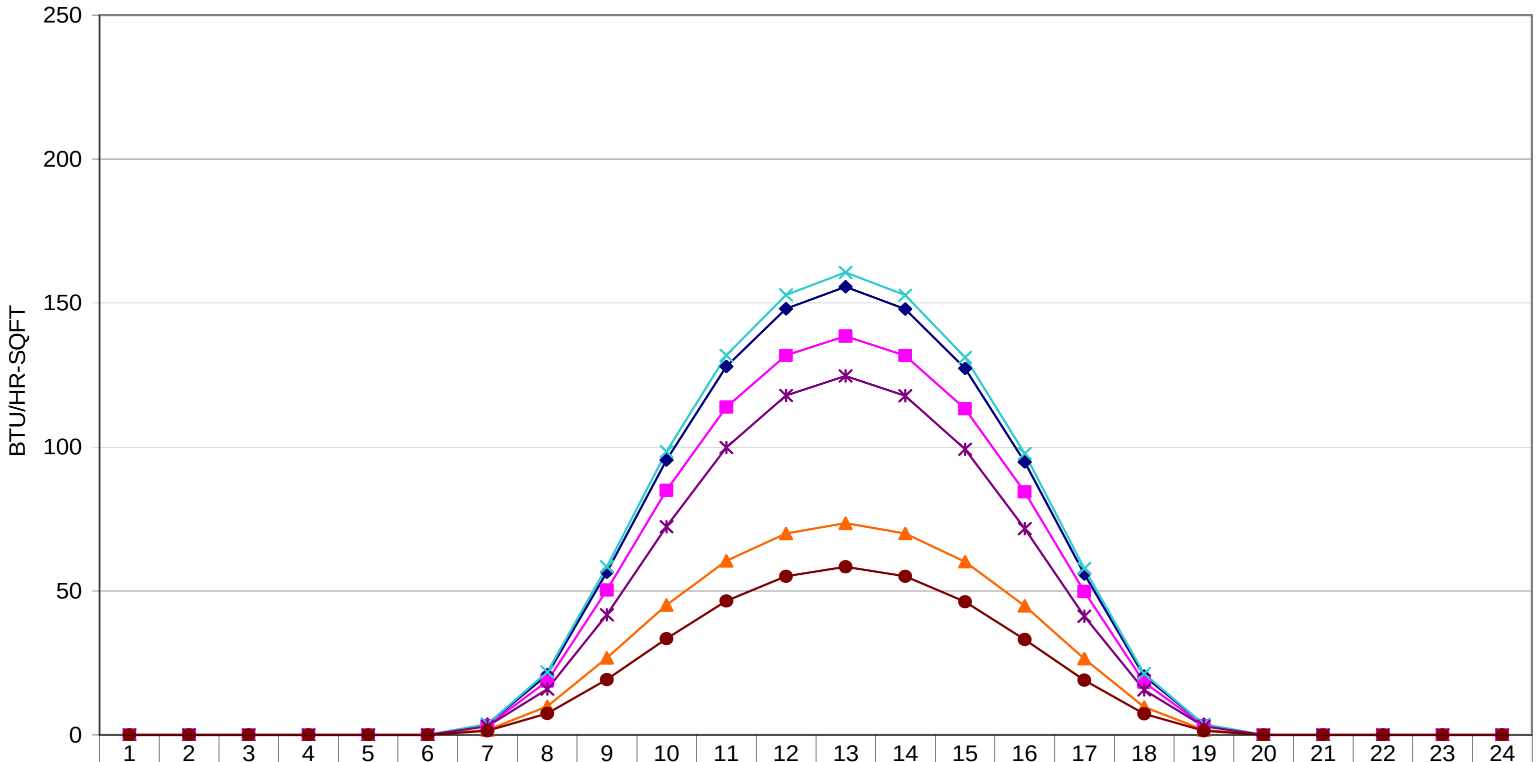
Figure 5.2 Transmittance properties for selected glazing



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SCSPC	0	0	0	0	0	0	0	16.5	86.5	144	185	206	215	207	184	145	85.2	16.5	0	0	0	0	0	0
SCDPC	0	0	0	0	0	0	0	14.7	77	128	165	184	191	184	164	129	75.8	14.7	0	0	0	0	0	0
SClowE	0	0	0	0	0	0	0	7.78	40.9	68.2	87.3	97.5	102	97.9	86.9	68.6	40.2	7.78	0	0	0	0	0	0
W5SPC	0	0	0	0	0	0	0	17	89.4	150	193	216	226	217	192	151	88.1	17	0	0	0	0	0	0
W5DPC	0	0	0	0	0	0	0	13.1	70.4	122	159	179	188	180	159	123	69.3	13.1	0	0	0	0	0	0
W5lowE	0	0	0	0	0	0	0	6.1	33.1	57.9	76.4	86.5	90.6	86.9	76.1	58.3	32.6	6.1	0	0	0	0	0	0

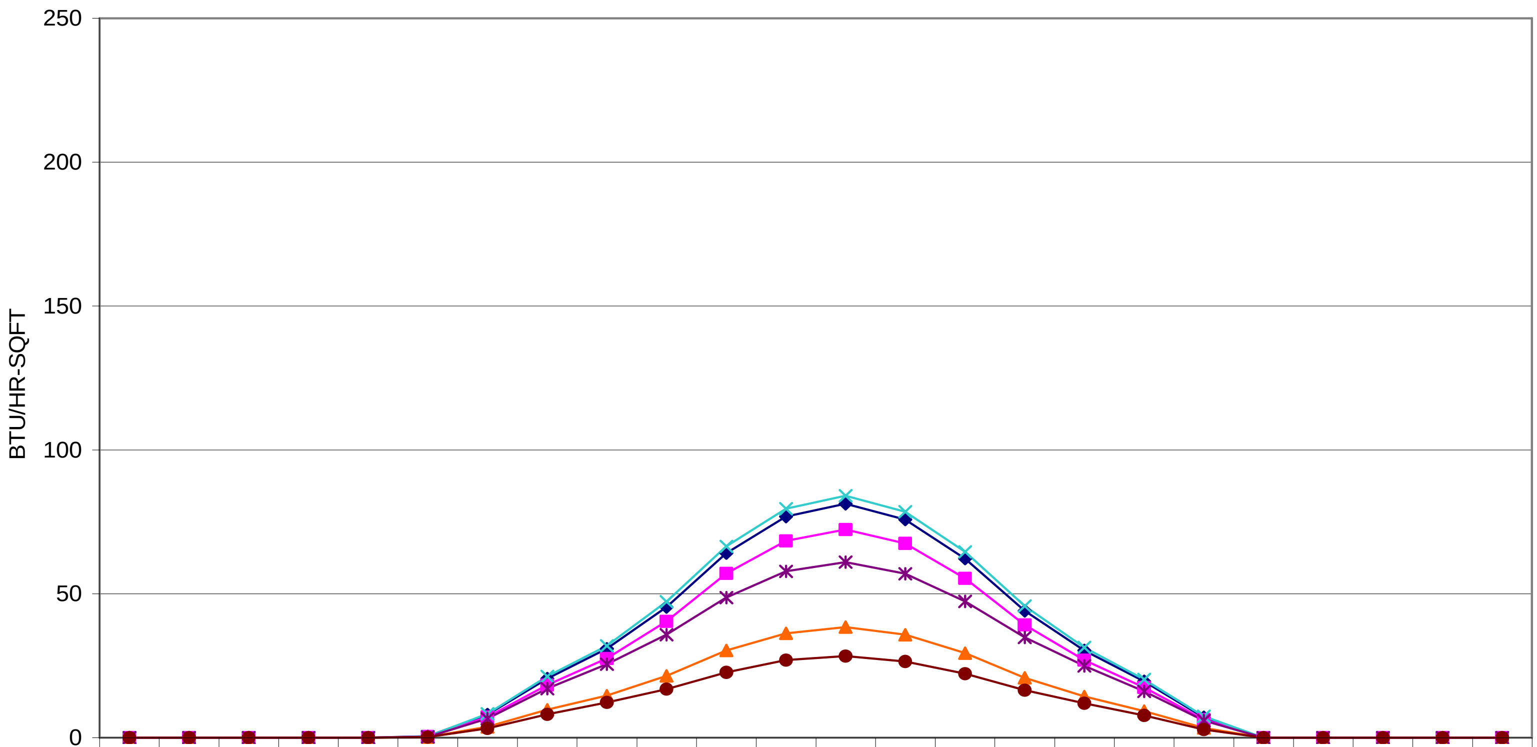
HOUR

Figure 5.3 Solar transmittance for January 14 for south facing window



HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SCSPC	0	0	0	0	0	0	3.64	20.9	56.5	95.5	128	148	156	148	127	94.8	56	20.5	3.64	0	0	0	0	0
SCDPC	0	0	0	0	0	0	3.24	18.6	50.3	85	114	132	139	132	113	84.4	49.8	18.2	3.24	0	0	0	0	0
SClowE	0	0	0	0	0	0	1.72	9.89	26.7	45.1	60.5	70	73.5	69.9	60.2	44.8	26.4	9.68	1.72	0	0	0	0	0
W5SPC	0	0	0	0	0	0	3.8	21.8	58.4	98.4	132	153	161	153	131	97.7	57.8	21.3	3.7	0	0	0	0	0
W5DPC	0	0	0	0	0	0	3	15.9	41.7	72.3	99.8	118	125	118	99.2	71.7	41.2	15.6	3	0	0	0	0	0
W5lowE	0	0	0	0	0	0	1.4	7.4	19.2	33.4	46.5	55.1	58.4	55.1	46.2	33.1	19	7.3	1.4	0	0	0	0	0

Figure 5.4 Solar transmittance for March 20 for south facing window



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SCSPC	0	0	0	0	0	0.46	8.01	20.6	30.8	45.4	64.2	76.8	81.3	75.8	62.2	44	30.3	19.6	7.1	0	0	0	0	0
SCDPC	0	0	0	0	0	0.41	7.13	18.3	27.5	40.4	57.1	68.4	72.3	67.5	55.4	39.2	27	17.4	6.32	0	0	0	0	0
SClowE	0	0	0	0	0	0.22	3.78	9.72	14.6	21.5	30.3	36.3	38.4	35.8	29.4	20.8	14.3	9.25	3.35	0	0	0	0	0
W5SPC	0	0	0	0	0	0.4	8.3	21.3	31.9	47.3	66.5	79.6	84.1	78.5	64.6	45.8	31.4	20.2	7.4	0	0	0	0	0
W5DPC	0	0	0	0	0	0.3	6.6	17	25.5	35.8	48.7	57.8	61	57	47.4	34.8	25	16.1	5.9	0	0	0	0	0
W5lowE	0	0	0	0	0	0.2	3.2	8.1	12.2	16.9	22.7	26.9	28.3	26.5	22.2	16.5	12	7.7	2.8	0	0	0	0	0

HOUR

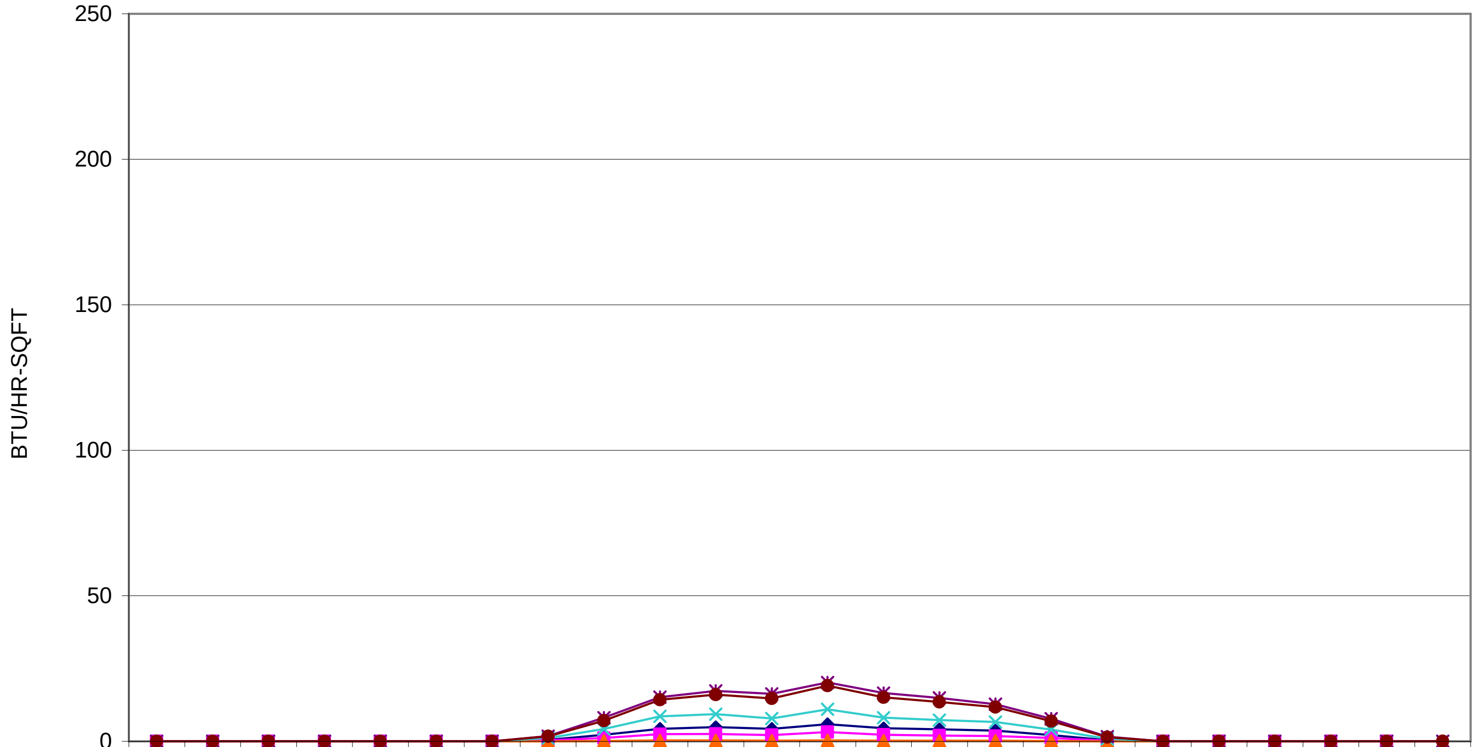
Figure 5.5 Solar transmittance for August 9 for south facing window

For the DPlow-E glazing option, the SC method results over-predict by up to 21.62%. For March (Figure 5..4), in the case of the SPC glazing option, the W5 method over-predicts the SC method by 4.39%. For the case of the double pane glazing options, the SC method over-predicts the W5 method results by 17.29%. For the case of DPlow-E glazing, the SC method over-predicts by up to 28.15%. For the month of August (Figure 5.5), in the case of SPC glazing, W5 over-predicts SC by 4.25%. For DPC glazing, SC over-predicts W5 by 15%, while in the case of DPlow-E glazing, SC over-predicts W5 by 26%.

In summary, varying trends are seen for the three selected days with lower discrepancy values for January and higher discrepancy values for August. This is because the angle of incidence for direct solar radiation on a southern face is smallest in January and highest in August. Moreover, it is seen that in the DPC and DPlow-E glazing options, the SC results over-predicted the W5 results. Conversely, in the SPC glazing option, the results from W5 method prove to be greater than those from the SC method. Another important observation is that the maximum discrepancy in predictions is seen in the DPLow-E glazing option, while the minimum discrepancy is seen in the SPC glazing option.

5.1.1.2 Solar absorptance

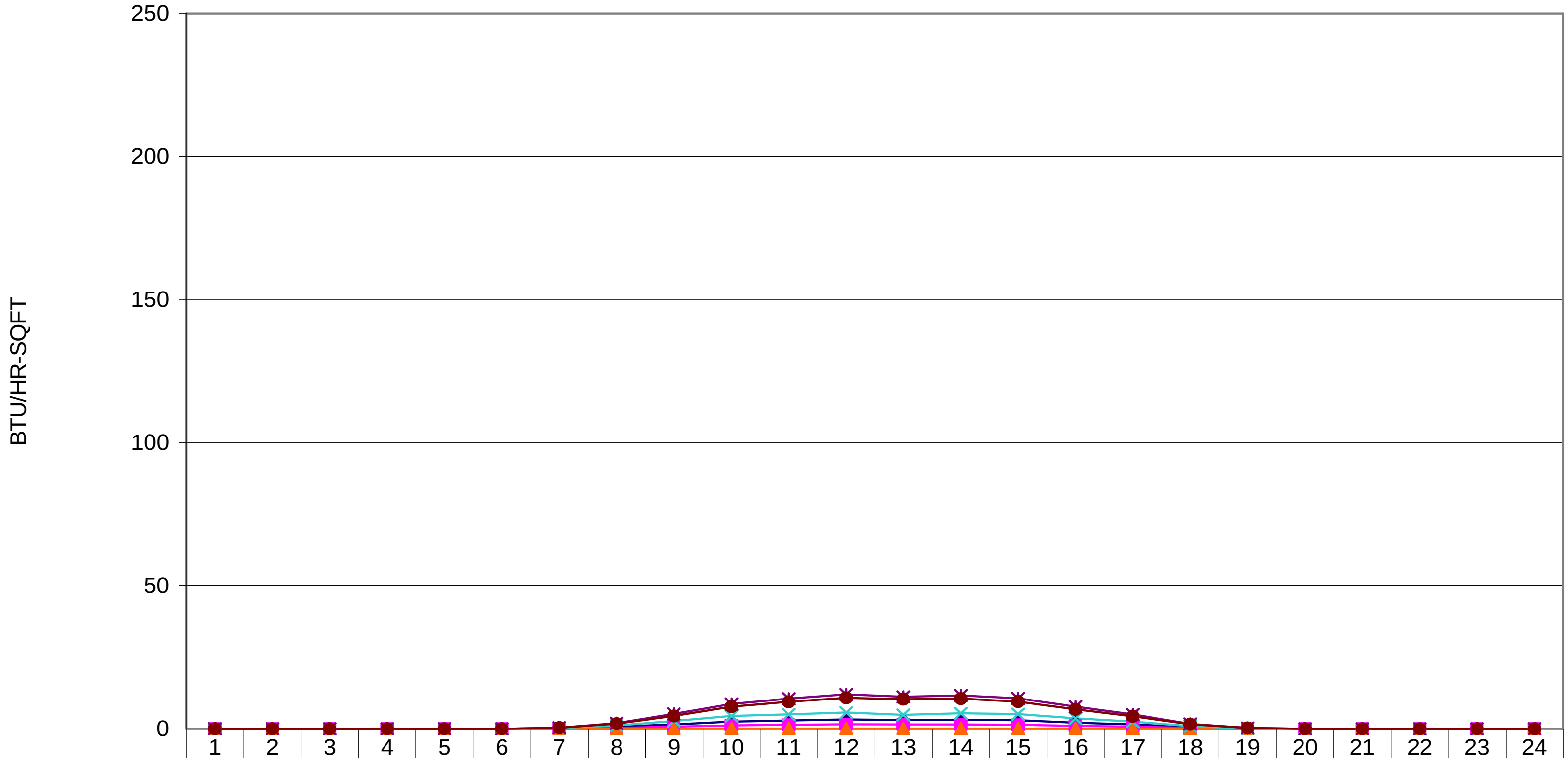
Figure 5.6 - 5.8 presents solar absorptance patterns of the three glazing options for January 14th, March 20th, and August 9th. In these hourly plots, it can be seen that for the SPC glazing option, the W5 method results are twice as large as the SC method (200%). For DPC glazing option, the W5 results are seven times the SC results (700%), while for DPlow-E glazing options, W5 results show 10.2 times the absorption of the SC calculations. Although there are large variations, the impact on the space is small because the overall magnitude of the solar absorptance by the glazing is small.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SCSPC	0	0	0	0	0	0	0	0.5	2.2	4.3	4.8	4.3	5.9	4.5	4.1	3.6	2.1	0.4	0	0	0	0	0	0
SCDPC	0	0	0	0	0	0	0	0.3	1.1	2.4	2.5	2.1	3.2	2.2	2	1.8	1.1	0.2	0	0	0	0	0	
SCDPlowE	0	0	0	0	0	0	0	0	0.1	0.3	0.3	0.2	0.3	0.2	0.2	0.2	0.1	0	0	0	0	0	0	0
W5SPC	0	0	0	0	0	0	0	1.1	4.2	8.6	9.3	7.8	11	8.1	7.3	6.6	4	0.8	0	0	0	0	0	0
W5DPC	0	0	0	0	0	0	0	1.8	8.1	15.2	17.3	16.3	20.2	16.6	14.9	12.8	7.7	1.6	0	0	0	0	0	0
W5DPlowE	0	0	0	0	0	0	0	1.7	7.1	14.2	16	14.7	19.1	15.1	13.5	11.7	6.9	1.4	0	0	0	0	0	0

HOUR

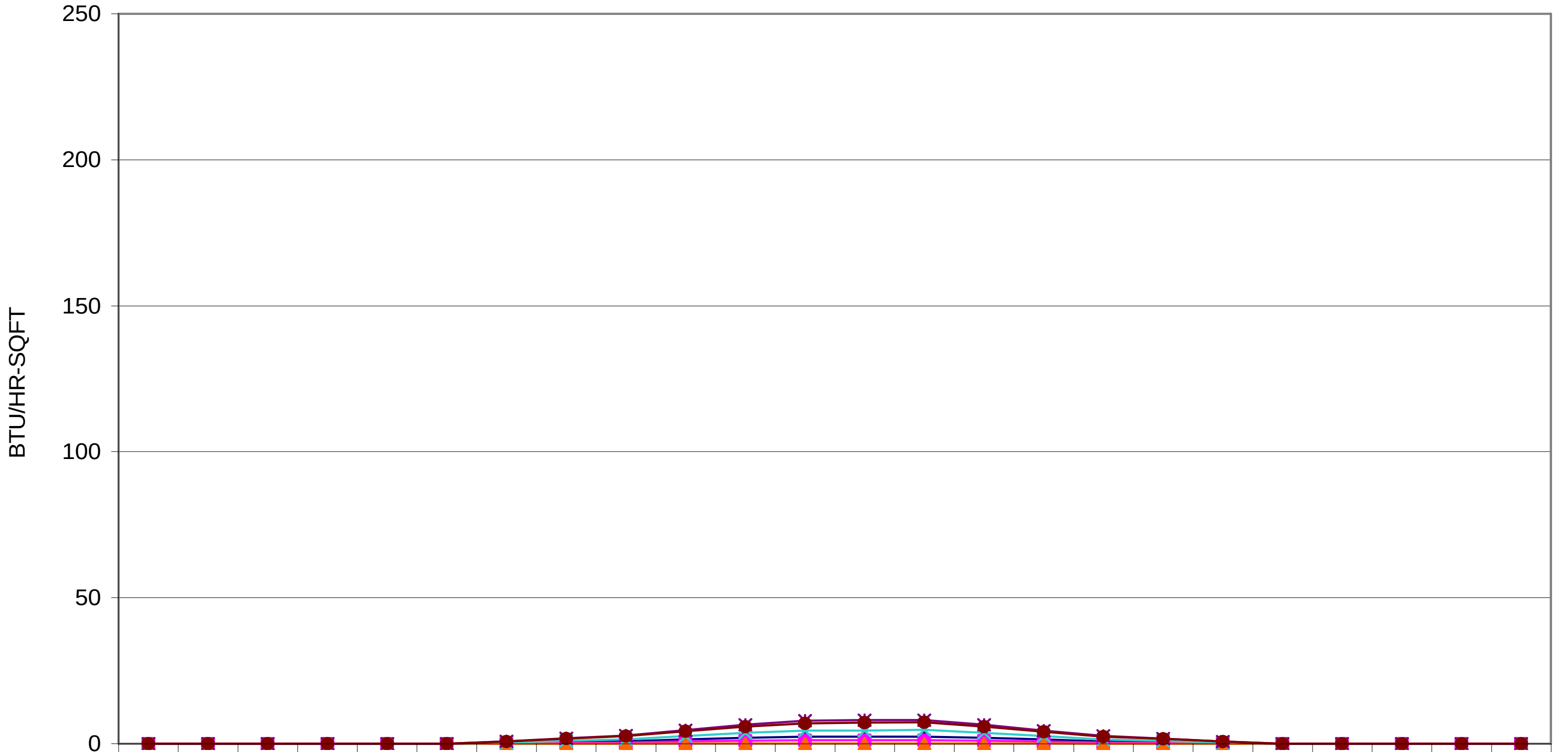
Figure 5.6 Solar absorptance for January 14 for south facing window



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SCSPC	0	0	0	0	0	0	0.1	0.7	1.5	2.5	2.9	3.3	3.1	3.2	3	2.1	1.5	0.6	0.1	0	0	0	0	0
SCDPC	0	0	0	0	0	0	0.1	0.3	0.7	1.2	1.4	1.6	1.5	1.5	1.4	1	0.7	0.3	0	0	0	0	0	0
SCDPlowE	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0	0	0	0	0
W5SPC	0	0	0	0	0	0	0.3	1.1	2.7	4.5	5	5.7	4.8	5.4	5.1	3.6	2.5	0.9	0.1	0	0	0	0	0
W5DPC	0	0	0	0	0	0	0.4	2	5.2	8.7	10.5	12	11.2	11.6	10.6	7.7	5	1.7	0.3	0	0	0	0	0
W5DPlowE	0	0	0	0	0	0	0.4	1.8	4.5	7.7	9.4	10.8	10.3	10.5	9.5	6.8	4.4	1.6	0.3	0	0	0	0	0

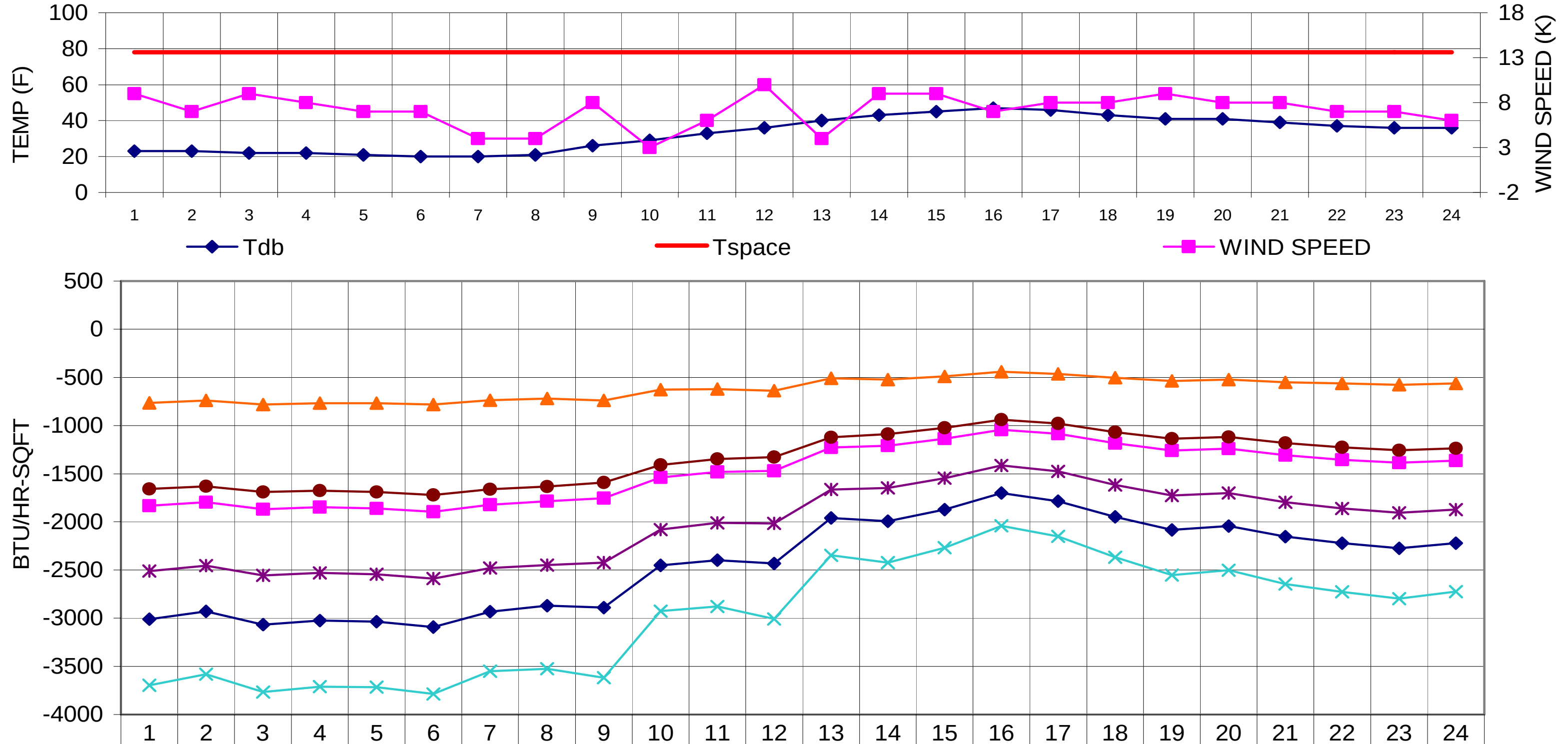
HOUR

Figure 5.7 Solar absorptance for March 20 for south facing window



HOUR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SCSPC	0	0	0	0	0	0	0.2	0.6	0.8	1.5	2	2.4	2.4	2.4	2	1.5	0.7	0.5	0.2	0	0	0	0	0
SCDPC	0	0	0	0	0	0	0.1	0.3	0.4	0.8	1	1.2	1.2	1.2	1	0.7	0.4	0.3	0.1	0	0	0	0	0
SClowE	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0	0	0	0	0	0
W5SPC	0	0	0	0	0	0	0.4	1	1.5	2.6	3.7	4.5	4.5	4.7	3.7	2.6	1.4	1	0.4	0	0	0	0	0
W5DPC	0	0	0	0	0	0	0.8	1.9	2.8	4.6	6.5	7.9	8.1	8.1	6.5	4.5	2.7	1.8	0.7	0	0	0	0	0
W5lowE	0	0	0	0	0	0	0.7	1.8	2.6	4.3	5.8	7	7.2	7.3	5.8	4.1	2.4	1.7	0.7	0	0	0	0	0

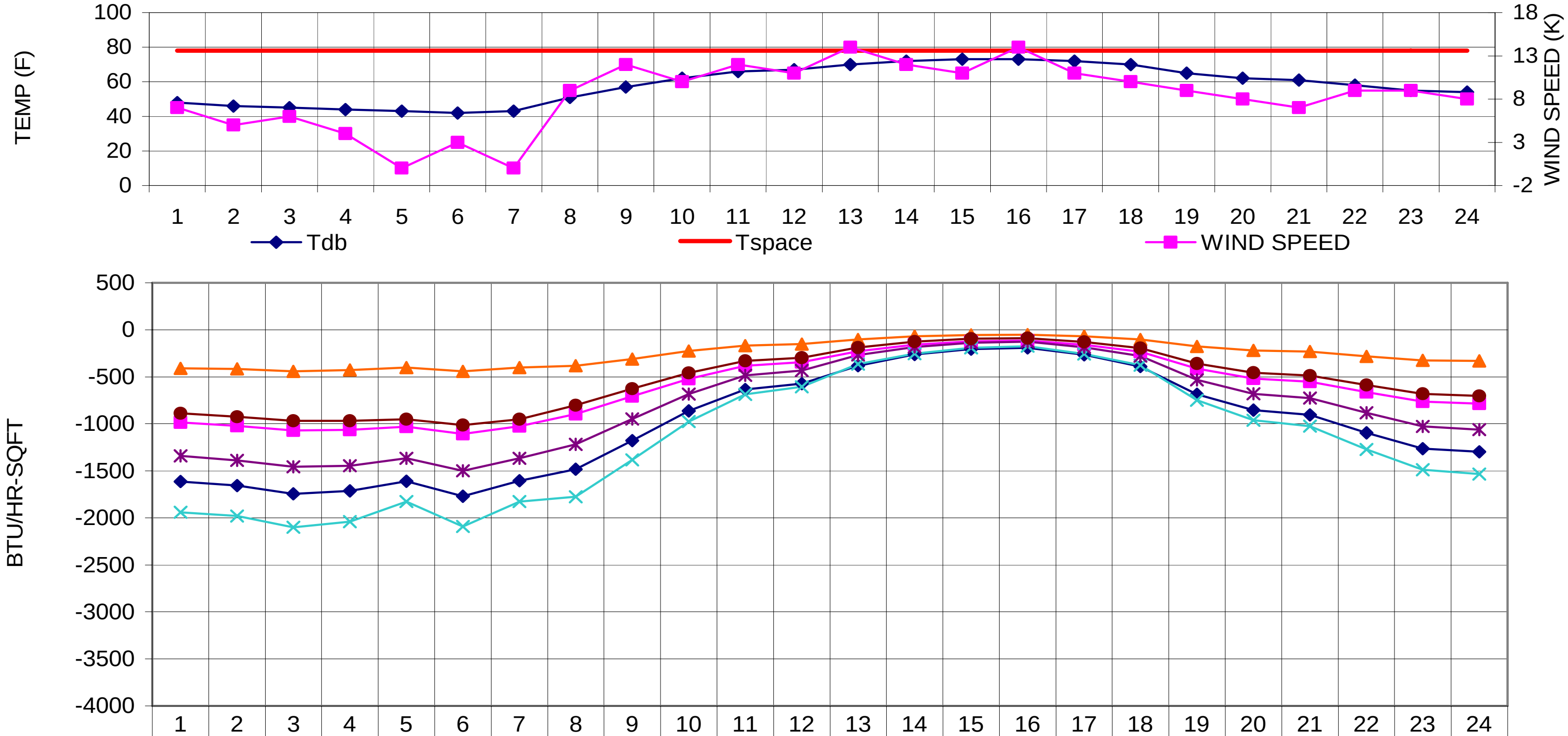
Figure 5.8 Solar absorptance for August 9 for south facing window



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SCSPC	-301	-292	-306	-302	-303	-309	-293	-287	-288	-245	-239	-243	-195	-199	-187	-170	-178	-194	-208	-204	-215	-222	-227	-222
SCDPC	-183	-179	-186	-184	-186	-189	-182	-178	-175	-153	-148	-146	-122	-120	-113	-104	-108	-118	-125	-124	-130	-135	-138	-136
SClowE	-766	-741	-781	-767	-768	-782	-736	-721	-741	-626	-620	-640	-509	-524	-491	-442	-464	-503	-536	-522	-550	-564	-578	-561
W5SPC	-369	-358	-376	-371	-371	-378	-355	-352	-361	-292	-287	-300	-234	-242	-227	-204	-215	-236	-255	-250	-264	-272	-279	-272
W5DPC	-250	-245	-255	-252	-254	-259	-247	-244	-242	-208	-200	-201	-166	-164	-154	-141	-147	-161	-172	-170	-179	-186	-190	-187
W5lowE	-165	-162	-169	-167	-168	-171	-166	-163	-159	-140	-134	-132	-112	-108	-102	-939	-978	-106	-113	-112	-118	-122	-125	-123

HOUR

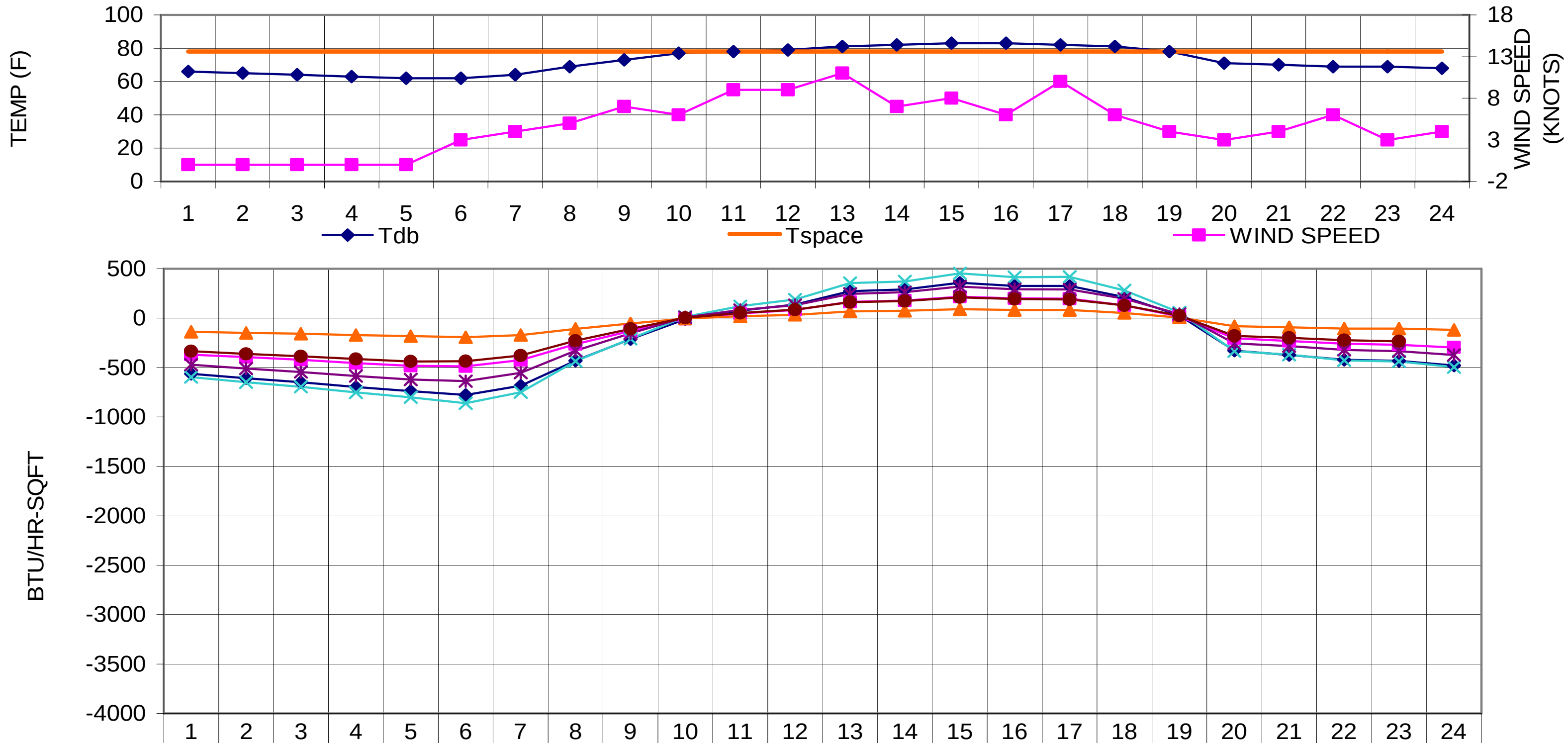
Figure 5.9 Window conduction for January 14 for south facing window



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SCSPC	-161	-165	-174	-171	-161	-177	-160	-148	-117	-864	-636	-573	-381	-263	-205	-191	-264	-391	-685	-854	-904	-109	-126	-129
SCDPC	-985	-102	-106	-106	-102	-110	-102	-896	-706	-520	-381	-344	-227	-157	-123	-114	-159	-235	-413	-518	-551	-662	-763	-787
SClowE	-410	-416	-440	-428	-402	-442	-401	-382	-310	-225	-168	-151	-102	-70	-54	-51	-70	-102	-177	-219	-230	-282	-325	-332
W5SPC	-193	-197	-210	-204	-182	-209	-182	-177	-138	-977	-687	-606	-366	-253	-190	-175	-256	-376	-749	-962	-102	-127	-148	-153
W5DPC	-134	-139	-145	-144	-136	-150	-136	-121	-947	-683	-485	-433	-269	-183	-137	-126	-185	-279	-532	-679	-725	-883	-102	-106
W5lowE	-887	-926	-967	-968	-952	-101	-951	-804	-628	-458	-329	-295	-188	-127	-96	-88	-128	-195	-360	-456	-487	-588	-681	-704

HOUR

Figure 5.10 Window conduction for March 20 for south facing window



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SCSPC	-564	-608	-648	-697	-738	-776	-683	-430	-211	-9.7	77.9	137	274	291	357	326	326	215	28.1	-328	-374	-423	-432	-479
SCDPC	-371	-395	-422	-454	-481	-486	-424	-264	-129	-6.8	46.8	83.1	165	177	217	199	196	130	15.9	-205	-231	-260	-269	-297
SClowE	-137	-148	-158	-171	-181	-192	-170	-108	-54	-4.3	19.2	34.9	70.3	74.4	91.1	82.1	82.4	51.6	5.17	-82	-93	-106	-107	-119
W5SPC	-597	-648	-696	-751	-800	-860	-749	-435	-210	15.7	120	190	354	373	454	415	417	281	59.3	-335	-369	-427	-437	-497
W5DPC	-472	-510	-545	-586	-622	-636	-552	-329	-156	8.69	83	133	247	263	319	294	291	198	40.5	-255	-284	-322	-335	-372
W5lowE	-335	-362	-385	-414	-439	-435	-378	-230	-108	3.11	52.9	86.4	161	174	210	194	190	129	24.8	-178	-200	-224	-235	

HOUR

Figure 5.11 Solar conduction for August 9 for south facing window

5.1.1.3 Window conductance

Figure 5.9 – Figure 5.11 present results of the window conduction for January 14, March 20, and August 9, respectively. Since the wind speed and the temperature difference between exterior and the interior play an important role in defining the heat gain due to conduction, they are included in the presentation of the results, in the upper graph of each figure.

In general, the window conduction results predicted by the W5 method are almost always greater than those predicted by the SC method. For January (Figure 5.9), in the case of the SPC glazing option the W5 method over-predicts the SC method by up to 25.19%. For DPC glazing, the W5 method over-predicts the SC method by up to 38.14%. While for the DPLow-E glazing, the W5 method over-predicts the SC results by 126.52 %. For March (Figure 5.10), in the case of the SPC glazing option the W5 method over-predicts the SC method by up to 20% while for some hours the SC method over-predicts the W5 method. For the DPC glazing, the W5 method over-predicts by up to 36.37%, while for the DPlow-E glazing option, the W5 method over-predicts by up to 137%. For August (Figure 5.11), in the case of the SPC glazing option, the W5 method over-predicts the SC method by up to 111.06%. For the DPC glazing option, the W5 method over-predicts by up to 154.6%, while for the DPlow-E glazing option the W5 method over-predicts by up to 378.72%. It is also interesting to note that the window experiences both heat gain and heat loss in August, with the outside ambient temperature fluctuations below and above the room temperature.

For the month of January (Figure 5.9), it is observed that the conduction for the SPC glazing option is greatly affected by the wind speed and the outdoor temperature, while the effect decreases in the case of double pane glazing options. It is also seen that the W5 method results are more dependent on wind speed and temperature than results obtained from the SC method.

On comparing performance trends of January it is seen that the W5 method results for the DPC glazing option closely traces the performance of the SC method's results for the SPC glazing option, while the W5 method's results for the DPlow-E glazing option closely traces the results obtained by using the SC method of calculation for the DPC glazing option. SClow-E shows very little sensitivity to the temperature and wind speed. With the increase in ambient temperature, a convergence is observed in the performance of all the glazing options.

For the month of March (Figure 5.10), the results project similar yet less pronounced trends to the ones observed for January (Figure 5.9). Results obtained using both the SC and W5 methods for the SPC glazing option yield the highest heat losses and are most sensitive to wind speed and outdoor temperature. However, the values provided by the SC method are substantially less than the ones calculated by the more accurate W5 method.

On comparing performance trends for March, it is observed is that results from using the SC method for the DPC glazing option are almost identical (yet slightly less) to the results from using W5 method for DPlow-E glazing option. While the performance of the W5, DPC glazing option is similar to the SPC options in terms of its sensitivity to outdoor temperature and wind speed conditions. Here, too, the SClow-E is least affected by either temperature or wind speed.

For the month of August (Figure 5.11), the convergence observed in the months of January and March becomes even more pronounced and displays a reversal in heat flow as the ambient temperature rises above the LOADS indoor temperature. The conductance properties exhibited by the glazing options tend to converge when the outside temperature approaches the space temperature.

While the performance of the SPC glazing option (predicted by the W5 method) is similar to that of the SPC glazing option (predicted by the SC method), the performance of the W5, low-E glazing option is substantially different from that of the SC, low-E glazing option. It is also observed that the results of both the W5 and SC method, low-E glazing options do not loose as much heat during the night as the DPC or SPC glazing, thus trapping the heat gained during the daytime hours within the space. On the other hand, for both the W5 and the SC methods, the SPC glazing options yield to high losses at night causing the heat gained during daytime hours to dissipate back to the outside during the night time. This provides a clue to the possible benefits of dynamic windows.

5.1.1.4 Discussion/summary of trends observed from comparing the performance of glazing properties using DOE-2's LOADS output

According to Lokmanhekim (1975) in the case of the SC method, the solar gain is first determined for a reference glass which is 1/8" thick double strength sheet glass with 0.86 transmittance, 0.08 reflectance and 0.06 absorptance at normal incidence angles. These properties are then multiplied by a shading coefficient value input by the user to obtain properties for a specific glazing option. However, it was shown in Figure 5.2b that the shading coefficient gives increasingly less accurate results when the angle of incidence for the selected glazing departs from the normal incidence angle. These normalized transmittance curves (Figure 5.2b) for the selected glazing options also show the maximum discrepancy in DPlow-E glazing option.

When considering solar heat gain patterns due to solar absorption in the glass pane, W5 results over-predict SC results. Although the resultant percentage differences are large, the net impact on the building's heating/cooling loads are small because the solar radiation absorbed by the glass pane is small.

The next section examines the extent of the impact in using CWFs vs. ASHRAE Pre-calculated Weighting Factors for the DOE-2.1e simulations.

5.1.2 Assessing the impact of using custom weighting factors (CWFs) as compared to ASHRAE pre-calculated weighting factors (Quick mode) in terms of solar and conduction loads through the windows

To examine the impact of using CWFs vs. ASHRAE pre-calculated weighting factors in the DOE-2.1e simulations, a week in August as well as in January was again considered by the study. The SC method and the W5 method were then run separately in the DOE-2 simulations. The appropriate hourly data extracted from DOE-2's hourly reports were plotted to acquire a more detailed picture of the impact on the glazing performance. As previously mentioned in the literature review, it was shown that the W5 method gave more accurate results than the SC method; however, very little had been published about CWFs versus the use of pre-calculated weighting factors.

For this analysis, combined hourly solar and conduction loads were examined from the DOE-2 LOADS sub-program, while hourly zone temperature and cooling electricity use were analyzed from the DOE-2's SYSTEMS sub-program. Results are presented in Figure 5.12 –Figure 5.14.

5.1.2.1 Results from DOE-2s LOADS sub-program

An inspection of the results of the LOADS sub-program analysis (i.e., the upper plot in Figure 5.12–Figure 5.14) shows that the performance of the glazing options for both summer and winter conditions. Trends indicate that the Pre-calculated Weighting Factor option over-predicts the heat gain when compared to the Custom Weighting Factor (CWF) calculation method. Also, it is observed during the daytime hours that using the W5 method yield to lower results when compared to the SC method. The trends get reversed during night time hours. In this case W5 options record higher energy losses than their SC counter paths. This trend is more prominent for the week in winter than it is in summer. While this energy loss recorded by W5 option can be beneficial for energy consumption in summer season, it accounts for greater heating energy losses during winters. Results obtained when in Quick mode show greater diurnal variation in than when in Thermal mass mode. Also, results obtained when using the SC option show a greater variation in diurnal range than when compared to options using the W5 method. Greatest variation is seen in the case of the QSC glazing option, while least variation is seen in the ThW5 glazing option.

While switching from Quick to Thermal mode for both winter and summer conditions, there is on an average 30% to 40% drop from the combined solar and conduction loads for the three glazing options considered. For both cases the percentage difference increases in the case of clear days. But the use of the more accurate W5 method for fenestration input lowers the percentage difference in cooling a slight amount. When going from Quick mode to Thermal mass mode, the SC options record larger variations than the W5 options. The difference is the smallest for the DPlow-E glazing option and largest for the SPC glazing option. It is also observed that the percentage change of loads during the nighttime is highly erratic for all the glazing types.

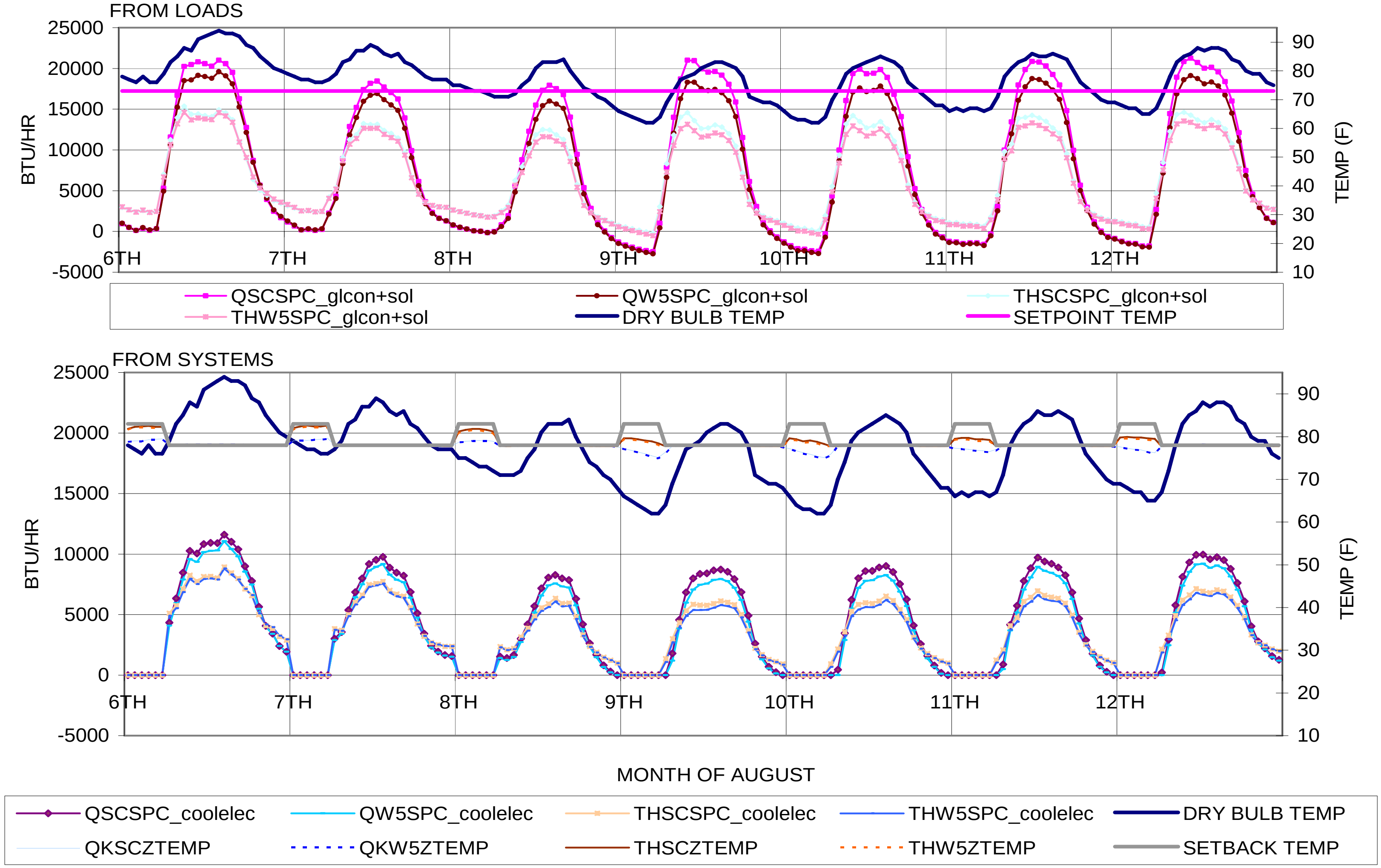


Figure 5.12 Cooling loads from loads and system data for SPC

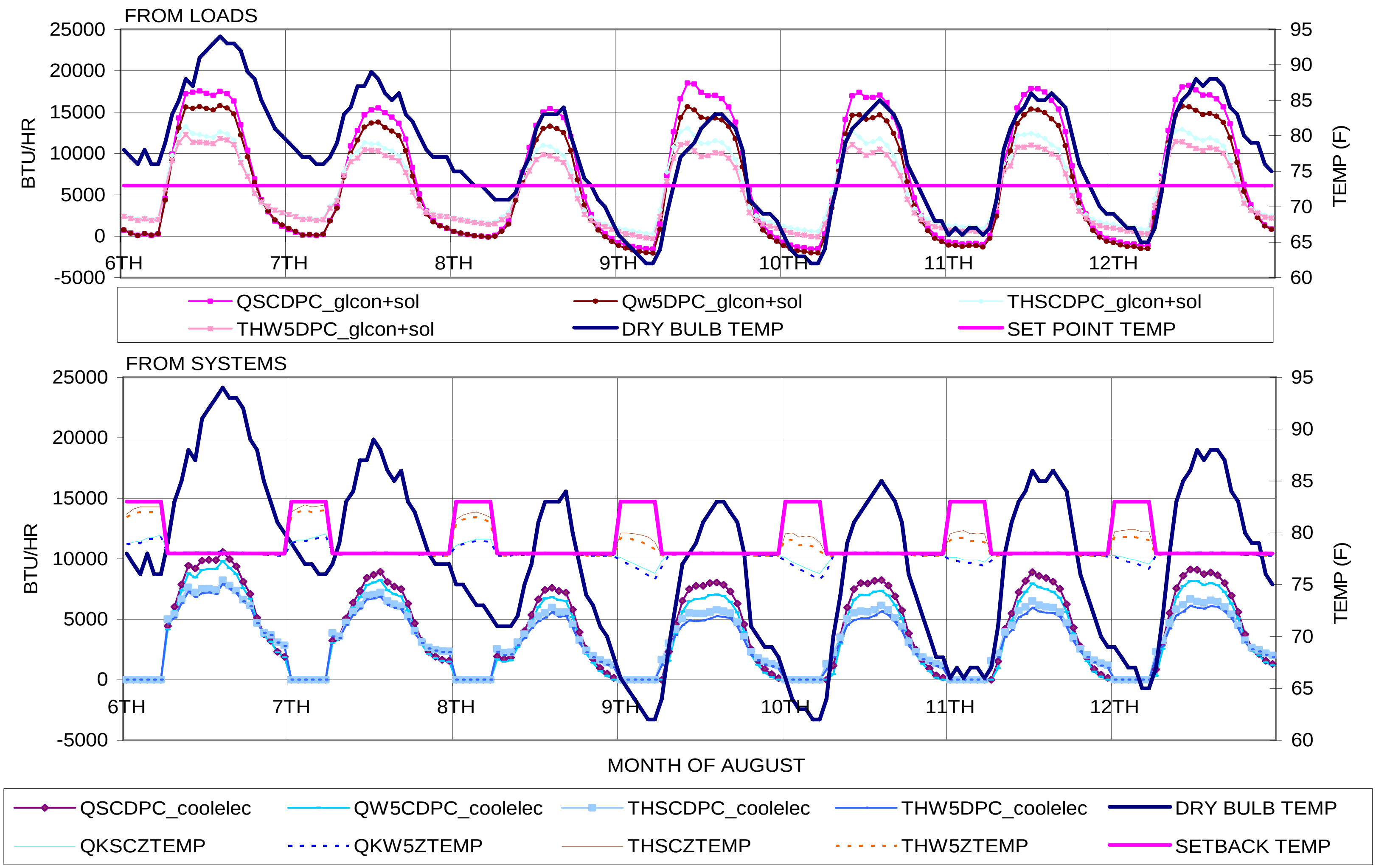


Figure 5.13 Cooling loads from loads and system data for DPC

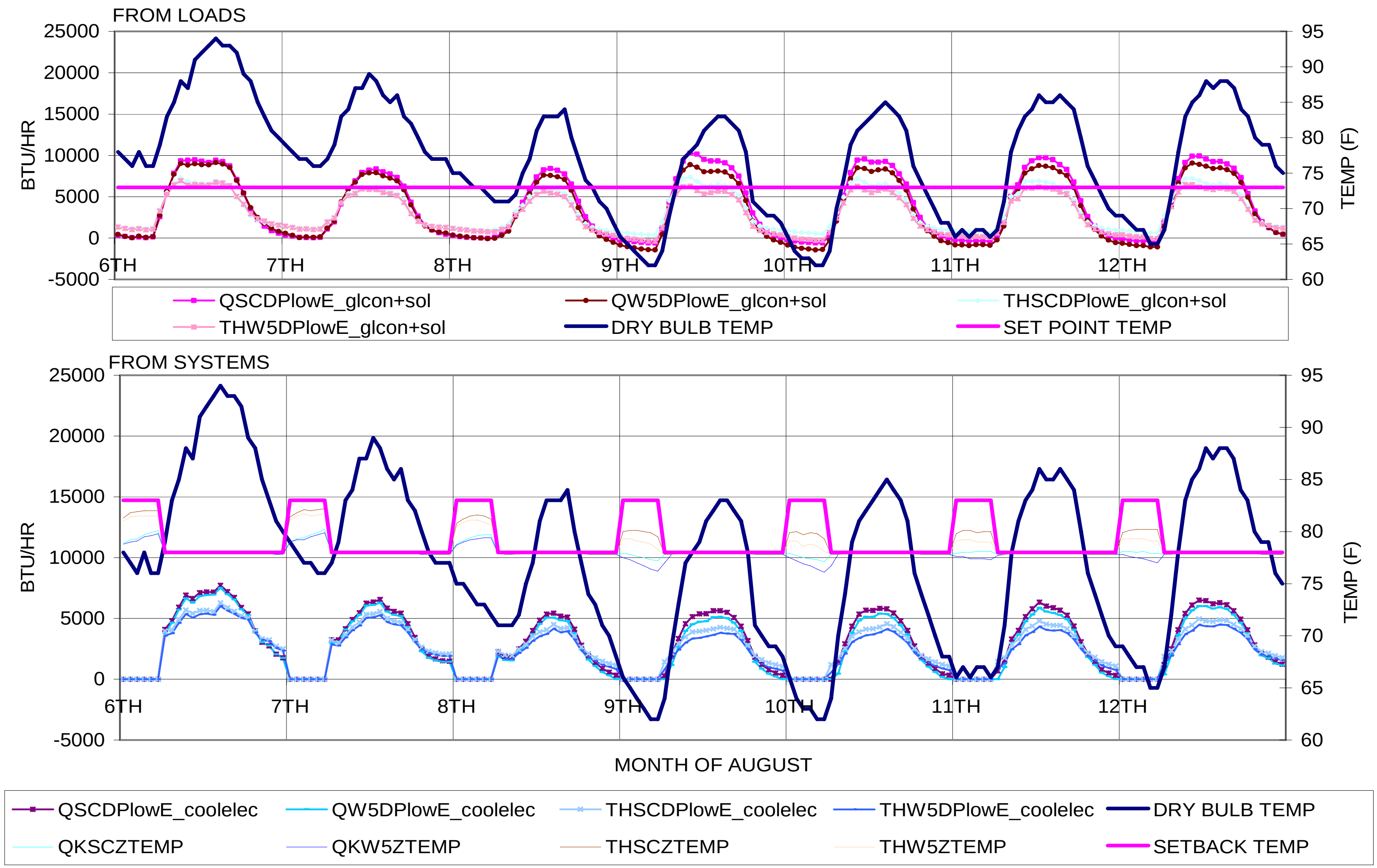


Figure 5.14 Cooling loads from loads and system data for DPlow-E glazing

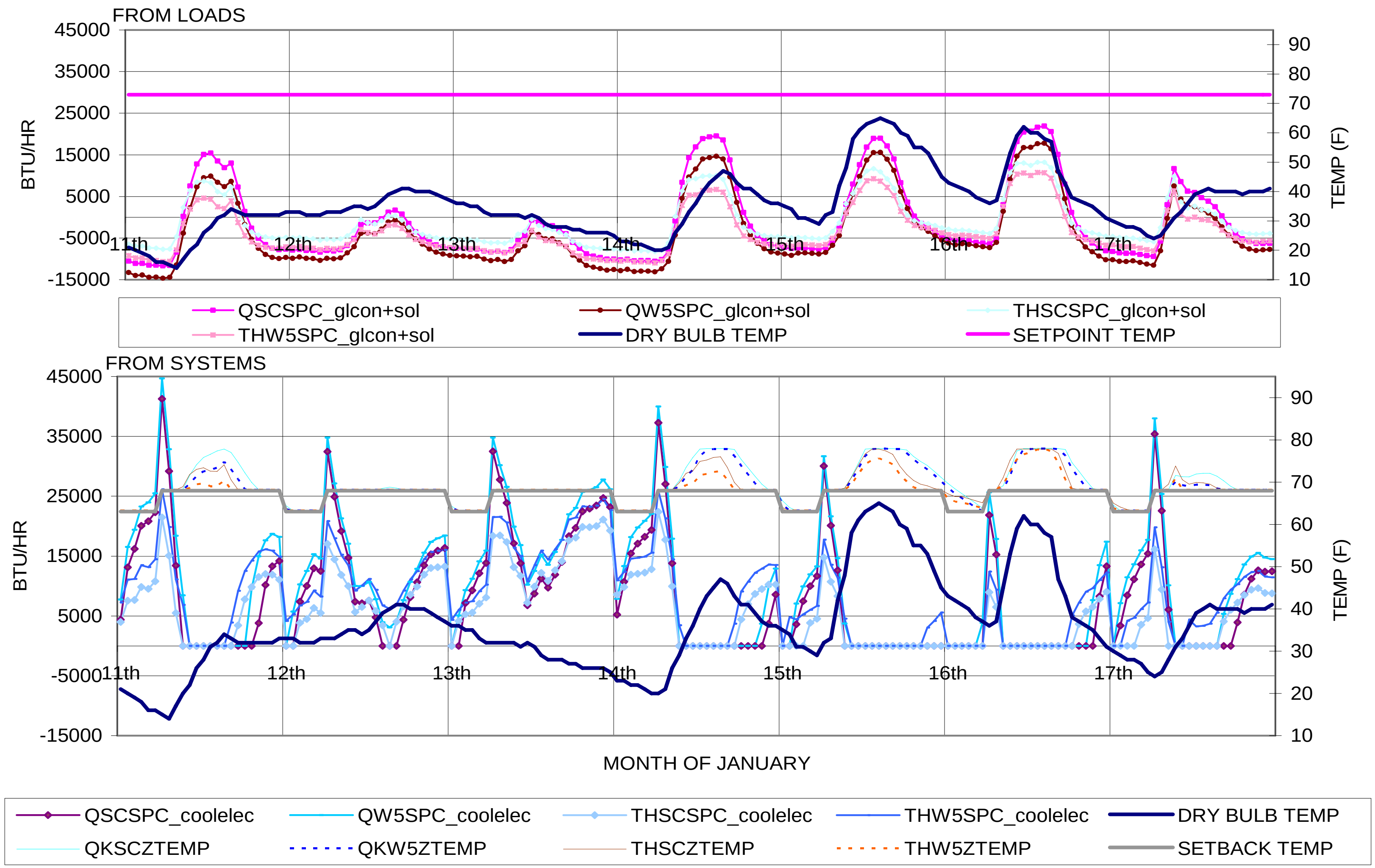


Figure 5.15 Heating loads from loads and system data for SPC glazing

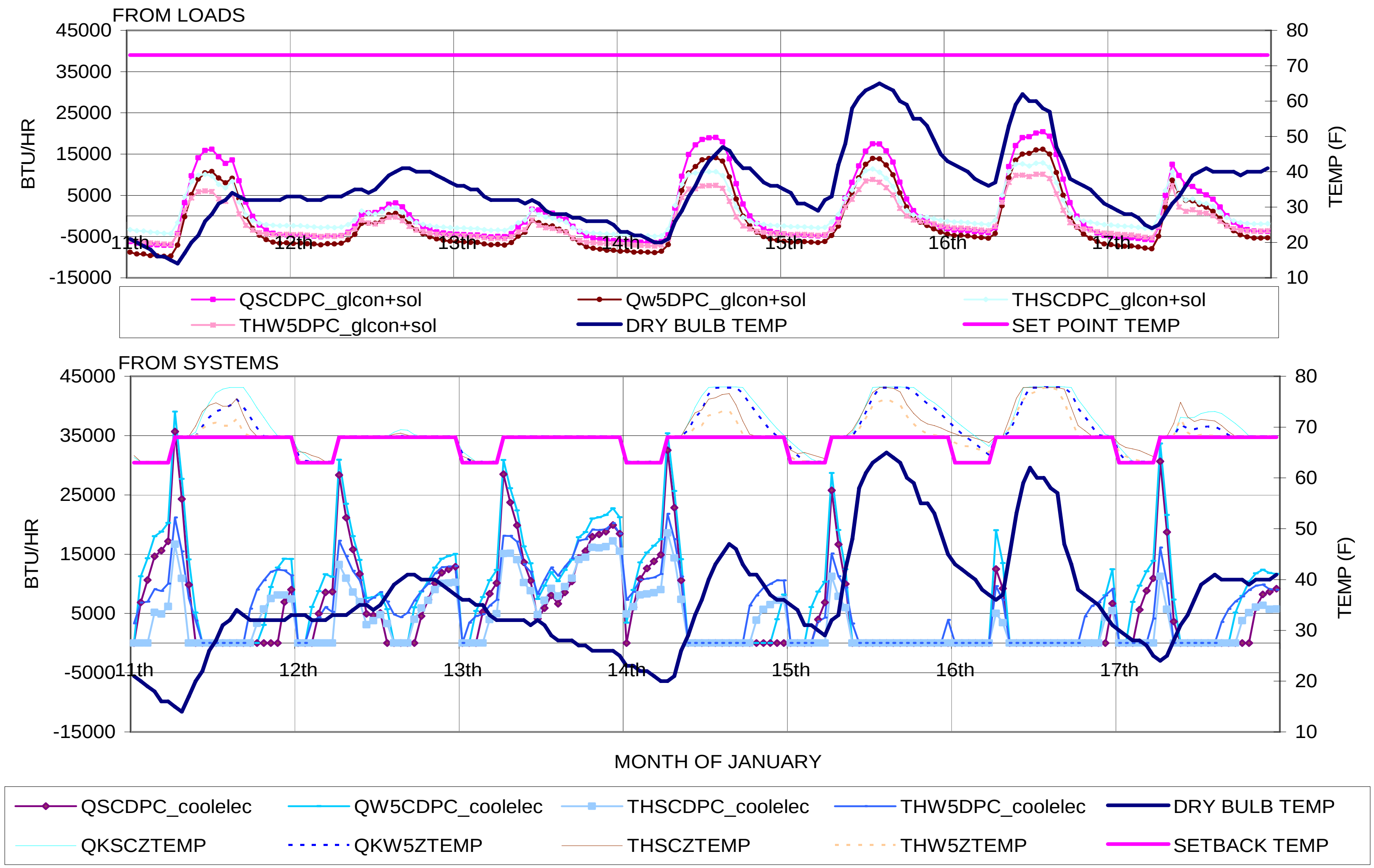


Figure 5.16 Heating loads from loads and system data for DPC glazing

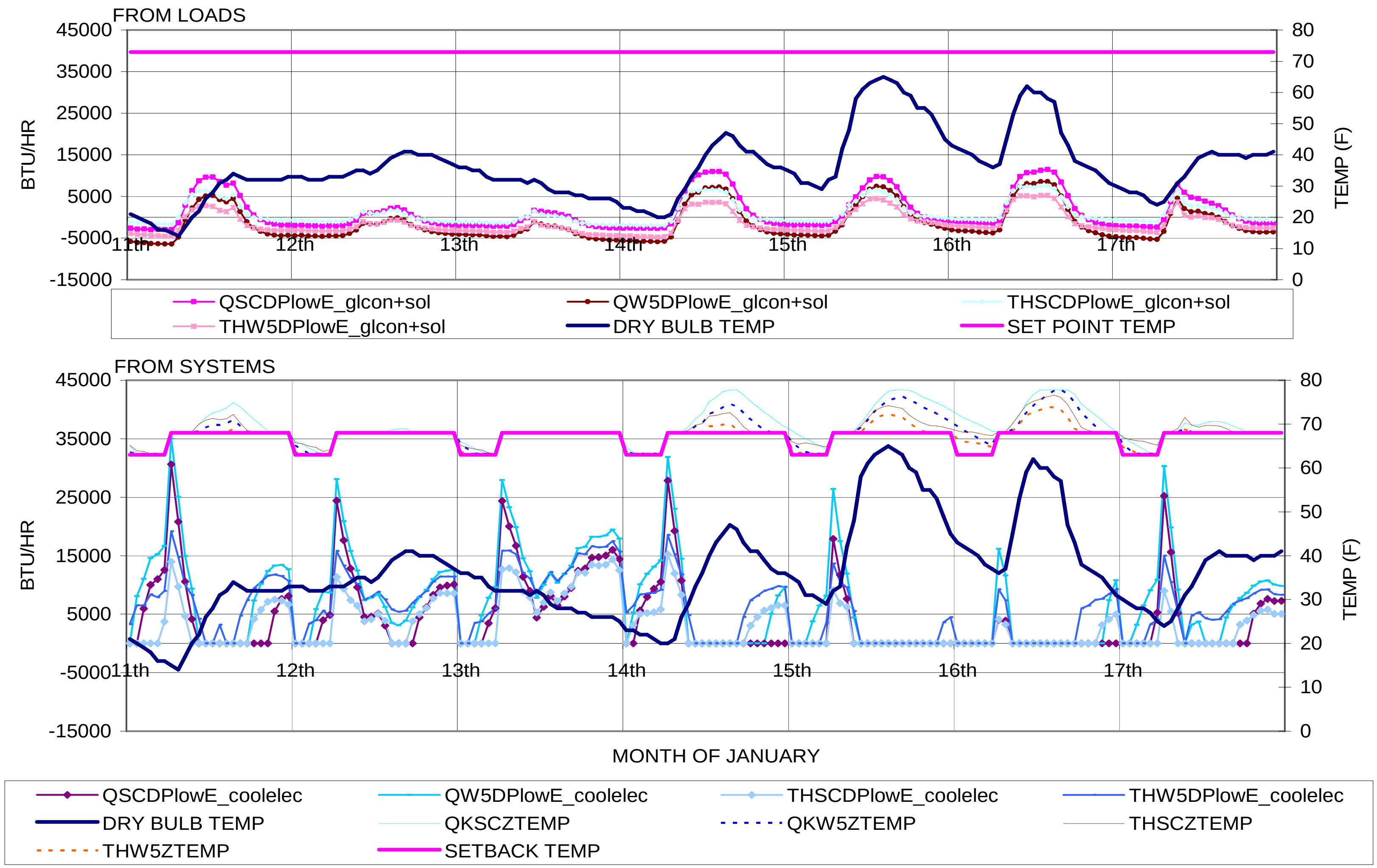


Figure 5.17 Heating loads from loads and system data for DP low-E glazing

5.1.2.2 Results from DOE-2's SYSTEM, sub-program

To analyze the impact on the HVAC loads, the required thermostat cooling setpoint temperature defined in the SYSTEMS section of the DOE-2 input file was set at 78°F from 7:00 p.m. to 12:00 a.m. midnight, and set back at 83°F between 1:00 a.m. and 6:00 a.m to accommodate the specifications in the 2000 IECC. While the heating setpoint temperature was defined at 68°F from 7:00 a.m. to 12:00 a.m. and set back at 63°F between 1:00 a.m. and 6 a.m.. These settings are defined in Section 402.1.3.5 in 2001 IECC specifications. At hours when the cooling temperature setback was at 83°F or the when heating setpoint temperature was set at 68°F, the resultant zone temperature in the simulated space is allowed to float in the DOE-2 simulation between the cooling and heating setpoints. This required thermostat setback has a significant impact on the influence of the window on zone heating and cooling load.

In the winter during the daytime hours (Figure 5.15 – 5.17), the zone temperatures were allowed to float above the heating setpoint temperature, at times approaching the cooling systems setpoint. This is primarily due to the solar heat gain through windows and can be seen on January 15 – 17th. During this time no heating is provided to the space.

A closer inspection of these floating temperatures help reveal one of the effects of the use of CWFs versus Quick method calculations. In general, it can be seen that the SC method yields higher zone temperatures than the W5 methods. In addition, the Quick option yields higher zone temperatures than the Thermal mass option. As a result the Quick mode option using the SC glazing yields the highest floating zone temperatures followed by the Quick mode option for W5 glazing. Next is the Thermal mass option using SC glazing while the Thermal mass option for W5 glazing yields to lowest floating zone temperatures. Although the heating system is off during this period, these lower space temperatures imply greater storage of heat in the Thermal mass and therefore less heating to warm up the space when the system is switched back on.

The spikes in heating fuel consumption reflect the amount of energy needed by the system to heat the zone beginning at 7:00 a.m. These spikes can be important when DOE-2 is autosizeing as they can often determine the furnace size. When the furnace is oversized, it can lead to greater periods of part-load performance and lower efficiency. In general, a difference in the early morning heat requirements can be seen from different options implemented with the Quick options yielding higher results than when compared to the Thermal Mass options. Heating fuel consumption for the glazing, when calculated using Quick and W5 options, yields to highest results, followed by results obtained from using the Quick and SC options. Results obtained from using Thermal mass and W5 options, as well as results obtained from using Thermal mass and SC options yield to the lowest heating fuel consumption. During the night-time when the zone temperatures drop and need to be maintained at specified levels, another spike is observed in the heating fuel consumption. For a given option, the fall in floating temperature below the set point temperature triggers off the spike in the corresponding heating fuel consumption. Heating fuel consumption for QW5 glazing yields highest results followed by the THW5 glazing and QSC glazing, while THSC glazing option yields lowest results.

For the week in the summer, a similar pattern of floating zone temperatures is observed when the zone temperature allowed to float as the cooling thermostat is set up to 83°F. In the case of the Quick mode, a drop in the zone temperatures is observed during the set back, which indicates very little sensitivity to thermal mass. While an inspection of the thermal mass mode reveals that the heat has been retained by materials in the space, it is released into the zone air after the thermostat is set up to 83°F, causing the zone temperature to rise.

Since the system is effectively turned off during this period, when the thermostat temperature is set back, a small spike in the cooling electric loads is observed when the cooling electric is turned back on, which is more prominent in the thermal mass options. Also, just before turning off, cooling electric loads for thermal mass options exhibit slightly higher values than results obtained from the Quick option which reflect an accelerated cooling-off trend, most likely due to reduced retention of heat in the thermal mass. When going from the Quick to Thermal mass option, the SPC glazing and the DPC glazing report percentage differences which are in the range of 17% to 25% for both SC and W5 options, while DPlow-E glazing records slightly lower percentage difference with 12% when using SC method and 8% when using W5 method of input.

5.1.2.3 Summary and discussion

From the results of these simulations, it has been shown that, when using the Quick mode, there is a large difference when going from the SC to the W5 option from both loads as well as the systems section of DOE-2.1e output file. However, when using the CWFs there is a decrease in the percentage difference when going from the SC to the W5 modes. This trend is exhibited for all the glazing options considered as it represents a heat gain storage increase when CWFs are in use. Hence, a small portion of the solar gain from the window gets translated into thermal mass storage when using the Quick option.

This heat storage potential of the simulated materials is more fully appreciated when examining the heating load patterns. In this case, the potential of the glazing options being modeled can be harnessed to aid the passive solar heat gain of the building components which, in turn, can lower heating energy costs. Examining the weekly performance graphs for the winter reveals that activating the thermal mass yields lower energy consumption rates as less heating energy is needed to heat the zone, which is already warmed by heat dissipating back into the zone from the enclosing building thermal components.

However, it has also been shown that the use of the W5 option, while beneficial during summer time, actually raises the heating energy consumption during the winter. This is because the option admits less solar heat gain into space, which results in more supplemental heating energy to be used to heat the space/zone up to the temperature specified.

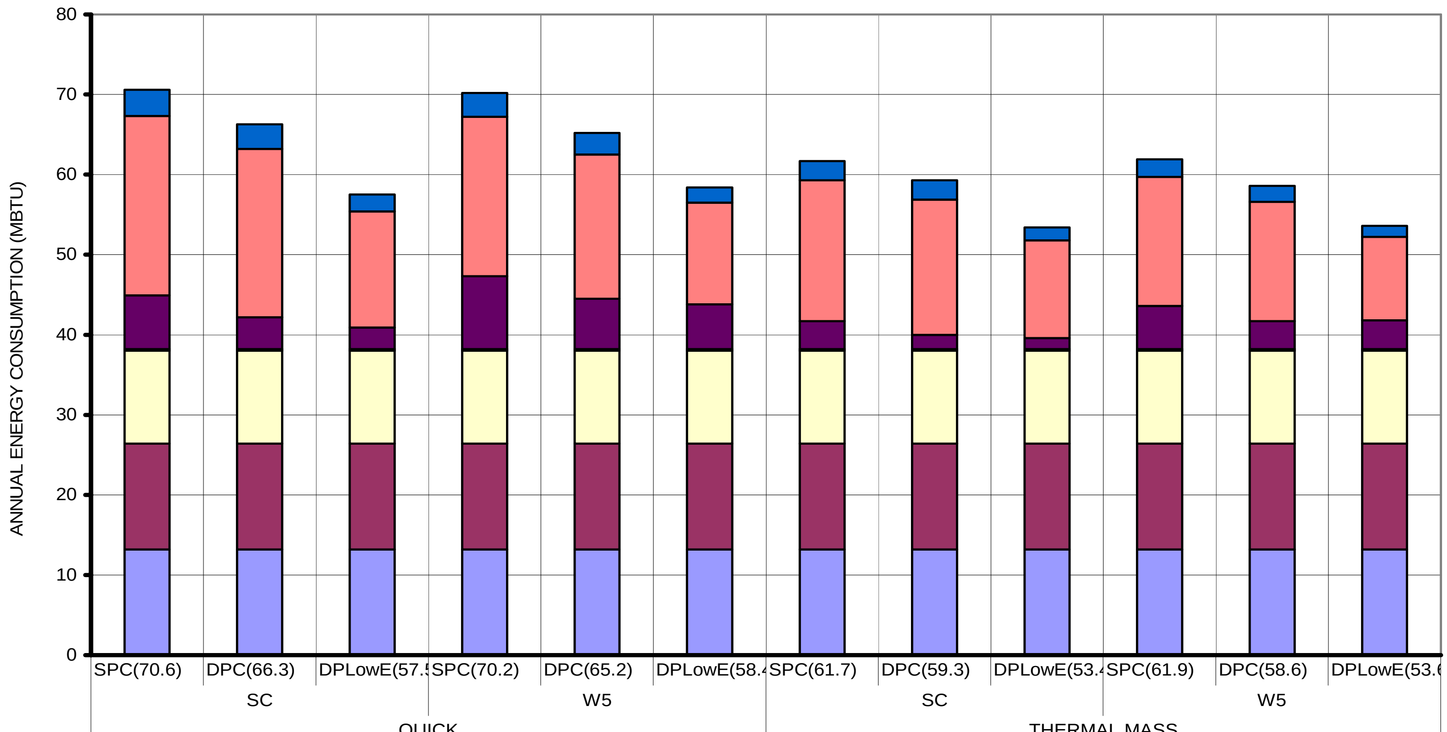
It has also been noted that the thermostat setback required by the 2000 IECC plays an important role in the resultant heating and cooling patterns. Hence, for a complete analysis of the heating and cooling patterns an interaction with the thermostat setback and its interaction with the buildings thermal mass needs to be further studied.

The analysis of results from the simulations discussed in this section established the importance of using the thermal mass/ W5 method in the DOE-2 simulations for determining a more accurate result for the heat gain or from windows. The next section analyses the annual and peak day impact of the W5 and thermal mass option in the 2000 IECC code traceable DOE-2 input file for a single family residence.

5.1.3 BEPS and peak load reports comparison of the SC vs. the W5 method, including an analysis of the Quick vs. CWF simulation options in the DOE-2.1e program files

In the previous subsection, a considerable difference in the performance of glazing was seen when using the WINDOW-5 method of input over the SC method of input. In addition, a considerable difference in results was seen from implementing the thermal mass method of input to define the envelope components. In the previous section, the impact of using these options was analyzed primarily in terms of the window properties and the resultant solar loads on the interior space. However, the full repercussion of these options on the overall building energy performance reports needs to be assessed. Therefore, in this section the base-case house as specified by the 2000 IECC code is modeled incorporating these options. The resultant DOE-2 Building Energy Performance Summary (BEPS) and space peak loads (from the LOADS sub-progam) are analyzed.

The analysis for this section is carried out in two parts. In the first part, results were obtained using options from DOE-2's BEPS reports (PLANT subprogram), as well as from the peak load reports from the LOADS sub-program are compared. Of particular interest to the energy code is the percentage saving that can be obtained by going from lower performance windows to higher performance windows. In the second subsection, the study uses this opportunity to demonstrate the advantages of using the more accurate methods for modeling thermal mass (i.e., the W5 and CWF modeling method) over conventionally used methods (i.e., SC and Quick mode of input). Subsequently, results are presented as total BEPS and peak-day energy use as well as a difference in percentage savings for SC and WINDOW5 for both Quick and Thermal mass methods of input.



	QUICK						THERMAL MASS					
	SC			W5			SC			W5		
	SPC(70.6)	DPC(66.3)	DPLowE(57.	SPC(70.2)	DPC(65.2)	DPLowE(58.	SPC(61.7)	DPC(59.3)	DPLowE(53.	SPC(61.9)	DPC(58.6)	DPLowE(53.
VENT FANS	3.3	3.1	2.1	3	2.7	1.9	2.4	2.4	1.6	2.2	2	1.4
SPACE COOLING	22.4	21	14.5	19.9	18	12.7	17.6	16.9	12.2	16.1	14.9	10.4
SPACE HEATING	6.7	4	2.7	9.1	6.3	5.6	3.5	1.8	1.4	5.4	3.5	3.6
PUMPS AND 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
DOM HOTWATER	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6
MISCELANEOUS EQPT	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2
AREA LIGHTS	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2

TYPE OF WINDOW

Figure 5.18 Annual building energy performance (BEPS) report

Table 5.2 Difference in energy consumption: a) Quick to Thermal mass mode b) SC to W5 option

TABLE: PERCENTAGE DIFFERENCE OBTAINED FROM USING DIFFERENT OPTIONS IN BEPS AND PEAK HEATING & COOLING REPORT						
				SC	**WINDOW5**	**DIFFERENCE**
		% SAVING FORMULA		SAVING	SAVING	SC-W5
			Annual BEPS (Mbtu/yr)	4.30	5.00	-0.70
			Annual Heating (Mbtu/yr)	2.70	2.80	-0.10
			Annual Cooling (Mbtu/yr)	1.40	1.90	-0.50
			Peak Hourly Heating (Kbtu/hr)	-4.13	-3.23	-0.90
	SP-DP	((SP-DP)/SP)*100	Peak Hourly Cooling (Kbtu/hr)	2.55	3.11	-0.55
			Annual BEPS (Mbtu/yr)	13.10	11.80	1.30
			Annual Heating (Mbtu/yr)	4.00	3.50	0.50
			Annual Cooling (Mbtu/yr)	7.90	7.20	0.70
			Peak Hourly Heating (Kbtu/hr)	-7.49	-5.40	-2.09
	SP-LOWE	((SP-LE)/SP)*100	Peak Hourly Cooling (Kbtu/hr)	10.09	9.19	0.90
			Annual BEPS (Mbtu/yr)	8.80	6.80	2.00
			Annual Heating (Mbtu/yr)	1.30	0.70	0.60
			Annual Cooling (Mbtu/yr)	6.50	5.30	1.20
			Peak Hourly Heating (Kbtu/hr)	-3.36	-2.17	-1.19
QUICK	**DP-LOWE**	((DP-LE)/SP)*100	Peak Hourly Cooling (Kbtu/hr)	7.53	6.09	1.45
			Annual BEPS (Mbtu/yr)	2.40	3.30	-0.90
			Annual Heating (Mbtu/yr)	1.70	1.90	-0.20
			Annual Cooling (Mbtu/yr)	0.70	1.20	-0.50
			Peak Hourly Heating (Kbtu/hr)	-3.23	-3.72	0.49
	SP-DP	((SP-DP)/SP)*100	Peak Hourly Cooling (Kbtu/hr)	1.49	1.80	-0.31
			Annual BEPS (Mbtu/yr)	8.30	8.30	0.00
			Annual Heating (Mbtu/yr)	2.10	1.80	0.30
			Annual Cooling (Mbtu/yr)	5.40	5.70	-0.30
			Peak Hourly Heating (Kbtu/hr)	-5.70	-6.15	0.45
	SP-LOWE	((SP-LE)/SP)*100	Peak Hourly Cooling (Kbtu/hr)	6.50	6.14	0.36
			Annual BEPS (Mbtu/yr)	5.90	5.00	0.90
			Annual Heating (Mbtu/yr)	0.40	-0.10	0.50
			Annual Cooling (Mbtu/yr)	4.70	4.50	0.20
			Peak Hourly Heating (Kbtu/hr)	-2.48	-2.43	-0.05
CWF	**DP-LOWE**	((DP-LE)/SP)*100	Peak Hourly Cooling (Kbtu/hr)	5.01	4.34	0.67

Table 5.3 Percentage difference in energy consumption: a) Quick to Thermal mass mode b) SC to W5 option

TABLE: PERCENTAGE DIFFERENCE OBTAINED FROM USING DIFFERENT OPTIONS IN BEPS AND PEAK HEATING & COOLING REPORT							
				SC	WINDOW5	DIFFERENCE	% DIFFERENCE
		% SAVING FORMULA		% SAVING	% SAVING	SC-W5	((SC-W5)/SC)*100
QUICK	SP-DP	((SP-DP)/SP)*100	Annual BEPS (Mbtu/yr)	6.09	7.12	-1.03	-16.94
			Annual Heating (Mbtu/yr)	40.30	30.77	9.53	23.65
			Annual Cooling (Mbtu/yr)	6.25	9.55	-3.30	-52.76
			Peak Hourly Heating (Kbtu/hr)	21.20	17.35	3.85	18.14
			Peak Hourly Cooling (Kbtu/hr)	9.06	11.95	-2.89	-31.88
	SP-LOWE	((SP-LE)/SP)*100	Annual BEPS (Mbtu/yr)	18.56	16.81	1.75	9.41
			Annual Heating (Mbtu/yr)	59.70	38.46	21.24	35.58
			Annual Cooling (Mbtu/yr)	35.27	36.18	-0.91	-2.59
			Peak Hourly Heating (Kbtu/hr)	38.44	29.01	9.43	24.52
			Peak Hourly Cooling (Kbtu/hr)	35.79	35.37	0.42	1.18
	DP-LOWE	((DP-LE)/SP)*100	Annual BEPS (Mbtu/yr)	13.27	10.43	2.84	21.42
			Annual Heating (Mbtu/yr)	32.50	11.11	21.39	65.81
			Annual Cooling (Mbtu/yr)	30.95	29.44	1.51	4.87
			Peak Hourly Heating (Kbtu/hr)	21.88	14.11	7.77	35.51
			Peak Hourly Cooling (Kbtu/hr)	29.39	26.59	2.80	9.52
CWF	SP-DP	((SP-DP)/SP)*100	Annual BEPS (Mbtu/yr)	3.89	5.33	-1.44	-37.06
			Annual Heating (Mbtu/yr)	48.57	35.19	13.39	27.56
			Annual Cooling (Mbtu/yr)	3.98	7.45	-3.48	-87.40
			Peak Hourly Heating (Kbtu/hr)	20.43	19.86	0.57	2.80
			Peak Hourly Cooling (Kbtu/hr)	7.43	9.44	-2.02	-27.15
	SP-LOWE	((SP-LE)/SP)*100	Annual BEPS (Mbtu/yr)	13.45	13.41	0.04	0.32
			Annual Heating (Mbtu/yr)	60.00	33.33	26.67	44.44
			Annual Cooling (Mbtu/yr)	30.68	35.40	-4.72	-15.39
			Peak Hourly Heating (Kbtu/hr)	36.12	32.83	3.28	9.09
			Peak Hourly Cooling (Kbtu/hr)	32.44	32.25	0.18	0.56
	DP-LOWE	((DP-LE)/SP)*100	Annual BEPS (Mbtu/yr)	9.95	8.53	1.42	14.24
			Annual Heating (Mbtu/yr)	22.22	-2.86	25.08	112.86
			Annual Cooling (Mbtu/yr)	27.81	30.20	-2.39	-8.60
			Peak Hourly Heating (Kbtu/hr)	19.71	16.18	3.53	17.89
			Peak Hourly Cooling (Kbtu/hr)	27.02	25.19	1.83	6.76

5.1.3.1 Comparing BEPS results of the different glazing options

Figure 5.18 presents the complete results obtained from the BEPS report. Apart from the results for space heating and space cooling, the energy consumption of the vent fans, pumps, and miscellaneous, domestic hot-water, miscellaneous equipment and area lights are also included in the totals required by the 2000 IECC. The results presented in Figure 5.18 for overall energy consumption, space heating and cooling are subsequently utilized by Tables 5.1.2 and Table 5.3 to compare the SC, W5, Quick, and CWF methods.

In comparing the overall energy consumption in Figure 5.18, by examining the results using the different options, a 12% difference is seen when going from the Quick option to the CWF option (i.e., for the case of the SPC glazing, when using the SC method to simulate fenestration, yeilds 70.6 MBtu of overall energy consumption when in Quick mode, while the results obtained on using CWF method yield 61.7 MBtu in total energy consumption, resulting in a difference of 12%). Surprizingly, very little difference is seen when comparing the W5 vs. SC results for all glazing for either the Quick or CWF method. However, a closer look reveals compensating changes in heating and cooling loads. These results are important to Texas because of changes in the summertime cooling loads during high pollution periods.

From Figure 5.18 and Table 5.2 and Table 5.3, the results show that a Quick mode of SPC glazing option going to DPC glazing option, using the SC method, the annual energy use goes from 70.6 MBtu to 66.3 MBtu, a difference of 4.3 MBtu, or a 6.09% drop in total consumption. For this simulation the heating use drops from 6.7 MBtu to 4 MBtu, a difference of 2.7 MBtu, or a 40.3% drop. Similarly, for this same simulation, the cooling energy use goes from 22.4 MBtu to 21 MBtu, a difference of 1.4 MBtu, which is a 6.25% decrease. When using the W5 method combined with the Quick method to simulate SPC glazing compared to DPC glazing, the annual energy use goes from 70.2 MBtu to 65.2 MBtu, a difference of 5.0 MBtu, which is a 7.12% drop. The heating energy use goes from 9.1 MBtu to 6.3 MBtu, a difference of 2.8 MBtu, which is a 30.77% decrease. The cooling energy use goes from 19.9 MBtu to 18 MBtu, a difference of 1.9 MBtu, which is a 9.55% decrease. This means that the use of the SC method, combined with the Quick mode understates the total savings by 16.94% when compared to the W5 method using the Quick mode. For these results, a difference of 1.03% is observed in the savings (i.e., SC – W5), which represents 16.94% of the savings. For the annual cooling, the difference observed is 3.3%, which means the use of the SC and Quick mode understates savings by 52.8% when compared to the W5 and Quick mode. For annual heating, the difference observed is 9.53% (an increase of 23.65%).

When going from SPC glazing option to DPlow-E glazing option in Quick mode, the annual energy use goes from 70.6 MBtu to 57.5 MBtu, a difference of 13.10 MBtu, which is a 18.56% decrease. The heating energy use goes from 6.7 MBtu to 2.7 MBtu, a difference of 4 MBtu, which is a 59.70% decrease. Cooling energy use goes from 22.4 MBtu to 14.5 MBtu a decrease of 7.9 MBtu, which is a 35.27% decrease. When using the W-5 method, going from a SPC glazing option to a DPlow-E glazing option, the annual energy use goes from 70.2 MBtu to 58.4 MBtu, a decrease of 11.80 MBtu, which is a 16.81% decrease. The heating energy use goes from 9.1 MBtu to 5.6 MBtu, a difference of 3.50 MBtu, which is a decrease of 38.46%, while the cooling energy use goes from 19.9 MBtu to 12.7 MBtu, a difference of 7.20 MBtu, which is a 36.18% decrease. The comparison of the SC versus the W5 results for the Quick mode shows that a difference of 1.75% is observed in the savings, which represents 9.41% of the SC savings. The annual heating savings decreases by 21.24%, which represents 35.58% of the SC savings. While for the annual cooling, the difference observed is -0.91%, which is a change in savings of 2.54%. This means that the use of the SC method, combined with Quick mode, overstates the total savings by 35.58%, when compared to the W5 method using Quick mode.

For the results for the DPC glazing option compared to the DPlow-E glazing option when in Quick mode, the annual energy use decreases from 66.3 MBtu to 57.5 MBtu, a difference of 8.80 MBtu, which is a 13.27% decrease. The heating energy use goes from 4 MBtu to 2.7 MBtu, a difference of 1.30 MBtu, which is a 32.50% decrease. For this same analysis, the cooling energy use goes from 21 MBtu to 14.5 MBtu, a difference of 6.50 MBtu, which is 30.95% decrease. When using the W5 method, the results of the DPC glazing compared to DPlow-E glazing option yield an annual energy use of 65.2 MBtu, which drops to 58.4 MBtu, a difference of 6.80 MBtu, which is 10.43% decrease. The heating energy use goes from 6.3 MBtu to 5.6 MBtu, a difference of 0.7 MBtu, which is a decrease of 11.11%, while the cooling energy use goes from 18 MBtu to 12.7 MBtu, a difference of 5.30 MBtu, which is a decrease of 29.44%. When comparing the results from the SC and W5 methods, savings decrease by 2.84%, which represents a change in savings of 21.42%. For annual heating, the difference is 21.39%, which represents 65.81% of the SC savings. For annual cooling, the change is 1.51%, which is a 4.87% change in savings compared to the SC method.

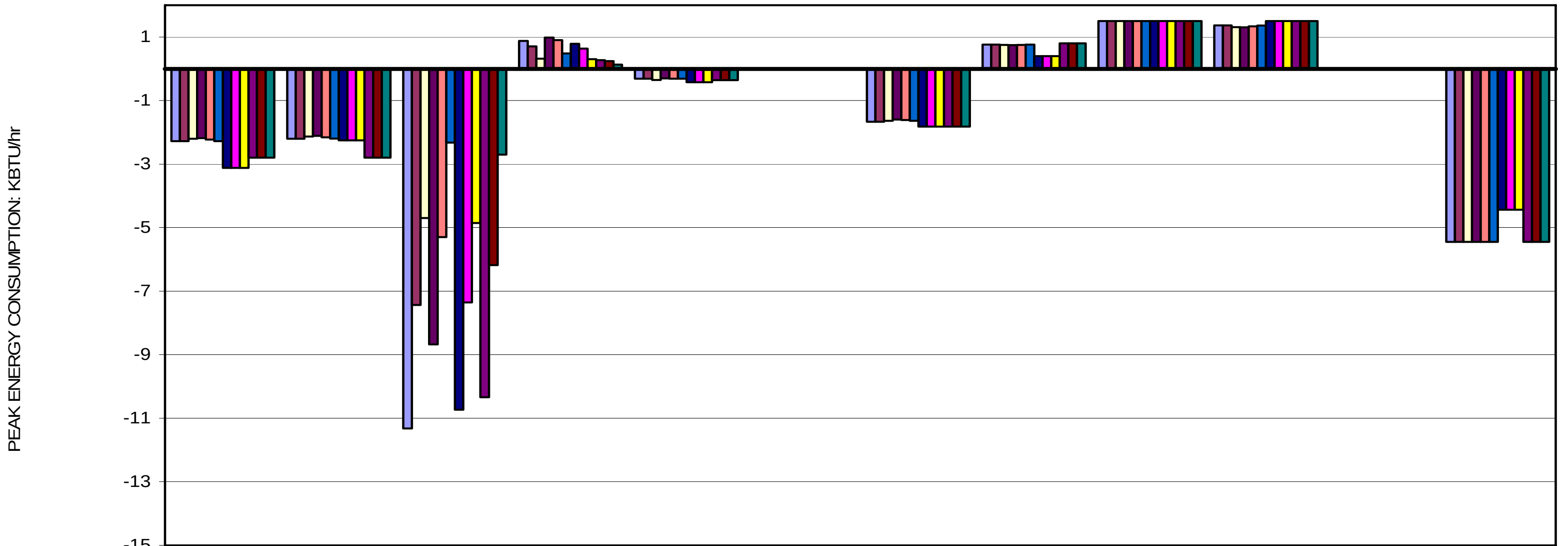
On activating the CWF mode, when using the SC method, a change from the SPC glazing option to the DPC glazing option results in annual energy consumption going from 61.7 MBtu to 59.3 MBtu, a difference of 2.40 MBtu, which is a 3.89% drop. The heating energy use goes from 3.5 MBtu to 1.8 MBtu, a difference of 1.70 MBtu, which is a 48.57% decrease, while the cooling energy use goes from 17.6 MBtu to 16.9 MBtu, a difference of 0.7 MBtu, which is a decrease of 3.98%. When using the W5 method, going from SPC glazing option to DPC glazing option, the annual energy use goes from 61.9 MBtu to 58.6 MBtu, a difference of 3.30 MBtu, which is a 5.33% decrease. The heating energy use goes from 5.4 MBtu to 3.5 MBtu, a difference of 1.9 MBtu, which is a 35.19% decrease, while the cooling energy use goes from 16.10 MBtu to 14.90 MBtu, a difference of 1.20 MBtu, which is a difference of 7.45%. While comparing the SC and W5 methods, a difference of -1.44% was observed in the total percentage savings, which is 37.06% of the SC savings, and for the annual cooling, a decrease of 3.48% is seen, which is 87.40% of the SC savings in favor of the W5 method. For annual heating, a decrease of 13.39% is observed, which is a 27.56% savings in favor of the SC method.

On going from the SPC glazing option to the DPlow-E glazing option, using the SC method with CWFs, the annual energy use goes from 61.7 MBtu to 53.4 MBtu, a difference of 8.3 MBtu, which is a drop of 13.45%. The heating energy use goes from 3.5 MBtu to 1.4 MBtu, a difference of 2.1 MBtu, which is a drop of 60%. The cooling energy use goes from 17.6 MBtu to 12.2 MBtu, a difference of 5.40 MBtu, which is a drop of 30.68%. When using the W5 method, going from the SPC glazing option to the DPlow-E glazing option, the annual energy use goes from 61.9 MBtu to 53.6 MBtu, a difference of 8.3 MBtu, which is a drop of 13.45%. The heating energy use goes from 5.4 MBtu to 3.6 MBtu, a difference of 1.80 MBtu, which is a drop of 33.33%, while the cooling energy use goes from 16.1 MBtu to 10.4 MBtu, a difference of 5.70 MBtu, which is a difference of 35.40%. While comparing the SC and W5 methods, a difference of 0.04% is observed in the savings which is a 0.32% decrease in the savings when compared to the SC method for the total energy consumption. For annual heating the difference is 26.67%, which is a 44.44% decrease, while for annual cooling, the cooling savings increases by 4.72%, which represents 15.39% of the SC savings.

Finally, on going from DPC glazing option to DPlow-E glazing option when in the CWFs and SC modes, the annual energy use goes from 59.3 MBtu to 53.4 MBtu, a difference of 5.90 MBtu, which is a drop of 9.95%. The heating energy use goes from 1.8 MBtu to 1.4 MBtu, a difference of 0.40 MBtu, which is a drop of 22.22%. The cooling energy use goes from 16.9 MBtu to 12.2 MBtu, a difference of 4.70 MBtu, which is a difference of 27.81%. When using the W5 method, going from the DPC glazing option to the DPlow-E glazing option, the annual energy use goes from 58.6 MBtu to 53.6 MBtu, a difference of 5.0 MBtu, which is a drop of 8.53%. The heating energy use rises from 3.5 MBtu to 3.6 MBtu, a difference of 0.10 MBtu, which is a increase of 2.86%, while the cooling energy use goes from 14.9 MBtu to 10.4 MBtu, a decrease of 4.50 MBtu, which is a 30.20% drop. When comparing the results from the SC and W5 methods while using CWFs, a decrease of 1.42% is observed, which is a 14.24% savings in overall energy consumption. For annual heating, the difference observed is 25.08%, which is a 112.86% change that includes a sign change. For the annual cooling, the savings increase by 2.39%, which is 8.60% of the SC savings.

5.1.3.2 Analyzing peak heating and cooling load components

Figure 5.19 presents the results of the analysis of the peak heating loads from different building envelope components as reported by DOE-2's LOADS program. The analysis showed that 11:00 PM on January 11th was reported as the coldest temperature of the year and was used to examine hourly peak heating loads. The ambient temperature at this hour is 32°F, and the resulting temperature difference (ΔT) between the interior and the exterior is 41°F, which can be considered a substantial difference for the Houston location. Hence, the window glass + frame conduction becomes the primary contributor to the peak heating load. The large ΔT also explains the significant contribution from the wall conduction, roof conduction, underground surfaces, and infiltration components, which are less significant in the results from peak cooling loads. Total peak loads are listed with the simulation labels in the lower left of the figure. For example, −18.73 is the total peak heating load for the simulation of the SPC glazing using the W5 and the CWF options.



	WALL COND	ROOF COND	WINGLS+FRM COND	WIN GLS SOLAR	DOOR COND	INT SURFACE COND	UNDERGROUND SURF	OCCUPANTS TO SPACE	LIGHT TO SPACE	EQUIP TO SPACE	PROCESS TO SPACE	INFILTRATION
THW5SPC(-18.73)	-2.278	-2.203	-11.32599	0.87883	-0.314	0	-1.67	0.764	1.5	1.366	0	-5.446
THW5DPC(-15.01)	-2.278	-2.203	-7.43488	0.70849	-0.314	0	-1.671	0.764	1.5	1.366	0	-5.446
THW5DPlowE(-12.58)	-2.206	-2.132	-4.69417	0.32176	-0.351	0	-1.638	0.75	1.5	1.316	0	-5.446
THSCSPC(-15.78)	-2.184	-2.112	-8.67282	0.98213	-0.30173	0	-1.598	0.747	1.5	1.302	0	-5.446
THSCDPC(-12.55)	-2.232	-2.159	-5.29553	0.90137	-0.308	0	-1.61	0.756	1.5	1.335	0	-5.446
THSCDPlowE(-10.08)	-2.274	-2.199	-2.32522	0.48619	-0.314	0	-1.638	0.763	1.5	1.364	0	-5.446
QW5SPC(-18.60)	-3.122	-2.252	-10.73547	0.78829	-0.424	0	-1.82	0.4	1.502	1.502	0	-4.44
QW5DPC(-15.37)	-3.122	-2.252	-7.35391	0.6342	-0.424	0	-1.82	0.4	1.502	1.502	0	-4.44
QW5DPlowE(-13.20)	-3.122	-2.252	-4.85279	0.30193	-0.424	0	-1.82	0.4	1.502	1.502	0	-4.44
QSCSPC(-19.48)	-2.798	-2.796	-10.3391	0.27465	-0.361	0	-1.82	0.8	1.502	1.502	0	-5.446
QSCDPC(-15.35)	-2.798	-2.796	-6.17793	0.24296	-0.361	0	-1.82	0.8	1.502	1.502	0	-5.446
QSCDPlowE(-11.99)	-2.798	-2.796	-2.70355	0.12708	-0.361	0	-1.82	0.8	1.502	1.502	0	-5.446

Figure 5.19 Peak hourly heating report: January 11 at 11:00 PM

An inspection of the peak loads reveals several interesting features. First, the CWF and W5 methods yield the highest conduction losses, while the DPlow-E glazing type simulated with CWFs and SC methods of input yields the lowest conduction loads. Also of importance is the corresponding change in the other building components for the peak heating loads in Figure 5.19, where unexpected changes were observed when going from one option to another. In the case of the wall conduction, when in the Quick mode, a decrease in the loads is observed when going from the W5 to SC method of input. On the other hand, for the case of the roof conduction, an unexpected increase in results is also observed when going from W5 to SC method. For the case of the underground surface conduction and for equipment to space loads, while there is no change in results between the W5 or SC methods, there is a difference in the Quick and CWF modes. When observing the occupants to space as well as infiltration parameter an unexpected dip in results is seen in the case of the W5 option, while results from other options are similar. Although these individual unexpected chages are small, the sum of the differences contribute significantly to the total.

From Figure 5.19 Table 5.2 and Table 5.3, it is observed that when in Quick mode and using the SC method for fenestration input, going from SPC glazing option to DPC glazing option, the total peak heating loads decreases from −19.48 KBtu/hr to −15.36 KBtu/hr, a difference of 4.13 KBtu/hr, which in is a drop of 21.20%. When using the W5 method, on going from SPC glazing option to DPC glazing option, the total peak heating loads decreases from −18.60KBtu/hr to −15.37KBtu/hr, a difference of 3.23KBtu/hr, which is a drop of 17.35%. On comparing the SC and W5 methods the savings decrease by 3.85%, which represents 18.14% of the SC savings.

When in the Quick mode and using the SC method for fenestration input, on going from the SPC glazing option to the DPlow-E glazing option, the total peak heating loads decreases from −19.48KBtu/hr to −11.99KBtu/hr, a difference of 7.49 KBtu/hr, which is a drop of 38.44%. When using the W5 method, on going from the SPC glazing option to the DPlow-E glazing option, the total peak heating loads decreases from −18.60KBtu/hr to −13.20KBtu/hr, a difference of 5.40KBtu/hr, which is a drop of 29.01%. In comparing the SC and W5 methods there is a decrease of 9.43%, which represents 24.52% of the SC savings.

When in the Quick mode and using the SC method for fenestration input, on going from the DPC glazing option to the DPlow-E glazing option, the total peak heating loads decreases from −15.36KBtu/hr to −11.99KBtu/hr, a difference of 3.36KBtu/hr, which is a drop of 21.88%. When using the W5 method, going from the DPC glazing option to the DPlow-E glazing option, the total peak heating loads decreases from −15.37KBtu/hr to −13.20KBtu/hr, a difference of 2.17KBtu/hr, which is a drop of 14.11%. On comparing the SC and W5 methods there is a decrease of 7.77% in heating loads, which is 35.51% of the SC peak heating load.

When in the CWF mode and using the SC method for fenestration input, going from the SPC glazing option to the DPC glazing option, the total peak heating loads decreased from −15.78KBtu/hr to −12.55KBtu/hr, a difference of 3.23KBtu/hr, which is a drop of 20.43%. When using the W5 method, going from the DPC glazing option to the DPlow-E glazing option, the total peak heating loads decreases from −18.73KBtu/hr to −15.01KBtu/hr, a difference of 3.72KBtu/hr, which is a drop of 19.86%. On comparing the SC and W5 methods, a decrease of only 0.57% is observed, which represents a 2.80% change in the SC results.

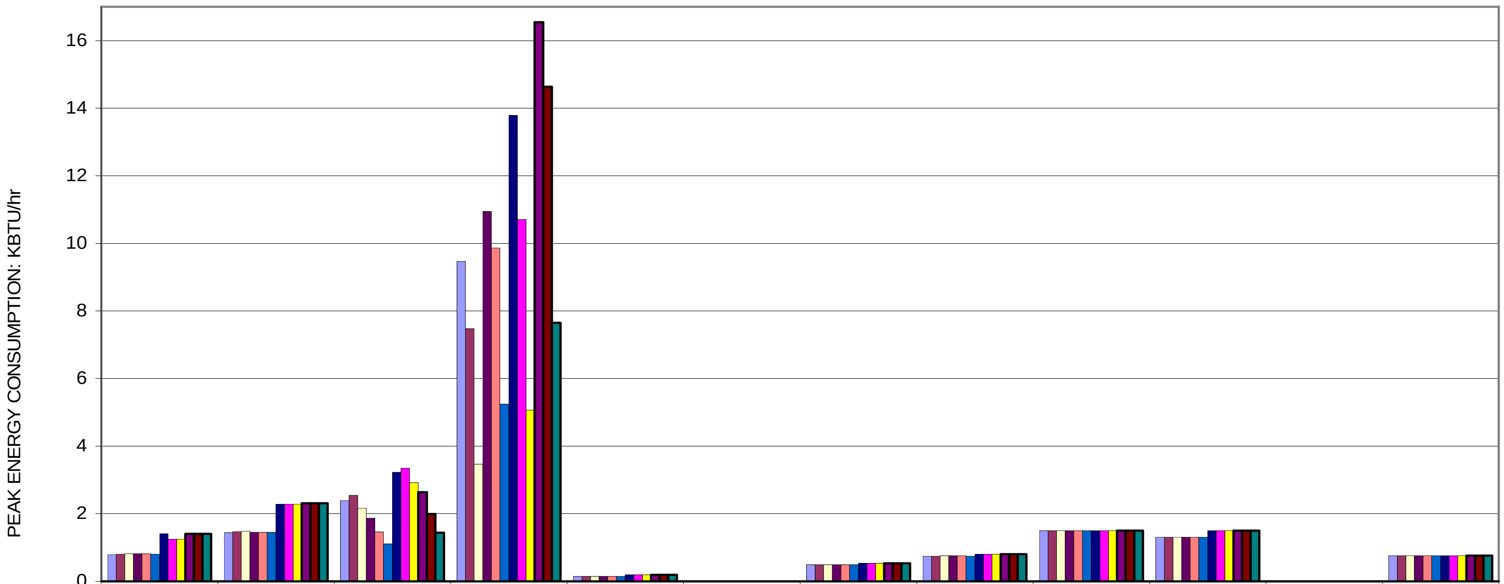
When in the CWF mode and using SC method for fenestration input, going from the SPC glazing option to the DPlow-E glazing option, the total peak heating loads decreases from −15.78KBtu/hr to −10.08KBtu/hr, a difference of 5.70KBtu/hr, which is a drop of 36.12%. When using the W5 method, on going from the DPC glazing option to the DPlow-E glazing option, the total peak heating loads decreases from −18.73KBtu/hr to −12.58KBtu/hr, a difference of 6.15KBtu/hr, which is a drop of 32.83%. In comparing the SC and W5 methods, a decrease of 3.28% is observed, which represents 9.09% of the SC results.

Finally, when in the CWF mode and using SC method for fenestration input, going from the DPC glazing option to the DPlow-E glazing option, the total peak heating loads decreases from −12.56KBtu/hr to −10.08KBtu/hr, a difference of 2.48KBtu/hr, which is a drop of 19.71%. When using the W5 method, going from the DPC glazing option to the DPlow-E glazing option, the total peak heating loads decreases from −15.01KBtu/hr to −12.58KBtu/hr, a difference of 2.43KBtu/hr, which is a drop of 16.18%. On comparing the SC and W5 methods, a decrease of 3.53% is observed, which represents 17.89% of the savings from the SC method.

Figure 5.20 presents the results of the analysis of peak cooling loads from different building envelope components as reported by DOE-2's LOADS program. 4:00 PM on the August 9th was one of the highest temperatures of the year, and therefore was used to examine hourly peak cooling loads. The ambient temperature at this hour was 83°F. The resulting temperature difference (ΔT) between the interior and the exterior was 10°F. It is important to note that ΔT in this case was not as pronounced as the ΔT observed in peak heating loads. Hence, the window glass solar load becomes the primary contributor to the peak cooling loads, while contribution from the wall conduction, roof conduction, underground surfaces and infiltration components of the hourly peak load report were not as significant as seen in the peak heating loads.

An inspection of the peak cooling loads in Figure 5.20 shows different trends from the peak heating loads. For example, the SPC glazing type using Quick and SC methods of input yields the highest results, while the DPlow-E glazing type, simulated with CWF and W5 methods of input yield the lowest results. Results from the other components show similarities to those noted on the peak heating loads.

From Figure 5.20 and Tables 5.1.2 and Table 5.3, it can be seen that when the Quick mode using the SC method is used for fenestration input, to analyze the SPC glazing versus the DPC glazing options, the total peak cooling loads decreases from 28.19 KBtu/hr to 25.63 KBtu/hr, a difference of 2.55KBtu/hr, which is a drop of 9.06%. When using the W5 method, going from the SPC glazing option to the DPC glazing option, the total peak cooling loads decrease from −18.60 KBtu/hr to −15.37KBtu/hr, a difference of 3.11KBtu/hr, which is a drop of 11.95%. In comparing the SC and the W5 methods, cooling loads increase by 2.89%, which represents 31.88% of the SC cooling loads.



	WALL COND	ROOF COND	WINGLS+FRM COND	WIN GLS SOLAR	DOOR COND	INT SURFACE COND	UNDERGROUND SURF	OCCUPANTS TO SPACE	LIGHT TO SPACE	EQUIP TO SPACE	PROCESS TO SPACE	INFILTRATION
THW5SPC(19.04)	0.793	1.44	2.39353	9.46418	0.14	0	0.49	0.747	1.5	1.31	0	0.76
THW5DPC(17.24)	0.807	1.47	2.53974	7.47634	0.14	0	0.49	0.747	1.5	1.31	0	0.76
THW5DPlowE(12.90)	0.821	1.49	2.1664	3.4668	0.14	0	0.49	0.753	1.5	1.31	0	0.76
THSCSPC(20.05)	0.821	1.45	1.8697	10.94684	0.14	0	0.49	0.764	1.5	1.31	0	0.76
THSCDPC(18.56)	0.821	1.45	1.45888	9.86859	0.14	0	0.49	0.764	1.5	1.31	0	0.76
THSCDPlowE(13.55)	0.799	1.45	1.10715	5.24443	0.14	0	0.49	0.747	1.5	1.31	0	0.76
QW5SPC(25.99)	1.405	2.285	3.22833	13.78628	0.19	0	0.535	0.8	1.5	1.5	0	0.76
QW5DPC(22.88)	1.245	2.285	3.35682	10.71136	0.19	0	0.535	0.8	1.5	1.5	0	0.76
QW5DPlowE(16.80)	1.245	2.285	2.91283	5.07009	0.19	0	0.535	0.8	1.5	1.5	0	0.76
QSCSPC(28.19)	1.405	2.312	2.64019	16.5448	0.19	0	0.535	0.8	1.5	1.5	0	0.76
QSCDPC(25.63)	1.405	2.312	1.99448	14.63579	0.19	0	0.535	0.8	1.5	1.5	0	0.76
QSClowE(18.10)	1.405	2.312	1.44129	7.65535	0.19	0	0.535	0.8	1.5	1.5	0	0.76

Figure 5.20 Peak hourly cooling report: August 9 at 4:00 PM

When using the Quick mode combined with the SC method for fenestration input, going from the SPC glazing option to the DPlow-E glazing option, the total peak cooling loads decrease from 28.19KBtu/hr to 18.10KBtu/hr, a difference of 10.09KBtu/hr, which is a drop of 35.79%. When using the W5 method, going from thr SPC glazing option to the DPlow-E glazing option, the total peak cooling loads decrease from 25.99KBtu/hr to 16.80KBtu/hr, a difference of 9.19KBtu/hr, which is a drop of 35.37%. On comparing SC and W5 methods the cooling loads decrease by 0.42%, which represents 1.18% of the SC cooling loads.

When using the Quick mode together with the SC method for fenestration input, going from the DPC glazing option to the DPlow-E glazing option, the total peak cooling loads decrease from 25.63 KBtu/hr to 18.10 KBtu/hr, a difference of 7.53KBtu/hr, which is a drop of 29.39%. When using the W5 method, on going from the DPC glazing option to the DPlow-E glazing option, the total peak cooling loads decreases from 22.88KBtu/hr to 16.80KBtu/hr, a difference of 6.09KBtu/hr, which is a drop of 26.59%. In comparing SC and W5 methods, there is a decrease in cooling of 2.80%, which represents 9.52% of the SC peak cooling loads.

When in the CWF mode, the SC method for fenestration input, going from the SPC glazing option to the DPC glazing option, the total peak cooling loads decrease from 20.05KBtu/hr to 13.55KBtu/hr, a difference of 1.49KBtu/hr, which is a drop of 7.43%. When using the W5 method, going from the SPC glazing option to DPC glazing option, the total peak cooling loads decreases from 19.03KBtu/hr to 17.24KBtu/hr, a difference of 1.80KBtu/hr, which is a drop of 9.44%. In comparing SC and W5 methods, there is an increase in cooling loads of 2.02%, which represents 27.15% of the SC peak cooling loads. This means that the SC method, when combined with the CWFs, underpredicts peak cooling loads when compared to the W5 method using CWFs.

When using the CWs and the SC method for fenestration input, going from the SPC glazing option to the DPlow-E glazing option, the total peak cooling loads decreases from 20.05KBtu/hr to 13.55KBtu/hr, a difference of 6.50KBtu/hr, which is a drop of 32.44%. When using the W5 method, going from SPC glazing option to DPlow-E glazing option, the total peak cooling loads decreases from

20.05KBtu/hr to 13.55KBtu/hr, a difference of 6.14KBtu/hr, which is a drop of 32.25%. In comparing SC and W5 methods there is a decrease of 0.18%, which represents 0.56% of the SC peak cooling loads.

When using the CWF and the SC method for fenestration input, on going from the DPC glazing option to the DPlow-E glazing option, the total peak cooling loads decrease from 18.56KBtu/hr to 13.55KBtu/hr, a difference of 5.01KBtu/hr, which is a drop of 27.02%. When using the W5 method, going from the DPC glazing option to the DPlow-E glazing option, the total peak cooling loads decreases from 17.24KBtu/hr to 12.90KBtu/hr, a difference of 4.34KBtu/hr, which is a drop of 25.19%. In comparing the SC and W5 methods, there is a decrease of 1.83%, which represents 6.76% of the SC peak cooling loads.

5.1.3.3 Summary and discussion

This section of the thesis compared the results from a code-compliant residential building, which was simulated using Quick mode and CWFs as well as the SC and W5 input options. Results from annual building and peak load energy performance were considered. The analysis was performed by comparing the savings obtained on going from a lower performance configuration to a higher performance configuration of glazing types taken up by this study (i.e., SPC, DPC, DPlow-E).

In general, the comparison of the performance of the different glazing types (i.e., SPC, DPC, DPlow-E), using the SC or W5 methods, and the Quick or CWF options, shows that the CWF options have lower annual energy use than the Quick options. For the case of the peak cooling loads, the use of Thermal mass and W5 methods yields the lowest peak cooling loads. While for the case of peak heating the use of CWF option, combined with the W5 method, yields the highest peak heating/cooling loads. A closer examination of the peak heating/cooling loads also reveals that switching from CWFs to Quick or from SC to W5 produce changes in the other building components, some of which are unexpected.

When comparing the percent savings from lower performance glazing to a higher performance glazing, while using either the SC or W5 methods, it is observed that the percent savings obtained from using the SC method are usually greater than the percent savings obtained from using the W5 method for almost all the cases, for both annual and peak loads. However, on activating the CWFs, the percentage of annual heating savings increased, while the percentage of annual cooling and overall energy consumption are decreased. The percentage savings from the peak loads are also reduced.

5.1.4 General conclusions

The CWF mode of input was compared to the Pre-calculated ASHRAE weighting Factor mode (Quick) mode of input for the DOE-2.1e building simulation input file. Also, the WINDOW-5 method of input for fenestration was compared to the Shading Coefficient (SC) method of input for fenestration. Three glazing options were considered. They are: Single Pane Clear (SPC), Double Pane Clear (DPC) and Double Pane Low-E (DPlow-E). The building model considered for simulation was based on specifications laid down by the 2000 IECC. The system type included in this building model uses electricity for cooling and natural gas for heating and DHW.

When comparing Thermal mass input mode to Quick input mode, the primary conclusion was that the use of Thermal mass input mode substantially decreases the peak and annual energy consumption results.

While comparing the SC method of defining fenestration to the W-5 method of defining fenestration, it is clearly seen that the W-5 method had more reasonable results as evidenced by the temperature swings, etc. Nevertheless, on closer examination, this study showed that the use of Quick versus CWF and SC versus W5 inputs yielded very large differences, which depend on the glazing comparison. In general, for peak cooling loads, the W5 method reports substantially lower loads, while in contrast, in the case of peak heating loads the W5 method reports yield substantially higher loads. Therefore, although the experimental results from the LBNL MoWITT facility have shown the W5 calculation to br more accurate, it is not easy to make a generalized statement about the impact of the difference in the results of the W5 method versus the SC method without referring to specific glazing types.

Discrepancy in results from the two methods increases when going from SPC glazing to low-E glazing implying that although the resultant difference in energy consumption is marginal for low-performance glazing (i.e., SPC), use of the SC method to simulate high-performance glazing can create a considerably large errror. Hence it is suggested that the W5 method be used in future code traceable building simulation models, where, hopefully, simulation of high performance glazing is required for code compliance.

Also, it is important to note that the use of CWFs in a DOE-2 simulation gives a substantially more accurate representation of the thermal mass effects, and therefore must also be considered in future code compliant simulations.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary of the intent of study and procedure used

The prime intention of this study was to justify the advantage of using less efficient windows with overhangs over un-shaded high performance windows as specified by the 2000 IECC. In addition, the potential of glazing as an energy provider was discussed by examining the performance of a number of high-performance glazing options (see Appendix B). The knowledge of how these glazing options perform could be useful for specifying residential glazing in future building energy codes.

For this purpose the residential building model was used in DOE-2.1e, which is based on specifications laid down by the 2000 IECC. The mode of calculating included the thermal mass properties of the building envelope components. The method implemented to calculate heat transfer through windows employed the use of WINDOW-5 specifications for the glazing.

6.2 Conclusions from Chapter V – comparing the method of input for fenestration in the building simulation model

6.2.1 Summary of intent and procedure used

The first section of this analysis considered improving the accuracy of results obtained from implementing glazing strategies. For this purpose two options are considered, which deal with the input method for building envelope components (fenestration as well as other building envelope components) in the DOE-2 simulation model. On an overall level, in order to define building envelope components, results obtained from activation of Custom Weighting Factors are compared to results obtained from Pre-calculated Weighting Factors. Focusing on defining fenestration in the DOE-2 simulation model, the traditionally used method of fenestration input, which uses shading coefficient value of glazing, is compared with a more accurate method that uses results from the WINDOW-5 simulation program.

In order to compare the options of input for fenestration, observations were made at two levels – examining solar heat gain and examining the impact on overall building energy performance. For the case of comparing methods of input for building envelope components in the simulation model, annual, weekly, and hourly reports from both systems as well as loads were considered. Results in terms of percentage savings that can be obtained by going from lower performance windows to higher performance windows are also presented and discussed.

6.2.2 Conclusions and recommendations

Examining the results from the method of input for fenestration in the simulation model, it is seen that using the WINDOW-5 method gives very different results than the SC method. When comparing solar heat gain, discrepancy in predictions increases when going from the SPC glazing option to the DPC glazing option, or to the the DPLow-E glazing option. This discrepancy is attributed to wavelength as well as angle dependent approximation of solar heat gain and is most prominent in the DPlow-E glazing option. This implies that although performance of the WINDOW-5 method is comparable to the SC method for less efficient glazing, as in the case of the SPC glazing, it is a better option when considering high-performance glazing. In comparing overall energy performance, the difference in results is not as substantial. This is because specifications set by the IECC and incorporated in the simulation model such as internal heat gain and domestic hot water usage outweigh the heat gains and losses through the windows. Revising these assigned values may be considered for future updates of the IECC.

Activating the Custom Weighting Factors introduces a realistic time lag in the heat transfer properties of building components by introducing heat storage capacity of the building components. This, in turn, reduces the combined solar and conduction loads as well as the resultant space heating and cooling from the windows by up to 30%. It is observed that the introduction of heat storage capacity can vastly enhance the passive solar heat gain potential of materials being simulated in the building model.

In examining the annual heating and cooling energy performance, the impact of using both Thermal mass option as well as results from W5 is considerable, although not necessarily for lowering the results for energy consumption. On switching from Quick to Thermal mode, while using SC method for fenestration input, the highest percentage difference is obtained from model using SPC glazing option, while the lowest percentage difference is obtained from model using DPlow-E glazing. This is because SPC allows maximum solar gain to pass through, accentuating the impact of turning on the Thermal mass option. On the other hand, when using the W5 method of input for fenestration, the simulation model using the DPlow-E glazing option yields the highest percentage difference, while models using DPC glazing yield the lowest percentage difference.

Analysis of peak heating and cooling loads reveal that the use of the WINDOW-5 tremendously reduces the resultant window conduction and solar loads for cooling, but considerably increases the loads in the case of peak heating. The SPC glazing option yields to the lowest percentage difference, while the DPlow-E glazing option yields to a greater percentage difference. Peak load results from other building components are marginal. On the other hand, switching on the thermal mass option creates a uniform decrease in heat gain/loss results. In this case, the percentage difference in heat gain/loss for other building load components contributes significantly.

A more accurate simulation model, which is constructed using the WINDOW-5 program and the Thermal mass option for input, can bring down the energy consumption assessment by up to 7% on an overall basis. For peak cooling loads, the drop recorded by using the W5/Thermal mass model is around 30%, while for peak heating an increase is recorded using W5/Thermal mass model by up to 5%.

Considering the percentage savings obtained when going from lower performance windows to higher performance windows, it is noted that a greater percentage savings are achieved by using the traditional methods (i.e., SC and Pre-calculated Weighting Factors) over the use of more accurate methods (i.e., WINDOW-5 and Custom Weighting Factors) of defining input in the DOE-2.1e input file, overestimating the benefits of using high-performance glazing such as low-E to lower both annual and peak energy consumptions.

6.2.3 Recommendations

The percentage reduction in total annual energy consumption due to the use of WINDOW-5 in defining glazing type is not significant. However, the potential of this model can be fully realized on incorporating high-performance glazing, whose properties are vastly different from single pane glazing. It is hoped that the code will make such provisions in the future. The impact of the Thermal mass model is considerable for all options of glazing used. Also, a Hence the use of a new, more accurate model while carrying out simulations for code compliance is highly recommended.

6.3 Conclusions from Appendix A – dependence of energy consumption on parameters such as orientation, shading, glazing type and WWAR

6.3.1 Brief summary of intent and procedure used

In order to ascertain whether the use of horizontal overhangs with less efficient glazing will yield an energy consumption performance which is comparable to that specified by the IECC, the second section of this analysis compared the performance of optimally-shaded, less-efficient windows with the performance of code-compliant, un-shaded windows. Dependence of energy consumption on parameters such as orientation, shading, glazing type and WWAR was analysed. Double pane clear (SHGC = 0.76, U-value = 0.273) glazing is taken up for analysis and is compared to double pane low-E option (SHGC = 0.4 , U-value = 0.273) glazing. Exterior horizontal shading was the shading strategy considered by this analysis.

The analysis was performed in two steps. In the first step, the performance of selected glazing and proposed horizontal shading alterations were analyzed for each orientation. These orientation specific results were then combined into one single model in the second step of this analysis.

6.3.2 Conclusions

On analyzing the performance of glazing and optimum shading on each orientation, it can be concluded that the optimally-shaded, double-pane, low-E (DPlow-E) glazing option yields the lowest energy consumption results for the north and east orientations. However, for the south orientation, optimally-shaded (horizontal shading), double-pane, clear (DPC) glazing option yields the lowest results. These observations reiterate the hypothesis assumed by this thesis stating that shading, in combination with less efficient glazing, is comparable to the use of glazing specified by the IECC.

It was observed that the impact of variation in glazing options is more prominent for larger house sizes (i.e., 5000 ft^2), than for smaller house sizes (i.e., 500 ft^2). This is because the fixed internal loads specified by the 2000 IECC for residential building simulation models make larger houses more building envelope dependent, and hence more sensitive to variations in glazing types and WWARs.

For the north and the east orientations, the overall energy consumption was directly proportional to the WWAR as well as the width of horizontal shading. This trend implies the benefit of using smaller windows in these orientations, especially for the climate of Houston. However, for the south orientation, an optimum area for glazing and horizontal shading width can be used to lower overall energy consumption.

Several combinations are achieved on combining these orientation specific results in a single simulation model. These combinations consist of optimum choice of glazing, optimum width of horizontal shading and optimum WWAR specific for each orientation. The potential of using the south orientation for passive solar heat gain is harnessed in these combinations. Resultant energy consumption trends are lower than the energy consumption trends obtained from the code specifications.

In comparing the performance of these combinations with the results obtained from implementing the 18% WFAR specified by the code for simulating a standard house, against which all the other simulations are to be compared, significant discrepancies are observed. For the case of the 1500 ft^2 house size, the results obtained from the model implementing 18% WFAR set a stringent standard. This energy performance standard can only be met with energy performance results obtained from a simulation model implementing code specified (or more efficient) glazing. Trends are reversed for the case of the 5000 ft^2 house size. In this case all the glazing options yield energy performance results which meet the standards set by the standard simulation model, which uses an 18% WFAR.

6.3.3 Recommendations

The 2000 IECC requires equal horizontal shading, same specifications for glazing type, and an equal WWAR the on all orientations. However, as observed by this study, horizontal overhangs, glazing specifications, and wall-to-window area ratio specified by the code are to be orientation specific to lower energy consumption levels. Moreover, special attention needs to be given in designing fenestration for the south orientation, wherein mobilizing the passive solar heat gain potential associated with this orientation can prove to be beneficial.

The standard house specified by the IECC currently uses 18% window to floor area ratio. It was noted that current specifications, although stringent for smaller house sizes, get more flexible for houses with larger areas. Hence a new set of specifications needs to be devised for the standard house used by the IECC. These specifications are to be based on window to wall area ratios which makes the standard house comparable to the user input houses.

6.4 Conclusions from Appendix B – analysis of alternative strategies for shading and glazing

6.4.1 Brief summary of intent and procedure used

The purpose of this section was to assess the potential of windows as net energy providers. The conclusions obtained from this analysis could be incorporated by the glazing specifications of future building energy codes. Both practical as well as hypothetical high performance glazing options were considered and compared to the glazing options specified by the 2000 IECC, as well as to a window-less building model. The glazing options selected were: the low-E low solar (LELS) glazing option, the super low-E low solar (SULLS) glazing option and its dynamic counter path (DySULLS), and the ultra low-E low solar (ULLS) glazing option and its dynamic counter path (DyULLS). All of these glazing options were modeled using the DOE-2.1e and WINDOW-5 simulation programs.

Analysis was carried out in two steps. In the first step, a building model was considered which had provisions for glazing in one orientation only. The impact of varying glazing options, WWAR, and house size on energy consumption was assessed for each orientation. In the second step of analysis, a building model which has provisions for glazing on all orientations is considered. The impact of varying glazing options, WWAR, and house size on energy consumption was assessed for the whole model. For both the steps, energy performance trends were analyzed in terms of annual heating, annual cooling, and overall energy consumption.

6.4.2 Conclusions

When looking at the performance of high performance window options in each orientation, it was observed that the impact of selection of glazing on orientation is greatly diminished when using high performance options. A maximum of 5% variation in overall energy consumption is seen when examining the performance of the options on each orientation. House sizes and wall to window area ratios also impact the performance of glazing options to a certain degree, with the impact of building envelope more clearly outlined for the case of bigger house sizes. Also observed is that in the case of smaller houses, U-factors gains precedence, while in the case of larger houses, SHGC gains precedence.

For the static high-performance low solar options, the significant reduction in cooling loads were evened out by a significant increment in heating loads. The resultant overall energy performances were only marginally lower than the code specified low-E glazing. However, dynamic options yielded the lowest energy consumption results for both heating as well as cooling energy loads. The resultant overall energy consumption results were significantly lower than the energy consumption results obtained by the low-E glazing option specified by the IECC. It should be noted that the implementation of dynamic glazing resulted in an increase of about 5% in total annual energy consumption savings, which cannot be achieved with either the specifications laid down in the current code or with currently available high performance glazing options The findings reiterating the conclusions from Apte et al., (2003).

In comparing the high-performance glazing options to the windowless base-case, here too the dynamic glazing options yielded the lowest energy consumption results which were in some cases lower than the energy consumption results obtained from the windowless base-case.

6.4.3 Recommendations

Contrary to conclusions from earlier sections where recommendations for orientation specific specifications are to be made, results from high-performance windows are not drastically affected by orientation. In addition to the WWAR categorization, which is currently specified in the code, house size needs to be taken into consideration when specifying the maximum U-values and SHGC for the glazing. From the results it is seen that incorporating switachable options in the energy code proves to be highly beneficial in achieving zero-energy homes – a concept which energy codes of the future should try to achieve.

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APPENDIX A

DEPENDENCE OF ENERGY CONSUMPTION ON PARAMETERS SUCH AS ORIENTATION, SHADING AND GLAZING TYPE, AND WWAR

A.1 Overview

This section of the study compares the use of optimally-shaded windows with the use of code-compliant, un-shaded windows. The dependence of optimal shading on orientation, window size, house size, and type of glazing are also considered.

The input files described in Table 4.6 of Chapter 4 were used as a basis for most of the simulations in this section. The procedure for this analysis is outlined in Table 4.13 and Table 4.14. The analysis was conducted by observing the performance of two glazing options: Double Pane Clear (DPC) and Double Pane low-E (DPlow-E). These were tested considering the following: a) three orientations (i.e., north, south, and east); b) three house sizes (1500, 2500, and 5000 ft^2); and c) three window-to-wall area ratios WWARs (15%, 20%, and 25%). The shading for the window was restricted to fixed exterior, horizontal overhangs, which best describes the most common shading provided by the eaves of the house.

To proceed with the analysis it was necessary to determine the optimum shading for each orientation provided by the horizontal eaves, house size and window-to-wall area ratios (WWARs). The procedure adopted is outlined in the next section.

A.1.1 Determining optimum horizontal shading on each orientation

The traditional method of assessing the impact of shading has usually been performed using the concept of projection factors. The projection factor characterizes the shading impact of horizontal overhangs or canopies that project outwards from the window as shown in Figure A.1. The projection factor is the ratio of the distance of the projection to its height above the sill of the window it shades.

Figure A.1 shows a horizontal shade for the building model and also includes the method of calculating the projection factor. However, the model used in this study has a fixed sill height, so it was found more convenient to report results by simply varying the horizontal projection 'a' over the window as shown in the figure. Using this procedure the horizontal shading was chosen for each of the three orientations, house sizes, and WWARs. The impact of the horizontal shading on DOE-2's BEPS report for south, north, and east orientations is presented in Figure A.2. For each of these orientations the house was configured such that only the wall facing the orientation had the 15%, 20%, or 25% WWAR being studied. All other orientations had no windows (i.e., WWAR = 0)

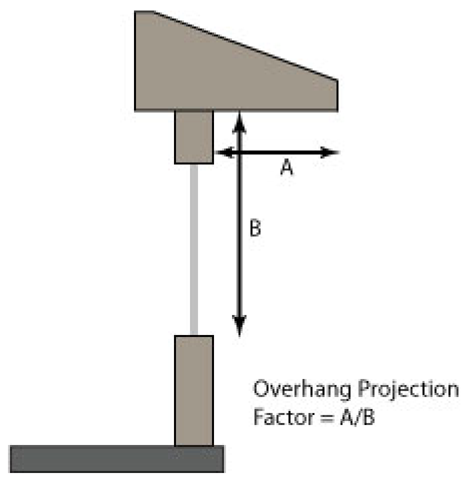


Figure A.1 Schematic representation of horizontal shading implemented in building simulation model

A.1.1.1 Horizontal shading of the south orientation

As shown in Figure A.2, for windows facing the south, the total annual energy consumption trend due to shading follows a curvilinear path. The curve is more pronounced in the case of the 5000 ft^2 house because of the fixed internal load prescribed by the 2000 IECC (IECC2000) as modified by the 2001 Supplement (IECC2001). This fixed internal load has the effect of making the smaller houses less sensitive to envelope loads. The optimum shading was determined by calculating the lowest point on the curve for the total annual energy use.

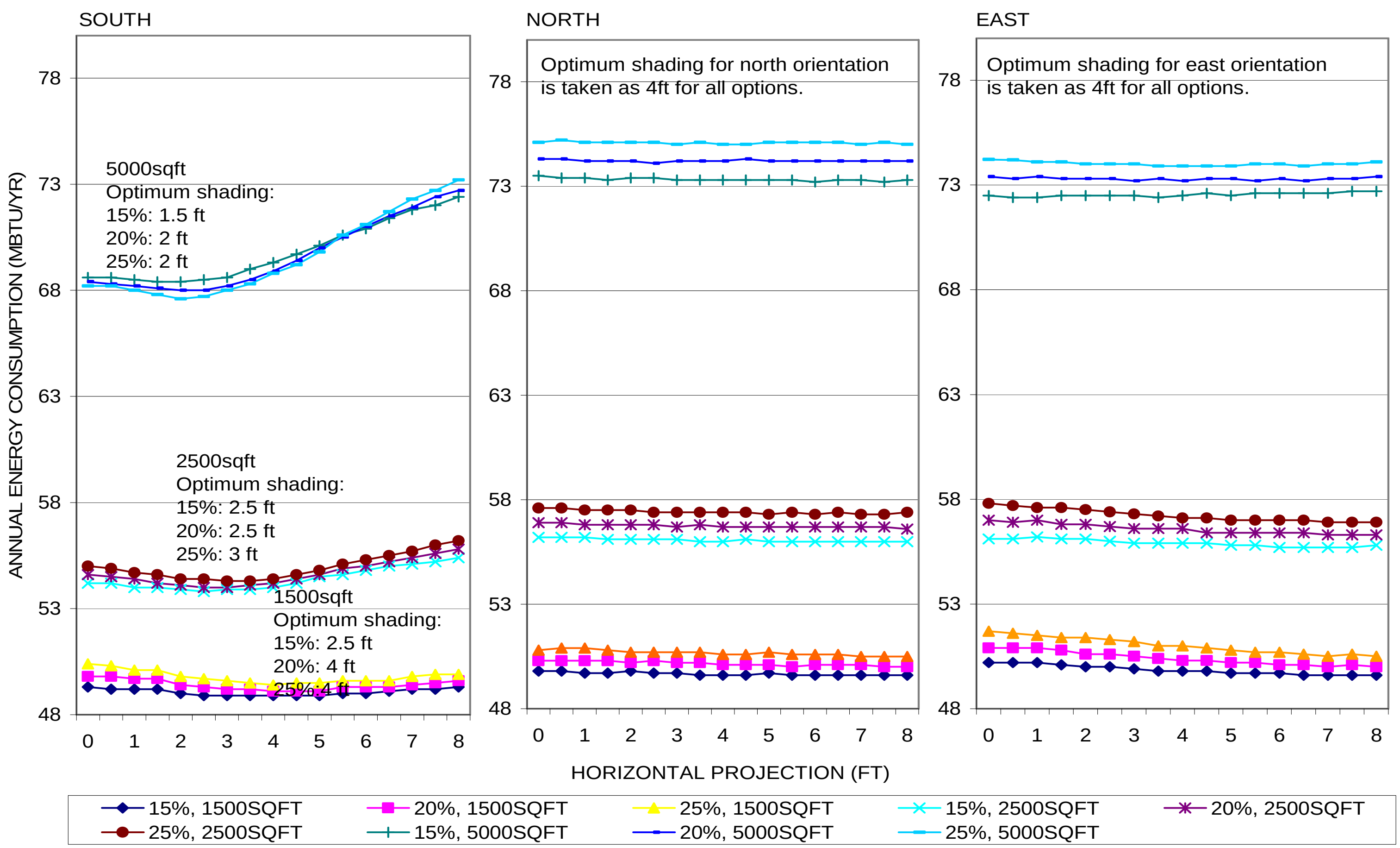


Figure A.2 Selecting optimum shading for south, north and east orientation

For the DPC option in the 1500 ft^2 and 2500 ft^2 houses, the trends are predictable with 15% WWAR yielding the lowest annual energy consumption and the 25% WWAR yielding the highest annual energy consumption. In the case of the 5000 ft^2 house, there is a reversal of the trends when going from 0 to 8 ft horizontal projection. For the horizontal projection of 0 to 5.5 ft, the 25% WWAR yields the lowest annual energy consumption levels, while the 15% WWAR yields the highest energy consumption levels. For projections greater than 5.5 ft, the annual energy consumption pattern reverses to the trends observed for the other house sizes (i.e., the energy consumption patterns for 25% WWAR start going up while those for 15% WWAR start going down because of the decreased passive solar effect due to excessive shading from longer projections). This trend is more carefully considered in the later sections for the passive solar heating potential. It is also observed that the optimal shading projection decreases when going from a 1500 $ft.^2$ to a 5000 $ft.^2$ house. Results of the simulation runs are presented in Table . Results obtained are similar to those for the DPC option. These same, optimal horizontal projections were used in the low-E glazing analysis.

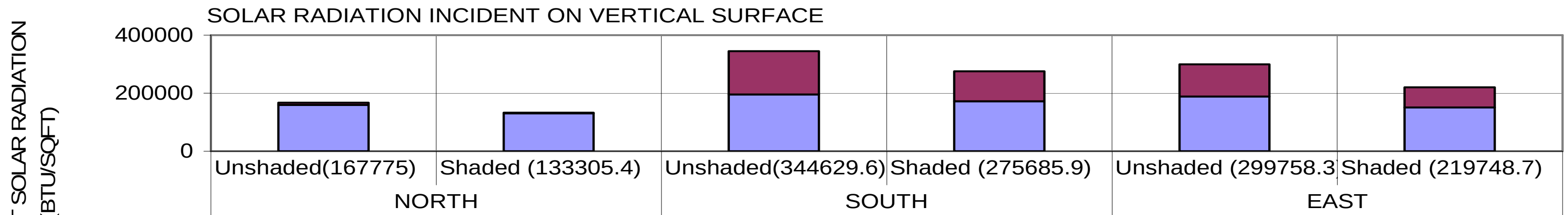
A1.1.2 East (west) and north orientation for DPC glazing

For east (and west) as well as north orientations, the energy consumption trend takes on a decreasing linear shape. Therefore, 4 ft. was assumed as the optimal horizontal width for these orientations. Table A.2 given below summarizes the results.

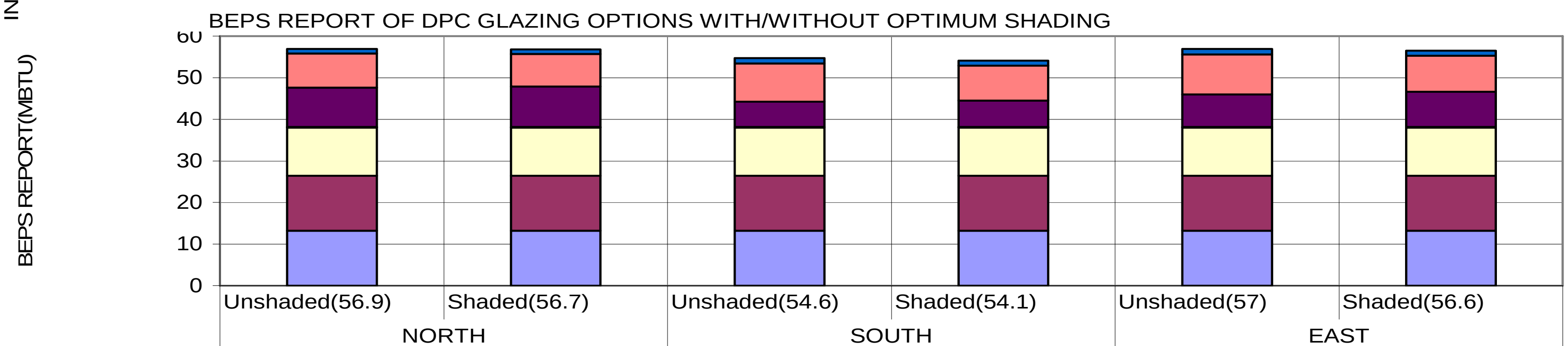
Table A.1 Optimal horizontal shading for each orientation for DPC and DPlow-E glazing options

GLAZING TYPE	ORIENTATION	HOUSE SIZE	% GLAZING	OPTIMUM SHADING (ft)
Double Pane Clear (DPC)	South	1500	15	2.5
			20	4
			25	4
		2500	15	2.5
			20	2.5
			25	3
		5000	15	1.5
			20	2
			25	2
	East	All House sizes	All GWARs	4
	North	All house sizes	All GWARs	4
Double Pane Low-E (DPlow-E)	South	1500	15	2.5
			20	2.5
			25	2.5
		2500	15	2
			20	2.5
			25	3
		5000	15	1.5
			20	1.5
			25	1.5
	East	All House sizes	All GWARs	4
	North	All house sizes	All GWARs	4

A.1.2 Impact of optimum shading on each orientation



	NORTH Unshaded(167775)	NORTH Shaded (133305.4)	SOUTH Unshaded(344629.6)	SOUTH Shaded (275685.9)	EAST Unshaded (299758.3	EAST Shaded (219748.7)
DIR COMP	8037.4	3175.4	149013	102929.1	111071.9	69402.5
DIFF COMP	159737.6	130130	195616.6	172756.8	188686.4	150346.2



	NORTH Unshaded(56.9)	NORTH Shaded(56.7)	SOUTH Unshaded(54.6)	SOUTH Shaded(54.1)	EAST Unshaded(57)	EAST Shaded(56.6)
VENT FANS	1.1	1.1	1.3	1.2	1.3	1.2
SPACE COOL	8.2	7.8	9.2	8.4	9.6	8.7
SPACE HEAT	9.4	9.7	6	6.3	7.8	8.4
PUMPS & MISC	0.2	0.2	0.2	0.2	0.2	0.2
DOMHOT WATER	11.6	11.6	11.6	11.6	11.6	11.6
MISC EQUIPMT	13.2	13.2	13.2	13.2	13.2	13.2
AREA LIGHTS	13.2	13.2	13.2	13.2	13.2	13.2

Figure A.3 Diffuse and direct components for annual solar radiation incident on a vertical surface for north, south and east orientations with corresponding BEPS report for DPC glazing option

Table A.2 Percentage decrease of solar radiation incident on a window due to optimum shading

ORIENTATION	SOLAR RADIATION INCIDENT ON VERTICAL SURFACE FROM LOADS		BEPS FROM DPC GLAZINGOPTION 20%WWAR, 2500SQFT HOUSE	
	COMPONENT	% DECREASE DUE TO SHADING	COMPONENT	% DECREASE DUE TO SHADING
North	Diffuse Direct	-18.5% -60.9%	Heating Cooling Total	+3.19 -4.88 -0.351
South	Diffuse Direct	-11.69% -30.93%	Heating Cooling Total	+5 -8.69 -0.92
East	Diffuse Direct	-20.32% -37.52%	Heating Cooling Total	+7.69 -9.37 -0.701

A.1.3 Impact of orientation

The 2000 IECC, including the 2001 IECC supplement, specifies an equal area of glazing on all orientations (Section: 402.1.3.1.1, IECC 2000, IECC 2001) and with no recommendations regarding the orientation-dependent selection of glazing as well as shading. On the contrary, a number of studies cited by the literature review show the importance of orientation in window design (). Therefore, this section investigates the performance of selected glazing and proposed horizontal shading alternatives on each orientation and suggests alternate solutions for glazing specifications with respect to orientation. For the simulation, the building model considered was the Base-case II model, which is described in Table 4.6 of Chapter IV. The model uses custom weighting factors and the output files from WINDOW-5. It also makes provisions for glazing in a single orientation.

In order to systematically analyze the impact of orientation on house size and the WWAR on resultant energy consumption, the analysis was carried out in three sections, using the method adapted from Carmody et al. (2004). Three variables – glazing option (i.e., glazing type as well as shading strategies), house size, and WWAR were identified and varied with respect to orientation. In the first section, only the window options were altered. In the second section, window options as well as house sizes were altered. While in the third section, window options, house sizes, and WWARs were modified.

A.1.3.1 Varying orientation and glazing options; general trends

The first step of the analysis was to ascertain the general trends in energy consumption patterns on varying the window options in each orientation. For this purpose a 2500 ft^2 house with 20% window to wall area ratio was examined.

A.1.3.1.1Annual energy consumption

Figure A.4 presents the annual energy consumption trends with varying windows in the simulation model in one particular orientation. The purpose of this graph is to understand the impact of using the various fenestration options (i.e., DPC un-shaded, DPC optimally shaded, DPlow-E un-shaded, DPlow-E optimally shaded) on annual energy consumption for each orientation. In this analysis the annual energy consumption is given in terms of space heating, space cooling, and total energy from DOE-2's BEPS report.

For space cooling, it is shown that the un-shaded DPC yields higher energy use results than the un-shaded DPlow-E glazing for all the orientations (For un-shaded north: DPC = 8.2 MBtu, DPlow-E = 7.3 MBtu; for un-shaded South: DPC = 9.2 MBtu, DPlow-E = 7.8 MBtu; for un-shaded East: DPC = 9.6 MBtu, DPlow-E = 8.1 MBtu). While for space heating loads, the trends show DPC yielding greater results than DPlow-E for north orientations (DPC = 9.4 MBtu, DPlow-E = 9.3 MBtu). The trends are reversed for the south and east orientation (For un-shaded South: DPC = 6.0 MBtu, DPlow-E = 7.1 MBtu; for un-shaded East: DPC = 7.8 MBtu, DPlow-E = 8.3 MBtu). Comparing overall trends for all three orientations, it is observed that un-shaded DPC yields higher annual energy use than un-shaded DPlow-E for all the cases (for un-shaded North: DPC = 56.9 MBtu, DPlow-E = 55.7 MBtu; for un-shaded South: DPC = 54.6 MBtu, Dplow-E = 54.2 MBtu; for un-shaded East: DPC = 57 MBtu, DPlow-E = 55.7 MBtu). It is also observed that the use of low-E glazing causes less variation in energy consumption for all the orientations, especially in the case of cooling.

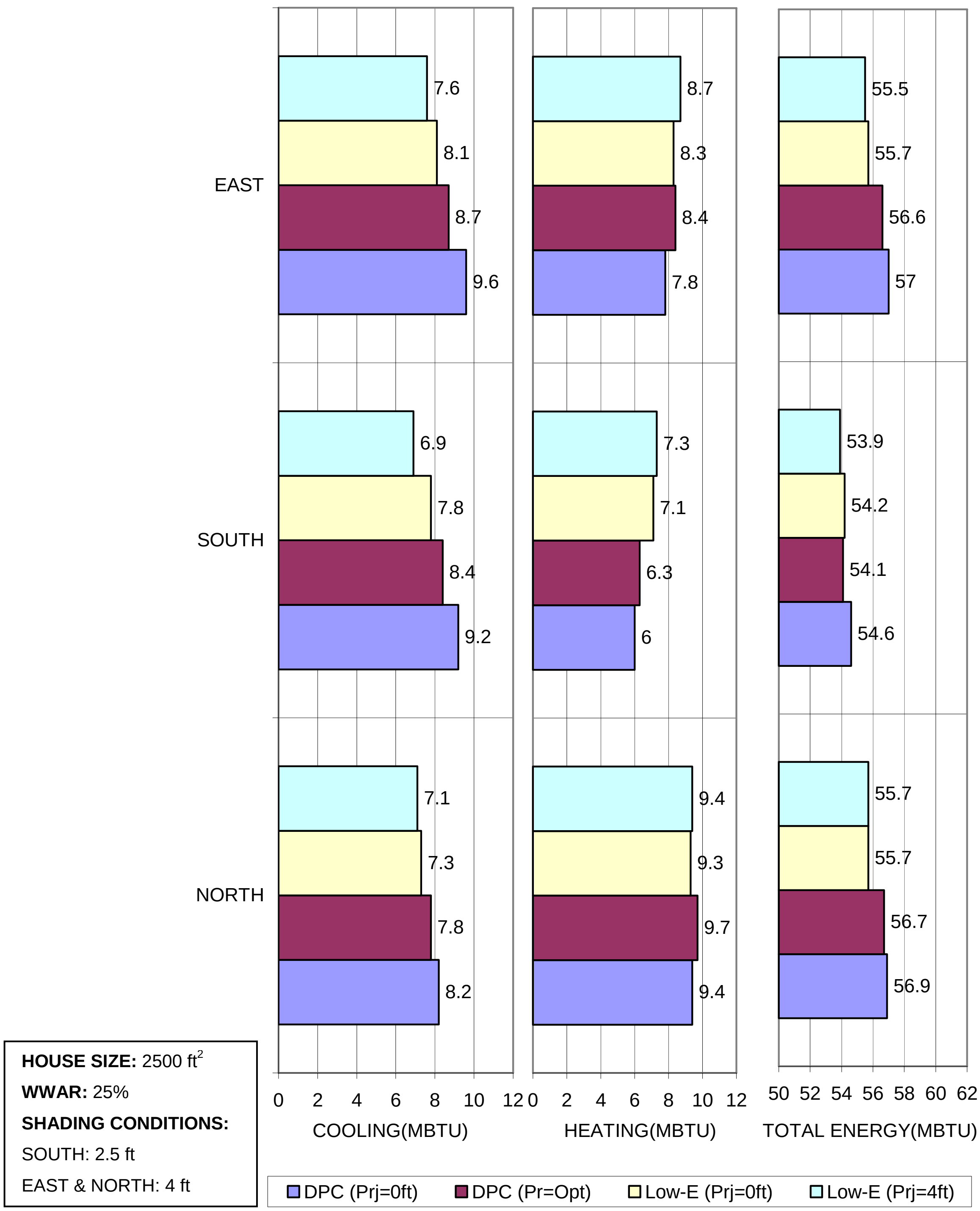


Figure A.4 Annual energy consumption trends: A comparison by varying window options

As previously seen, annual energy use can be reduced by the selection of the appropriate glazing and by the use of appropriate shading. In this analysis fixed horizontal exterior shading decreases cooling loads when compared to un-shaded options (for North: shaded DPC = 7.8 MBtu, un-shaded DPC = 8.2 MBtu, shaded DPlow-E-E = 7.1 MBtu, un-shaded DPlow-E-E = 7.3; for South: shaded DPC = 8.4 MBtu, un-shaded DPC = 9.2 MBtu, shaded DPlow-E-E = 6.9 MBtu, un-shaded DPlow-E-E = 7.8; for East: shaded DPC = 9.6 MBtu, un-shaded DPC = 9.6 MBtu, shaded DPlow-E-E =8.1 MBtu, un-shaded DPlow-E-E = 8.1 MBtu) but increases heating loads when compared to un-shaded options (for North: shaded DPC = 9.7 MBtu, un-shaded DPC =9.4 shaded DPlow-E-E = 9.4 MBtu, un-shaded DPlow-E-E = 9.3 MBtu; for South: shaded DPC = 6.3 MBtu, un-shaded DPC = 6 MBtu, shaded DPlow-E-E = 7.3 MBtu, un-shaded DPlow-E = 7.1 MBtu ; for East: shaded DPC = 8.4 MBtu, un-shaded DPC = 7.8 MBtu, shaded DPlow-E-E =8.7 MBtu, un-shaded DPlow-E = 8.3 MBtu). Optimally shaded DPlow-E yields the lowest annual loads for space cooling, but yields the highest loads for space heating. It is also observed that for the south orientation, the impact of shading is more pronounced than for the other two orientations as it is easier to shade with the assumed horizontal shading. The shaded south orientation has lower annual cooling loads, but conversely higher annual loads for heating. Interestingly, the results show that glazing on the south orientation is the least consumptive, with total annual loads for glazing on the north and east sides approximately equal. Also, shaded DPC glazing on the south orientation has slightly less total annual energy use than unshaded DPlow-E glazing.

A.1.3.1.2 Peak cooling energy and heating energy consumption

Figure A.5 presents peak heating and cooling energy consumption values from LOADS for shaded and un-shaded DPC and DPlow-E window types on north, east, and south. Each result shows the impact of each glazing type on the selected orientation only (i.e., all other walls have no glazing).

As seen from Figure A.5, the peak cooling demands follow patterns that are similar to the annual cooling energy use, with the exception that the north-facing orientation has the lowest peak demands, the results are comparable to peak loads obtained from the other orientations. Introduction of the low-E option reduces the variations in results from different orientations as well as results from the implementation of shading. South and east orientations were the most affected by the introduction of horizontal shading, while the north orientation was most affected by the choice of glazing type.

Figure A.5 also shows peak heating loads. Peak heating demands were not significanty affected by the shading because peak heating occurs during the nighttime hours. The variation in glazing type did have a considerable impact on the peak heating loads.

A.1.3.1.3 General trends

From the above results it can be seen that cooling and heating are affected in almost equal but opposite changes from varying the shading and glazing type. It is also observed that the introduction of low-E and shading options yield to results which are less dependent on orientation.

In the case of space heating, for all the orientations, the DPC glazing option yields the lowest total heating energy consumption. While for space cooling and overall energy performance the trends favor shaded the DPlow-E glazing option. Optimally shaded DPlow-E glazing yields the lowest results for total energy consumption for all the orientations, making it the best selection. However, it is important to note that for the south orientation, the overall energy consumption results from all the options are comparable. Moreover, the optimally shaded DPC glazing option yields to lower results than the un-shaded DPlow-E option which is specified by the code. In addition, the south orientation shows a potential for reducing energy consumption by implementing the horizontally shaded DPC option. On the other hand, it is observed that the choice of glazing has a greater impact than shading on the north orientation for reducing total energy consumption. These results confirm the conclusions drawn from other studies. These studies concluded that the SHGC (which is significantly affected by the implementation of shading strategies) plays an important role in the south orientation, while the U-factor (which is significantly affected by the choice of glazing) plays an important in the north orientation. The results of the peak heating and peak cooling loads showed that both un-shaded and optimally shaded DPlow-E options of glazing perform better than the un-shaded and shaded DPC glazing options, respectively.

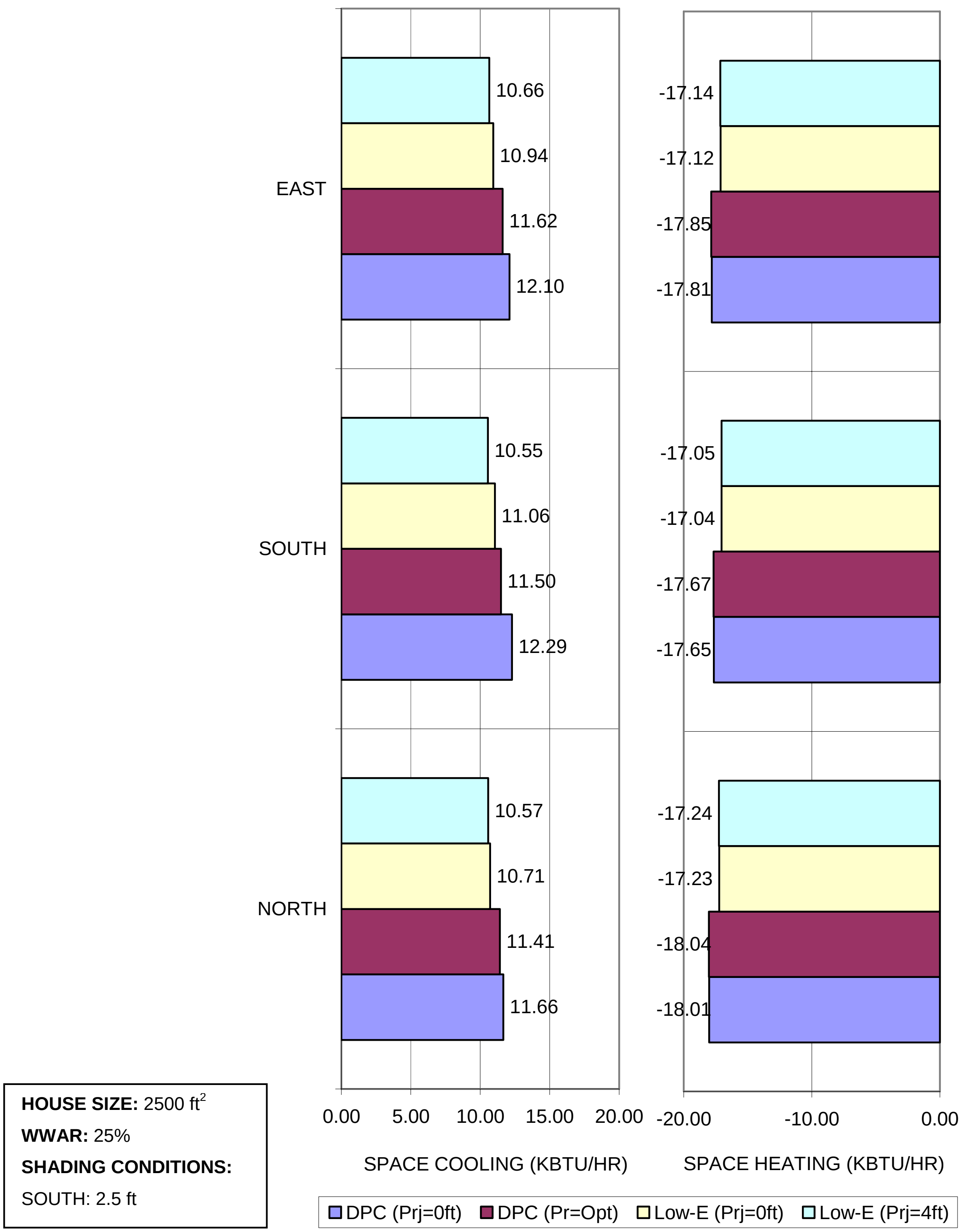


Figure A.5 Peak cooling and heating energy consumption trends: A comparison by altering window options. Peak cooling hour: August 9, 4:00PM. Peak heating hour: January 14, 11:00PM.

A.1.3.2 Varying orientation, glazing option, house size

The next step of the analysis was to extend the conclusions drawn from the previous section to different house sizes. In this section three house sizes (i.e., 1500 ft^2, 2500 ft^2, and 5000 ft^2) were considered for simulation, while the window-to-wall area ratio remained fixed at 20%. Results are graphically presented in Figure A.6 and Figure A.7.

A.1.3.2.1 Annual space heating, cooling and overall loads

When comparing the heating and cooling loads in Figure A.6, heating was more affected by change in house size than the cooling energy consumption results. The results for annual heating energy consumption were in the range of 0 to 5 MBtu for the 1500 ft^2 house, 5-10 MBtu for the 2500 ft^2 house, and 15-25 MBtu for the 5000 ft^2 house. However, cooling loads were in the range of 5-15 MBtu for all the house sizes. It was also observed that DPC glazing options were more affected by orientation than the DPlow-E options both for cooling as well as for heating. For the case of space heating, glazing options facing north yield the highest annual energy consumption with similar results being obtained from options. While glazing options facing the south yield the lowest results. However in this case, both optimally shaded and un-shaded DPC options yield lower results than the corresponding DPlow-E glazing options. While shading has no impact on the north orientation, its impact is marginally felt in the case of south and east orientation. It is also observed that the difference in the results for space heating becomes more pronounced for the 5000 ft^2 house size. However for space cooling, the lowest energy consumption results were obtained from the glazing options facing the north, while highest energy consumption levels were obtained from the glazing options facing the east. In this instance, shading has a big impact on the energy consumption for all the orientations with results becoming more distinct in the case of 5000 ft^2 house size.

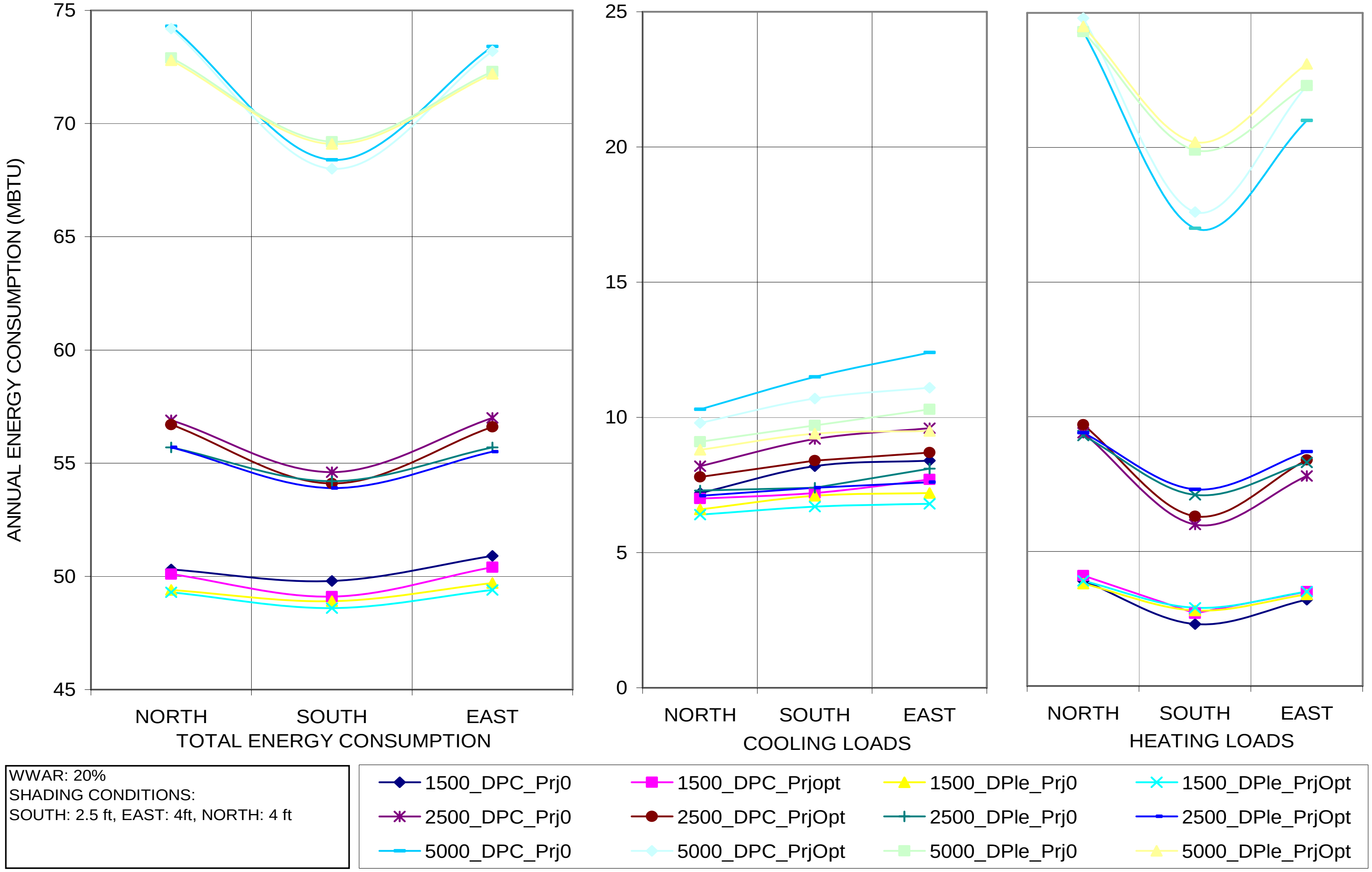


Figure A.6 Annual total, cooling and heating energy consumption comparison by varying orientation and house size

In analyzing the impact of variations in orientation for glazing options for overall energy performance, predictable trends were seen for the 1500 ft^2 house in all the cases of window-to-wall area ratios. The un-shaded DPC glazing option yielded the highest overall energy consumption results for all the orientations followed by the optimally shaded DPC glazing option, the un-shaded DPlow-E glazing option, and lastly, the optimally shaded DPlow-E glazing option. When considering the performance of a 2500 ft^2 house, a different trend begins to emerge. For north and east orientations, the DPlow-E glazing options outperform the DPC glazing options, but for the south orientation, the energy consumption patterns recorded by all the options converge. Optimally shaded DPC gazing option yields similar or marginally lower total annual use than those obtained by un shaded DPlow-E options. For the case of the 5000 ft^2 house, while for north and east orientations both the DPC glazing options are out-performed by the both the DPlow-E options. On the south orientation, energy consumption results obtained from both shaded and unshaded DPC glazing options marginally out-perform the energy consumption results obtained from both the DPlow-E glazing options.

A.1.3.2.3 Peak heating and cooling loads

Figure A.7 presents peak heating and cooling energy consumption results when provision for windows in the simulation model is given only on one particular orientation. In this analysis the purpose of this graph is to understand the impact of using various fenestration options (i.e., DPC un-shaded, DPC optimally shaded, DPlow-E un-shaded, DPlow-E optimally shaded) as well as the impact of varying the house sizes (i.e., 1500 ft^2, 2500 ft^2, 5000 ft^2) on peak energy loads for each orientation was investigated.

As seen from Figure A.7, the peak cooling loads follow patterns similar to the annual cooling loads. The choice of glazing as well as the use of optimal shading had a significant impact on the peak cooling loads. However, neither the variation in orientation nor the variation in the house size had a considerable impact on the peak cooling loads. Similar to annual heating loads, the peak heating loads were dependent on the house size and to some extent on the choice of glazing. However, neither orientation nor the implementation of optimal shading had an impact on the results.

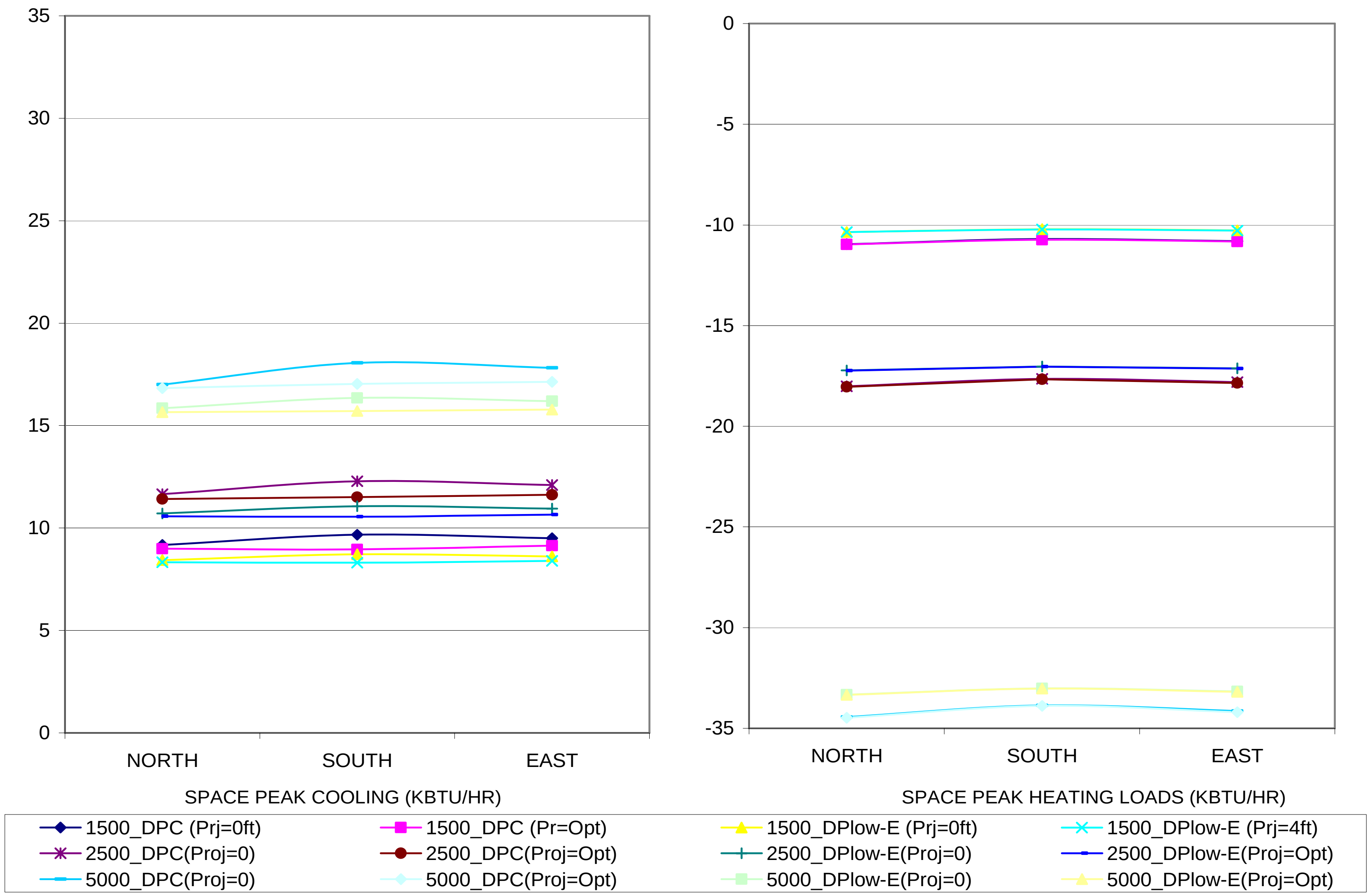


Figure A.7 Peak cooling and heating energy consumption comparison by varying orientation and house size. Peak cooling hour: August 9 at 4:00 PM Peak heating hour: January 14 at 11:00 PM

A.1.3.2.4 General trends

First, as a reminder, the simulation of the 2000 IECC with the 2001 Supplement code compliant house requires a fixed internal load that does not vary with the house size. This made smaller houses less dependent on envelope loads. The introduction of varying house size reinforces trends projected in the preceding section of this analysis by widening the range of results. It is observed that for cooling loads, the glazing type was a more significant factor affecting the energy consumption, while the house size and orientation assume secondary importance. Whereas, for space heating loads, orientation and house size were more significant factors affecting the energy consumption, with the choice of glazing type playing a secondary role.

From this analysis it was observed that annual heating energy consumption obtained from glazing options facing the south were lower than annual heating energy consumption obtained from other orientations. This difference in heating energy consumption results obtained from different orientation is especially prominent when using DPC glazing options. This trend is reflected in the overall energy consumption results. Moreover, the advantage of using the double-pane shaded option on the south orientation becomes more prominent in the case of larger house sizes (i.e., 5000 ft^2) with the overall energy consumption results obtained from the south facing windows dipping below the results obtained from the DPlow-E glazing options. These trends indicate the passive solar heat gain potential exhibited by windows facing the south which becomes more pronounced for larger houses. Again, this is because fixed internal energy loads prescribed by the IECC code makes the energy consumption from larger houses sizes more dependent on the building envelope.

In this final step of analyzing the impact of orientation on the performance of windows, the choice of glazing, WWARs, and house size was varied. Both shaded as well as un-shaded options of DPC and DPlow-E (i.e., DPC un-shaded, DPC optimally shaded, DPlow-E un-shaded, DPlow-E optimally shaded); three house sizes (i.e., 1500 ft^2, 2500 ft^2, and 5000 ft^2) and three WWAR's (i.e., 15%, 20%, and 25%) were considered for the simulation. The results are presented graphically in Figure A.6 and Figure A.7.

A.1.3.3.1 Impact of varying orientation, glazing option, house size and WWAR on annual heating, cooling, and overall energy performance

In this analysis, various window types were analysed for each orientation. The purpose of this analysis was to understand the impact of using various fenestration options, house sizes, and WWAR's on annual energy consumption for each orientation, including annual space heating, space cooling, and total energy.

Space heating for the south orientation: A decrease in heating energy consumption is observed when going from 15% to 25% WWAR. The rate of decrease becomes steeper when going from smaller to larger house sizes. For DPC glazing options, the decrease in heating energy consumption is between 10% and 15%, while for low-E options the decrease in heating energy consumption is between 5% and 10%. A distinct difference is seen in the performance of DPC and DPlow-E glazing options with both shaded and un-shaded options of DPC outperforming the shaded and un-shaded options of DPlow-E glazing options for all the three house sizes and WWARs.

Space heating for the north orientation: There is an increase in heating energy when going from smaller WWARs to larger WWARs. Up to 10% difference in heating energy consumption is observed when going from 15% to 25% WWAR, for all the house sizes as well as for both DPC and DPlow-E glazing options. The rate of increase in heating energy consumption decreases when going from a smaller house to a larger house size for all the glazing options is considered. The percentage increase for DPC options is greater than for low-E options. Shading and glazing type options do not have any substantial impact on this orientation.

Space heating for the east orientation: A small change is observed in space heating when going from small WWAR to a large WWAR for this orientation. The change is in the range of 5%. This decrease inheating energy use almost disappears entirely for smaller houses. Here too, DPlow-E glazing options yield to less differences than DPC glazing options.

Space cooling for the south orientation: An increase in cooling energy consumption is observed when going from 15% to 25% WWAR. The rate of increase becomes larger when going from smaller to bigger house sizes. For the DPC glazing options the increase is between 15% and 20%, while for the

DPlow-E options the increase is within 5% to 10%. The un-shaded DPC glazing option yields to highest cooling energy consumption levels, while the shaded DPC glazing option performs comparably to the un-shaded DPlow-E glazing option. However, the shaded DPlow-E glazing option yields to lowest cooling energy consumption levels.

Space cooling for the north orientation: The rate of increase in the north orientation is not as pronounced as it is in the south and east orientations. The percentage increase for the DPC glazing options is greater than for the DPlow-E glazing options. For the DPC glazing options, the percentage difference is usually within 10% to 15%. While for the DPlow-E glazing options the percentage difference is within 10%. The DPlow-E options perform better than the DPC glazing options.

Space cooling for the east orientation: This orientation shows the maximum variation in cooling loads due to the change in the WWAR, with differences in annual cooling energy consumption of 20%. Here too, the DPlow-E glazing options perform better than the DPC glazing options. The use of shading has a large impact on the DPC glazing option, while the impact on the DPlow-E glazing options is not as pronounced.

Total energy consumption for the south: On an overall basis the south orientation yields the lowest total energy use. The results are more distinct for the 5000 sqft house, with shaded options performing better than un-shaded options. For the 1500 ft^2 and the 2500 ft^2 size of house, the optimally shaded DPlow-E glazing option yields the lowest results. However, for the 5000 ft^2 house, shaded DPC yields the lowest results. There is a marginal increase in total energy consumption when going from 15% to 25% for the 1500 ft^2 and the 2500 ft^2 house. However, there is a decrease in the total energy consumption in the case of 5000 ft^2 house. This difference in overall energy consumption is in the range of 1-2%.

Total energy consumption loads for the north and east orientation: Shading does not seem to impact the energy consumption on the north orientation, although the energy consumption seems to decrease slightly, while the choice glazing option brings down the total energy consumption by 1-2% for all house sizes. The change in the choice of glazing brings down the total consumption by up to 2%. Similarly for the east, shading doesn’t really play an important role in the total energy consumption.

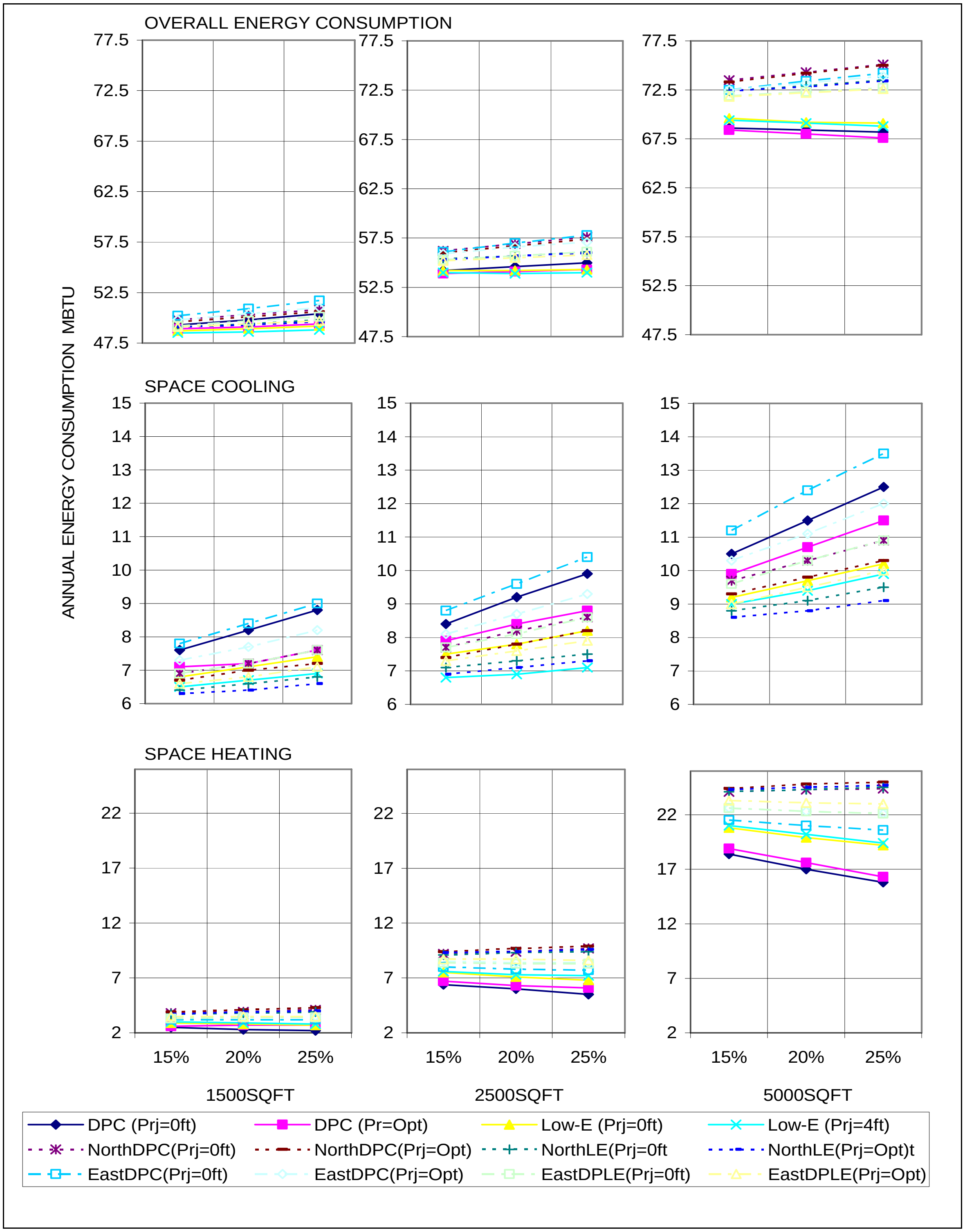


Figure A.8 Annual total cooling and heating energy consumption comparison by variation in orientation, house size, WWAR and glazing type

A.1.3.3.2 General trends

For space heating, it is observed that the south-facing, un-shaded DPC glazing option is the best performing window for all three house sizes and all WWARs. While for the north facing orientation the optimally shaded DPC glazing option is the worst performing option. For the case of space cooling, it is observed that the east-facing, un-shaded DPC option is the worst performing window for all the three house sizes and all WWARs. Its performance is closely followed by the un-shaded south facing DPC. While the north facing windows yields the lowest energy consumption rates. The optimally shaded, DPlow-E glazing option is the best performing glazing option.

When considering the overall energy performance results it is observed that for 1500 ft^2, the un-shaded east facing DPC glazing option yields to highest results, while the optimally shaded south facing DPlow-E glazing option yields to lowest results. For 2500 ft^2 house, energy consumption results from the south facing windows are distinctly better than energy consumption results from other orientations. The un-shaded east facing DPC glazing options still yields to highest overall energy consumption results while the south facing optimally shaded DPlow-E glazing option yields to lowest overall energy consumption results. For the case of 5000 ft^2 house a change in trends is observed. The north facing DPC glazing options yield the highest results while the south facing DPC glazing options yields the lowest results. The trends observed from this analysis encourage bigger openings on south orientation. Also, it is observed that for the case of a 5000 ft^2 house, the optimally shaded DPC glazing option when used on the south orientation yields to minimum results. This observation reinforces the hypothesis of the study which states that the use of the optimally shaded DPC glazing instead of glazing options specified by the code can perform just as well.

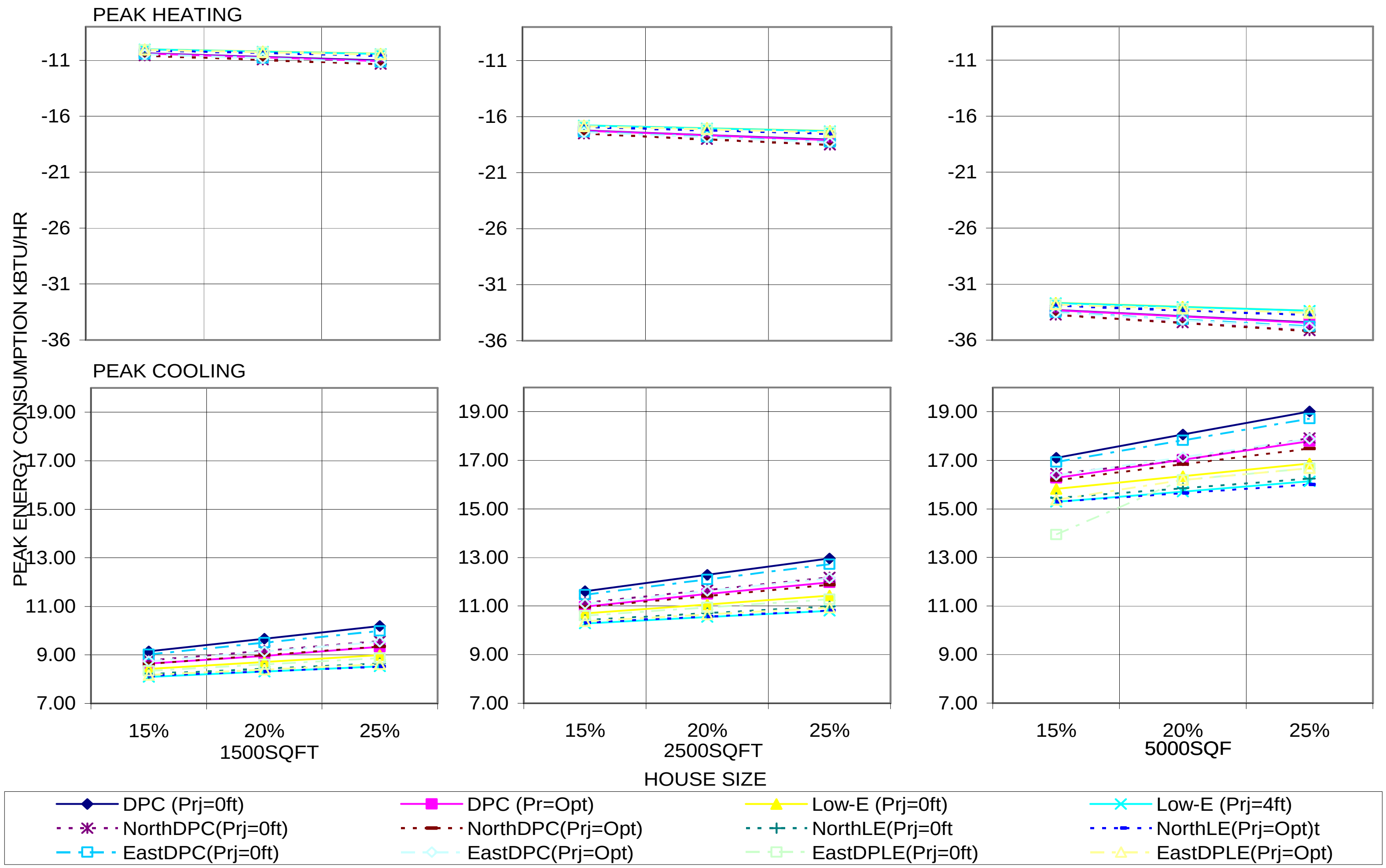


Figure A.9 Peak energy consumption loads. Peak cooling hour: August 9 at 4:00 PM. Peak heating hour: January 14 at 11:00 PM

A.1.3.3.3 Peak energy consumption loads

Figure A.9 presents peak heating and cooling energy consumption values when the provision for windows in the simulation model is given only on one particular orientation. Here too, the purpose of this graph is to understand the impact of using various fenestration options (i.e., DPC un-shaded, DPC optimally shaded, DPlow-E un-shaded, DPlow-E optimally shaded), the impact of varying the house sizes (i.e., 1500 ft^2, 2500 ft^2, 5000 ft^2) as well as the impact of varying WWAR (i.e., 15%, 20%, 25%) on peak heating and cooling loads for each orientation.

In the case of peak cooling load results, for north orientation optimal horizontal shading does not make much of an impact. A difference of up to 2.5% is observed in the peak energy loads when going from un-shaded to shaded DPC glazing options. The performance of the DPLow-E options show even less difference in the cooling energy consumption results. Results imply that choice of glazing makes a significant impact on the peak cooling loads in this orientation. While up to 10% reduction in peak cooling loads is observed when going from one glazing type to another. Results of peak cooling loads for east orientation show that both shading as well as the choice of glazing makes a significant impact on peak cooling loads in this orientation. In the case of double pane clear glazing, switching from un-shaded to shaded option saves up to 4.5%, while for the DPlow-E option saving associated with this switch are slightly lower with 3.5% difference in peak loads consumption for all the house sizes. When going from un-shaded DPC to shaded DPlow-E, saving up to 11% are observed. On analyzing peak cooling loads results for south orientation, substantial reductions are seen due to implementation of shading. Up to 6-8% savings are recorded when going from un-shaded to shaded options for both DPC glazing option as well as DPlow-E glazing options.

For the case of peak heating loads results for all the three orientations, there is no significant impact from shading as peak heating loads occur during night time hours. Change in glazing options affects the peak heating load significantly. For north orientation the percentage difference recorded in the 1500 ft^2 house when going from one option to another is up to 7%, while for the 5000 ft^2 house the percentage difference is up to 4%. Similar trends are reported for south and east orientations. Impact of WWAR for peak heating as well as peak cooling is a maximum for the 1500 ft^2 house with up to a 10%

difference achieved when going from 15% to 25% WWAR and minimum for 5000 ft^2 house with up to 5% difference achieved when going from 15% to 25%.

A,1.3.3.4 General trends

For all cases of peak cooling, energy consumption increases when going from 15% to 25% WWAR, the rate of increase becoming steeper for bigger house sizes (i.e., 5000 ft^2). South facing un-shaded DPC glazing option performs the worst yielding to highest peak cooling energy loads. While south facing optimally shaded DPlow-E glazing option performs the best yielding the lowest cooling energy loads.

For all the cases of peak heating, peak heating consumption decreases when going from 15% to 25% WWAR, the rate of decrease becomes steeper in the case of 5000 ft^2 house. While the DPC glazing option on north orientation performs the worst yielding to highest peak heating energy, the DPlow-E glazing option on the south orientation performs the best.

A.1.4 Comparing the implementation of alternate options to specifications outlined in the code

In the previous section, conclusions were drawn from the results which were specific to each orientation. Recommendations were made accordingly. In this section, these recommendations are combined into a single simulation model and are compared to the specifications laid down in the IECC.

It is also seen in the previous section, BEPS analysis of south orientation showed that the WWAR for both the DPC and DPlow-E glazing options when used in conjunction with horizontal shading could be optimized to minimize energy consumption. For this purpose a number of simulation runs are carried out in which the both the shading as well as WWAR were varied to optimize energy consumption. It is observed that varying the WWAR and shading for 1500 ft^2 and 2500 ft^2 house sizes results in linear trends for energy consumption, whereas in the case of 5000 ft^2 house curvilinear trends for energy consumption are observed. Optimum values for shading and WWAR for the south orientation are summarized in Table A.3. The optimum specifications for the 5000 ft^2 house size are used as the basis in subsequent calculations for overall performance results which are reported in the discussion for this section.

Table A.3 Optimum horizontal shading and WWAR for south orientation. Glazing options: DPC and DPlow-E; House size options: 1500ft^2, 2500 ft^2, 5000 ft^2

WINDOW/GLAZING OPTIONS	OPT SHADING (if applicable)	OPT WWAR %
Un shaded DPC		For 1500sqft: 5% For 2500sqft: 10% For 5000sqft: 25%
Optimally shaded DPC	4 4 4	For 1500sqft: 5% For 2500sqft: 10% For 5000sqft: 30%
Un shaded low-E		For 1500sqft: 5% For 2500sqft: 5% For 5000sqft: 30%
Optimally shaded low-E	4 4 4	For 1500sqft: 5% For 2500sqft: 20% For 5000sqft: 45%

In order to analyze the impact of using alternate shading and glazing strategies to the ones specified in the IECC, 4 cases are being compared. They are:

- Case 1: DPC (Proj = Opt) on all orientations,
- Case 2: Low-E (Proj = Opt) on all orientations,
- COM1: DPC glazing with optimal horizontal shading on the south orientation. The other orientations have optimally shaded DPlow-E glazing.
- COM2: A fixed WWAR of 30% along with optimally shaded DPC glazing with an overhang of 2.5 ft on the south orientation.

These options are compared against 3 base-cases, details of which are described in Table 4.6 of this report:

- Base-case II which is a building prototype model using custom weighting factors and WINDOW-5 library. This model implements the use of un-shaded DPlow-E glazing for fenestration.
- Base-case II implementing the use of un-shaded DPC glazing for fenestration (This case is considered in order to establish the upper boundary of the simulation model's energy performance).
- Base-case III which is a code compliant house with 18% window to floor area ratio and is presented as the grey shaded area on each graph. This window to floor area ratio is a requirement

in Chapter 4 of the IECC which is used to compare the whole building energy performance of the proposed designs against a standard residential building simulation model.

Results are graphically presented in Figure A.10 and Figure A.11. Both annual loads as well as peak loads are analyzed.

A.1.4.1 Space heating

As seen from graphs presenting space heating in Figure A.10, not much of an impact is felt by choice of glazing or shading strategies in either the 1500 ft^2 or the 2500 ft^2 house. Choice of glazing makes a substantial impact in the case of 5000 ft^2 house with un-shaded DPC glazing option yielding the lowest results, while optimally shaded DPlow-E glazing option yields the highest results. Results obtained from COM1 are comparable to optimally shaded DPC glazing option, while COM2 projects the lowest results.

A.1.4.2 Space cooling

As seen from graphs presenting space cooling in Figure A.10, choice of glazing has a considerable impact in the case of cooling loads. The impact is augmented on going from 1500 ft^2 house size to 5000 ft^2 house size. For all the cases of WWAR and house sizes the DPC glazing options yield the higher results. Whereas DPlow-E options along with COM1 and COM2 option performs marginally better than the code specifications. Performance of COM1 option is marginally lower than un-shaded DPlow-E option. Although the performance of COM2 is slightly higher than un-shaded low-E option for 15% and 20% GWAR, its performance is comparable to un-shaded DPlow-E option for 25% GWAR. Lowest energy performance is recorded by the optimally shaded low-E option for all the house sizes and WWARs.

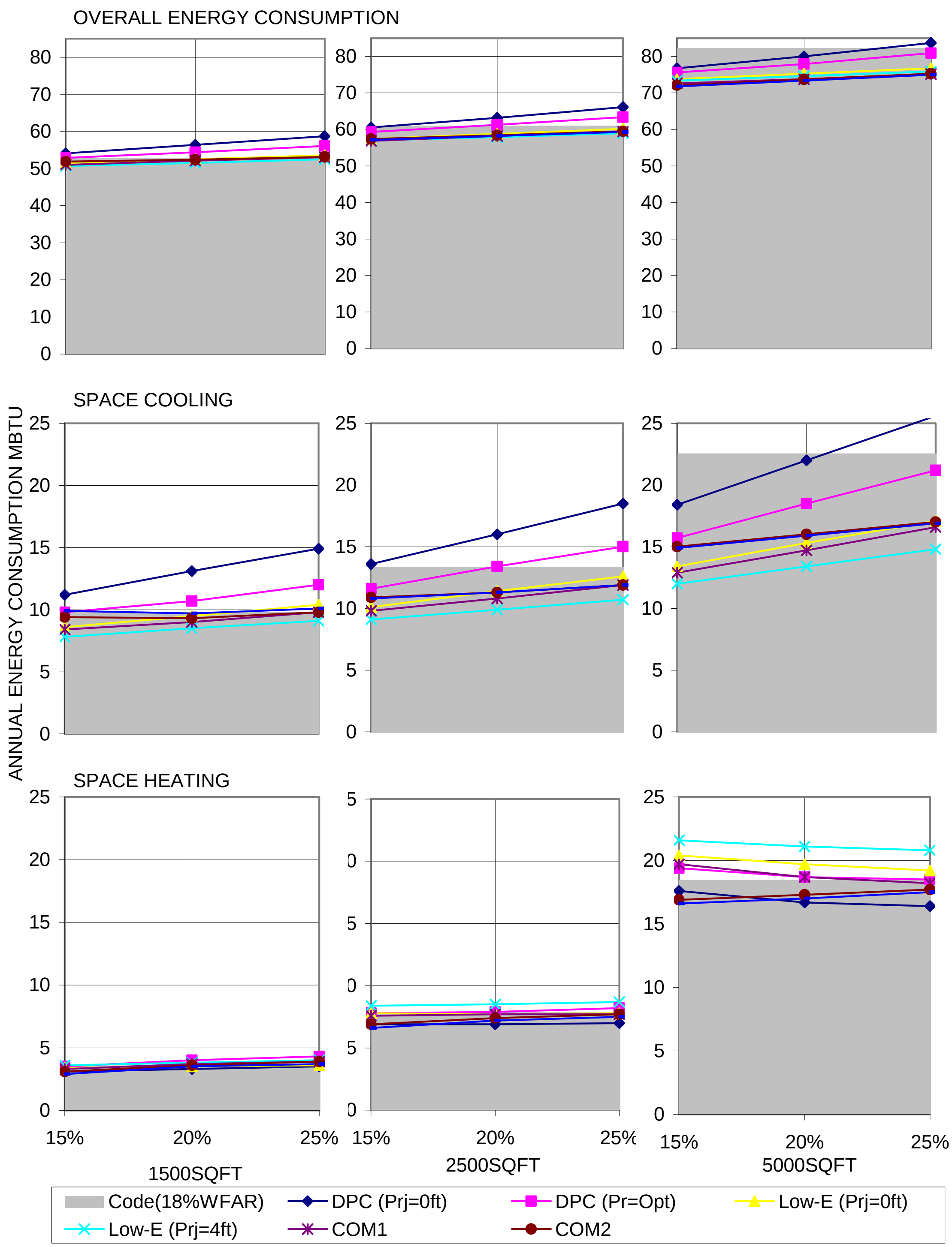


Figure A.10 Overall performance of glazing options

A.1.4.3 Overall BEPS

As seen from graphs presenting overall energy consumption in Figure A.10, overall BEPS performance follows the trends set by space cooling results. It is observed that choice of glazing as well as shading makes a substantial impact on the overall energy consumption. While a substantial difference is observed in the results from BEPS report of un-shaded and optimally shaded DPC glazing option, results from other options i.e., both options of DPlow-E glazing option, COM1and COM2 are comparable to each other. While optimally shaded DPlow-E glazing option yields the lowest results for 1500 ft^2 and 2500 ft^2 house sizes, COM1 and COM2 yield to lowest results for 5000 ft^2 house size.

It is observed that the performance of COM1 and COM2 can be compared to un-shaded DPlow-E glazing option. For the 1500ft^2 option, COM1 performs marginally better than the un-shaded DPlow-E glazing option for all the cases of WWAR. While COM2 yields to marginally higher results for 15% WWAR, the option records lower results for 20% and 25% WWAR. Optimally shaded DPlow-E glazing option yields to lowest results for all the WWAR options. Similar trends are seen in the case of 2500 ft^2 house. Overall the difference in results due to choice of glazing increases when going from 15% to 25% WWAR. While in the case of 5000 ft^2, both COM1 and 2 outperform the other glazing options.

When compared to the limit set by the code based on a performance of 18% window to floor area ratio, it is seen that the code imposes more stringent conditions for smaller houses with larger WWARs. This is demonstrated in the case of 1500 ft^2 house in which case only DPow-E glazing options qualify. However, the conditions are less stringent in the case of bigger houses which can be seen in the case of the 5000 ft^2 house. In this case, almost all the glazing options yield lower values than that specified by the code.

A.1.4.4 Overall peak heating loads

As seen from the graphs for overall peak heating loads in Figure A.11 minor differences are seen for peak heating load results for the different glazing options implemented. Also, not much change for heating loads is recorded when going from lower glazing to wall area ratios to higher glazing to wall area ratios. Differences in peak heating loads increase to a slight degree when going from smaller house size to a bigger house size.

In comparing against the 18% WFAR specifications laid down by the code, when looking at 1500 ft^2 house size both the DPC glazing options as well as unshaded DPlow-E option perform better than the code specifications for all the WWARs. While for 25% WWAR the code specifications yield better results than DPlow-E, COM-1 and COM-2. While for the 2500 ft^2 as well as for the $5000ft^2$ house all the options yield lower results than the results obtained from the code specifications.

A.1.4.5 Overall peak cooling loads

For the case of smaller houses the choice of glazing has a moderate impact on peak loads with un-shaded DPC yielding to highest results and optimally shaded low-E yielding to lowest results for all glazing to wall area ratios. Differences in results from peak cooling obtained from different options increase with the increase in house size although the trend remains the same with un-shaded DPC yielding to highest peak loads while optimally shaded low-E yields to lowest peak loads.

A decrease in hourly peak cooling loads is observed when going from un-shaded to shaded options of both DPC as well as Low-E glazing types reinforcing the conclusions drawn from literature review regarding the effectiveness of shading devices in reducing peak cooling loads. But the effectiveness of shaded DPC as compared to un-shaded low-E option is not observed. Also results from COM-1 and COM-2 options are comparable to the results from DPlow-E options.

When comparing results from various options implemented against the code specified option of 18% window to floor area ratio, trends similar to results from annual energy consumption are observed. It is seen that the limit to peak cooling loads created by the 18% option is more stringent for smaller floor areas as demonstrated in the case of 1500sqft. Also, the stringency increases with glazing to wall area ratios. While in the case of 5000 ft^2, almost all the options outperform the peak loads set by 18% floor to wall area ratio.

The COM-1 and COM-2 options yield to results which are comparable to the results obtained from both shaded and un-shaded DPlow-E options.

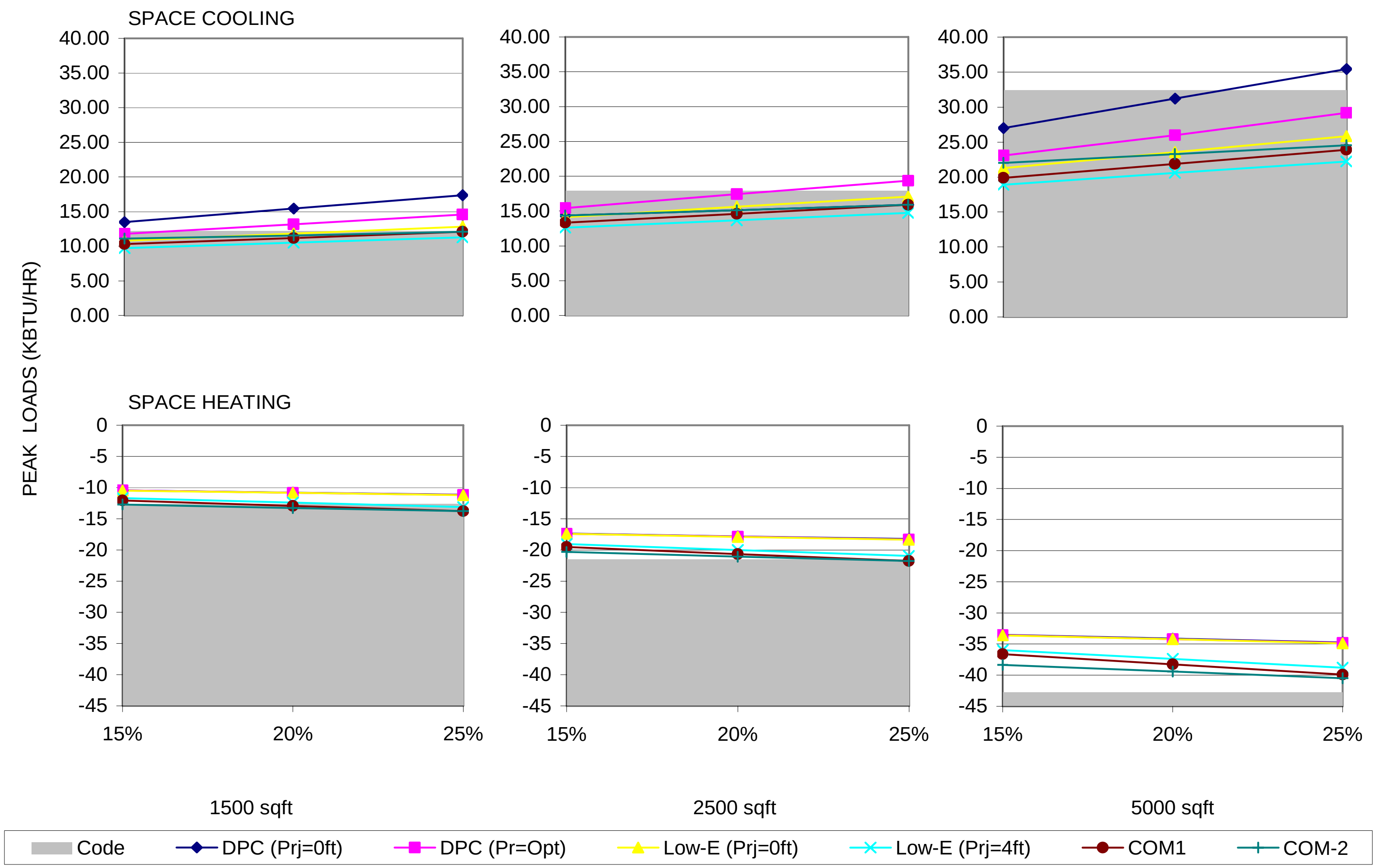


Figure A.11 Peak heating and cooling loads Peak cooling hour: August 9 at 4:00 PM. Peak heating hour: January 14 at 11:00 PM

A.1.4.6 General trends

Several broad conclusions can be drawn from observing the trends projected in the above section. It is seen that for all the house sizes, COM1 and COM2 perform marginally better than the specified DPlow-E glazing option. This trend especially becomes evident in case of the 5000ft^2 house. This trend makes both these options viable alternatives to the current code specifications.

Also observed was that the 18% WFAR specification specified by the code was less stringent for bigger houses implying more flexibility in the use of glazing for bigger houses.

A.1.5 Summary and conclusions

This section compares the options of using horizontal shading strategies in combination with DPC glazing option with the specifications for fenestration laid down by the IECC building energ y code, which usually points to the use of un-shaded DPlow-E glazing option. Dependence on orientation, house size and WWAR in the selection of optimum shading and glazing is examined.

In the first step, the impact of glazing and shading options on individual orientations was analyzed. Observations indicate that orientation specific variations in glazing and shading options play a significant role in optimizing energy consumption. While reduction in energy consumption for north orientations was dictated by the choice of glazing, optimum implementation of shading strategies on east and south orientations significantly contributed in dictating resultant energy consumption patterns. It is also observed that south orientation exhibits a significant potential to reduce energy consumption by implementing the alternate shading and glazing strategies which were not necessarily in adherence to energy code specifications.

Accordingly, the second step involved the identification of such alternate strategies for south orientation and examining the impact of using these strategies on overall energy consumption of the simulated house. In this case glazing on all four orientations was considered. It was concluded that orientation specific optimal shading strategies, choice of glazing and optimized GWAR amounts to results which are comparable to or in the case of 5000 ft^2 house lower than the specifications laid down by the building energy code. This finding reinforces the hypothesis assumed by this study which states that shading in combination with less efficient glazing when strategically used can be comparable to using higher efficiency glazing specified in the IECC.

It is also observed a set of choices performs well for either heating or cooling conditions but never for both conditions. This leads the study to consider the option of dynamic glazing which changes properties according to seasonal variations and requirements. This option although hypothetical in nature could generate a discussion on the future of fenestration specifications in building energy codes and is duly considered in the next section.

APPENDIX B

PERFORMANCE OF HIGH-PERFORMANCE GLAZING IN IECC COMPLAINT BUILDING SIMULATION MODEL

This section of the study was set to explore various practical and hypothetical high performance alternatives of glazing strategies which could be available in the future to reduce energy consumption. The concept of 'zero-energy' fenestration, which is achieved by installing practical as well as hypothetical high performance glazing and a reinterpretation of the current IECC code form the basis of this section.

B.1 Impact of high performance glazing options on energy performance

The previously reviewed study conducted by Apte et al. (2001) discussed the performance of high performance glazing which will be adapted for analysis in this section. A number of high-performance glazing options were selected based on their performance in cooling dominated climate of Houston, Texas. Also considered are hypothetical options of 'dynamic' glazing which switch thermal properties depending upon environmental conditions.

B.2.1 Choosing a set of options for dynamic glazing

There are several methods by which dynamic glazing can be simulated in DOE-2.1e. These are discussed in Appendix G. The method chosen by this study is the 'Switchable glazing' method in which the glazing changes properties when subjected to a change in environmental conditions (Figure B.1).

```
CLEAR-IG-1  = GLASS-TYPE
              GLASS-TYPE-CODE = 2003  ..
TINTED-IG-1 = GLASS-TYPE
              GLASS-TYPE-CODE = 2203  ..
SUMMER-1    =  SCHEDULE THRU MAY 31 (ALL)(1,24)(0)
              THRU SEP 30  (ALL)(1,24)(1)
              THRU DEC 31 (ALL)(1,24)(0)
WIN-1       =  WINDOW
              GLASS-TYPE = CLEAR-IG-1
              GLASS-TYPE-SW = TINTED-IG-1
              SWITCH-CONTROL = TOT-SOL-INC
              SWITCH-SET-LO = 20
              SWITCH-SET-HI = 100
              SWITCH-SCH = SUMMER-1
```

Figure B.1 Sample DOE-2.1e input code for switchable glazing (Source:LBNL 1993a)

B.1.1.1 Choosing the type of switching schedule for dynamic glazing

Several options are available to set the switching schedule for the glazing pairs. Table B.1 provides a list of possible options that can be selected to activate the switching schedule in the DOE-2.1e program

Table B.1 List of options for switching schedule (Source: LBNL 1993a)

NO-SWITCH	No switching
DIR-SOL-INC	Direct solar incident on the glazing, after shading
TOT-SOL-INC	Total solar radiation incident on the glazing after shading
DIR-SOL-TR	Direct solar radiation transmitted by the glazing in an unswitched state
TOT-SOL-TR	Total solar radiation transmitted by the glazing in an unswitched state
TOT-SOL-HOR	Total solar radiation incident on an unobstructed horizontal plane
OUTSIDE-TEMP	Outside drybulb temperature
SPACE-LOAD	Previous-hour thermal load per square foot area of space that contains the window
DAYLIGHT-LEVEL	The visible transmittance of the glazing is adjusted continuously between the values of the two glazing options input in order to provide a daylight illuminance that is as close as possible to the illuminance set point at the first daylight reference point

From the above mentioned choices, the OUTSIDE-TEMP option was considered most appropriate as it was found to be the most sensitive to the acceptance or rejection of solar loads in the space.

B.1.1.2 Optimizing the switching temperature

The high solar option of glass type is selected for the un-switched state while a low solar counter path is selected for the switched state. A switching temperature controls the switch from unswitched to switched state. When the ambient temperature is above this point, the low-solar option gets activated. A series of runs were carried out by varying the switching temperature from 55F to 75F in order to establish an optimum switching temperature for each house size and window-to-wall area ratio. Table B.2 summarizes the results of the runs for the three house sizes selected:

Table B.2 Optimum switching temperature for the three house sizes selected

House size (Sqft)	Optimum switching temperature
1500	**63**
2500	**67**
5000	**73**

B.1.1.3 Optimizing the switching schedule

DOE-2.1e provides a switch to activate/deactivate the switching schedule. A set of simulations were run to optimize the period in which the switching schedule would be activated in order to maximize the benefits of switching the glazing properties. Table B.3 summarizes the results of these simulation runs. The switching schedule is either turned on (i.e., All year = 1), or off (i.e., All year = 0) through out the year, or is turned on during selected months of the year (i.e., Dec-Jan = 0; Feb-Nov = 1). Results are presented in terms of annual heating, annual cooling and overall annual energy consumption from BEPS report extracted from the simulation runs. It was found that the maximum benefit was obtained with a switching schedule turned-on all through the year.

Table B.3 Optimizing the switching schedule

Switching schedule	BEPS (MMBtu)		
	Heating energy consumption	**Cooling energy consumption**	**Overall energy consumption**
All year = 0	2	12.5	54.2
All year = 1	2.3	8.4	50.01
Dec-Jan = 0 Feb-Nov =1	2.1	8.9	50.36

B.1.1.4 Optimizing shading coefficient and conduction schedules

While it was possible to achieve window systems with suitable SHGCs, it was not possible to locate corresponding low U-factors associated with high performance glazing in the WINDOW-5 library which this study uses to simulate high performance glazing. Therefore, the conduction schedule needed to be adjusted to obtain the desired results. In order for the conduction schedule to be activated, a certain number other than "1" needs to be defined in the corresponding Shading Coefficient schedule. After some investigation "1.001" was found to have a negligible effect on the glazing performance while at the same time activating the conduction schedule. The procedure of assigning the schedules in the DOE-2 input code is shown in Figure B.2. In order to be activated, the conduction schedule was set on a minimum temperature basis which is equal to the optimum switching temperature. When the ambient temperature dips below the assigned minimum temperature, the conduction schedule gets switched on. The U-factor multipliers for switchable glazing are given in Table B.4:

Table B.4 U-factor multipliers for switchable glazing

Glazing option	U-factor multiplier
All year = 0	
All year = 1	

B.1.1.5 Resultant DOE2.1e input code

```
P-SWITCHTEMP = 65                                   $ IN THIS EXAMPLE THE OPTIMUM
                                                    $ SWITCHING TEMPERATURE IS SET AT
                                                    $ 65oF

ALLYEAR-1    =  SCHEDULE THRU DEC 31 (ALL)(1,24)(1) ..

SC-MULT-1    =  SCHEDULE THRU DEC 31 (ALL)(1,24)(1.001)   ..
COND-MULT-1  =  SCHEDULE THRU DEC 31 (ALL)(1,24)(.86)  ..
COND-TMIN-1  =  SCHEDULE THRU DEC 31 (ALL)(1,24)(P-SWITCHTEMP) ..

W-F-1        = WINDOW
               GLASS-TYPE = W-1
               GLASS-TYPE-SW = W-2

               SWITCH-CONTROL = OUTSIDE-TEMP
               SWITCH-SET-LO = P-SWITCHTEMP[]
               SWITCH-SET-HI = P-SWITCHTEMP[]
               SWITCH-SCH = ALLYEAR-1

               WIN-SHADE-TYPE = MOVABLE-EXTERIOR
               SHADING-SCHEDULE = SC-MULT-1
               CONDUCT-SCHEDULE = COND-MULT-1
               CONDUCT-TMIN-SCH = COND-TMIN-1
```

Note: Switching control is in effect only during sun up hours. It does not work at night.

Figure B.2 Resultant DOE-2.1e input code as used in the simulation runs

B.1.1.6 Selection of high performance glazing

Six glazing options were selected for this set of simulations to represent a range of current and potential window types. An attempt was made to simulate window options which could be practically assembled. The first option is a base-case model, which is currently implemented by the IECC (CODE). The next three options i.e low-E low-solar (LELS), super low-E low-solar (SULS) and ultra low-E low-solar (ULLS) represent a range of currently available high performance windows used in residential construction. The last two options i.e., the dynamic windows represent a range of next generation products. These windows are assumed to have the heating season performance of a high gain super window and the cooling season performance of the low gain super window. A detailed description of the properties of the high-performance glazing selected is given in Table B.5 and Table B.6 below:

Table B.5 Description of glazing alternates used in the simulation: Part A

Glazing Type	Code name	Description	Specifications (Center of glass)	Product / input code description	W-5 code	U-factor Multipliers
BASE CASE Low-E glazing		Double glazing with low-E coating on clear glass	U = 0. SHGC = 0.4 SC = VT =	Exterior lite: Comfort TiAC on clear/ AGF Industries Gap1: Air 1/2 inch Interior lite: Clear glass (¼ inch)	2661	
Low-E low-solar	**LELS**	Double glazing with low-solar gain low-E coating on spectrally selective tinted glass	U = 0.29 SHGC = 0.29 SC= VT = 0.573	Exterior lite: Silver Hi%T low-E on green Gap: Air ½ inch Interior lite: Clear glass (¼ inch)	8004	
Super low-solar	**SULS**	Triple glazing with low-e coating on exterior glazing and low-e coating on plastic film	U = 0.123 SHGC = 0.284 SC = 0.32 VT = 0.521	Exterior lite: Comfort TiAC on clear/ AGF Industries Gap1: Krypton 1/4 inch Film1: Heat mirror, single coat suspended film/ Southwall Technologies Gap2: Krypton 1/4 inch Interior lite: Clear glass (¼ inch)	8002	

Dynamic super low-solar	**DySULS**	Triple glazing with low-e coating on exterior glazing and low-e coating on plastic film.
		
		Minimum set temperature used to regulate switching temperature. Defined in the input file as: P-SWITCHTEMP[]
		
		Conductance property of high solar option of glazing adjusted to yield lower results.
			U = 0.191
			SHGC = 0.615
			SC = 0.709
			VT = 0.718
				Exterior lite: Starphir / PPG Industries
				Gap1: Krypton 1/4 inch
				Film1: Heat mirror, twin coat 88 suspended film/ Southwall Tech
				Gap2: Krypton 1/4 inch
				Interior lite: Clear glass (¼ inch)
				`P-SWITCHTEMP = USER INPUT`
				`ALLYEAR-1 = SCHEDULE THRU DEC 31 (ALL)(1,24)(1) ..`
				`SC-MULT-1 = SCHEDULE THRU DEC 31 (ALL)(1,24)(1.001) ..`
				`COND-MULT-1 = SCHEDULE THRU DEC 31 (ALL)(1,24)(.86) ..`
				`COND-TMIN-1 = SCHEDULE THRU DEC 31 (ALL)(1,24)(P-SWITCHTEMP) ..`
				`W-F-1 = WINDOW`
				`GLASS-TYPE = W-1 GLASS-TYPE-SW = W-2`
				`SWITCH-CONTROL = OUTSIDE-TEMP`
				`SWITCH-SET-LO = P-SWITCHTEMP[]`
				`SWITCH-SET-HI = P-SWITCHTEMP[]`
				`SWITCH-SCH = ALLYEAR-1`
				`WIN-SHADE-TYPE = MOVABLE-EXTERIOR`
				`SHADING-SCHEDULE = SC-MULT-1`
				`CONDUCT-SCHEDULE = COND-MULT-1`
				`CONDUCT-TMIN-SCH = COND-TMIN-1`
					8002-03	0.64

Note: WINDOW-5 output reports of the selected windows are given in Appendix G.

Table B.6 Description of glazing alternates used in the simulation: Part B

Glazing Type	Code name	Description	Specifications (Center of glass)	Product / input code description	W-5 code	U-factor Multipliers
Ultra low solar	**ULLS**	Quadruple glazing with exterior low-e glazing and low-E coating applied to 2 suspended plastic films	U = 0.085 SHGC = 0.230 SC = 0.265 VT = 0.407	Exterior lite: Silver Hi%T low-E on green Gap1: Krypton 1/4 inch Film1: Heat mirror, single coat suspended film/ Southwall Technologies Gap2: Krypton 1/4 inch Film2: Heat mirror, single coat suspended film/ Southwall Technologies Gap3: Krypton 1/4 inch Interior lite: Clear glass (¼ inch)	8001	

Dynamic ultra low solar	**DyULLS**	Quadruple glazing with exterior low-e glazing and low-E coating applied to 2 suspended plastic films
		
		Minimum set temperature used to regulate switching temperature. Defined in the input file as: P-SWITCHTEMP[]
		
		Conductance property of high solar option of glazing adjusted to yield lower results.
			U = 0.122
			SHGC = 0.531
			SC = 0.612
			VT = 0.661
				Exterior lite: Starphir / PPG Industries
				Gap1: Krypton 1/4 inch
				Film1: Heat mirror, twin coat 88 suspended film/ Southwall Technologies
				Gap2: Krypton 1/4 inch
				Film2: Heat mirror, twin coat 88 suspended film/ Southwall Technologies
				Gap3: Krypton 1/4 inch
				Interior lite: Clear glass (¼ inch)
				`P-SWITCHTEMP = USER INPUT`
				`ALLYEAR-1 = SCHEDULE THRU DEC 31 (ALL)(1,24)(1) ..`
				`SC-MULT-1 = SCHEDULE THRU DEC 31 (ALL)(1,24)(1.001) ..`
				`COND-MULT-1 = SCHEDULE THRU DEC 31 (ALL)(1,24)(.45) ..`
				`COND-TMIN-1 = SCHEDULE THRU DEC 31 (ALL)(1,24)(P-SWITCHTEMP) ..`
				`W-F-1 = WINDOW`
				`GLASS-TYPE = W-1 GLASS-TYPE-SW = W-2`
				`SWITCH-CONTROL = OUTSIDE-TEMP`
				`SWITCH-SET-LO = P-SWITCHTEMP[]`
				`SWITCH-SET-HI = P-SWITCHTEMP[]`
				`SWITCH-SCH = ALLYEAR-1`
				`WIN-SHADE-TYPE = MOVABLE-EXTERIOR`
				`VIS-TRANS-SCH = TVIS-SCH-1`
				`SHADING-SCHEDULE = SC-MULT-1`
				`CONDUCT-SCHEDULE = COND-MULT-1`
				`CONDUCT-TMIN-SCH = COND-TMIN-1`
					8000-01	0.69

B.1.2 Hourly performance of selected high-performance fenestration

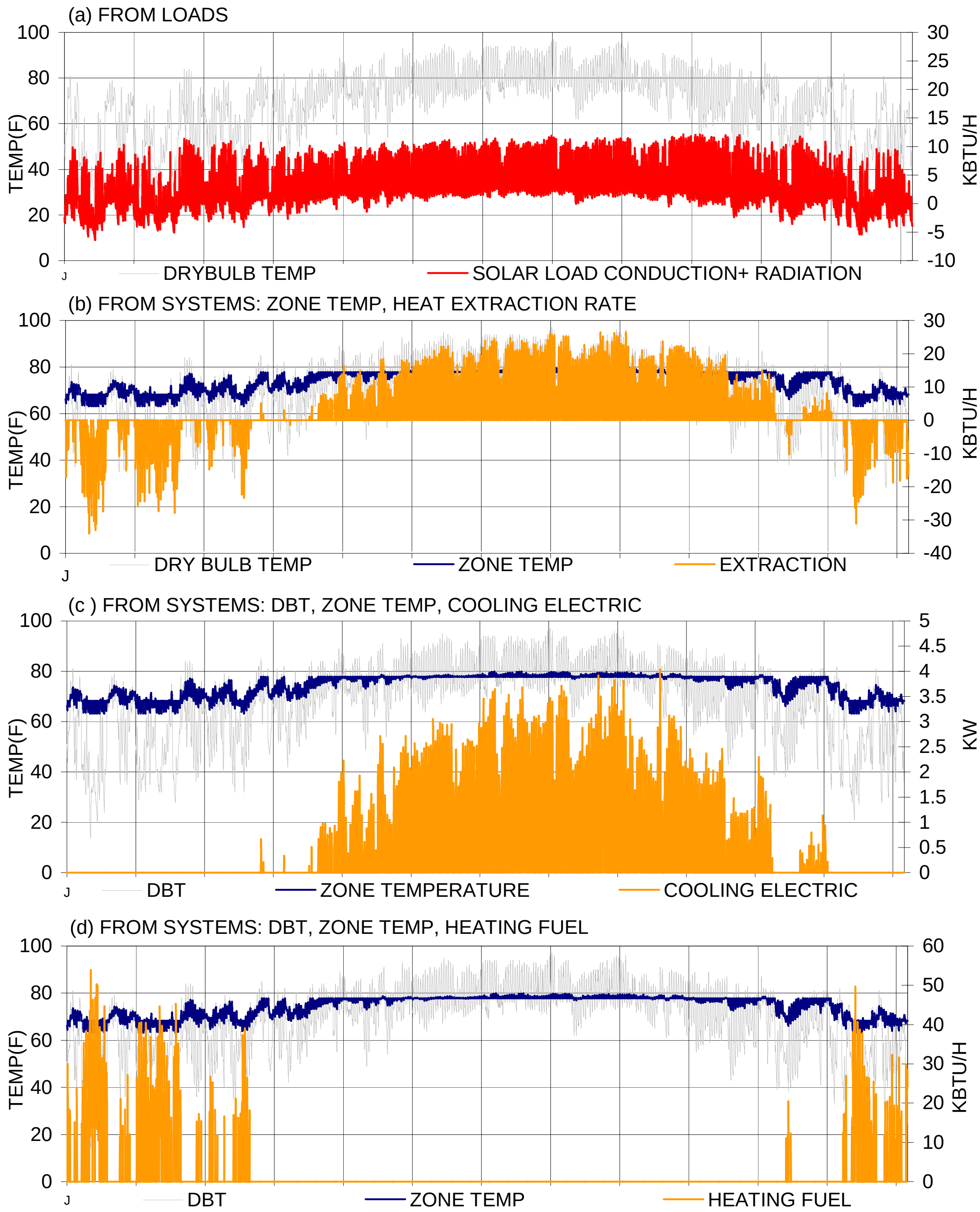


Figure B.3 Annual performance of selected code specified low-E window

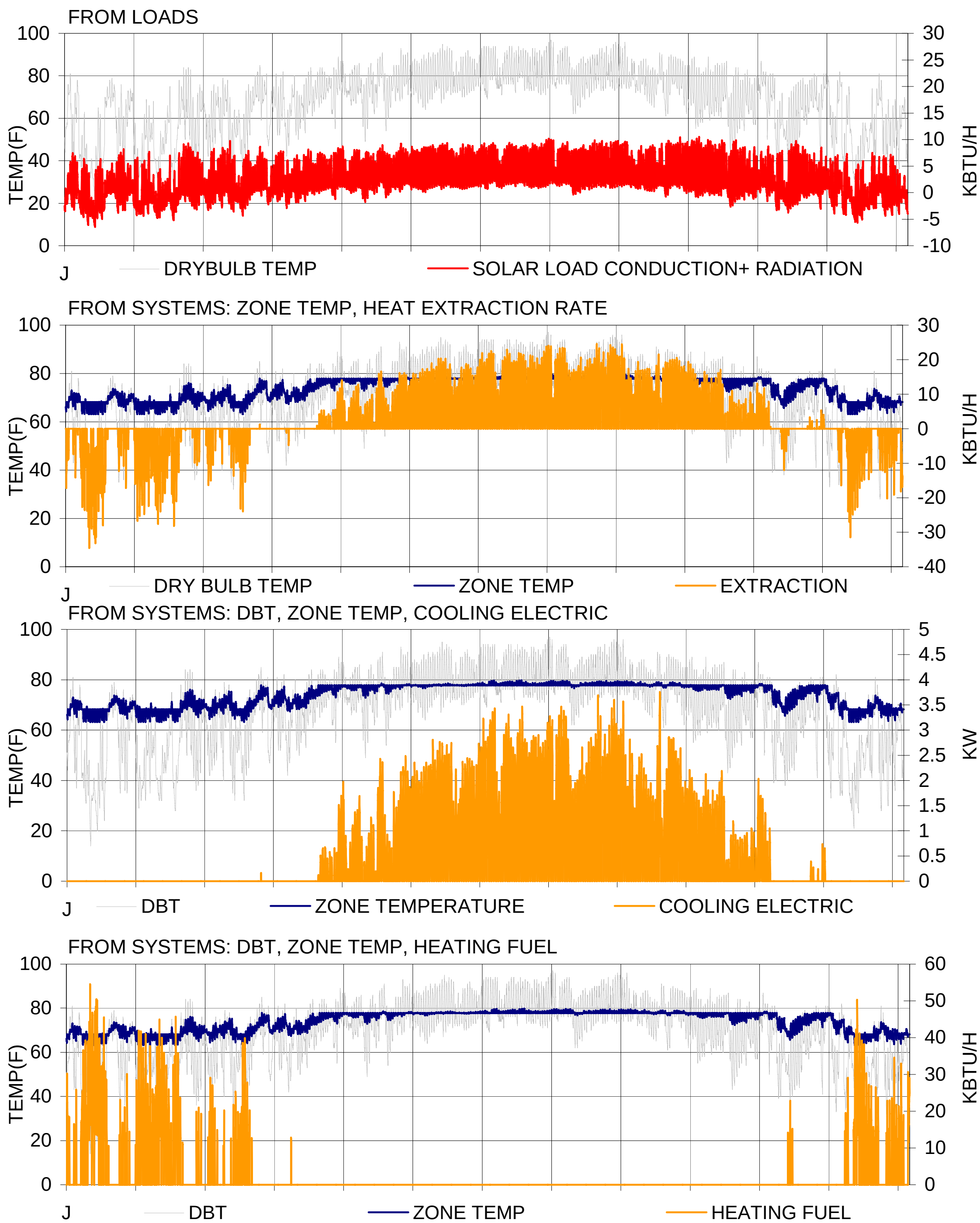


Figure B.4 Annual performance of low-E low-solar (LELS) window

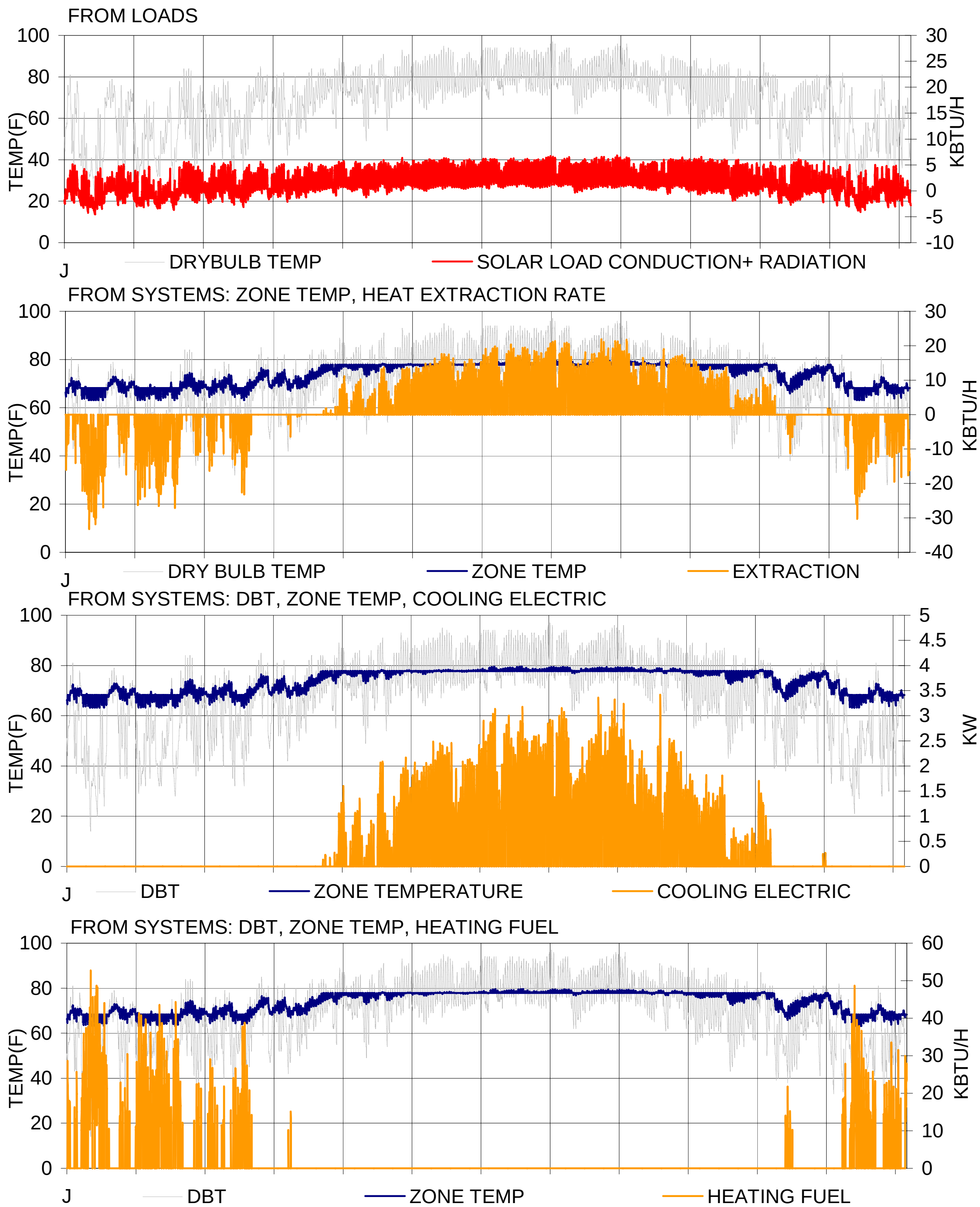


Figure B.5 Annual performance of super low-E low-solar (SULLS) window

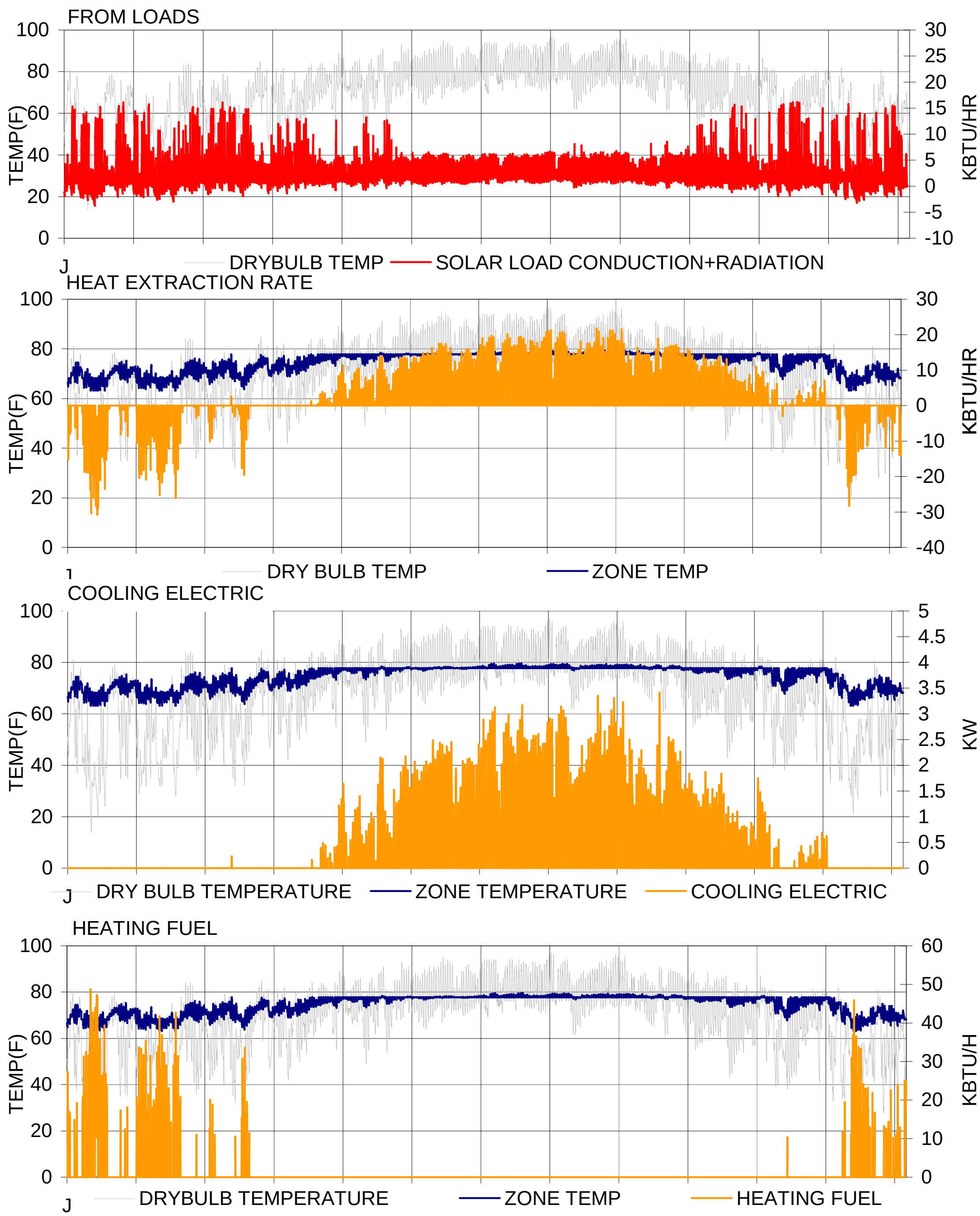


Figure B.6 Annual performance of dynamic option of super low-E low-solar (DySULLS) window

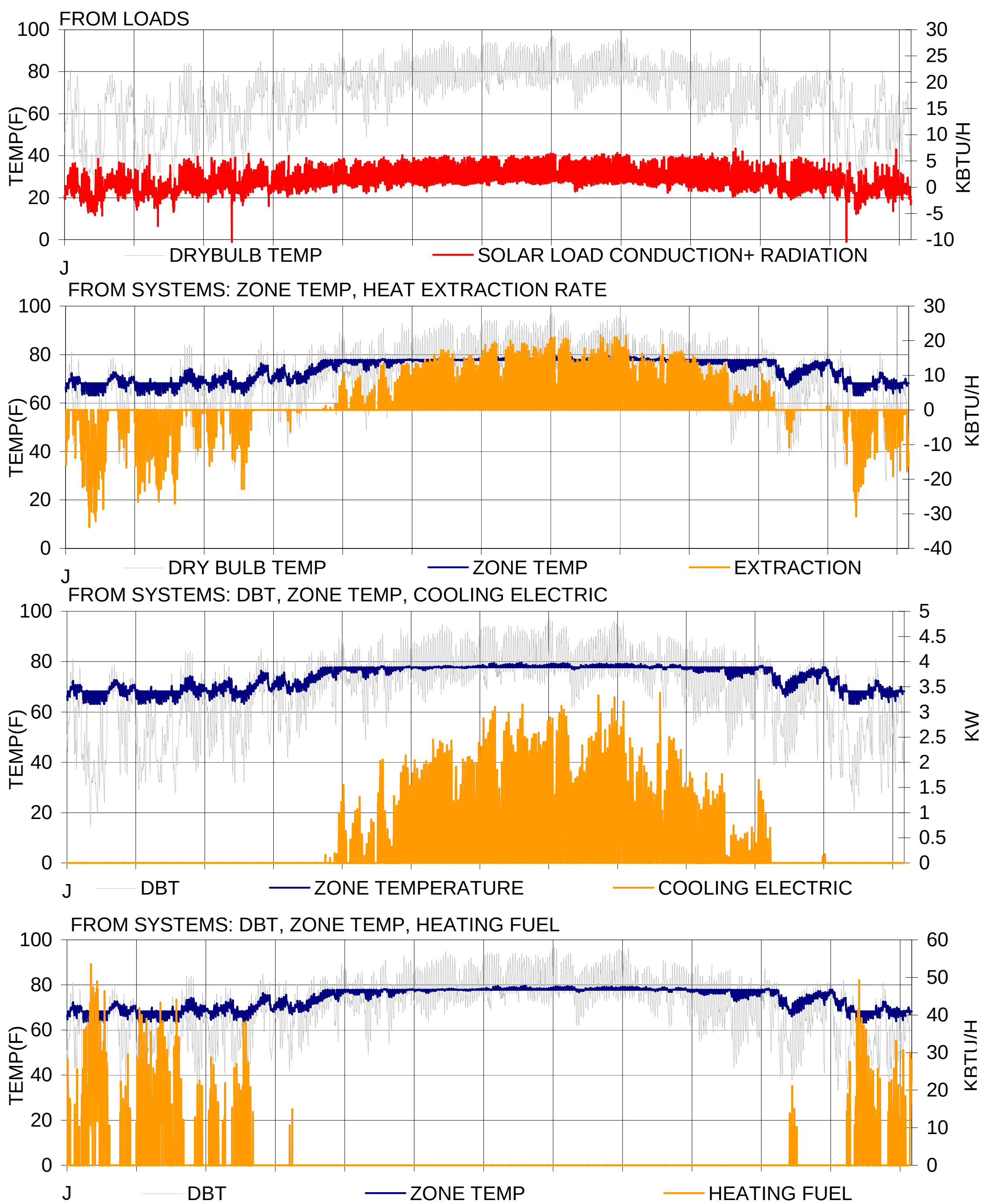


Figure B.7 Annual performance of ultra low-E low-solar (ULLS) window

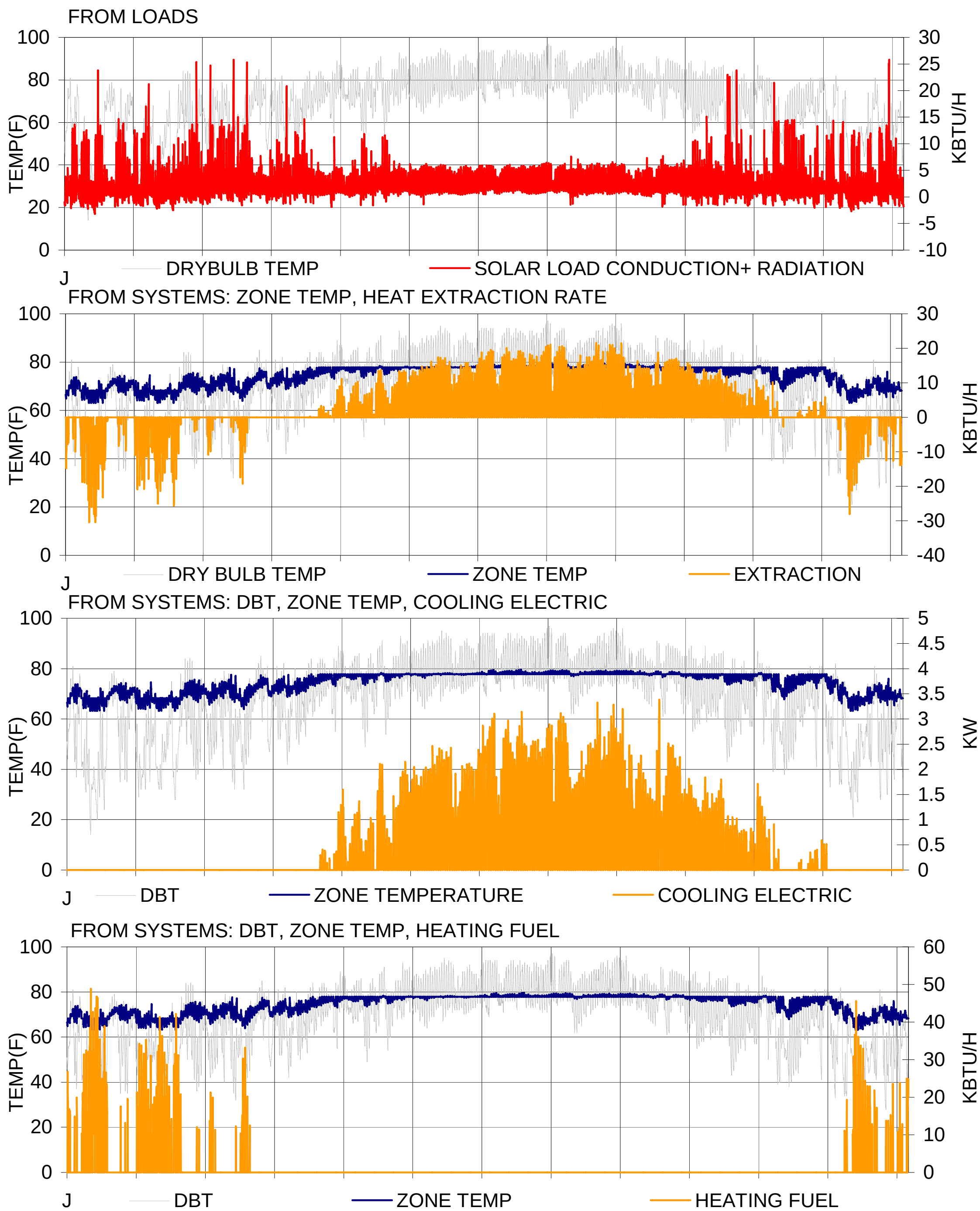


Figure B.8 Annual performance of dynamic option of ultra low-E low-solar (DyULLS) window

To gauge the performance of the selected high performance windows two data sets are extracted:

- Data projecting annual performance of selected windows. These datasets allow a comparative look at the window performance across the year.
- Data projecting weekly performance for a specified week in January and August of the selected windows. These datasets allow a detailed lok at the windows performance one week of peak heating and peak cooling data.

In Figures B.4 - B.9 hourly reports from both the LOADS and SYSTEMS sub-programs of the DOE-2.1e program were examined for the purpose of this analysis. From the LOADS sub-program, the dry-bulb temperature is plotted alongside the hourly solar conduction + radiation loads. From the SYSTEMS sub-program, the dry-bulb temperature and the zone-temperature were considered in addition to the cooling electric and heating fuel consumption rates extracted from the hourly reports.

Looking at the annual performance of the glazing options selected as seen in Figures B.4 - B.9, several trends are observed. For the static options, although the ULLS glazing option (Figure B.7) and the SULS glazing option (Figure B.5) perform better than the LELS glazing option (Figure B.4) and CODE glazing option (Figure B.3) in terms of cooling, both the ULLS and the SULLS glazing options are outperformed by the LELS glazing option in the heating season. Table B.7 presents results from BEPU and BEPS reports pointing out the variations in the heating, cooling and overall performances of the glazing options selected.

Table B.7 Results from BEPU and BEPS reports for the selected glazing options

Glazing Option considered	BEPU Report		BEPS Report		
	Heating NG Therms	Cooling electric KWH	Electricity	Natural Gas	Total annual energy consumption
Low-E Code specified	296	12918	44.1	29.6	73.67
LELS	319	12341	42.1	31.9	74.04
SULS	329	11675	39.8	32.9	72.71
DySULS	237	11795	40.3	23.7	63.99
ULLS	330	11592	39.6	33	72.60
DyULLS	242	11717	40	24.2	64.21

Compared to the significant difference seen in results from solar loads in the LOADS sub-program (i.e., the first graph in Figure B.3 – B.8) the difference in results obtained from the SYSTEMS sub-program is virtually insignificant. It is important to note that previous studies have been found to quote results from LOADS section in their findings. However on looking at the same results in SYSTEMS sub-program of the DOE-2 program, the differences in results become insignificant.

Comparing the dynamic options (Figure B.6 and Figure B.8) to static counterparts (Figure B.5 and Figure B.7), while the performance in terms of cooling is identical, for the dynamic options there is a considerable reduction in heating due to the un-switched state of high-solar option glazing mode during periods when the ambient temperature falls below the switch point temperature. This drop in temperature deactivates the switch set in the simulation program resorting back to the high solar properties of glazing in the un-switched state. However, during transition seasons of the year where the outside temperature is only marginally lower than the switch point temperature, the un-switched state of the window allows more than necessary solar heat gain. Examples of these discrepancies can be seen in section (a) of Figure and Figure B.8 Hence several surges are seen in the hourly solar load results given in the LOADS section. The excessive solar heat gain causes the internal temperatures to rise above the thermostat set point which produces several surges in the observed extraction rates and cooling electric trends. These spikes get reflected in the results from SYSTEMS (sections (b), (c) and (e) of Figure B.6 and Figure), although in these reports, the spikes are not as prominent. This can be optimized by giving a cut-off temperature to cooling, below which the cooling equipment will be turned off. The heat gain absorbed by the envelope components can be later released to fulfill the heating requirements, harnessing the passive solar heating potential of the window. However, delving into the issue of optimal thermostat control and regulation is outside the scope of this thesis.

Figure B.9 and Figure B.10 give a closer look at window solar gain and conduction performance for the glazing options considered by focusing on one week in the winter (i.e., the 10^{th} -16^{th} of January) and one week in the summer (i.e., the 6^{th} -12^{th} August). In these graphs the total solar radiation and the cloud amount are shown in the upper graph of the figure, while the lower graph represents various temperatures, which come in play regulating the performance of the glazing options.

From Figure B.9 and Figure B.10 it is seen that LELS option and the CODE glazing option yield higher results when compared to static as well as dynamic alternates of high performance SULLS and ULLS glazing counterparts. When focusing on dynamic options, it is observed that the DyULLS glazing option is not consistent in its performance. Several surges for solar gain and conduction are observed. An explanation to this behavior of the glazing option can be explained by examining the method of input for the dynamic glazing in DOE-2.1e. As mentioned earlier, the dynamic properties are activated after the ambient temperature crosses the switch point temperature. Moreover, in order to better regulate the U-value of the dynamic glazing a conduction schedule is set up. Here too the conductance values are regulated by the switch point temperature which is used to regulate the SHGC properties of the window. During night time hours, the dynamic glazing is in the un-switched state, which is the high solar mode. In this mode the U-value is adjusted to its lower limit for better insulation properties. During day-time hours the window acquires dynamic properties and a low-E state is achieved as soon as the ambient temperature crosses the user specified switch point temperature. During the transition periods of morning and evening hours where the temperature crosses the switch point but the sun is not up, the U-value gets reduced while the glazing is still in the high solar mode for the next hour causing the surge in loads from solar conduction and solar gain. Several surges are observed in the ULLS performance during night time hours. On close scrutiny it is seen that these surges are generated by conduction loads and cannot be understood by this study.

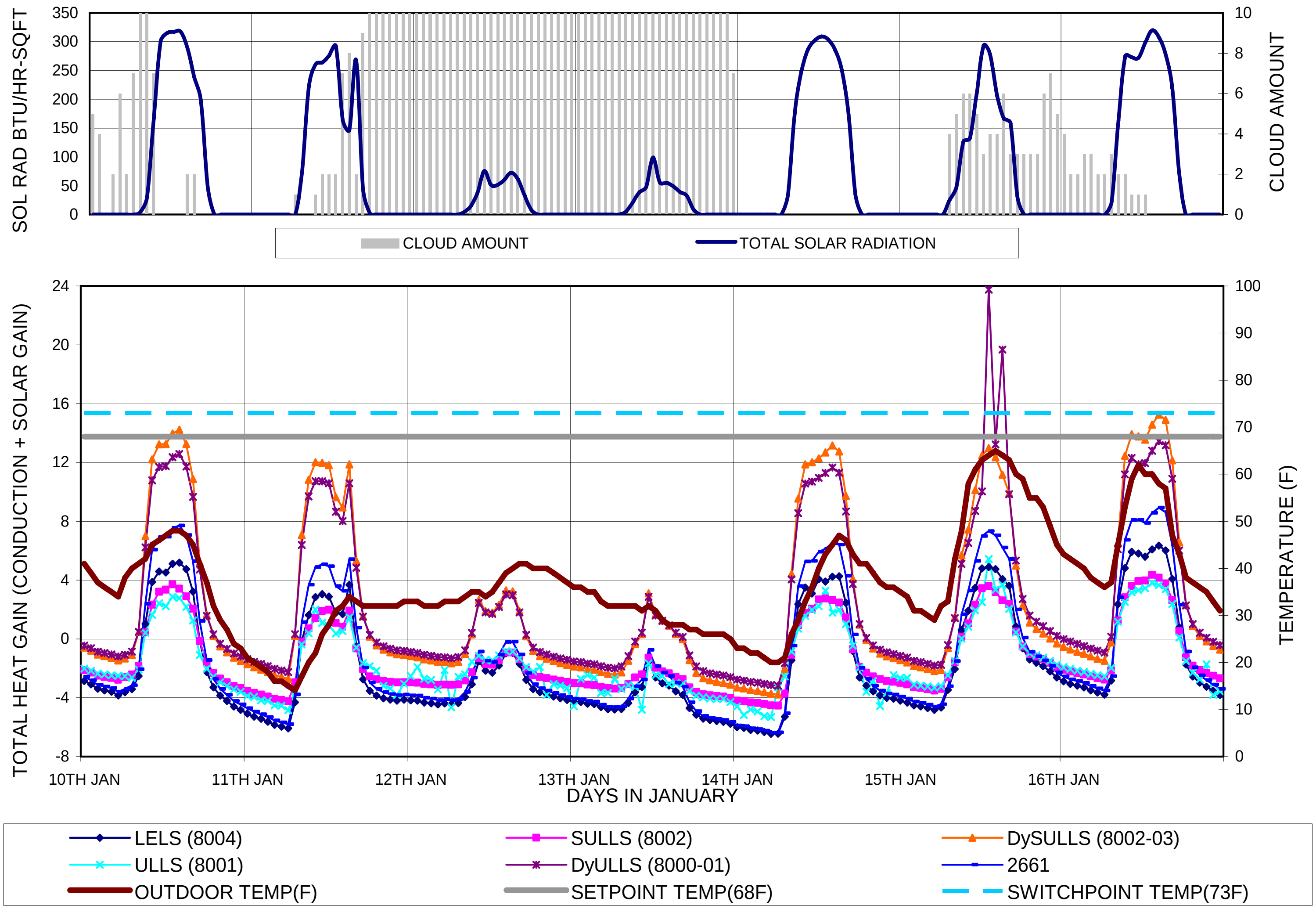


Figure B.9 Weekly conduction + solar gain performance of selected glazing types (Jan 10 – 16)

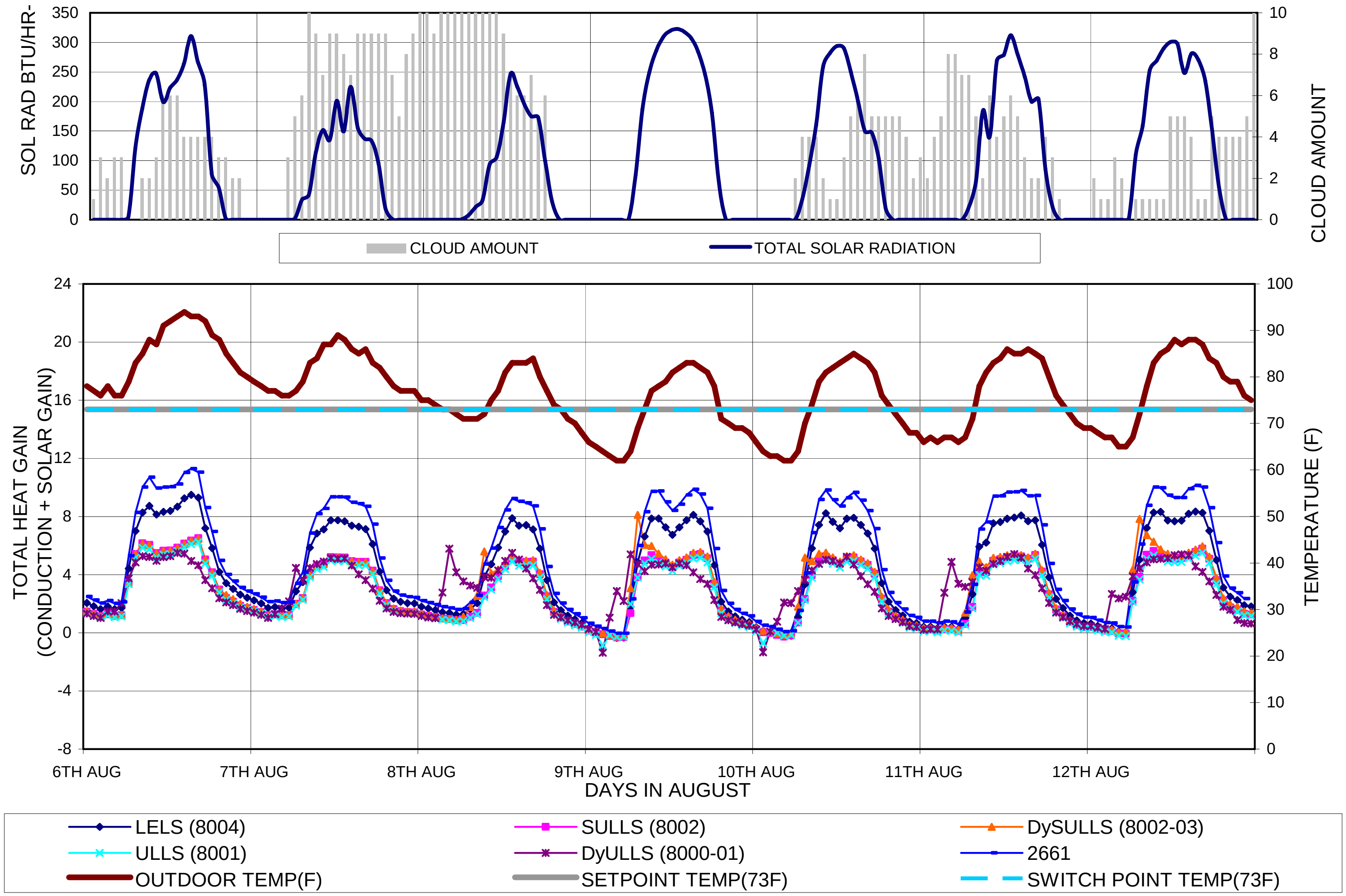


Figure B.10 Weekly conduction + solar gain performance of selected glazing type (Aug 6 – 12)

The ambient temperature always remains below the switch point temperature for this time of the year. Hence, glazing properties in Figure B.10 are always in the un-switched (i.e., high solar) mode. The resulting performance of glazing options is predictable with high performance – high solar glazing yielding to higher solar heat gain + conduction gain than the low-solar counter parts. Here too the performance of DYULLS contains surges in the total (Solar + Conduction) heat gain from LOADS sub-program which cannot be completely explained.

B.2 Impact of orientation

Once the glazing options were established, their performance was compared. The pattern of analysis was based on a similar framework established in Appendix A. The first step examined the performance of glazing options on each orientation enabling the optimized energy consumption due to choice of glazing on each orientation. For the basis of comparison, two base-case models were used. These base-cases are elaborated upon in Table 4.6 in Chapter IV. The two base-cases are:

- Base-case II which is a house with IECC-2000 code compliant windows on a single orientation. This model uses custom weighting factors and the output files from WINDOW-5.
- Base–case IV which is a windowless house in which the window area is set to be equal to zero.

The house with code compliant windows was chosen to assess the performance of high performance options comparing them with the specifications laid down by the code. The windowless house is taken up for comparison in order to focus on the extent of the total impact of windows on annual energy consumption. Only annual energy consumption trends are reported in this section.

B.2.1 Varying orientation and glazing options; general trends

In the first step of the study, the impact of the orientation on the fenestration performance was analyzed. In this analysis the house size was fixed at 2500ft^2 and the WWAR was fixed at 20%. Heating, cooling, and total energy use from BEPS were used as a basis of comparison. Figure B.11 graphically presents this comparison.

B.2.1.1 Annual energy consumption

Figure B.11 presents the annual energy consumption trends when provision for windows in the simulation model is given only on one particular orientation. The purpose of this graph is to compare the annual energy consumption performance of high-performance glazing options (i.e., LELS, SULLS, DySULLS, ULLS, DyULLS) with the glazing option prescribed in the IECC as well as the windowless base-case. Annual energy consumption is given in terms of space heating, space cooling and total energy consumption.

Examination of the results for cooling loads in Figure B.11 reveals that the windowless base-case yields to the lowest results for all orientations with energy consumption of 6.4 MBtu while the CODE glazing option yields the highest results for all orientations. It is also observed that results for the annual cooling loads obtained from the glazing options facing the north orientation are the lowest and hence are closest to the results obtained from the windowless base case. On the other hand, the results of annual cooling loads obtained from the glazing options facing the east orientation are the highest. For north, both dynamic and static options of the ULLS glazing yield the lowest results with 6.8 MBtu while the CODE glazing option yields the highest results with 7.4 MBtu. For the east orientation, all the high performance glazing options perform similarly with 7.4 MBtu while the CODE glazing option yields the highest results with 8.3 MBtu. When considering the performance of the south orientation, the dynamic and static options of SULS and ULLS glazing options yield the lowest results with 7.1 MBtu while the CODE glazing option yields the highest results with 7.8 MBtu.

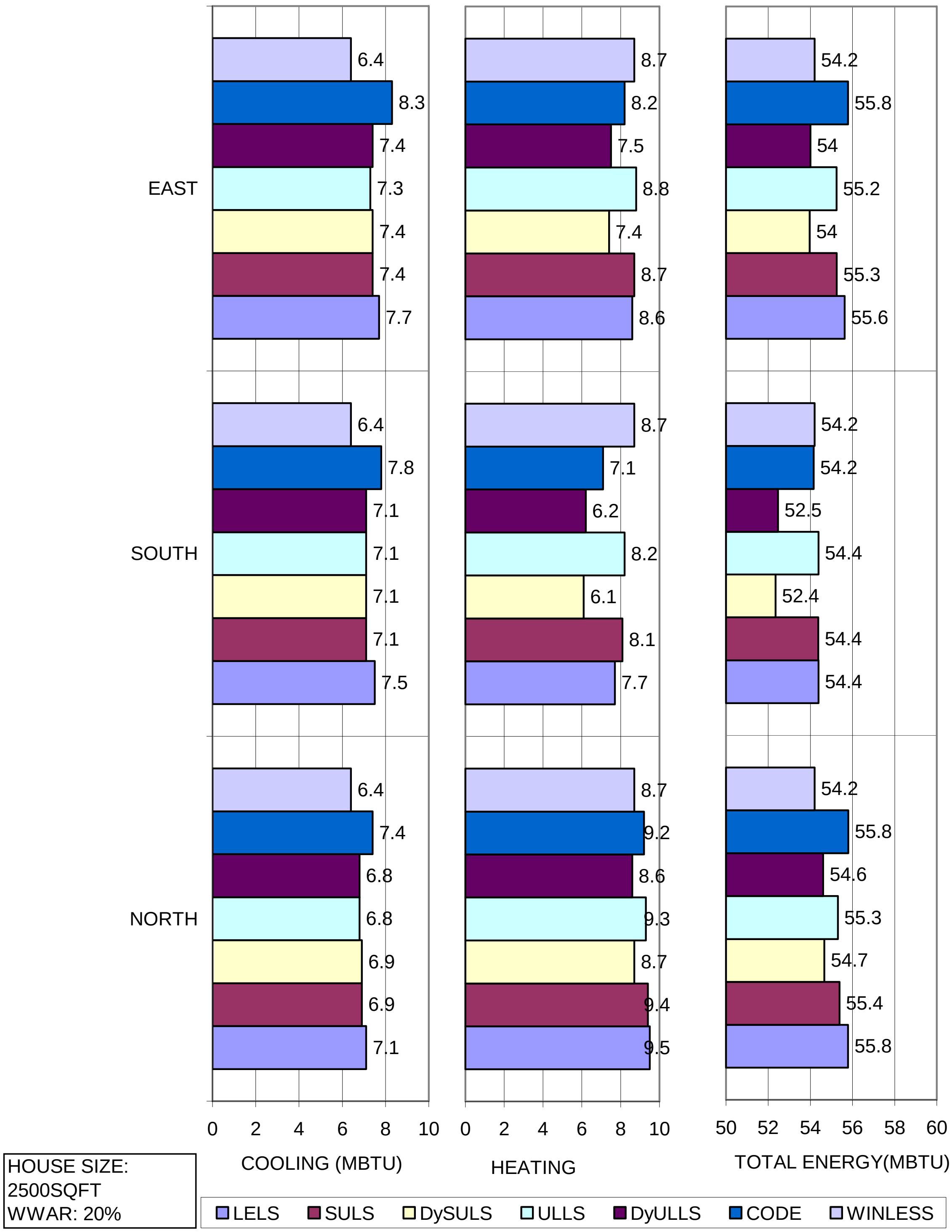


Figure B.11 Annual energy consumption trends: A comparison by varying glazing type and orientation

In examining the heating loads in Figure B., highest heating energy consumption results are obtained from building models with glazing facing the north orientation while the lowest heating energy consumption results are obtained from building models with glazing facing the south orientation. The windowless option yields a heating energy consumption result of 8.7MBtu. This is the highest recorded result for south and east orientations. The dynamic options of both the high-performance glazing selections yield the lowest results for all the orientations. When examining the results from north orientation, almost all the energy consumption values are greater than the windowless base-case. The lowest energy consumption values are recorded by dynamic options of high performance glazing with 8.6 MBtu for the DySULS glazing option and 8.7 MBtu for the DyULLS glazing option. While the static options of the SULS and ULLS glazing selections yield 9.3 MBtu and 9.4 MBtu respectively. The highest energy consumption is recorded by the LELS glazing option with 9.5 MBtu, while CODE glazing option yields a heating energy consumption result of 9.2 MBtu. For the south orientation, the dynamic options for the high performance glazing yield the lowest results with 6.2 MBtu followed closely by the CODE glazing option at 7.1 MBtu and the LELS option at 7.7 MBtu. While the static options of ULLS and SULS glazing selections yield 8.2 MBtu and 8.1 MBtu, respectively. For the east orientation, the highest results are recorded for the ULLS with 8.8 MBtu followed closely by the SULS glazing option with 8.7 MBtu and theLELS glazing option with 8.6 MBtu, while CODE glazing option yields 8.2 MBtu.

While examining the total annual performance in Figure B.11, the energy consumption results from the windowless base-case yields 54.2 MBtu. For the north orientation, the highest energy consumption is demonstrated by the CODE and LELS glazing options with a result of 55.8 MBtu, while the lowest energy consumption is demonstrated by DyULLS glazing option with 54.6 MBtu followed closely by DySULS glazing option with 54.7 MBtu. For the south orientation, all the high performance glazing options yield similar results which are slightly higher than the windowless base-case. The SULS glazing option yields 54.37 MBtu and the ULLS glazing option yields 54.39 MBtu. On the other hand, dynamic options yield to lowest energy consumption levels which are substantially lower than the energy consumption levels obtained from the windowless base-case with a heating energy consumption of 52.35 MBtu from the DySULS glazing option and a result of 52.47 MBtu is obtained from the DyULLS glazing option. The low-E glazing option yields 54.16 MBtu which also is lower than the results obtained from the windowless base-case. For the east orientation, dynamic options of SULS and ULLS glazing selection yield results which are lower than the windowless base-case (i.e., the DySULS glazing option yields to 53.97 MBtu and the DyULLS glazing option yields to 54 MBtu). The highest results are obtained by the LELS glazing option with 55.62 MBtu.

B.2.1.2 General trends

When considering the total (i.e., both heating and cooling) energy consumption trends, building models with glazing facing the south orientation yield the lowest results.

On comparing the performance of various glazing options considered by this analysis, it is observed that when considering the results from cooling loads as well as the overall loads, the code specified glazing CODE is always outperformed by both static as well as dynamic options of the high performance glazing selected by this study (i.e., LELS, SULLS, DySULLS, ULLS, DyULLS). However, this is not the case for results from heating loads. In this case, the low solar properties of the high performance glazing selections yield higher heating load results.

It is observed that the static high-performance low-solar glazing options (i.e., LELS, ULLS, SULLS) perform exceedingly well for cooling loads. However, the benefits of low cooling energy consumption results get cancelled with exceedingly high heating energy consumption results. Due to the potential of switching from low-solar to high-solar state, dynamic windows considered by this study (i.e., DySULS and DyULLS) yield the lowest results for heating as well as cooling energy consumption and subsequently the overall energy consumption loads making them the best options for all the orientations. It is important to note that when considering overall energy consumption, dynamic options perform comparably or considerably better (as in the case of south orientation) than the window-less base-case. These performance trends reinforce the concept stated by several researchers about harnessing the potential of windows as net energy producers.

B.2.2 Varying the orientation, glazing options and house size

In this second step of analysis, a variation in house size is introduced to assess the impact of the variation in house size in addition to orientation for the options of glazing types used. The house size was varied at 1500 ft^2, 2500 ft^2, and 5000 ft^2, while the WWAR was fixed at 20% and internal loads were fixed as per specifications in IECC2000. Results are graphically presented in Figure B.12. Similar to the graph presented in the previous section, Figure B.12 presents the annual energy consumption trends for a building simulation model in which provision for windows is given only for one particular orientation. However the results are presented for three different house sizes, bringing to notice the variation in performance of the selected glazing options when varying the house sizes. The annual energy consumption results are presented in terms of heating energy consumption, cooling energy consumption and overall energy consumption.

B.2.2.1 Annual space heating, cooling and overall loads

As seen from the heating and cooling loads in Figure B.12, heating was most affected by changes in orientation, house size as well as glazing type. However, for cooling, a variation in any of these parameters doesn't create as extensive an impact. It is also noted that during cooling mode, solar gain from fenestration always adds to energy loads, while for heating solar gain is beneficial and reduces the resultant heating loads. Benefits of heat gain from south facing fenestration is seen in the south orientation for all the house sizes and becomes more prominent when going from smaller house size to bigger house size.

Trends projected in heating and cooling are reflected in the results from overall energy consumption loads. Analyzing impact of variations in orientation for glazing options, predictable trends were seen for 1500 ft^2 house. The CODE glazing option yields to highest energy consumption for all orientations followed by the LELS glazing option then the static options of ULLS and SULS glazing selections. Dynamic options record the lowest energy consumption for the three orientations (i.e., north, south and east). In the case of 2500 ft^2 house, a different set of trends begin to emerge.

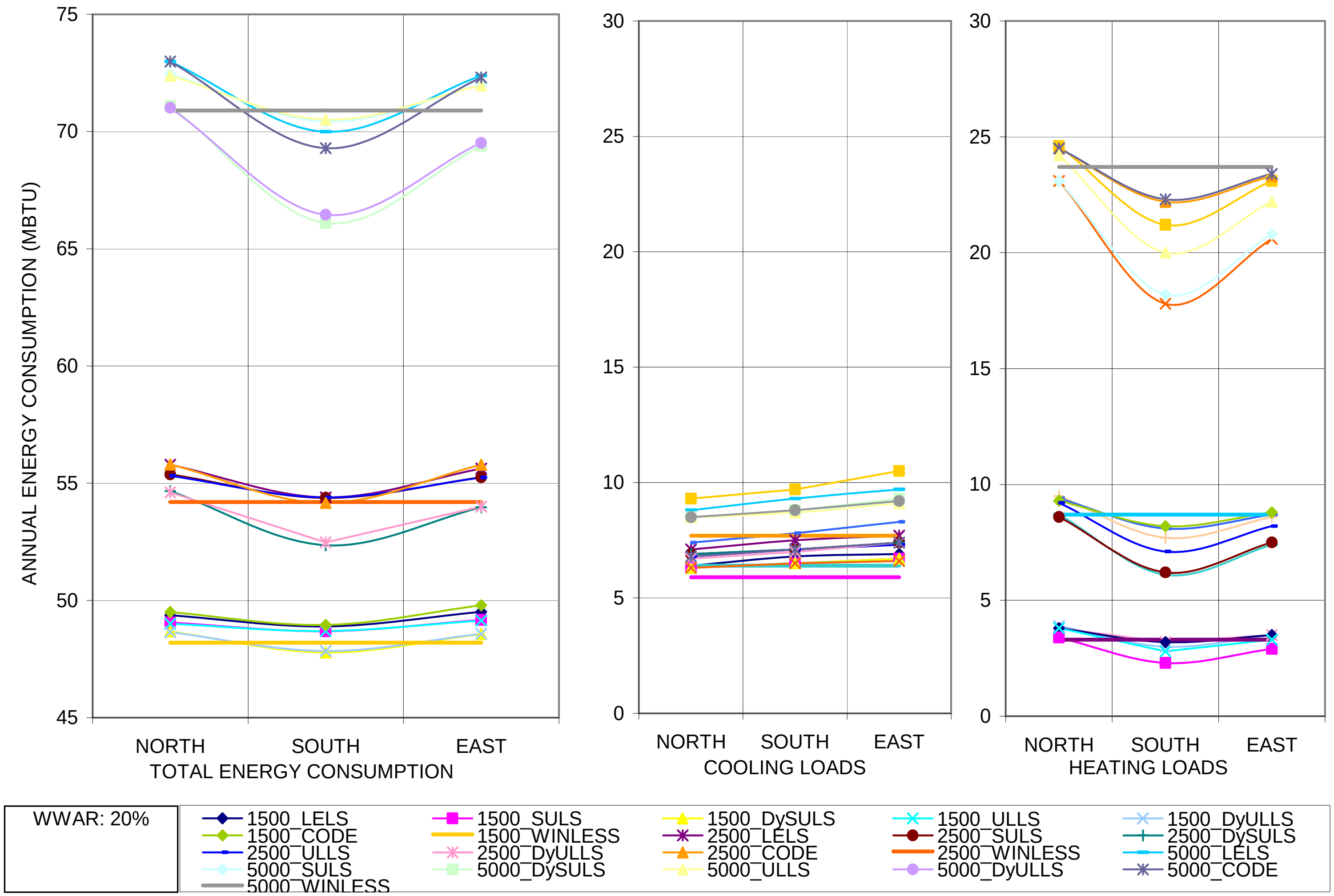


Figure B.12 Annual energy consumption trends: A comparison by varying glazing type, orientation and house size

The CODE glazing option yields the highest energy consumption results for north and east orientations. While on the south orientation the results are reversed with the CODE glazing option yielding the lowest results. For the 5000 ft^2 house, for the north and east orientations, CODE and LELS glazing options yield to higher energy consumption rates when compared to results obtained from SULS and ULLS glazing options. However, on the south orientation, the results from these options outperform the results from the SULS and ULLS glazing options. Both the dynamic glazing options yield to considerably lower results.

The thickly marked horizontal lines which are drawn along with trend-lines representing the results from glazing options in Figure B.12 represent the heating, cooling as well as the overall energy consumption of the windowless building simulation model. For heating loads, in case of the south and east orientations, almost all the glazing options yield results which are lower than results obtained from the windowless base-case. While for the north orientation, the results obtained from the glazing options are marginally higher than the results obtained from the windowless base-case. The only exception is the performance of dynamic glazing which yields lower heating energy consumption values than the windowless base-case. For cooling loads all the glazing options yield higher results than results obtained from the windowless base-case.

The following discussion compares the results from overall energy consumption loads for selected glazing options with the results from the windowless options. For the case of 1500 ft^2 house, on the north and east orientation, all the glazing options yielded higher annual energy consumption results than the results from the windowless model. However, for the south orientation, the dynamic options yielded marginally lower energy consumption results than the results obtained from the windowless base case. For the 2500 ft^2 house, a different trend emerged. For the north and east orientation, energy consumption results from all the options yield higher results than the results obtained from the windowless option. However for the south orientation, results of all the glazing options yield results which are comparable or marginally lower than the results from the windowless base-case. For the 5000 ft^2 house all the options perform considerably better than the windowless option for the south, while the dynamic options perform considerably better for north orientations as well.

B.2.2.2 General trends

The introduction of varying house sizes reinforces trends projected in the preceeding section of this analysis by widening the range of results. Considering the heating, cooling as well as overall energy consumption performance of the selected glazing for almost all the cases of house sizes, WWAR's and orientation, code specified glazing CODE yields the highest results. However, on the south orientation the code specified glazing option CODE performed better than the static options of high performance glazing (i.e., SULLS and ULLS) and the low-E low-solar glazing option (i.e., LELS). It is also observed that the dynamic options (i.e., DySULS and DyULLS) performed better than the static glazing counter paths (i.e., SULLS, ULLS) yielding to lowest heating, cooling, and overall energy performance results. It is important to note that the impact of glazing on energy performance increases with the increase in house size. This is due to the fixed internal energy values specified by the IECC2000 which makes bigger house sizes more dependent on building envelope loads.

Several conclusions can be drawn from comparing performance of the selected high-performance glazing options with the window-less base-case. Trends observed from overall energy consumption indicate that for the south orientation all the glazing options yield overall energy consumption results which are either comparable or lower than the results obtained from the window-less base-case. Beneficial solar heat gain obtained from direct solar radiation in this orientation reduces the heating loads in turn reducing the overall energy consumption. With the increase in house size a reduction in energy consumption is seen for all the glazing options considered. However for the north orientation, all the glazing options yield higher results than the window-less base-case. This reiterates the fact that performance of glazing options on the north orientation is primarily U-value driven. While the wall U-value (R-13 as per the IECC specifications) is greater than the U-values of most of the windows, U-values for dynamic glazing options are comparable. Hence, when coupled with marginal but beneficial solar heat gain during heating season, these options manage outperforming the window less option especially in the case of bigger house sizes.

B.2.3 Varying orientation, glazing options, house size and WWAR

In the third and final step for analyzing impact of orientation, the impact of variation in WWAR is introduced in addition to varying the glazing options, orientation and house size. The choice of glazing options is the same as that adopted in the previous sections (i.e., CODE, LELS, SULLS, ULLS, DySULS, and DyULLS). Apart from the glazing specifications, three house sizes (i.e., 1500ft^2, 2500 ft^2, and 5000 ft^2) and three WWAR's (i.e., 15%, 20%, and 25%) are considered for simulation. Results are graphically presented in Figure B.13.

B.2.3.1 Impact of varying orientation, glazing optio, house size and WWAR on annual heating, cooling and overall energy performance

Figure B.13 presents the annual energy consumption trends using a building energy simulation model which has provision for glazing only on one particular orientation. The purpose of this graph is to understand the impact on annual energy consumption by varying glazing options, house size and WWAR options. Annual energy consumption is given in terms of space heating, space cooling and total energy consumption.

When analyzing space heating for south, it is observed that while LELS performs comparably to high-performance windows in 1500sqft and 2500sqft house sizes, it records highest heating requirements in the case of 5000sqft house. Dynamic options yield to lowest results for all the three house sizes. As seen from Figure B.13, a decrease in energy consumption is observed when going from 15% to 25% WWAR. It is also seen that the rate of increase for dynamic options of high performance glazing is substantially steeper than static options. It is also noted that DySULS option performs better than DyULLS glazing option.

For the north orientation it is observed that LELS option yields the highest heating requirements for all the three house sizes and is followed closely by the static options of high performance glazing (i.e., SULS, ULLS). The dynamic options of the high performance glazing (i.e., DySULS and DyULLS) yield to lowest results. There is an overall increase in energy consumption when going from smaller WWAR to

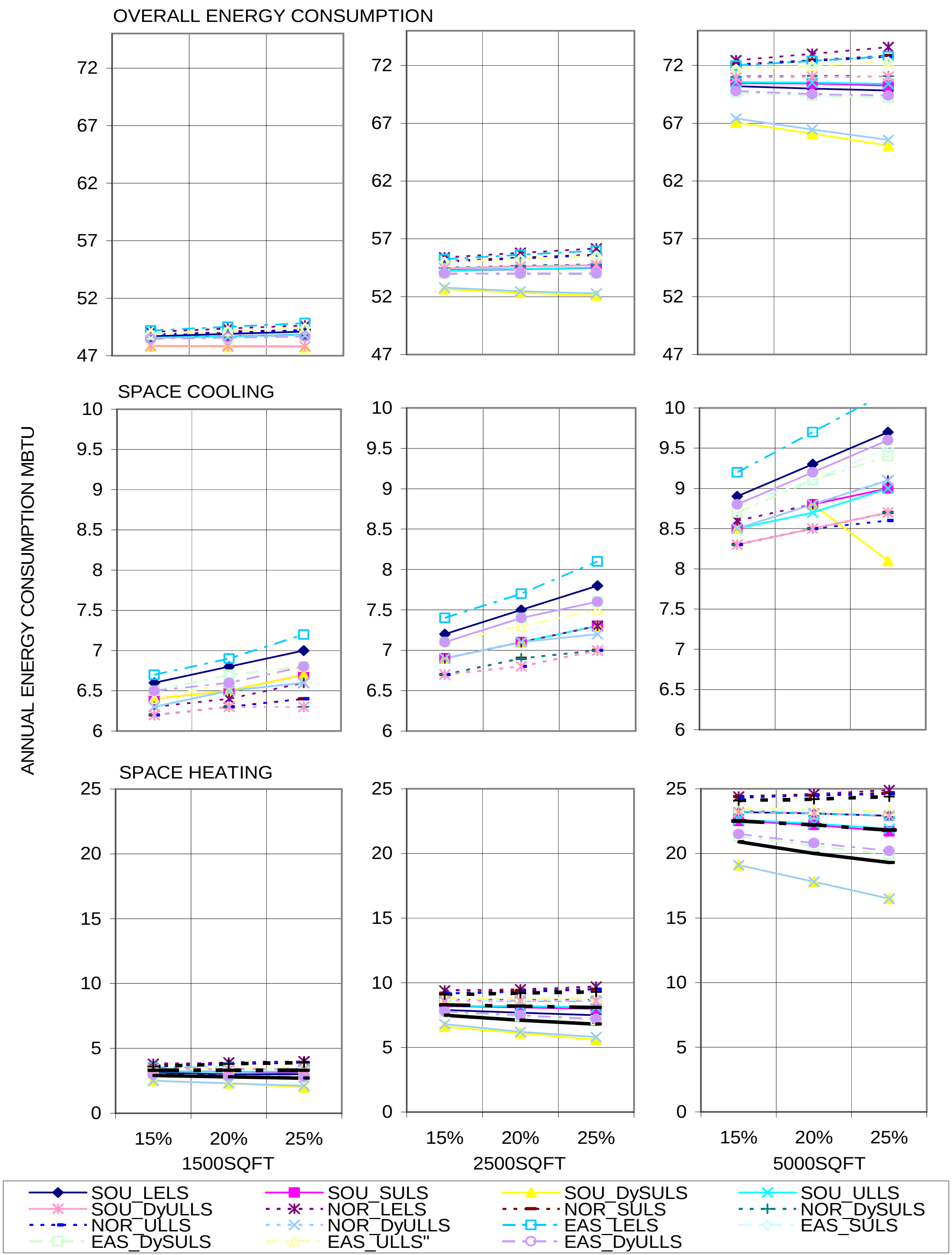


Figure B.13 Annual energy consumption trends: A comparison by varying glazing type, orientation, house size and WWAR

bigger WWAR as documented by Figure B.13. Similar trends in energy consumption are projected in the case of 2500 ft^2 to 5000 ft^2 houses for all the glazing options considered.

For the east orientation, LELS and the static options of high performance glazing (i.e., SULS, ULLS) yield the highest heating energy requirements for all the house sizes followed by the CODE glazing option. For this orientation too, dynamic options yield the lowest heating requirements performing better than their static counter paths. In the case of smaller house sizes, there is an increase in energy consumption for static high-performance glazing options when going from 15% to 25% as seen from Figure B.13. The trend gradually changes when going to larger house sizes. For 5000 ft^2 house there is decrease in energy consumption when going from smaller to bigger WWAR. However, for Dynamic options, there is a decrease in energy consumption when going from 15% WWAR to 25% WWAR for all the house sizes considered.

When examining space cooling for the south orientation, the LELS option yields the highest cooling requiremnts followed by both dynamic and static options of SULS. While dynamic and static options of ULLS yield the lowest cooling requirements. This trend is observed for all three house sizes. An increase in energy consumption is observed when going from 15% to 25% WWAR. As seen from Figure B.13 the rate of increase becomes marginally steeper when going from a smaller house to a larger house.

Space cooling for the east orientation also shows an increase in energy consumption when going from 15% to 25% WWAR. The rate of increase in this orientation is higher than the rate of increase seen in the south orientation. A closer look at the performance of glazing types reveals that LELS glazing option yields the highest cooling requirements while DyULLS glazing option yields lowest annual cooling loads.

When examining space cooling for the north orientation, cooling energy on this orientation has the lowest cooling requirements. The rate of cooling is not as pronounced as it is in the south and east orientations. Furthermore, the rate of increase in the LELS glazing option is greater than that of the SULS glazing option and the ULLS glazing option. Performance of LELS glazing option on east orientation yields the maximum results followed by the LELS glazing option on windows facing the south. Also, the

LELS glazing option records highest cooling requirements as well as biggest difference while the ULLS glazing option records lowest cooling loads as well as well as smallest variation when going from 15% to 25% WWAR. Finally, it is important to note that maximum variation is recorded in this orientation due to change in WWAR.

An inspection of the total annual results reveals that the south orientation has the lowest total energy use. It is also observed that the dynamic options of glazing yield substantially lower total energy use than the other options for all the house sizes. An increase in energy consumption is observed when going from 15% to 25% in the smaller house sizes. The trends change when looking at larger house sizes where a decrease in energy consumption is observed when going from 15% to 25% for all the glazing options. The rate of decrease is steeper for dynamic options (i.e., DySULS, DyULLS) than for any of the other options (i.e CODE, LELS, SULS, and ULLS). For the other options, a small increase in overall energy consumption requirements is seen in the smaller house sizes, while a marginal decrease in the overall energy consumption requirements is seen in the larger house sizes.

For the north orientation, a marginal increase in total energy consumption is seen for all the glazing options when going from 15% to 25% WWAR. The maximum increase is seen in the LELS option. While dynamic glazing options yield the lowest energy consumption results.

The east orientation shows a marginal increase in the total energy consumption in almost all the cases when going from 15% to 25% WWAR. An exception is recorded in the case of dynamic glazing options, where a small decrease in the total energy consumption is observed.

B.2.3.4 General trends

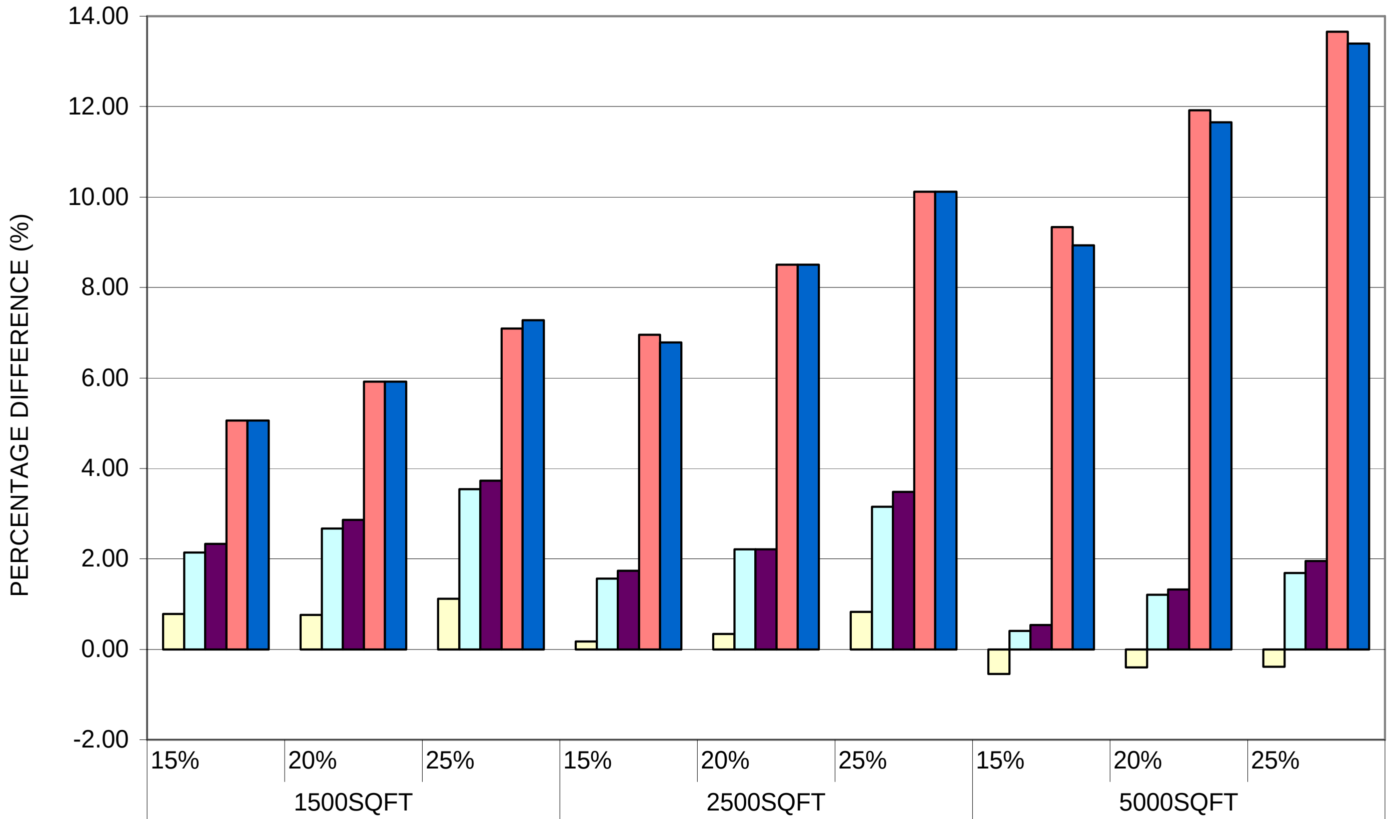
For annual space heating, the north-facing windows yield to the highest annual energy use while south-facing windows yield to lowest annual energy use. The worst performing glazing is theLELS glazing option, while the best performing glazing options are the DyULLS and Dy SULS glazing options. For the total space cooling, the east facing windows yield the highest annual cooling loads while north facing windows yield the lowest annual cooling loads. The worst performing glazing is the LELS glazing option while best performing glazing are the ULLS and DyULLS glazing options. For the total energy consumption performance results, the north-facing windows yield the highest energy consumption, while south facing windows yield the lowest energy consumption The worst performing glazing is the LELS, while the best performing glazing options are the dynamic glazing options of high performance glazing i.e., DyULLS and DySULS.

B.3 Overall comparisons

Typically a residential building has provisions for glazing on all the orientations. The last section discussed the results obtained from simulating a building model which had provisions made for glazing in one orientation only. While the analysis of this model helped in assessing the impact of orientation on energy consumption trends, an overall assessment could not be made. This section considers a building simulation model which has provisions for glazing on all orientations. The performance of high-performance windows are compared with the performance of code specified windows (CODE) as well as the window-less building model. Accordingly, the analysis is divided into two subsections. In the first sub-section the performance of high-performance glazing options are compared against the code specified low-E glazing (CODE). In the second sub-section the performance of high-performance glazing options are compared against the windowless base-case.

B.3.1 BEPS report comparison using low-E as base-case

A comparison of high performance glazing options (i.e., LELS, SULLS, ULLS, DySULS and DyULLS) with the low-E glazing option(CODE) specified by the IECC 2000 is given in Figure B.3 – B8. Results are presented in terms of percentage difference of annual heating, cooling and overall energy consumption results obtained from the high-performance glazing options and the results obtained from the code specified low-E option. The purpose of this graph is to acquire an estimate of the saving which can be obtained by using high-performance glazing options instead of low-E option specified by the code.



	1500SQFT 15%	1500SQFT 20%	1500SQFT 25%	2500SQFT 15%	2500SQFT 20%	2500SQFT 25%	5000SQFT 15%	5000SQFT 20%	5000SQFT 25%
LOW-E - LELS	0.78	0.76	1.12	0.17	0.34	0.83	-0.54	-0.40	-0.39
LOW-E - SULS	2.14	2.67	3.54	1.57	2.21	3.15	0.41	1.21	1.69
LOW-E - ULLS	2.33	2.86	3.73	1.74	2.21	3.48	0.54	1.32	1.95
LOW-E - DYSULS	5.06	5.92	7.09	6.96	8.50	10.12	9.34	11.92	13.65
LOW-E - DYULLS	5.06	5.92	7.28	6.78	8.50	10.12	8.93	11.66	13.39

Figure B.14 Percentage difference between low-E glazing and high-performance options: Annual energy consumption

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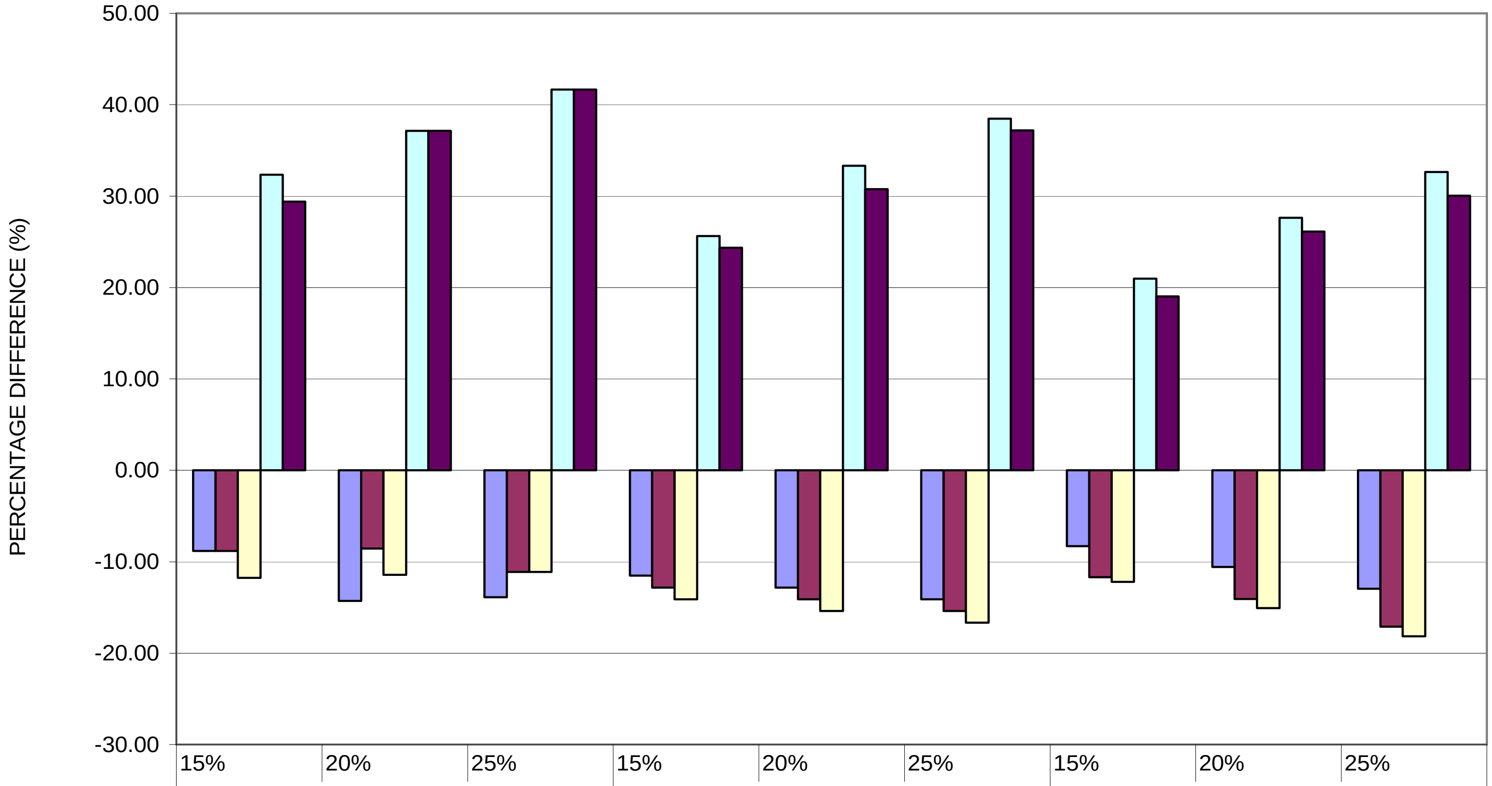
B.3.1.1 Overall BEPS performance

Figure B.14 presents the percentage difference between annual energy consumption results obtained low-E glazing and annual energy consumption results obtained from high performance options. For the 1500ft^2 house, when going from the CODE glazing option to the LELS glazing option, for a 15% WWAR there is a savings of 0.78%, for a 20% WWAR there is a savings of 0.76%, and for a 25% WWAR there is a savings of 1.12%. When going from the CODE glazing option to the SULS glazing option, for a 15% WWAR there is a drop in energy consumption by 2.14%, for a 20% WWAR there is a drop in 2.86%, and for a 25%WWAR there is a drop of 3.54%. When going from the CODE glazing option to the ULLS glazing option, for a 15% WWAR the percentage decrease in energy consumption goes down by 2.33%, for a 20% WWAR the percentage decrease goes down by 2.86%, and for a 25% WWAR the percentage decrease goes down by 3.73%.When going from the CODE glazing option to the DySULS glazing option, for a 15% WWAR there is a drop in energy consumption up to 5.06%, for a 20% WWAR there is a drop in energy consumption by 5.92%, and for 25% WWAR the drop in energy consumption is up to 7.09%. When going from the CODE glazing option to the DyULLS glazing option, the percentage difference is similar to the percentage difference recorded in the previous case. For a 15% WWAR the difference is 5.06%, for a 20% WWAR the percentage difference is 5.92%, while for a 25% WWAR the percentage difference is 7.28%. The difference of going from the CODE glazing option to a high- performance glazing option is within 10% of reported annual energy consumption rates for all WWARs and for all the glazing options. It is observed that the SULS and ULLS glazing options perform better than the LELS glazing option. The dynamic options (i.e., DySULS and DyULLS) yield greater percentage savings than results obtained from other high-performance options.

For the case of a 2500 ft^2 house, the change from the CODE glazing option to the LELS glazing option is negligible for all the three WWARs. The change from the CODE glazing option to the LELS glazing option for a 15% WWAR is 0.17%. The percentage difference for a 20% WWAR is 0.34%, while the percentage difference for a 25% WWAR is 0.84%. The change from the CODE glazing option to the SULS glazing option is within 5%. For a 15% WWAR the percentage difference is 1.74%, for a 20% WWAR the percentage difference is 2.21%, and for a 25% WWAR the percentage difference is 3.15%.

The change from the CODE glazing option to the ULLS glazing for a 15% WWAR is 1.74%, for a 20% WWAR the percentage difference is 2.21%, while for a 25% WWAR the percentage difference is 3.48%. When going from the CODE glazing option to both the DySULS and DyULLS glazing options, results are comparable. In the case of the DySULS glazing option for a 15% WWAR the percentage change is 6.96%, for a 20% WWAR the percentage change is 8.50%, while for a 25% WWAR the percentage change is 10.12%. While for the case of the DyULLS glazing option for a 15% WWAR the percentage change is 6.78%, while for the other two WWARs, the percentage differences remain the same as reported for the previous case. Both the dynamic glazing options (i.e., DySULS and DyYULLS) outperform their static counterparts in almost all cases and yield the lowest results.

For the case of the 5000ft^2 house, unlike in other cases, for change from the CODE glazing option to the LELS glazing option, the CODE glazing option performs marginally better than the LELS glazing option for all the three window configurations for this house size. For a 15% WWAR the percentage decrease is 0.54%, for a 20% WWAR the percentage decrease is 0.40%, while for a 25% WWAR the percent decrease is 0.39%.When going from the CODE glazing option to the SULS glazing option, for a 15% WWAR there is an increase of 0.41%, for a 20% WWAR the percentage increase is 1.21%, for a 25% WWAR the percentage increase is 1.69%. When going from the CODE glazing option to the ULLS glazing option, for a 15% WWAR the percentage increase is 0.54%, for a 20% WWAR the percentage increase is 1.32%, for a 25% WWAR the percentage increase is 1.95%. On going from the CODE glazing option to the ULLS glazing option, for a 15% WWAR the percentage increase is 0.54%, for a 20% WWAR the percentage increase is 1.32%, and for a 25% WWAR the percent increase is 1.95%. When going from the CODE glazing option to the DyULLS glazing option, for a 15% WWAR there is an increase of 9.34%, for a 20% WWAR the percentage increase is 11.92%, and for a 25% WWAR the percentage increase is 13.65%. When going from the CODE glazing option to the DySULS glazing option, for a 15% WWAR the percentage increase is 8.93%, for a 20% WWAR the percentage increase is 11.661%, and for a 25% WWAR the percentage increase is 13.39%. For the 5000ft^2 house, the CODE glazing option performs better than the LELS glazing option. For all the cases of WWARs, the dynamic glazing options outperform the other options by a considerable extent.



	1500SQFT			2500SQFT			5000SQFT		
	15%	20%	25%	15%	20%	25%	15%	20%	25%
LOW-E - LELS	-8.82	-14.29	-13.89	-11.54	-12.82	-14.10	-8.29	-10.55	-12.95
LOW-E - SULS	-8.82	-8.57	-11.11	-12.82	-14.10	-15.38	-11.71	-14.07	-17.10
LOW-E - ULLS	-11.76	-11.43	-11.11	-14.10	-15.38	-16.67	-12.20	-15.08	-18.13
LOW-E - DYSULS	32.35	37.14	41.67	25.64	33.33	38.46	20.98	27.64	32.64
LOW-E - DYULLS	29.41	37.14	41.67	24.36	30.77	37.18	19.02	26.13	30.05

Figure B.15 Percentage difference between low-E glazing and high-performance options: Space heating

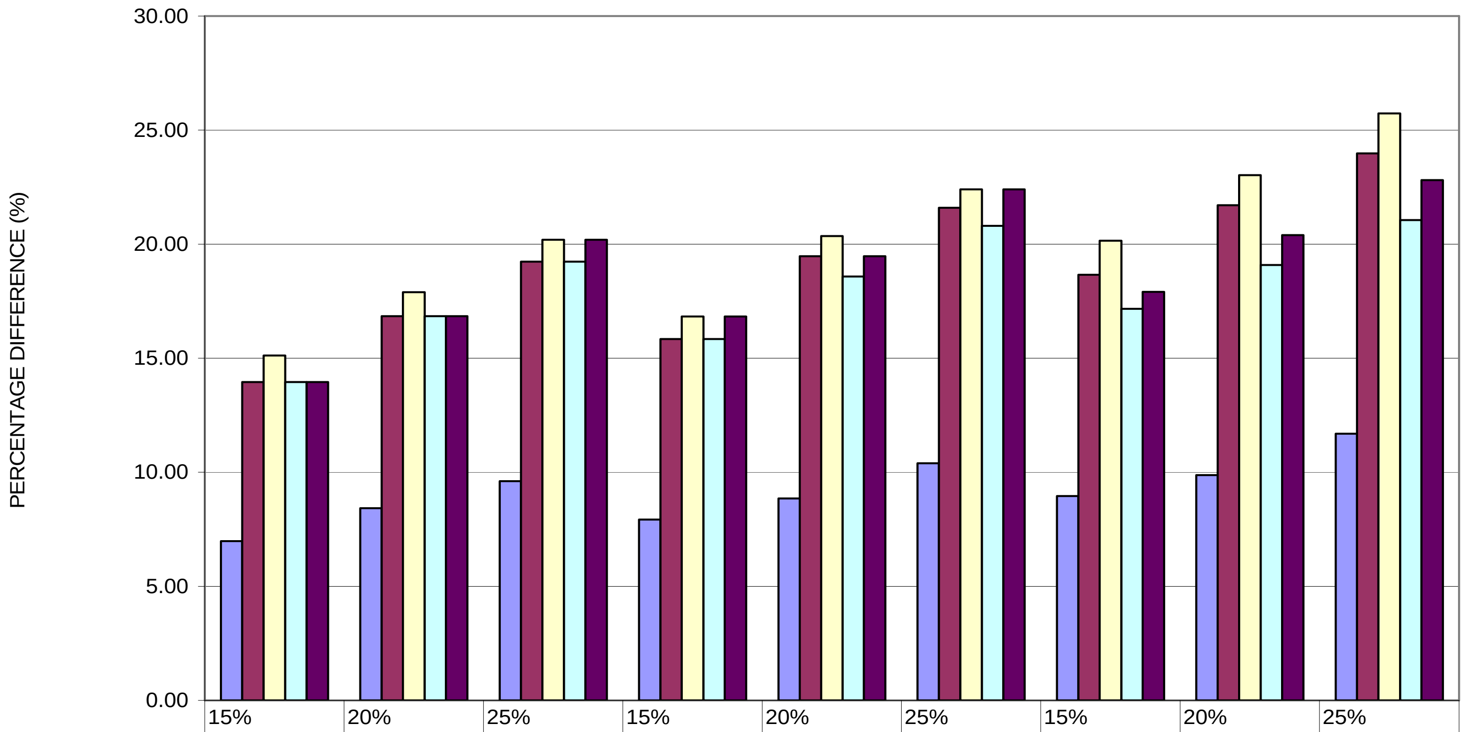
B.3.1.2 BEPS space-heating performance

Figure B.15 presents the percentage difference between annual energy consumption results obtained low-E glazing and annual energy consumption results obtained from high performance options. For the 1500ft^2 house, when going from the CODE glazing option to the LELS glazing option, for a 15% WWAR there is a savings of 0.78%, for a 20% WWAR there is a savings of 0.76%, and for a 25% WWAR there is a savings of 1.12%. When going from the CODE glazing option to the SULS glazing option, for a 15% WWAR there is a drop in energy consumption by 2.14%, for a 20% WWAR there is a drop in 2.86%, and for a 25%WWAR there is a drop of 3.54%. When going from the CODE glazing option to the ULLS glazing option, for a 15% WWAR the percentage decrease in energy consumption goes down by 2.33%, for a 20% WWAR the percentage decrease goes down by 2.86%, and for a 25% WWAR the percentage decrease goes down by 3.73%.When going from the CODE glazing option to the DySULS glazing option, for a 15% WWAR there is a drop in energy consumption up to 5.06%, for a 20% WWAR there is a drop in energy consumption by 5.92%, and for 25% WWAR the drop in energy consumption is up to 7.09%. When going from the CODE glazing option to the DyULLS glazing option, the percentage difference is similar to the percentage difference recorded in the previous case. For a 15% WWAR the difference is 5.06%, for a 20% WWAR the percentage difference is 5.92%, while for a 25% WWAR the percentage difference is 7.28%. The difference of going from the CODE glazing option to a high- performance glazing option is within 10% of reported annual energy consumption rates for all WWARs and for all the glazing options. It is observed that the SULS and ULLS glazing options perform better than the LELS glazing option. The dynamic options (i.e., DySULS and DyULLS) yield greater percentage savings than results obtained from other high-performance options.

For the case of a 2500ft^2 house, the change from the CODE glazing option to the LELS glazing option is negligible for all the three WWARs. The change from the CODE glazing option to the LELS glazing option, for a 15% WWAR is 0.17%, the percentage difference for a 20% WWAR is 0.34%, while the percentage difference for a 25% WWAR is 0.84%. The change from the CODE glazing option to the SULS glazing option is within 5%. For a 15% WWAR the percentage difference is 1.74%, for a 20% WWAR the percentage difference is 2.21%, and for a 25% WWAR the percentage difference is 3.15%.

The change from the CODE glazing option to the ULLS glazing for a 15% WWAR is 1.74%, for a 20% WWAR the percentage difference is 2.21%, while for a 25% WWAR the percentage difference is 3.48%. When going from the CODE glazing option to both the DySULS and DyULLS glazing options, results are comparable. In the case of the DySULS glazing option for a 15% WWAR the percentage change is 6.96%, for a 20% WWAR the percentage change is 8.50%, while for a 25% WWAR the percentage change is 10.12%. While for the case of the DyULLS glazing option for a 15% WWAR the percentage change is 6.78%, while for the other two WWARs the percentage differences remain the same as reported for the previous case. Both the dynamic glazing options (i.e., DySULS and DyYULLS) outperform their static counterparts in almost all cases and yield the lowest results.

For the case of the 5000 ft^2 house, unlike in other cases, for change from the CODE glazing option to the LELS glazing option, the CODE glazing option performs marginally better than the LELS glazing option for all the three window configurations for this house size. For a 15% WWAR the percentage decrease is 0.54%, for a 20% WWAR the percentage decrease is 0.40%, while for a 25% WWAR the percent decrease is 0.39%. When going from the CODE glazing option to the SULS glazing option, for a 15% WWAR there is an increase of 0.41%, for a 20% WWAR the percentage increase is 1.21%, amd for a 25% WWAR the percentage increase is 1.69%. When going from the CODE glazing option to the ULLS glazing option, for a 15% WWAR the percentage increase is 0.54%, for a 20% WWAR the percentage increase is 1.32%, and for a 25% WWAR the percentage increase is 1.95%. On going from the CODE glazing option to the ULLS glazing option, for a 15% WWAR the percentage increase is 0.54%, for a 20% WWAR the percentage increase is 1.32%, and for a 25% WWAR the percent increase is 1.95%. When going from the CODE glazing option to the DyULLS glazing option, for a 15% WWAR there is an increase of 9.34%, for a 20% WWAR the percentage increase is 11.92%, and for a 25% WWAR the percentage increase is 13.65%. When going from the CODE glazing option to the DySULS glazing option for a 15% WWAR the percentage increase is 8.93%, for a 20% WWAR the percentage increase is 11.661%, and for a 25% WWAR the percentage increase is 13.39%. For the 5000 ft^2 house, the CODE glazing option performs better than the LELS glazing option. For all the cases of WWARs, the dynamic glazing options outperform the other options by a considerable extent.



	1500SQFT 15%	1500SQFT 20%	1500SQFT 25%	2500SQFT 15%	2500SQFT 20%	2500SQFT 25%	5000SQFT 15%	5000SQFT 20%	5000SQFT 25%
LOW-E - LELS	6.98	8.42	9.62	7.92	8.85	10.40	8.96	9.87	11.70
LOW-E - SULS	13.95	16.84	19.23	15.84	19.47	21.60	18.66	21.71	23.98
LOW-E - ULLS	15.12	17.89	20.19	16.83	20.35	22.40	20.15	23.03	25.73
LOW-E - DYSULS	13.95	16.84	19.23	15.84	18.58	20.80	17.16	19.08	21.05
LOW-E - DYULLS	13.95	16.84	20.19	16.83	19.47	22.40	17.91	20.39	22.81

Figure B.16 Percentage difference between low-E glazing and high-performance options: Space cooling

B.3.1.3 BEPS space-cooling performance:

Figure B.16 presents the percentage difference between annual cooling energy consumption results obtained the CODE glazing option which is specified by the IECC and annual cooling energy consumption results obtained from high performance options. For the case of the 1500 ft^2 house, for a 15% WWAR the percentage decrease for annual space cooling is by 6.98%. For a 20% WWAR the percentage decrease for annual space cooling is by 8.42%, while for a 25%WWAR the percentage decrease for annual space cooling is by 9.62%. The SULS glazing option performs considerably better. For a 15% WWAR the percentage decrease for annual space cooling is by 13.95%, for a 20%WWAR the percentage decrease for annual space cooling is by 16.84%, while for a 25% WWAR the percentage decrease in cooling energy is by 19.23%. The ULLS option outperforms the other options by a considerable amount. For a 15% WWAR the percentage increase for annual space cooling is by 15.12%, while for a 20%WWAR the percentage increase for annual space cooling is by 17.89%, and for a 25% WWAR the percentage increase for annual space cooling is by 20.19%. The performance of the DySULS glazing option is comparable to the SULS glazing option. For a 15% WWAR the percentage decrease for annual space cooling is by 13.95%, for a 20% WWAR the percentage for annual space cooling is by 16.84%, while for a 25% WWAR the percentage decrease for annual space cooling is by 19.23%. The DyULLS glazing option performs considerable well. As against other options, for a 15%WWAR the percentage decrease for annual space cooling is by 13.95%, for a 20% WWAR the percentage decrease for annual space cooling is by 16.84%, while for a 25% WWAR the percentage decrease for annual space cooling is by 20.19%. The percentage difference increases when going from lower GWAR to higher GWAR. Both ULLS option out performs all other options. Both the dynamic options do not perform as well as the ULLS glazing option.

For the 2500ft^2 it is observed in the case of the LELS glazing option, for a 15% WWAR the percentage decrease for annual space cooling is by a marginal 7.92%, for a 20% WWAR the percentage decrease for annual space cooling is by 8.85%, while for 25% WWAR the percentage decrease for annual space cooling is by 10.40%. For the case of the SULS glazing option, the percentage decrease for annual space cooling observed for a 15% WWAR is by 15.84%, for a 20% WWAR the percentage decrease for annual space cooling is by 19.47%, while for a 25% WWAR the percentage decrease for annual space cooling is by 21.60%. For the case of the ULLS glazing option, the percentage decrease for annual space cooling for a 15% WWAR is 16.83%, for a 20% WWAR the percentage decrease for annual space cooling is by 20.35%, and for a 25% WWAR the percentage decrease for annual space cooling is by 22.40%. For the case of the DySULS glazing option, for a 15% WWAR the percentage decrease for annual space cooling is by 15.84%, for a 20% WWAR the percent decrease for annual space cooling is by 18.58%, while for a 25% WWAR the percentage decrease for annual space cooling is by 20.80%. For the case of the DyULLS glazing option for a 15% WWAR the percentage decrease for annual space cooling is by 16.83%, for the 20% WWAR the percent decrease for annual space cooling is by 19.47%, while for 25% WWAR the percentage decrease for annual space cooling is by 22.40%. Predictable trends are seen for all the three WWARS, with ULLS option yielding to highest predictions.

In the case of the 5000 ft^2 house for the LELS glazing option, for a 15% WWAR the percentage decrease for annual cooling energy consumption is by 8.96%, for a 20% WWAR the percentage decrease for annual cooling energy consumption is by 9.87%, while for a 25%WWAR the percentage decrease in cooling energy consumption is 11.70%. For the case of the SULS glazing option, for a 15% WWAR the percentage decrease for annual cooling energy consumption is by 18.66%, for a 20% WWAR the percentage decrease for annual cooling energy consumption is by 21.71%, while for a 25% WWAR the percentage decrease for annual cooling energy consumption is by 23.98%. For the case of the ULLS glazing option, the percentage decrease for annual cooling energy consumption is 20.15% for a 15% WWAR, while a 23.03% percentage decrease for annual cooling energy consumption is observed for a 20% WWAR, and a 25.73% percentage decrease for annual cooling energy consumption is observed for a 25% WWAR. For the DySULS glazing option a decrease of 17.16% in cooling energy consumption is observed for a 15% WWAR, for the case of a 20% WWAR a decrease of 19.08% in cooling energy consumption is observed, while for the case of a 25% WWAR, a decrease of 21.05%, is observed. For DyULLS a decrease of 17.91% in cooling energy consumption for a 15% WWAR is observed, for the case of a 20% WWAR a decrease of 20.39% in energy consumption is observed, while for the case of a 25% WWAR a decrease of 22.81% is observed. The SULLS and ULLS glazing options outperform the other options including the dynamic options. There is a predictable increasing trend when going from 15% WWAR to 25% WWAR.

B.3.1.4 General trends

Summarizing the overall energy consumption trends observed when comparing high-performance glazing to the CODE glazing option, it is seen that for smaller house size of 1500 ft^2, the dynamic option of the ULLS glazing option outperforms the dynamic version of the SULS glazing option. The performance trends change for house size 2500 ft^2. In this case, for smaller WWARs the DySULS glazing option outperforms the DyULLS glazing option marginally, while in the case of larger house size the DySULS glazing option outperforms DyULLS glazing option marginally. For the 5000 ft^2 house, DySULS outperforms the DyULLS.

As seen in Table B.5 and Table B.6, the DySULS glazing option has a higher SHGC value than the DyULLS glazing option, while the DyULLS glazing option has higher U-values when compared to the DySULS glazing option. This implies that while lowering the U-values can be beneficial, optimally regulated SHGC (as in the case of dynamic options) plays a bigger role in regulating heat gain through windows than the U-value specifications for climatic conditions specific to Houston. Also observed in increasing house size, high performance glazing options make less of an impact. While the dynamic options made a greater impact, and always perform better than their static counter paths. This is because beneficial cuts in cooling energy consumption get evened out by increased heating energy losses for static glazing options in the case of envelope loads dominated bigger house sizes.

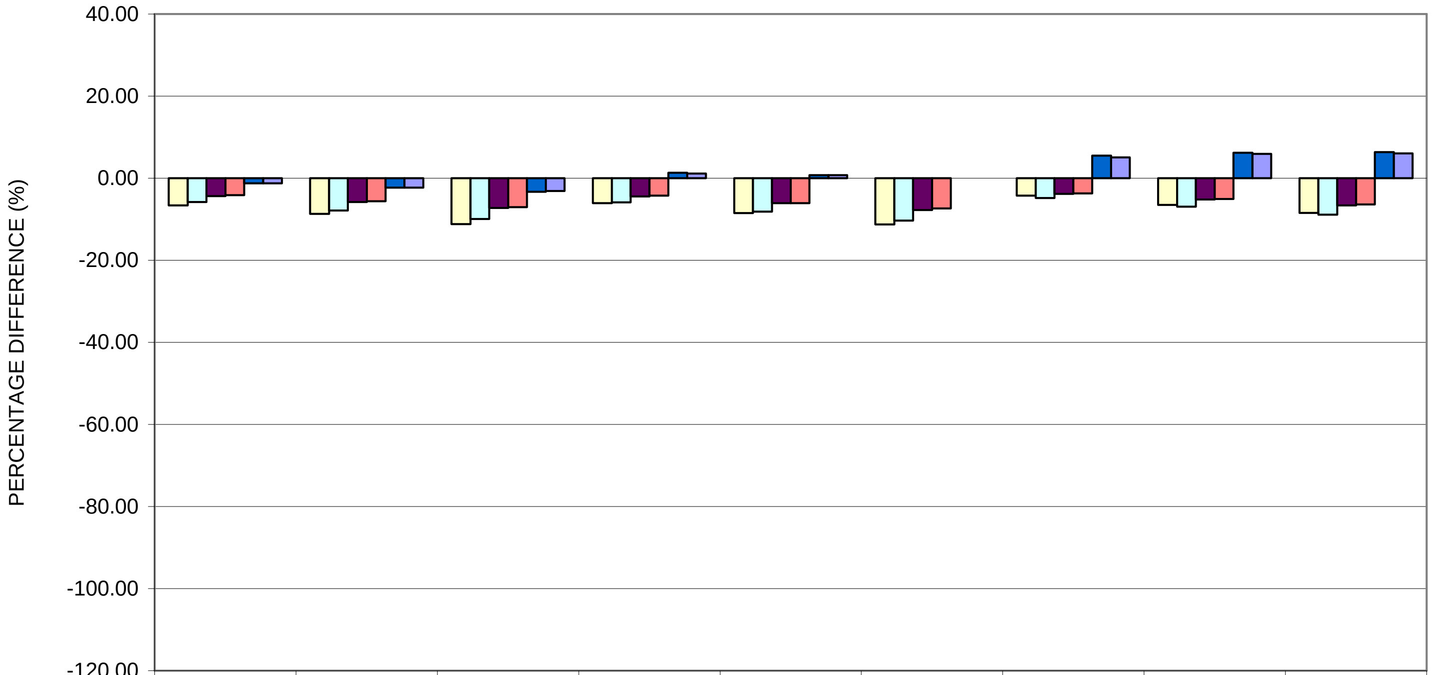
For the case of heating energy consumption, it is observed that static options yield to net heating energy losses while dynamic options yield to net heating energy gains. The DySULS glazing option performs better than the DyULLS glazing option for all the cases. As seen in Table B.5 and Table B.6, the SHGC and U-values are higher for DYSULS option as compared to DYULLS option implying the precedence of SHGC over U-values for lowering heating energy consumption for Houston's climatic conditions.

For the case of cooling energy consumption, similar trends are observed for all the house sizes and for all the WWARs. Trends are predictable in almost all the cases with percentage difference in cooling loads increasing when going from smaller to bigger house size and smaller to bigger WWARs. The ULLS glazing option yields to highest percentage difference in cooling energy consumption. Dynamic options do not perform as well as their static counter paths for cooling energy consumption option due to the switch temperature settings in the DOE-2 input code for the building model. Detailed explanation is given in Section B.3.1.2.

B.3.2 BEPS report comparison using windowless model as base-case

Figure B.17 presents the percentage difference between annual energy consumption results obtained from the windowless base-case and annual energy consumption results obtained from high performance options. For the 1500 ft^2 house, in the case of the CODE glazing option, for a 15% WWAR the percentage increase in annual energy consumption is by 6.64%, for a 20% WWAR the percentage increase in annual energy consumption is 8.71%, and for a 25% WWAR the percentage increase in annual energy consumption is 11.20%. For the LELS glazing option, the percentage increase in annual energy consumption is comparable to that of the CODE glazing option. For a 15% WWAR, the percentage increase in annual energy consumption is 5.81%, while for a 20% WWAR the percentage increase in annual energy consumption is 7.88%, and for a 25% WWAR the percentage increase in annual energy consumption is 9.96%. For the SULS glazing option, there is a further drop in the energy consumption percentage decrease. For a 15% WWAR the percentage increase in annual energy consumption 4.36%, for a 20% WWAR the percentage increase in annual energy consumption is 5.81%, while for a 25% WWAR the percentage increase in the annual energy consumption is 7.26%. For the ULLS glazing option the drop in annual energy consumption increases further. For a 15% WWAR the percentage increase in annual energy consumption is 4.15%, for a 20% WWAR the percentage increase in annual energy consumption is 5.60%, and for a 25% WWAR the percentage increase in annual energy consumption is 7.05%. For the DySULS glazing option the results drastically lower than the SULS glazing option. For the DySULS glazing option the results are lower than the SULS glazing option. For a 15% WWAR the percentage increase in annual energy consumption is 1.8724%, for a 20% WWAR the percentage increase in annual energy consumption is 2.9028%, while for a 25% WWAR the percentage increase in the annual energy consumption is 3.9432%. In the case of the DyULLS glazing option, the percentage difference in energy consumption is similar to the DySULS glazing option. A 15% WWAR reports an increase of 1.8724% in annual energy consumption. A 20% WWAR reports an increase of 2.7028%, while a 25% WWAR reports an increase of 3.7311% in the annual energy consumption. When comparing results from different WWARs, an increasing trend in energy consumption is observed. There is a drop in energy consumption difference when going from CODE to DyULLS but the zero-energy consumption levels are still not achieved. The performance of DySULS and DyULLS glazing options come marginally close to achieving the zero-energy performance.

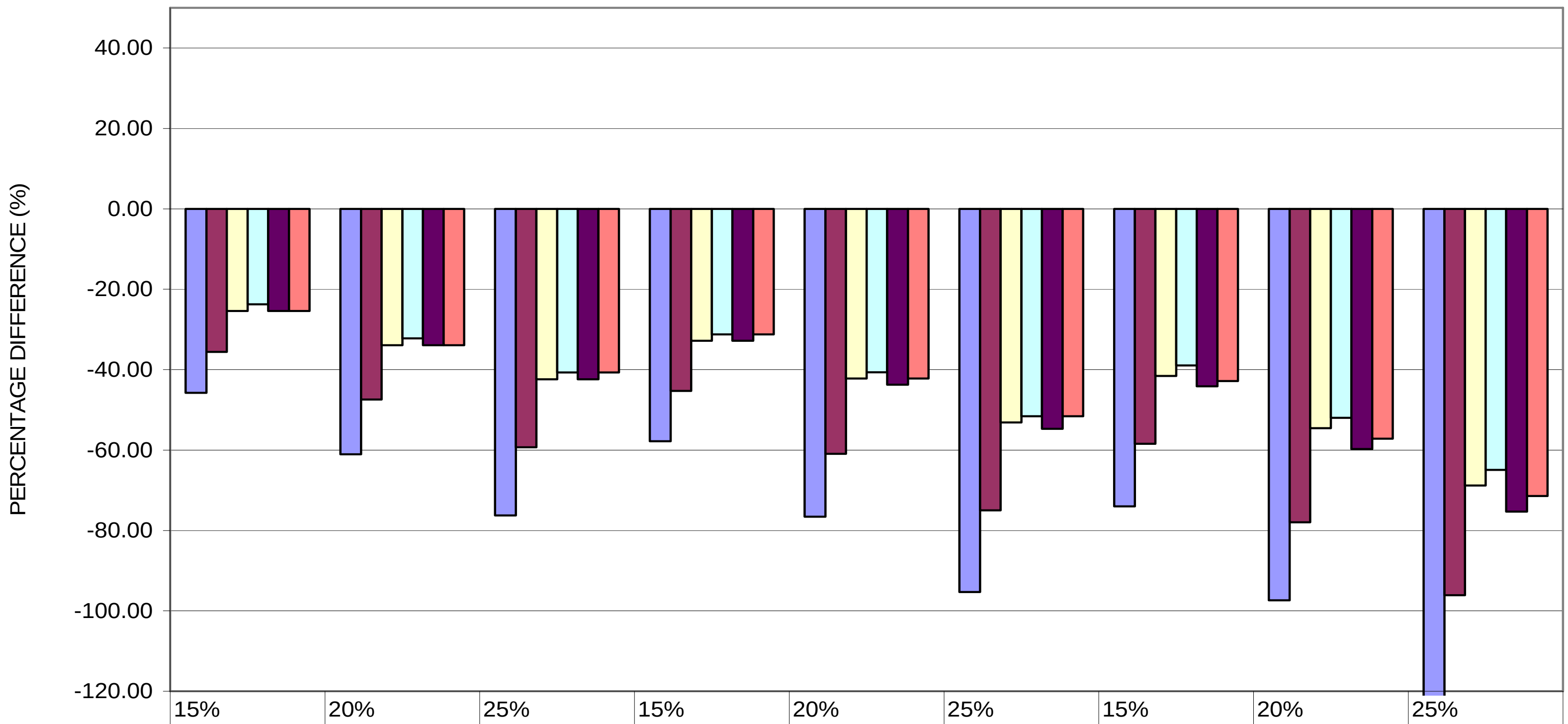
For the 2500ft^2 house, in the case of the CODE glazing option, for a 15% WWAR the percentage increase in annual energy consumption is by 5.906 %. For a 20% WWAR the percentage increase in annual energy consumption is by 8.49%, and for a 25%WWARthe percentage increase in annual energy consumption is by 11.25%. For the LELS glazing performance, the percentage increase is comparable to the CODE option. For a 15% WWAR the percentage increase in annual energy consumption is by 5.90%, for a 20% WWAR the percentage increase in annual energy consumption is by 8.12%, while for a 25% WWAR the percentage increase in annual energy consumption is by 10.33%. In the case of the SULS glazing option, the percentage difference in annual energy consumption is by 4.43% for a 15% WWAR. For a 20% WWAR the percentage difference in annual energy consumption is by 6.09%, while for a 25% WWAR the percentage difference in annual energy consumption is by 7.75%. For the case of the ULLS glazing option, the percentage difference in annual energy consumption is 4.24% for a 15% WWAR, 6.09% for a 20% WWAR, and 7.38% for a 25% WWAR. For dynamic options a marginal decrease in energy consumption is observed. For the case of the DySULS glazing option the percentage decrease in annual energy consumption for a 15%WWAR is by 0.3719%, for a 20% WWAR the percentage decrease is by 0.1874%, while for a 25% WWAR the percentage decrease is by a 0.92%. Similarly for DYULLS option, the percentage increase for a 15% WWAR is 1.11%, for a 20% WWAR the percentage increase is 0.74%, while for a 25% WWAR no change is observed. Performance of both LOWE and LELS can be compared to each other. Performance of SULLS and ULLS can be compared to each other, ULLS option performing marginally better than SULS option. Dynamic options DYSULS and DYULLS perform comparably to the windowless base case for all the three WWARs. For the case of a 15% WWAR, their performance is marginally better with DYSULS yielding to marginally better results when compared to DYULLS.



	1500SQFT			2500SQFT			5000SQFT		
	15%	20%	25%	15%	20%	25%	15%	20%	25%
BC - LOWE	-6.64	-8.71	-11.20	-6.09	-8.49	-11.25	-4.23	-6.49	-8.46
BC - LELS	-5.81	-7.88	-9.96	-5.90	-8.12	-10.33	-4.80	-6.91	-8.89
BC - SULS	-4.36	-5.81	-7.26	-4.43	-6.09	-7.75	-3.81	-5.22	-6.63
BC-ULLS	-4.15	-5.60	-7.05	-4.24	-6.09	-7.38	-3.67	-5.08	-6.35
BC-DYSULS	-1.24	-2.28	-3.32	1.29	0.74	0.00	5.50	6.21	6.35
BC-DYULLS	-1.24	-2.28	-3.11	1.11	0.74	0.00	5.08	5.92	6.06

Figure B.17 Percentage difference between windowless base-case and high-performance options: Overall energy consumption

For a 5000 ft^2 house, the percentage increase in annual energy consumption for CODE option for a 15% WWAR is by 4.23%. For a 20% WWAR the percentage increase in annual energy consumption is by 6.49%, and for a 25%WWAR the percentage increase in annual energy consumption is by 8.46%. When going to the LELS glazing option the percentage increase in annual energy consumption is comparable to the CODE glazing option. For a 15% WWAR the percentage increase in the annual energy consumption is by 4.80%, for a 20% WWAR the percentage increase is by 6.91%, while for a 25% WWAR the percentage increase is 8.89%. In the case of the SULS glazing option, the percentage difference in annual energy consumption is an increase of 3.81% for a 15% WWAR, for a 20% WWAR the percentage increase in annual energy consumption is 5.22%, while for a 25% WWAR the percentage increase in annual energy consumption is 6.63%. For the case of the ULLS glazing option, the percentage difference in annual energy consumption is 3.67% for a 15% WWAR, the percentage increase in annual energy consumption is by 5.08% for a 20% WWAR, and the percentage increase in annual energy consumption is by 6.35% for a 25% WWAR. Dynamic options perform better than windowless option. For both the DySULS and DyULLS glazing options a percentage decrease in annual energy consumption is observed. For a 15% WWAR the percentage decrease in annual energy consumption is by 5.50%, for a 20% WWAR the percentage decrease in annual energy consumption is by 6.21%, while for a 25% WWAR the percentage decrease in energy consumption is by 6.35%. While for the DyULLS glazing option, the percentage decrease in energy consumption for a 15% WWAR is by 5.08%, for a 20% WWAR the percentage decrease in energy consumption is by 5.92%, while for a 25% WWAR the percentage decrease in energy consumption is by 6.06%. It is observed that the CODE and LELS glazing options perform similarly for all the three WWARS. There is a drop in percentage increase in annual energy consumption for the case of the SULS glazing option and a further drop for the case of the ULLS glazing option. But the performance of the SULS and ULLS glazing options is comparable. Dynamic versions considerably outperform the static versions. Both the dynamic options perform better than the windowless base-case for all the three WWARs by approximately upto 6% decrease in energy consumption.



	1500SQFT			2500SQFT			5000SQFT		
	15%	20%	25%	15%	20%	25%	15%	20%	25%
BC - LOWE	-45.76	-61.02	-76.27	-57.81	-76.56	-95.31	-74.03	-97.40	-122.08
BC - LELS	-35.59	-47.46	-59.32	-45.31	-60.94	-75.00	-58.44	-77.92	-96.10
BC - SULS	-25.42	-33.90	-42.37	-32.81	-42.19	-53.13	-41.56	-54.55	-68.83
BC-ULLS	-23.73	-32.20	-40.68	-31.25	-40.63	-51.56	-38.96	-51.95	-64.94
BC-DYSULS	-25.42	-33.90	-42.37	-32.81	-43.75	-54.69	-44.16	-59.74	-75.32
BC-DYULLS	-25.42	-33.90	-40.68	-31.25	-42.19	-51.56	-42.86	-57.14	-71.43

Figure B.18 Percentage difference between windowless base-case and high-performance options: Cooling energy consumption

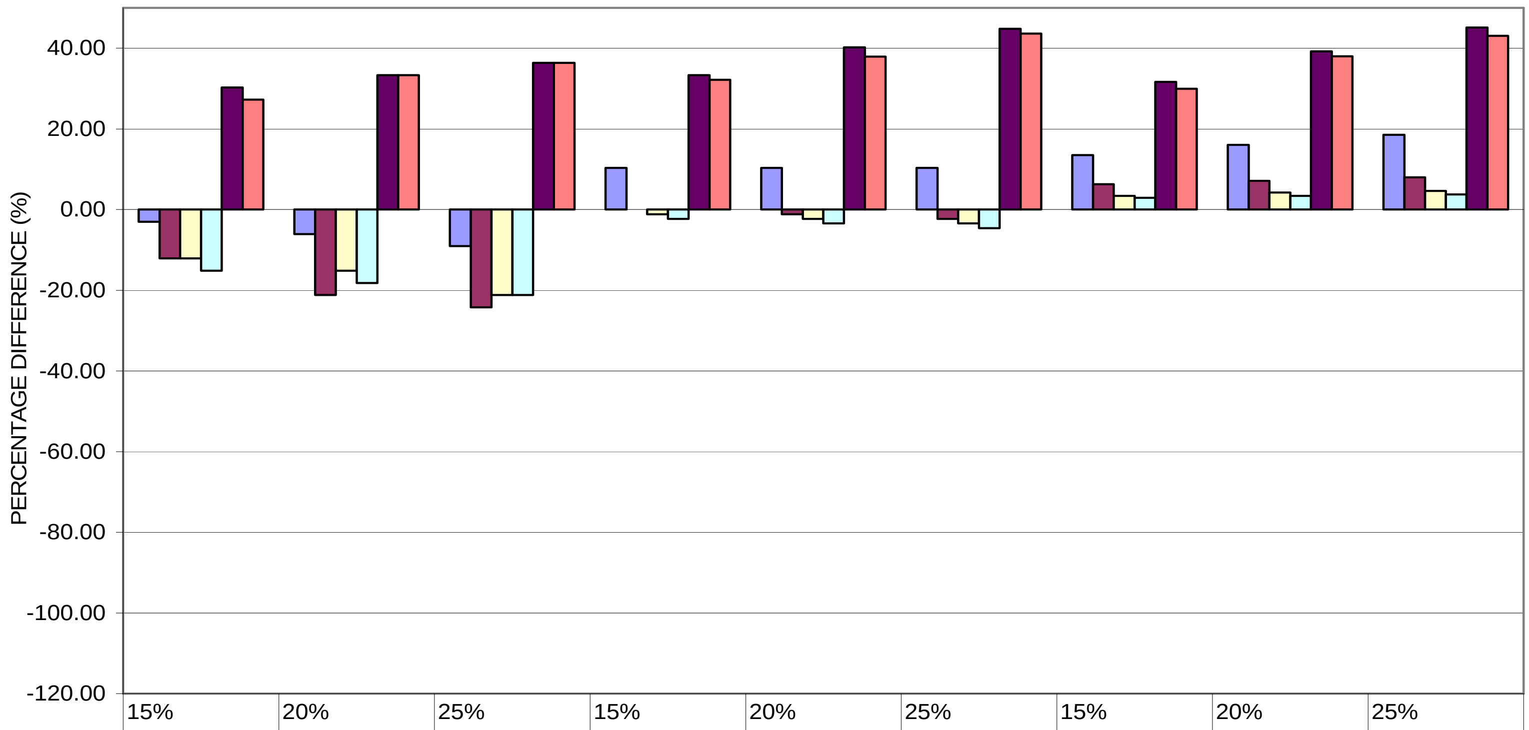
B.3.2.2 BEPS cooling performance

Figure B.18 presents the percentage difference between annual cooling energy consumption results obtained from the windowless base-case and annual cooling energy consumption results obtained from high performance options. For the 1500 ft^2 house, in the case of the CODE glazing option, for a 15% WWAR the percentage increase in annual cooling energy consumption is by 45.76%, tor a 20% WWAR the percentage increase in the annual cooling consumption is by 61.02%, and for a 25% WWAR the percentage increase in the annual cooling energy consumption is by 76.27%. For the LELS glazing option, the percentage increase is comparable to the CODE option. The percentage increase in annual cooling energy for a 15% WWAR is by 44.07%, the percent increase in annual cooling energy for a 20% WWAR is by 57.63%, and the percent increase in the annual cooling energy for a 25% WWAR is by 72.88%. For the SULS glazing option, the percentage increase in cooling energy consumption for a 15% WWAR is by 37.29%, for a 20%WWAR the percentage increase in annual cooling energy consumption is by 47.46%, and for a 25% the percentage increase in the annual cooling energy consumption is by 59.32%. For the ULLS glazing option, the percentage increase in the cooling energy consumption for a 15% WWAR is by 15.25%, for a 20% WWAR the percentage increase in cooling energy consumption is by 20.34%, and for a 25% WWAR the percentage increase in the cooling energy consumption is by 25.42%. For the DySULS glazing option, the percentage increase for 15% WWAR is 37.29%, for a 20% WWAR the percentage increase in cooling energy consumption is by 47.46%, and for a 25% WWAR the percentage increase in the cooling energy consumption is by 59.62%.

For the 2500 ft^2 house, the percentage increase in annual cooling energy consumption using the CODE glazing option for a 15% WWAR is by 57.81%. For a 20% WWAR the percentage increase in the cooling energy consumption is by 78.13%, and for a 25%WWAR the percentage increase in the cooling energy consumption is by 96.88%. In the case of the LELS glazing option, the increase in cooling energy consumption for a 15% WWAR is by 40.11%, the increase in the cooling energy consumption for a 20% WWAR is by 60.94% and the increase in the cooling energy consumption for a 25% WWAR is by 75%. For the SULS glazing option, the percentage increase in cooling energy consumption for a 15% WWAR is by 32.81%, for a 20% WWAR the increase in cooling energy consumption is by 42.19%, and for a 25%

WWAR the increase in cooling energy consumption is by 53.13%. For the ULLS glazing option, the percentage increase for a 15% WWAR is by 31.25%, for a 20% the percentage increase in cooling energy consumption is by 40.63%, and for a 25% WWAR the percentage increase in the cooling energy consumption is by 51.56%. For the DySULS glazing option the percentage increase in the annual cooling loads for a 15% WWAR is by 32.81%, while for a 20% WWAR the percentage increase in the annual cooling loads is by 43.75%, and for a 25% WWAR the percentage increase in the annual cooling loads is by 54.69%. While for the DySULS glazing option, the percentage increase in cooling energy consumption for a 15% WWAR is by 31.25%, for a 20% WWAR the percentage increase in the annual cooling energy consumption is by 42.19%, and for a 25% WWAR the percentage increase in the annual cooling energy consumption by 53.13%.

For the 5000 ft^2 house, the percentage increase in annual cooling energy consumption for the CODE glazing option for a 15% WWAR is by 74.03%. For a 20% WWAR the percentage increase in the cooling loads is by 98.70%, and for a 25% WWAR the percentage increase in the cooling loads is by 122.03%. In the case of the LELS glazing option, the increase in cooling loads for a 15% WWAR is by 58.44%, the increase in the cooling loads for a 20% WWAR is by 77.92%, and the increase in cooling loads for a 25% WWAR is by 96.10%. For the SULS glazing option, the percentage increase in cooling loads for a 15% WWAR is by 41.56%, for a 20% WWAR the percentage increase in cooling loads is by 54.55% and for a 25% WWAR the percentage increase in cooling loads is by 68.83%. For the ULLS glazing option, the percentage increase in the cooling loads for a 15% WWAR is by 38.96%, for a 20% WWAR the percentage increase in cooling loads is by 51.95%, and for a 25% WWAR the percentage increase in cooling loads is 64.94%. For the DySULS glazing option the percentage increase in cooling loads for a 15% WWAR is by 44.16%, for a 20% WWAR the percentage increase in cooling loads is by 59.74%, and for a 25% WWAR the percentage increase in cooling loads is by 75.32%. While for the DyULLS glazing option, the percentage increase in cooling loads for a 15% WWAR is by 42.86%, for a 20% WWAR the percentage increase in cooling loads is by 55.84%, and for a 25% WWAR the percentage increase in cooling loads is by 70.13%.



	15%	20%	25%	15%	20%	25%	15%	20%	25%
	1500SQFT			2500SQFT			5000SQFT		
BC - LOWE	-3.03	-6.06	-9.09	10.34	10.34	10.34	13.50	16.03	18.57
BC - LELS	-12.12	-21.21	-24.24	0.00	-1.15	-2.30	6.33	7.17	8.02
BC - SULS	-12.12	-15.15	-21.21	-1.15	-2.30	-3.45	3.38	4.22	4.64
BC-ULLS	-15.15	-18.18	-21.21	-2.30	-3.45	-4.60	2.95	3.38	3.80
BC-DYSULS	30.30	33.33	36.36	33.33	40.23	44.83	31.65	39.24	45.15
BC-DYULLS	27.27	33.33	36.36	32.18	37.93	43.68	29.96	37.97	43.04

Figure B.19 Percentage difference between windowless base-case and high-performance options: Heating energy consumption

B.3.2.3 BEPS heating performance

Figure B.19 presents the percentage difference between the annual heating energy consumption results obtained from the windowless base-case and the annual heating energy consumption results obtained from the high performance options. For the 1500 ft^2 house, in the case of the CODE glazing option, for a 15% WWAR the percentage increase in annual heating energy consumption is by 3.03%. For a 20% WWAR the percentage increase in the heating energy consumption is by 6.06%, and for a 25% WWAR the percentage increase in heating energy consumption is by 9.09%. For the LELS glazing option, the percentage increase in heating energy consumption for a 15% WWAR is by 12.12%, the increase in heating energy consumption for a 20% WWAR is by 21.21%, and the increase in heating energy consumption for a 25% WWAR is by 24.24%. For the SULS glazing option, the percentage increase in heating energy consumption for a 15% WWAR is by 12.12%, for a 20% WWAR the increase in heating energy consumption is by 15.15%, and for a 25% WWAR the increase in heating energy consumption is by 21.21%. For the ULLS glazing option, the percentage increase in heating energy consumption for a 15% WWAR is by 15.15%, for a 20% WWAR the percentage increase in heating energy consumption is by 18.18%, and for a 25% WWAR the percentage increase in the heating energy consumption is by 21.21%. There is a reversal of trends on considering the dynamic options. For the DySULS glazing option the percentage decrease in heating energy consumption for a 15% WWAR is 30.30%, for a 20% WWAR the percentage decrease in heating energy consumption is by 33.33%, and for a 25% WWAR the percentage decrease in heating energy consumption is by 36.36%. While for the DyULLS glazing option the percentage decrease in heating energy consumption for a 15% WWAR is by 27.27%, for a 20% WWAR the percentage decrease in heating energy consumption is by 33.33%, and for a 25% WWAR the percentage decrease in heating energy consumption is by 30.36%. There is an increase in heating energy consumption when results from static options are compared to the results obtained from the windowless base-case. While both the dynamic options, perform comparably to each other and yield to net decrease of heating energy consumption.

For the 2500 ft^2 house, there is a percentage decrease in annual heating energy consumption for CODE glazing option. For a 15% WWAR the percentage decrease in heating energy consumption is by

10.34%. For a 20% WWAR the percentage decrease in heating energy consumption is by 11.49%, and for a 25% WWAR the percentage decrease in heating energy consumption is by 10.34%. For the LELS glazing option, there is no change in the heating energy consumption for a 15% WWAR, for a 20% WWAR the increase in heating energy is by 1.15%, and the percentage increase in heating energy consumption for a 25% WWAR is by 2.30%. For the SULS glazing option, the percentage increase in heating energy consumption for a 15% WWAR is by 1.15%, for a 20% WWAR the increase in heating energy consumption is by 2.30%, and for a 25% WWAR the increase in heating energy consumption is by 3.45%. For the ULLS glazing option, the percentage increase in heating energy consumption for a 15% WWAR is by 2.30%, for a 20% WWAR the percentage increase in heating energy consumption is by 3.45%, and for a 25% WWAR the percentage increase in heating energy consumption is by 4.60%. A reversal of trends is observed for dynamic glazing options. Dynamic options perform considerably better than their static counter paths. For the DySULS glazing option, the percentage decrease in heating energy consumption for a 15% WWAR is 33.33%, for a 20% WWAR the percentage decrease in the heating energy consumption is by 40.23%, and for a 25% WWAR the percentage decrease in heating energy consumption is by 44.83%. While for the DyULLS glazing option the percentage decrease for a 15% WWAR is 32.18%, for a 20% WWAR the percentage decrease in heating energy consumption is by 37.93%, and for a 25% WWAR the percentage decrease in energy consumption is by 43.68%. Trends in the heating energy consumption patterns begin to change in the case of the 2500 ft^2 house. The CODE glazing option, as well as the dynamic options of high-performance glazing, yield lower heating energy consumption results when compared to the heating consumption results of a windowless base-case. While an increase in heating energy consumption is observed from the static options of the high-performance glazing selections when compared to the heating consumption results of a windowless base-case.

For the 5000 ft^2 house, there is a percentage decrease in heating energy consumption for all the glazing options considered. The percentage decrease in annual heating energy consumption for the CODE glazing option for 15% WWAR is by 13. 50%. For a 20% WWAR the percentage decrease in heating energy consumption is by 16. 03%, and for a 25% the percentage decrease in heating energy consumption is 18.57%. For the LELS glazing option, the percentage decrease in the heating energy consumption for a

15% WWAR is by 6.33%, the percentage decrease in the heating energy consumption for a 20% WWAR is by 7.17%, and the decrease in heating energy consumption for a 25% WWAR is by 8.02%. For the SULS glazing option, the percentage decrease in the heating energy consumption for a 15% WWAR is 3.38%, for a 20% WWAR the decrease in the heating energy consumption is by 4.22%, and for a 25% WWAR the percentage decrease in heating energy consumption is by 4.64%. For the ULLS glazing option, the percentage decrease in heating energy consumption for a 15% WWAR is by 2.95%, for a 20% WWAR the percentage decrease in heating energy consumption is by 3.38%, and for a 25% WWAR the percentage decrease in heating energy consumption is by 3.80%. For the DySULS the percentage decrease in heating energy consumption for a 15% WWAR is 31.65%, for a 20% WWAR the percentage decrease in heating energy consumption is by 39.24%, and for a 25% WWAR the percentage decrease in heating energy consumption is by 45.15%. For the DyULLS glazing option, the percentage decrease in heating energy consumption for a 15% WWAR is 29.96%, for a 20% WWAR the percentage decrease in heating energy consumption is by 37.97%, and for a 25% WWAR the percentage decrease in heating energy consumption is by 43.04%. For the 5000 ft^2 house, all the options show a net energy gain. Dynamic options outperform the static options considerably. Among the static options the CODE glazing option yields the highest percent difference in the heating energy consumption results while ULLS yields the lowest percent difference in the heating energy consumption results.

B.3.2.4 General trends

For the case of space heating, the window-less base case outperforms the static glazing options for the case of 1500 ft^2 house while the trends are reversed for larger house sizes. Dynamic options of the glazing types selected always yield to heating energy consumption results which are lower than the results obtained from the window-less base-case. For the case of space cooling performance, a predictable percentage increase in cooling energy consumption is observed for all the house sizes as well as WWARs. The ULLS and the DyULLS glazing options yields the lowest cooling energy consumption results for all the house sizes and WWARs. Dynamic options yield to slightly higher cooling energy consumption results when compared to their static counter paths. The answer to this observation is found in section 5.3.1.2 of this study wherein surges in cooling loads are observed during intermediate seasons in the performance of dynamic options.

When compared to windowless base case, all the glazing options typically consume more annual energy for smaller houses than in bigger house sizes i.e windows prove to be more beneficial in bigger houses. Also, simulation models incorporating dynamic windows use as little or at times lesser energy than the windowless base case. The percentage increase in energy consumption of the dynamic options when compared to the windowless base-case is negligible for the 1500 ft^2 house, while for 5000 ft^2 house both the dynamic options perform better than the base-case.

B.4 Summary and conclusions

In this section five window options were considered and compared to the code compliant low-E window CODE. Of these, LELS and SULS can be categorized under high performance glazing, while ULLS, DYSULS and DYULLS are technology trajectories for future fenestration products. The SULS option had a low SHGC property while the ULLS option had an extremely low SHGC property. The dynamic options had variable SHGCs and to some extend variable U-factors which are regulated by a schedule. The options were compared to code compliant low-E window glazing as well as to a windowless option of the simulated building model.

For the cooling climate of Houston which has a substantial number of Heating Degree Days, the primary conclusion was that DYSULS and DYULLS offered a greater potential to significantly increase energy consumption savings that cannot be achieved with currently code specified glazing or even currently available high-performance glazing LELS. Dynamic options working on an optimally regulated schedule yield to lower heating energy costs than static options with the same U-factors, with very slight changes in space cooling loads. This decrease is because there is a significant difference in the summer and winter SHGCs and U-values which are regulated by an optimum schedule.

But Dynamic options do not yield to any major peak reductions when compared to their Static counter paths. This is because in summer, both Static and Dynamic options have the same SHGC, while in winters the peak loads are U-value dependent.

House size and WWAR impacts the performance of glazing options to a certain degree. In the case of smaller house sizes U-value properties gain precedence in controlling heat loss, while the SHGC properties gain precedence in larger house sizes. This trend is seen when comparing the performance of DYSULS and DYULLS for space heating loads. While both the glazing options perform similarly for smaller house size, DYSULLS which has a higher SHGC value performs better in the case of larger house sizes.

APPENDIX C

OPTIONS FOR MODELING FENESTRATION IN DOE-2.1E

(Source: DOE-2.1e Manual (1993); Pg: 2.98-99)

DOE-2.1e provides three options for modeling windows. However using the Window Library is thought to give the most accurate window heat transfer calculation because of the following reasons:

1. The angular dependence of transmission and absorption of solar radiation is precisely modeled.
2. The temperature dependence of the window U-value is taken into account.

The following input examples show the three methods now available in DOE-2 to specify window properties:

Method 1: Shading Coefficient

```
u-name =   GLASS-TYPE                        Required for this method.
           SHADING-COEF = value              Default is 1.
           PANES = 1,2 or 3                  Default depends on PANES.
           GLASS-CONDUCTANCE = value         Required only for daylighting.
           VIS-TRANS = value                 Optional: Default if 0.434Btuh/hr-sqft-F.
           FRAME-CONDUCTANCE = value         Optional: Default is 0.7.
           FRAME-ABS = value
```

Method 2: GLASS-TYPE-CODE ≤ 11

```
u-name =   GLASS-TYPE                        Required for this method.
           GLASS-TYPE-CODE = 1 to 11         Default is 1.
           PANES = 1,2 or 3                  Default depends on PANES.
           GLASS-CONDUCTANCE = value
           VIS-TRANS = value                 Required only for daylighting.
           FRAME-CONDUCTANCE = value         Optional:Default is 0.434Btuh/hr-sqft-F.
           FRAME-ABS = value                 Optional: default is 0.7.
```

Method 3: Window Library GLASS-TYPE-CODE ≥ 1000

```
u-name =   GLASS-TYP-CODE = 1000 to 9999     Required for this method.
           FRAME-CONDUCTANCE = value         Optional: Default if 0.434Btuh/hr-sqft-F
           FRAME-ABS = value                 Optional: Default is 0.7
```

Figure C.1 Examples of different methods in DOE-2.1e input file for specifying window properties (Source: DOE-2.1e Manual)

The pros and cons of the different methods are compared in the following table:

Table C.1 Comparison of methods for specifying window properties (Source: LBNL 1993a)

Method	**Pro**	**Con**
Shading Coefficient	Convenient for conceptual design Can model tabular U-values and SHGC values specified by the code.	Inaccurate angular dependence for multiple glazing.
GLASS-TYPE-CODE ≤ 11	More accurate angular dependence	May not be good match to actual glazing
Window Library: GLASS-TYPE-CODE ≥ 1000	Highly accurate angular dependence and conduction; user can expand library	Causes increase in calculation time. Must use data from actual windows provided in WINDOW-5 library.

APPENDIX D

FENESTRATION SPECIFICATIONS IN BUILDING ENERGY CODES

D.1 Specifications in ASHRAE-90.2 2001

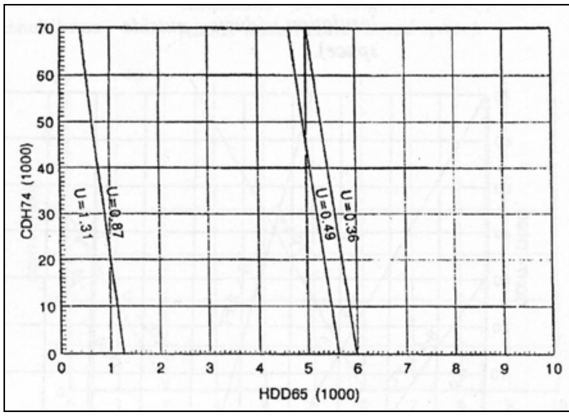


Figure D.1 Fenestration U-values for ducts within conditioned space (Source: ASHRAE Standard 90.2-2001)

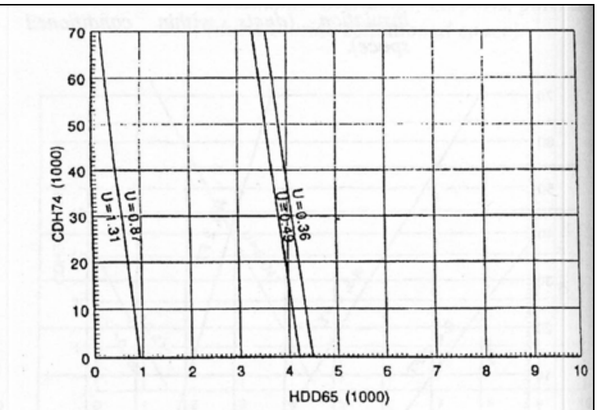


Figure D.2 Fenestration U-values for ducts outside conditioned space (Source: ASHRAE Standard 90.2-2001)

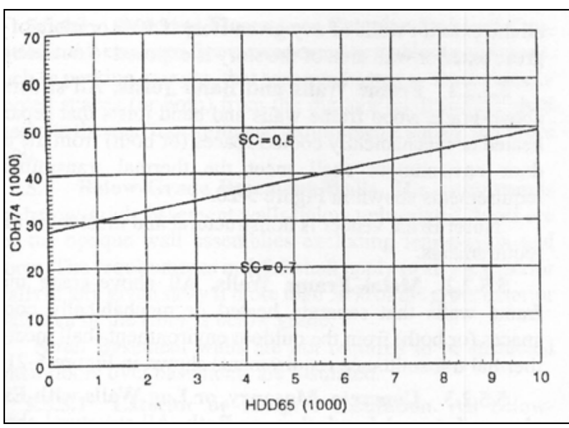


Figure D.3 Fenestration SC values for ducts within conditioned space (Source: ASHRAE Standard 90.2-2001)

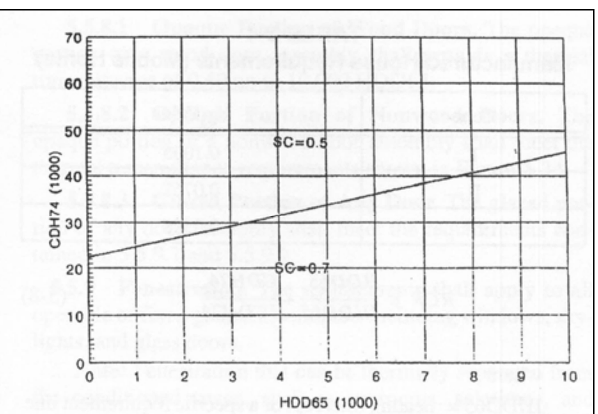


Figure D.4 Fenestration SC values for ducts outside conditioned space (Source: ASHRAE Standard 90.2-2001)

D.2 Specifications in IECC-2000 for Houston (Harris County HDD: 1500 – 1999)

Table D.1 Prescriptive building envelope requirements, type A-1 residential buildings window area 15 percent of gross exterior wall area

	MAXIMUM	MINIMUM					
HEATING DEGREE DAYS	Glazing *U*-factor	Ceiling *R*-value	Exterior wall *R*-value	Floor *R*-value	Basement wall *R*-value	Slab perimeter *R*-value and depth	Crawl space wall *R*-value
0-499	any	R-13	R-11	R-11	R-0	R-0	R-0
500-999	0.90	R-19	R-11	R-11	R-0	R-0	R-4
1,000-1,499	0.75	R-19	R-11	R-11	R-0	R-0	R-5
1,500-1,999	0.75	R-26	R-13	R-11	R-5	R-0	R-5
2,000-2,499	0.65	R-30	R-13	R-11	R-5	R-0	R-6
2,500-2,999	0.60	R-30	R-13	R-19	R-6	R-4, 2 ft.	R-7
3,000-3,499	0.55	R-30	R-13	R-19	R-7	R-4, 2 ft.	R-8
3,500-3,999	0.50	R-30	R-13	R-19	R-8	R-5, 2 ft.	R-10
4,000-4,499	0.45	R-38	R-13	R-19	R-8	R-5, 2 ft.	R-11
4,500-4,999	0.45	R-38	R-16	R-19	R-9	R-6, 2 ft.	R-17
5,000-5,499	0.45	R-38	R-18	R-19	R-9	R-6, 2 ft.	R-17
5,500-5,999	0.40	R-38	R-18	R-21	R-10	R-9, 2 ft.	R-19
6,000-6,499	0.35	R-38	R-18	R-21	R-10	R-9, 4 ft.	R-20
6,500-6,999	0.35	R-49	R-21	R-21	R-11	R-11, 4 ft.	R-20
7,000-8,499	0.35	R-49	R-21	R-21	R-11	R-13, 4 ft.	R-20
8,500-8,999	0.35	R-49	R-21	R-21	R-18	R-14, 4 ft.	R-20
9,000-12,999	0.35	R-49	R-21	R-21	R-19	R-18, 4 ft.	R-20

Table D.2 Prescriptive building envelope requirements, type A-1 residential buildings window area 20 percent of gross exterior wall area

	MAXIMUM	MINIMUM					
HEATING DEGREE DAYS	Glazing *U*-factor	Ceiling *R*-value	Exterior wall *R*-value	Floor *R*-value	Basement wall *R*-value	Slab perimeter *R*-value and depth	Crawl space wall *R*-value
0-499	0.80	R-19	R-11	R-11	R-0	R-0	R-0
500-999	0.75	R-30	R-13	R-11	R-0	R-0	R-4
1,000-1,499	0.70	R-30	R-13	R-11	R-0	R-0	R-5
1,500-1,999	0.60	R-30	R-13	R-11	R-5	R-0	R-5
2,000-2,499	0.52	R-38	R-13	R-11	R-5	R-0	R-6
2,500-2,999	0.50	R-38	R-13	R-19	R-6	R-0	R-7
3,000-3,499	0.46	R-38	R-13	R-19	R-7	R-0	R-9
3,500-3,999	0.42	R-38	R-13	R-19	R-8	R-6, 2 ft.	R-10
4,000-4,499	0.37	R-38	R-13	R-19	R-9	R-6, 2 ft.	R-13
4,500-4,999	0.37	R-38	R-16	R-19	R-9	R-6, 2 ft.	R-16
5,000-5,499	0.36	R-38	R-19	R-19	R-9	R-6, 2 ft.	R-16
5,500-5,999	0.33	R-49	R-20	R-19	R-10	R-7, 2 ft.	R-17
6,000-6,499	0.31	R-49	R-24	R-19	R-10	R-7, 4 ft.	R-17
6,500-6,999	0.30	R-49	R-26	R-21	R-11	R-10, 4 ft.	R-17
7,000-8,499	0.30	R-49	R-26	R-21	R-11	R-12, 4 ft.	R-19
8,500-8,999	0.30	R-49	R-26	R-21	R-19	R-12, 4 ft.	R-19
9,000-12,999	0.30	R-49	R-26	R-21	R-19	R-16, 4 ft.	R-19

Table D.3 Prescriptive building envelope requirements, type A-1 residential buildings window area 25 percent of gross exterior wall area

	MAXIMUM	MINIMUM					
HEATING DEGREE DAYS	Glazing *U*-factor	Ceiling *R*-value	Exterior wall *R*-value	Floor *R*-value	Basement Wall *R*-value	Slab perimeter *R*-value and depth	Crawl space wall *R*-value
0-499	0.70	R-30	R-11	R-11	R-0	R-0	R-0
500-999	0.65	R-30	R-13	R-11	R-0	R-0	R-4
1,000-1,499	0.55	R-30	R-13	R-11	R-0	R-0	R-5
1,500-1,999	0.52	R-30	R-13	R-13	R-6	R-0	R-6
2,000-2,499	0.50	R-38	R-13	R-19	R-8	R-0	R-10
2,500-2,999	0.46	R-38	R-16	R-19	R-6	R-0	R-7
3,000-3,499	0.45	R-38	R-19	R-19	R-7	R-0	R-9
3,500-3,999	0.41	R-38	R-19	R-19	R-8	R-6, 2 ft.	R-10
4,000-4,499	0.37	R-38	R-19	R-19	R-9	R-6, 2 ft.	R-13
4,500-4,999	0.33	R-38	R-19	R-19	R-9	R-6, 2 ft.	R-17
5,000-5,499	0.29	R-38	R-19	R-19	R-9	R-6, 2 ft.	R-17
5,500-5,999	0.27	R-38	R-19	R-21	R-10	Note a	R-22
6,000-6,499	0.25	R-49	R-19	R-21	R-10	R-9, 4 ft.	R-20
6,500-6,999	0.25	R-49	R-19	R-30	R-14	Note a	Note a
7,000-8,499	0.25	R-49	R-19	R-30	R-15	Note a	Note a
8,500-8,999	0.25	R-49	R-19	R-30	R-28	Note a	Note a
9,000-12,999	0.25	R-49	R-19	R-30	R-28	Note a	Note a

APPENDIX E

BUILDING MODEL DESCRIPTION

Source: ESL Report on Thermal Mass input vs. Quick Mode input; Authors: Kim and Haberl (2003)

E.1 Description of the input file

The original file used by this study is the SNGFAM2ST.inp VER1.11 (modified by Seongchan Kim, 22nd April 2004). The input file was created to incorporate both the Quick and the Thermal Mass input options described below. Either of the options can be activated by turning on a switch activated by a macro command in the file.

E.1.1 DOE code for thermal mass option switch of SNGFAM2ST.inp

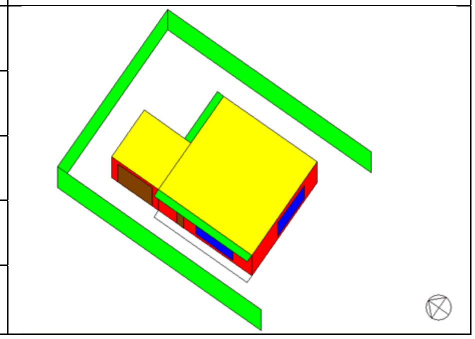
```
##IF #[b01 EQS "T"]                          $ T:THERMAL MASS WALL
     ##SET1 THERMALMASS #["O" // "N"]        $ ACTIVATING THE THERMAL MASS MODE
##ELSEIF #[b01 EQS "Q"]                      $ Q: QUICK WALL
     ##SET1 THERMALMASS #["O" // "FF"]       $ ACTIVATING QUICK WALL MODE
##ENDIF
```

Figure E. 1 DOE code of wall section of the Quick mode option (Source: Kim and Haberl 2003)

E.1.2 Description of the input file properties

The thermal properties construction materials such as wall, roof, window, and floor of base case model are based on International Energy Conservation Code 2000 (IECC 2000). The inputs include assumptions about chapter 4 and 5 of IECC 2000 to describe the standard house.

Table E.1 House dimension / heating and cooling controls assumed for the base case house (Source: Kim and Haberl 2003)

Parameter	Value	DrawBDL of IECC1103.inp
Length*Width*Height	38.73 * 38.73 * 8	
Room Temp.	73	
Heating	68	
Cooling	78	
Set back / Set up	5	

* Room temperature is the average value of winter and summer set points that are taken from Table 402.1.3.5 of IECC 2000. Set back is adjusted in systems.

E.2 Thermal properties of the input file – Quick mode version

The values used to develop model for input file are from Type A-1 Residential Buildings of IECC 2000 are given in the table below. These values apply when the Quick Mode option in the input file is turned on.

Table E.2 Thermal properties of SNGFAM2ST.inp VER1.11-Quick Mode (Source: Kim and Haberl 2003)

Heating Degree Days	Maximum	Minimum			
	Glazing U-factor	Ceiling R-value	Exterior wall R-value	Floor U-value	Floor weight (Lb/sq.ft)
1,500-1,999	0.75	R-26	R-13	1.56	11.5

E.3 Thermal properties of the input file -Thermal mass mode of input

Several options are provided SNGFAM2ST.inp VER1.11such as real roof, wall and new method for ground surface to perform the real residential house simulation – thermal mass mode. The R-value of all real materials that are applied to IECC1303 series is identical to the recommended R-value of Table

502.2.4(3), Type A-1 Residential Buildings and window area 15 percent of gross exterior wall area of IECC 2000.

E.3.1 Wall construction

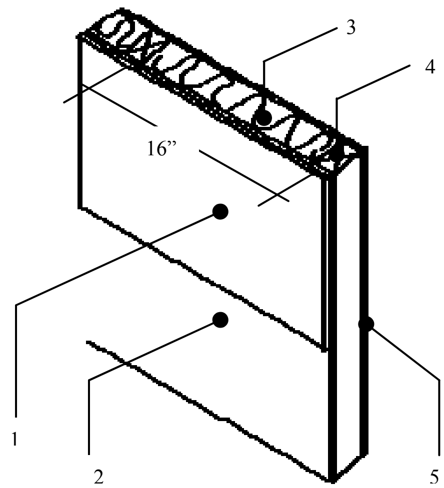
E.3.1.1 Thermal properties of wall construction

Table E.3 Thermal properties of wall construction of SNGFAM2ST.inp VER1.11: Thermal mass mode. (Source: Kim and Haberl 2003)

No	Name	Conductivity	R	Thickness	DOE code
		Btu-ft/Hr-ft2-F	Ft2.hr.F/Btu	Ft	
1	Asbestos-Vinyl Tile		0.05		AV01
2	Plywood ½”	0.0667	0.63	0.0417	PW03
3	Mineral wool / fiber Insulation	0.027	15	0.405	
4	2*4” stud	0.0667	4.37	0.3333	WD05

E.3.1.2 Calculated R-value

	Insulation Part	Frame Part
1	0.05	0.05
2	0.63	0.63
3	15	
4		4.37
5	0.45	0.45
Tot	16.13	5.5



Atot (12*16"): 192 in^2
Ains (14.5*12"): 174 in^2
Astud (12"*1 1/2"): 18in^2

Ut = 1/Rt = (1/At) * ((Astud/Rstud)+(Ains/Rins))
= (1/192)*((18/5.5)+(174/16.13))
= 0.073 Btu/h.ft^2.F

R_{tot}= 13.65568329 h.ft^2.F/Btu

The required R-value of wall of IECC 2000 code is R-13

Figure E.2 Wall dimension and calculated R-Value. (Source: Kim and Haberl 2003)

E.3.1.3 The comparison of Thermal mass mode to Quick mode options

While the Quick mode option uses U-value of the wall, the thermal mass option uses real layout to investigate thermal mass effects. The following excerpts from the code demonstrate the two options:

DOE code of Quick mode option for wall

```
##SET1 P-WALLUVALUE #[1 / c08]            $ U-VALUE OF WALL
                                          $ c08 =  13 RESISTANCE FOR EXTERNAL WALL
                                          $ SPECIFIED BY THE IECC 2000 CODE FOR
                                          $ GLAZING 15% OF WALL AREA(HR.FT^2.F/Btu)
                                          $ THIS VALUE IS INPUT BY THE USER WHICH WILL
                                          $ BE CONVERTED TO U-VALUE BY THE ##SET1 MACRO
                                          $ COMMAND

WALL-CON1 = CONSTRUCTION
$           LAYERS = WALL-LAY1
            ABSORPTANCE = P-WALLABSORPTANCE
            ROUGHNESS = P-WALLROUGHNESS
            U = P-WALLUVALUE ..

FRONT-1  =  EXTERIOR-WALL
            HEIGHT = P-WALLHEIGHTF[]              $ (FT)
            WIDTH = P-BUILDINGLENF[]              $ (FT)
            X = 0   Y = 0   Z = 0                 $ COORDINATES
            AZIMUTH = 180                         $ DEGREES
            GND-REFLECTANCE = P-GND-REFLECTANCE[] $ DOE-2 DEFAULT=0.2(0 TO 1)
            CONSTRUCTION = WALL-CON1
$           LOCATION =                              UNUSED
            SHADING-SURFACE = YES                 $ DOE-2 DEFAULT = NO
            SHADING-DIVISION = 10                 $ DOE-2 DEFAULT
$           INF-COEFF =                             USED WHEN INFILTRATION METHOD=CRACK
$                                                   IN SPACE OR SPACE-CONDITIONS
$                                                   (0 TO 160)
$           SKY-FORM-FACTOR = 0.5                   ARBITRARY(0 TO 1)
$           GND-FORM-FACTOR = 0.5                   ARBITRARY(0 TO 1)
$           SOLAR-FRACTION = 0.2                    EQUAL DIVISION AMONG THE
                                                    5 SURFACES(0 TO 1)
             INSIDE-VIS-REFL =  0.5               $ DOE-2 DEFAULT(0 TO 1)
             INSIDE-SOL-ABS = 0.5                 $ DOE-2 DEFAULT(0 TO 1)
             OUTSIDE-EMISS = P-WALLOUTEMISS[]     $ DOE-2 DEFAULT=0.9(0 TO 1)
$            FUNCTION                               UNUSED
                      ..                          $ END OF EXTERIOR WALL COMMAND
```

Figure E.3 DOE code of wall section of the Quick mode option. (Source: Kim and Haberl 2003)

DOE code of Thermal mass mode option for wall

```
WA-1  =  LAYERS
         MATERIAL = (VINYL-TILE, PLY-WOOD, INSULATION-R15, GYPSUM-BOARD)  ..
                                          $ Insulation Part of Wall
                                          $ VINYL-TILE = Asbestos Vinyl Siding
                                          $ PLY-WOOD = Plywood 1/2"
                                          $ INSULATION-R15 = MINERAL WOOL/FIBER
                                          $ GYPSUM-BOARD = Gypsum Board 1/2"
                                          $ The percentage of WA-1 = 87.5 %
WA-2  =  LAYERS
         MATERIAL = (VINYL-TILE, PLY-WOOD, STUD, GYPSUM-BOARD)  ..
                                          $ Stud Part of Wall
                                          $ VINYL-TILE = Asbestos Vinyl Siding
                                          $ PLY-WOOD = Plywood 1/2"
                                          $ STUD = 2*4 STUD
                                          $ GYPSUM-BOARD = Gypsum Board 1/2"
                                          $ The percentage of WA-2 = 12.5 %
WALL-1  = CONSTRUCTION
          LAYERS = WA-1   ..
WALL-2 =  CONSTRUCTION
          LAYERS = WA-2   ..

RIGHT-1_1 =  EXTERIOR-WALL                $ THE INSULATION PART OF WALL
$            HEIGHT = P-WALLHEIGHT          PLACED IN SET-DEFAULT(FT)
             WIDTH = 38.5                 $ (FT) S.KIM, CHANGE (P-BUILDINGWIDTH)
             X = 0  Y = 0   Z = 0         $ COORDINATES
             AZIMUTH = 180                $ DEGREES
             GND-REFLECTANCE = P-GND-REFLECTANCE
                                          $ DOE-2 DEFAULT=0.2(0 TO 1)
             CONSTRUCTION = WALL-1
$            LOCATION =                     UNUSED
             SHADING-SURFACE = YES
             SHADING-DIVISION = 10        $ DOE-2 DEFAULT
$            INF-COEFF =                    USED WHEN INFILTRATION METHOD=CRACK
                                            (0 TO 160)
             SKY-FORM-FACTOR = 0.5        $ ARBITRARY(0 TO 1)
             GND-FORM-FACTOR = 0.5        $ ARBITRARY(0 TO 1)
$            SOLAR-FRACTION = 0.2           EQUAL DIVISION AMONG THE 5 SURFACES(0 TO 1)
             INSIDE-VIS-REFL =  0.5       $ DOE-2 DEFAULT(0 TO 1)
             INSIDE-SOL-ABS = 0.5         $ DOE-2 DEFAULT(0 TO 1)
             OUTSIDE-EMISS = P-WALLOUTEMISS $ DOE-2 DEFAULT=0.9(0 TO 1)
$            FUNCTION                        UNUSED
             ..                           $ END OF EXTERIOR WALL COMMAND
RIGHT-1_2 = EXTERIOR-WALL                 $ THE STUD PART OF WALL
$            HEIGHT = P-WALLHEIGHT          PLACED IN SET-DEFAULT(FT)
             WIDTH = 5.5                  $(FT) S.KIM, CHANGE (P-BUILDINGWIDTH)
             X = 38.5  Y = 0   Z = 0      $ COORDINATES
             AZIMUTH = 180                $ DEGREES
             GND-REFLECTANCE = P-GND-REFLECTANCE
                                          $ DOE-2 DEFAULT=0.2(0 TO 1)
             CONSTRUCTION = WALL-2
$            LOCATION =                     UNUSED
             SHADING-SURFACE = YES
             SHADING-DIVISION = 10        $ DOE-2 DEFAULT
$            INF-COEFF =                    USED WHEN INFILTRATION METHOD=CRACK
                                          $ (0 TO 160)
             SKY-FORM-FACTOR = 0.5        $ ARBITRARY(0 TO 1)
             GND-FORM-FACTOR = 0.5        $ ARBITRARY(0 TO 1)
$            SOLAR-FRACTION = 0.2           EQUAL DIVISION AMONG THE 5 SURFACES
                                          $ (0 TO 1),
             INSIDE-VIS-REFL =  0.5       $ DOE-2 DEFAULT(0 TO 1)
             INSIDE-SOL-ABS = 0.5         $ DOE-2 DEFAULT(0 TO 1)
             OUTSIDE-EMISS = P-WALLOUTEMISS $ DOE-2 DEFAULT=0.9(0 TO 1)
             ..                           $ END OF EXTERIOR WALL COMMAND
```

Figure E.4 DOE code of wall section of the Thermal mass mode option. (Source: Kim and Haberl 2003)

E.3.2 Roof construction

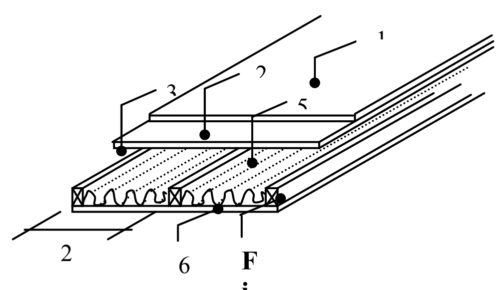
E.3.2.1 Thermal properties of roof construction

Table E.4 Thermal properties of roof construction of refined base case model. (Source: Kim and Haberl 2003)

No.	Name	Conductivity	R	Thickness	DOE code
		Btu-ft/Hr-ft2-F	Ft2.hr.F/Btu	Ft	
1	Asphalt shingle		0.44		AR02
2	Plywood ½”	0.0667	0.63	0.0417	PW03
3	Air gap 24"		0.92		AL33
4	2*6 Stud	0.0667	7.5	0.5	
5	Mineral wool / fiber Insulation	.027	27		
6	Gypsum board ½”	0.0926	0.45	0.0417	GP01

E.3.2.2 Calculated R-value

	Insulation Part	Frame Part
1	0.44	0.44
2	0.63	0.63
3	0.92	0.92
4		7.5
5	27	0.45
6	0.56	0.56
Tot	29.55	10.05



Atot (12*24"): 288 in^2
Ains (22.5*12"): 270 in^2
Astud (12"*1 1/2"): 18 in^2

Ut = 1/Rt = (1/At) * ((Astud/Rstud)+(Ains/Rins))
= (1/288)*((18/10.05)+(270/29.55))
= 0.038 Btu/h.ft^2.F

Rt= 26.35 h.ft^2.F/Btu

The required R-value of wall of IECC 2000 code is R-26

Figure E.5 Roof dimension and calculated R-value. (Source: Kim and Haberl 2003)

E.3.2.3 The comparison of Thermal mass mode to Quick mode options

While the Quick mode option uses U-value of the roof, the thermal mass option uses real layout to investigate thermal mass effects. The following excerpts from the code demonstrate the two options:

DOE code of Quick mode option for roof

```
##SET1 P-CLNGUVALUE #[1 / c04]          $ U-VALUE OF ROOF
                                         $ c04 =  26 RESISTANCE FOR ROOF
                                         $ SPECIFIED BY THE IECC 2000 CODE FOR
                                         $ GLAZING 15% OF WALL AREA(HR.FT^2.F/Btu)
                                         $ THIS VALUE IS INPUT BY THE USER WHICH WILL
                                         $ BE CONVERTED TO  A PARAMETER FOR U-VALUE BY
                                         $ THE ##SET1 MACRO COMMAND.

CLNG-CON1 =CONSTRUCTION
$          LAYERS = CLNG-LAY1
           U = P-CLNGUVALUE  ..          $ IECC 2001(RESIDENTIAL BUILDING)
                                           (Btu/HR.FT^2.F)

TOP-A1  =  ROOF
           HEIGHT = P-BUILDINGLENGTH     $ (FT)
           WIDTH = P-BUILDINGWIDTH       $ (FT)
           X = 0   Y = 0   Z = 8         $ COORDINATES
           AZIMUTH = 180                 $ (DEGREES)
           TILT = 0                      $ (DEGREES)
           CONSTRUCTION = CLNG-CON1
$          LOCATION =                       UNUSED
$          INF-COEFF =                      USED WHEN INFILTRATION METHOD=CRACK
                                            (0 TO 160)
           SKY-FORM-FACTOR = 0.5         $ ARBITRARY(0 TO 1)
           GND-FORM-FACTOR = 0.0         $ ARBITRARY(0 TO 1)
$          SOLAR-FRACTION = 0.2            APPROXIMATE VALUE(0 TO 1)
           INSIDE-VIS-REFL =  0.5        $ DEFAULT(0 TO 1)
           INSIDE-SOL-ABS = 0.5          $ DEFAULT(0 TO 1)
           SHADING-SURFACE = YES
           SHADING-DIVISION = 10         $ DEFAULT
           OUTSIDE-EMISS = P-ROOFOUTEMISS $ DOE-2 DEFAULT=0.9(0 TO 1)
$          FUNCTION                        UNUSED
           ..                            $ END OF ROOF COMMAND
```

Figure E.6 DOE code of roof section of the Quick mode option. (Source: Kim and Haberl 2003)

DOE code of Thermal mass option for roof

```
CL-1 = LAYERS
       MATERIAL = (ASPHALT-SIDING, PLY-WOOD, AIR-LAYER, INSULATION-R27, GYPSUM-BOARD) ..
                                             $ Insulation Part of Ceiling
                                             $ PLY-WOOD = THICKNESS 1/2"
                                             $ AIR-LAYER = 4 INCH OR MORE, HORIZONTAL ROOF
                                             $ INSULATION-R27 = MINERAL WOOL/FIBER
                                             $ GYPSUM-BOARD = Gypsum Board 1/2"
                                             $ The percentage of CL-1 = 91.7 %

CL-2 = LAYERS
       MATERIAL = (ASPHALT-SIDING, PLY-WOOD, AIR-LAYER, STUD6, GYPSUM-BOARD) ..
                                             $ Stud Part of Ceiling
                                             $ PLY-WOOD = THICKNESS 1/2"
                                             $ AIR-LAYER = 4 INCH OR MORE, HORIZONTAL ROOF
                                             $ STUD6 = 2*6 STUD
                                             $ The percentage of CL-2 = 8.3 %

CEIL-1    = CONSTRUCTION
            LAYERS = CL-1   ..
CEIL-2    = CONSTRUCTION
            LAYERS = CL-2   ..
TOP-A1   =  ROOF
            HEIGHT = 40.44               $ (FT)
            WIDTH = 44                   $ (FT)
            X = 0   Y = 0   Z = 8
            AZIMUTH = 180                $ (DEGREES)
            TILT = 0                     $ (DEGREES)
            CONSTRUCTION = CEIL-1
$           LOCATION =                     UNUSED
$           INF-COEFF =                    USED WHEN INFILTRATION METHOD=CRACK
                                         $ (0 TO 160)
            SKY-FORM-FACTOR = 0.5        $ ARBITRARY(0 TO 1)
            GND-FORM-FACTOR = 0.0        $ ARBITRARY(0 TO 1)
$           SOLAR-FRACTION = 0.2           APPROXIMATE VALUE(0 TO 1)
            INSIDE-VIS-REFL =  0.5       $ DEFAULT(0 TO 1)
            INSIDE-SOL-ABS = 0.5         $ DEFAULT(0 TO 1)
            SHADING-SURFACE = YES
            SHADING-DIVISION = 10        $ DEFAULT
            OUTSIDE-EMISS = P-ROOFOUTEMISS $ DOE-2 DEFAULT=0.9(0 TO 1)
$           FUNCTION                       UNUSED
                      ..                 $ END OF ROOF COMMAND

TOP-A2  =   ROOF
            HEIGHT = 3.67                $ (FT)
            WIDTH = 44                   $ (FT)
            X = 0   Y = 40.44   Z = 8
            AZIMUTH = 180                $ (DEGREES)
            TILT = 0                     $ (DEGREES)
            CONSTRUCTION = CEIL-2
$           LOCATION =                     UNUSED
$           INF-COEFF =                    USED WHEN INFILTRATION METHOD=CRACK
                                          (0 TO 160)
            SKY-FORM-FACTOR = 0.5        $ ARBITRARY(0 TO 1)
            GND-FORM-FACTOR = 0.0        $ ARBITRARY(0 TO 1)
$           SOLAR-FRACTION = 0.2           APPROXIMATE VALUE(0 TO 1)
            INSIDE-VIS-REFL =  0.5       $ DEFAULT(0 TO 1)
            INSIDE-SOL-ABS = 0.5         $ DEFAULT(0 TO 1)
            SHADING-SURFACE = YES
            SHADING-DIVISION = 10        $ DEFAULT
            OUTSIDE-EMISS = P-ROOFOUTEMISS $ DOE-2 DEFAULT=0.9(0 TO 1)
$           FUNCTION                       UNUSED
..                   $ END OF ROOF COMMAND
```

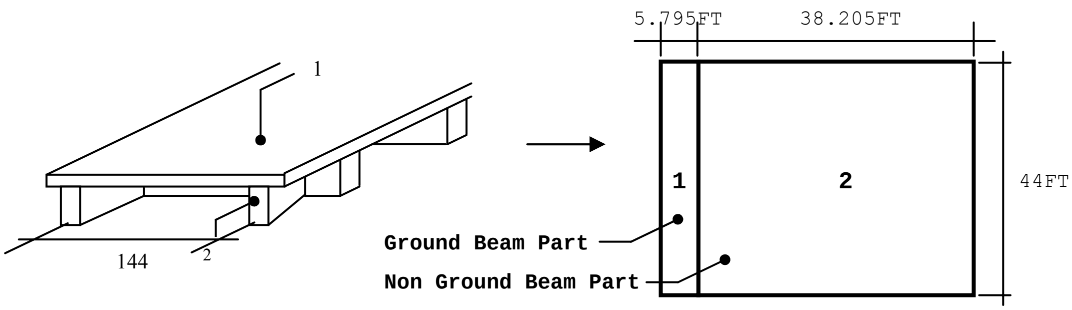
Figure E.7 DOE code of roof section for the Thermal mass mode option. (Source: Kim and Haberl 2003)

E.3.4 Floor construction

E.3.4.1 Thermal properties of floor construction

Table E.5 Thermal properties of floor construction common to both the options of input. (Source: Kim and Haberl 2003)

No	Name	Conductivity	R	Thickness	DOE code
		Btu-ft/Hr-ft2-F	Ft2.hr.F/Btu	Ft	
1	Concrete Slab	1.0417	0.32	0.3333	CC14



E.3.4.2 LBNL method for ground surface

According to Winkelmann (1998), DOE-2 will account for thermal mass only if the following conditions are met:

1. The underground surface is entered with a layers-type construction according to the procedure described below.

2. Custom weighting factors are calculated for the space, i.e., FLOOR-WEIGHT=0 in the SPACE or SPACE-CONDITIONS command.

The following paragraphs describe the procedure for defining the underground surface accounting for thermal mass in the input file:

1. Choose a value of the perimeter conduction factor, F2, from Table 1,2 or 3 for the configuration that best matches the type of surface.

F2=0.77

2. Using F2, calculating R_{eff}, the *effective resistance* of the underground surface.

$$R_{eff} = A / (F2 * P_{exp})$$

3. Set U-EFFECTIVE = 1 / R_{eff}

4. Define a construction

$$R_{eff} = R_{us} + R_{soil} + R_{fic}$$

$$R_{fic} = R_{eff} – R_{us} - R_{soil}$$

Actual slab resistance: R_{us1} = 2.4 + 0.77 = 3.17

Rfic = R_{eff1} – R_{us1} - R_{soil} = 5.96 – 3.17 – 1.0 = 1.79

The above specified method has been included in the input code.

E.3.4.3 Ground surface DOE input summary

```
##SET1 P-REFFECTIVE #[P-AREAF[] / #[PERIM-CON[] *
P-PARAMETER[]]]
                                  $ VALUE FOR CALCULATING P-REFFECTIVE
                                  $ Reff=A/(f2*Pexp), WHERE f2 FROM  WINKLEMAN'S ARTICLE
                                  $ VALUES FROM PERIM-CON[] IS OBTAINED FROM THE IECC
                                  $ SPECIFICATIONS FOR PERIMETER CONDUCTIVITY
##SET1 P-UEFFECTIVE #[1 / P-REFFECTIVE[]]
                                  $ U-EFFECTIVE = 1/Reff
##SET1 P-RUS #[c19 + c20]         $ Rus = Rcon + Rair
##SET1 P-RFIC #[P-REFFECTIVE[] - P-RUS[]]
                                  $ VALUE FOR NEXT LINES
##SET1 P-RFIC1 #[P-RFIC[] - 1]    $ Rfic = Reff - Rus - Rsoil
```

The values for the P-RFIC1 are then used to define the materials for a fictitious underground surface. The other two material representing soil and concrete are borrowed from the article:

```
MAT-FIC-1          = MATERIAL
                     RESISTANCE   = P-RFIC1[] ..    $(HR.FT^2.F/Btu), THE RFIC VALUE
SOIL-12IN          = MATERIAL                       $ FROM ARTICLE(UNDERGROUND SURFACE)
                     THICKNESS    = 1.0             $(FT)
                     CONDUCTIVITY = 1.0             $(Btu.FT/HR.FT^2.F)
                     DENSITY      = 115             $(LB/FT^3)
                     SPECIFIC-HEAT= 0.1  ..         $(Btu/LB.F)
CONCRETE-4IN       = MATERIAL                       $ CC03 IN DOE-2.1E LIBRARY
                     THICKNESS    = 0.3333          $(FT)
                     CONDUCTIVITY = 0.7576          $(Btu.FT/HR.FT^2.F)
                     DENSITY      = 140.0           $(LB/FT^3)
                     SPECIFIC-HEAT= 0.2  ..         $(Btu/LB.F)
LAY-SLAB-1        =  LAYERS
                     MATERIAL = (MAT-FIC-1,SOIL-12IN,CONCRETE-4IN)
                    INSIDE-FILM-RES = 0.77   ..
CON-SLAB-1 =         CONSTRUCTION
                     LAYERS = LAY-SLAB-1   ..

FLOOR1-R         =   UNDERGROUND-FLOOR
                     AREA = P-AREAF[]                $(FT^2)PERIMETER,
$                    HEIGHT =                          ALTERNATE METHODS FOR DEFINING
$                    WIDTH =                           UNDERGROUND-FLOOR(FT)
$                    LOCATION =                        UNUSED
                    CONSTRUCTION = CON-SLAB-1
                    TILT = 180                       $ DOE-2 DEFAULT = 90 (DEGREES)
                    U-EFFECTIVE = P-UEFFECTIVE[]     $ ONLY REQUIRED  WHEN CWF ACTIVATED
                                                     $ (Btu/HR.FT^2.F)
$                   MULTIPLIER = 1                     DOE-2 DEFAULT,UNUNSED
$                   INSIDE-SURFACE-TEMP = NO           DOE-2 DEFAULT,UNUNSED( OR YES)
                    INSIDE-VIS-REFL = 0.2            $ DOE-2 DEFAULT(0 TO 1)
                    SOLAR-FRACTION = 0.2             $ EQUAL DIVISION AMONG THE
                                                     $ 5 SURFACES(0 TO 1)
                    INSIDE-SOL-ABS = 0.8             $ DOE-2 DEFAULT(0 TO 1)
$                   FUNCTION = UNUSED
                     ..                              $ END OF UNDERFGROUND FLOOR COMMAND
```

Figure E.8 DOE code of floor section of the input file which will always be in thermal mass mode. (Source: Kim and Haberl 2003)

APPENDIX F

MODELING DYNAMIC PROPERTIES OF GLAZING IN DOE-2.1E

Source: DOE-2.1e Manual (1993); Pg: 2.118-126

In order to simulate the properties of glazing which change according to environmental conditions, DOE-2.1e lists two options:

- Model for switchable glazing option
- Schedule option

F.1 Model for switchable glazing option (*Source: DOE-2.1e Manual Pgs: 2.118 – 2.12)*

To model this type of glazing, a number of selections are to be made by the user:

- Glass type for un-switched state,
- Glass type for fully switched state,
- Control variable for switching set points,
- Switching schedule

If the value of the control variable is less than SWITCH-SET-LO, the glass is in unswitched state with solar-optical properties given by GLASS-TYPE. If the control variable is greater than SWITCH-SET-HI, the glass is in fully switched state, with solar-optical properties given by GLASS-TYPE-SW. If the control variable is between SWITCH-SET-LO and SWITCH-SET-HI, the glass is in partially switched state, with solar-optical properties given by the weighted average of GLASS-TYPE and GLASS-TYPE-SW, respectively, and V is the value of the control variable in a particular hour, then the resultant transmittance is:

$$\mathbf{T = T1 * (1\text{-}S) + T2 * S} \qquad \text{(Equation: 3.1)}$$

where S the "switching" factor for V ≤ SWITCH-SET-LO is given by:

$$\mathbf{S = 0} \qquad \text{(Equation: 3.2)}$$

if (SWITCH-SET-LO)<V<(SWITCH-SET-HI)

$$\mathbf{S = V - (SWITCH\text{-}SET\text{-}LO)/\ (SWITCH\text{-}SET\text{-}HI) - (SWITCH\text{-}SET\text{-}LO)} \qquad \text{(Equation: 3.3)}$$

if V ≥ SWITCH-SET-HI

$$S = 1.0 \quad \text{(Equation: 3.4)}$$

Thus, S varies from 0.0 for the unswitched state to 1.0 for the fully switched state. An example of the input code incorporating the setting of switching set points is given in Figure F.1.

```
CLEAR-IG-1  = GLASS-TYPE
              GLASS-TYPE-CODE = 2003  ..
TINTED-IG-1 = GLASS-TYPE
              GLASS-TYPE-CODE = 2203  ..
SUMMER-1    =  SCHEDULE THRU MAY 31 (ALL)(1,24)(0)
              THRU SEP 30  (ALL)(1,24)(1)
              THRU DEC 31 (ALL)(1,24)(0)
WIN-1       =  WINDOW
              GLASS-TYPE = CLEAR-IG-1
              GLASS-TYPE-SW = TINTED-IG-1
              SWITCH-CONTROL = TOT-SOL-INC
              SWITCH-SET-LO = 20
              SWITCH-SET-HI = 100
              SWITCH-SCH = SUMMER-1
```

Figure F.1 Example from DOE-2.1e input file showing the setting of switching setpoints

GLASS-TYPE accepts the u-name of the glass type for the unswitched state. For switchable glazing, glass types must be chosen from the window library.

GLASS-TYPE-SW accepts the u-name of the glass type for the fully switched state. For switchable glazing, glass types must be chosen from the window library.

SWITCH-CONTROL accepts a code-word that specifies the control variable for switching. Options for switch control are as follows:

NO-SWITCH	No switching
DIR-SOL-INC	Direct solar incident on the glazing, after shading by overhangs, setback, neighboring buildings, etc.
TOT-SOL-INC	Total solar radiation incident on glazing after shading by overhangs, setback,and neighboring buildings, etc.
DIR-SOL-TR	Direct solar radiation transmitted by the glazing in the unswitched state
TOT-SOL-TR	Total solar radiation transmitted by glazing in the unswitchable state.
TOT-SOL-HOR	Total solar radiation incident on an unobstructed horizontal plane.
OUTSIDE-TEMP	Outside drybulb temperature

SPACE-LOAD Previous hour thermal load per square fool of floor area for the space that contains the window. Note that the cooling loads in Doe-2 are positive and the heating loads are negative. Switching control is to be modeled only if the actual space temperature for hours that the control is in effect is within a few degrees of the LOADS calculations.

SWITCH-SET-LO is the lower set point value for the control variable.

SWITCH-SET-HI is the upper setpoint value for the control variable.

SWITCH-SCHEDULE accepts the u-name of a schedule that specifies when switching is allowed. and not allowed. This schedule allows switching to be disabled at times of the day or year when it may be

Relevant notes:

- Switching control is applicable only to exterior windows.
- Switching control is in effect only during sun-up hours. It does not work work at night and hence should not be used to switch between window U-values. The keyword CONDUCT-TMIN-SCH should be used instead.
- Shading devices such as blinds and drapes can be used in conjunction with switchable control of the glazing. In this case, the program decides what state the glazing should be switched to, ignoring the possible presence of shading devices, and then adjusts the solar intensity through the switched glazing for the presence of the shading device. For example if MAX-SOL-SCH is used to deploy a shading device when transmitted direct solar gain exceeds a trigger value, the program will first apply the switching controls to glazing and then calculate the transmitted solar intensity based on solar properties of the switched glass.

SWITCH-SET-LO is the lower setpoint value for the control variable.

SWITCH-SET-HI is the upper setpoint value for the control variable.

SWITCH-SCH accepts the u-name of a schedule that specifies when switching is allowed (schedule value = 1) and not allowed (schedule value = 0). This schedule allows switching to be disabled at times of the day or year when it might be disadvantageous. If SWITCH-SCH is not entered, the program will assume that switching is allowed all the time.

F.2 Schedule option ((Source: LBNL 1993a*)*

While specifying window properties in the DOE-2 input file, the properties of the window can be altered using two commands i.e., SHADING-SCHEDULE and CONDUCT-SCHEDULE. These are referred to as schedule controls. Specifications are given below:

- SHADING-SCHEDULE accepts as input the U-name of a previously entered schedule that defines hourly values of a multiplier on the SHADING-COEF. This represents the shading effect of movable devices such as blinds, curtains, or shutters, but in this study it is used to vary the SC of glazing.
- CONDUCT-SCHEDULE identifies the U-name of the schedule that describes any change in the heat conductance of the window relative to the GLASS-CONDUCTANCE. The factor in the schedule may be less than, equal to, or greater than 1.0. The factor is used as a multiplier against GLASS-CONDUCTANCE.

In addition to the above mentioned controls, there are options to control shading devices when either the solar gain, outside temperature, or daylight glare exceed user-specified threshold values. These are called "threshold controls". The following information for schedules to regulate window properties in the DOE-2 input:

WIN-SHADE-TYPE specifies a code word giving type of shading device present on the window for sun and/ or glare control.

- NO-SHADE – Bare window
- MOVABLE – INTERIOR: Interior shade which can be retraced, such as drapes.
- MOVABLE – EXTERIOR: Exterior shade which can be retraced.
- FIXED – INTERIOR: Interior shade which cannot be retraced.
- FIXED – EXTERIOR: Exterior shade which cannot be retraced.

VIS-TRANS –SCH is the u-name of a schedule which gives the daylight transmittance of the window shading device when it covers the window. A transmittance schedule is used, rather than a single fixed value, to allow seasonal change in the transmittance of the shading device.

MAX-SOLAR-SCH is the u-name of a schedule of direct solar gain values in Btu/sqft-hr. The program will automatically deploy a shading device if the heat gain per sqft from direct solar radiation transmitted through the window exceeds the specified value. If MAX-SOLAR-SCH is specified, a corresponding SHADING-SCHEDULE should be assigned to the window.

SUN-CTRL-PROB may be specified if the sun control device on the window is manually operated. This keyword gives the probability that the occupants of a space will deploy the shading device if the transmitted direct solar gain exceeds the MAX-SOLAR-SCH value.

GLARE-CTRL-PROB may be specified if manual operation of a window shading device for glare-control is desired. This keyword gives the propability that the occupants of a space will deploy a shading device when the MAX-GLARE value is exceeded.

CONDUCT-TMIN-SCH is a schedule of values of outside drybulb temperature below which movable insulation will be deployed on a window. If this keyword is specified, a corresponding SHADING_SCHEDULE and CONDUCT_SCHEDULE should be assigned to the window.

Various control options and their input requirements are summarized in Table F.6.

Table F.1 Window shading device control options (Source: DOE-2.1e manual)

Window Shading Device Control Options		
A. Windows in non-daylight spaces (DAYLIGHTING = NO)		
Control Type	**Input required**	**Effect**
Preset Schedule	SHADING-SCHEDULE	Shading coefficient of glazing is multiplied hourly by SHADING-SCHEDULE value
Solar gain control	MAX-SOLAR-SCH SHADING-SCHEDULE (SUN-CTRL-PROB and OPEN-SHADE-SCH optional)	Shade is fully closed if transmitted direct solar gain exceeds MAX-SOLAR_SCH value
Heat loss control with movable insulation	CONDUCT-TMIN-SCH CONDUCT-SCHEDULE SHADING-SCHEDULE	Insulation is moved into place if outside dry-bulb temperature falls below CONDUCT-TMIN-SCH value.
B. Windows in daylight spaces (DAYLIGHTING = YES)		
Control Type	**Input required**	**Effect**
Preset Schedule	VIS-TRANS-SCH SHADING-SCHEDULE	Glass visible transmittance and shading coefficient are multiplied hourly by VIS-TRANS-SCH and SHADING-SHCEDULE, respectively
Solar gain control	MAX-SOLAR-SCH SHADING-SCHEDULE (SUN-CTRL-PROB and OPEN-SHADE-SCH optional)	Shading is fully closed if transmotted direct solar gain exceeds MAX-SLOAR-SCH value
Heat loss control with movable insulation	CONDUCT-TMIN-SCH CONDUCT-SCHEDULE SHADING-SCHEDULE	Insulation is moved into place if outside drybulb temperature falls below CONDUCT-TMIN-SCH value
Glare control	MAX-GLARE VIS-TRANS-SCH SHADING-SCHEDULE WIN-SHADE-TYPE (OPEN-SHADE-SCH Optional)	Shade is fully closed if daylight glare is at either lighting reference point exceeds MAX-GLARE value

APPENDIX G

WINDOW-5 OUTPUT FILES

1. Single Pane Clear (SPC); WINDOW ID: 1000
2. Double Pane Clear (DPC); WINDOW ID: 2000
3. Low-E as per IECC specifications - Base-case; WINDOW ID: 2661
4. Low-E Low Solar (LELS); WINDOW ID: 8004
5. Super low-E Low Solar (SULLS); WINDOW ID: 8002
6. High solar switch option for SULLS WINDOW ID: 8003
7. Ultra low-E Low Solar (ULLS) WINDOW ID: 8001
8. High solar switch option for SULLS WINDOW ID: 8000

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

Unit System : SI
Name        : DOE-2 WINDOW LIB
Desc        : Picture
Window ID   : 1000
Tilt        : 90.0
Glazings    : 1
Frame       :  3 Al flush              3.970
Spacer      :  1 Class1                2.330  -0.010   0.138
Total Height: 1524.0 mm
Total Width : 4724.4 mm
Glass Height: 1409.7 mm
Glass Width : 4610.1 mm
Mullion     : None
Gap        Thick    Cond  dCond    Vis   dVis   Dens   dDens     Pr     dPr
1             0        0      0      0      0      0       0      0       0
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  0.834 0.833 0.831 0.827 0.818 0.797 0.749 0.637 0.389 0.000 0.753
Abs1  0.091 0.092 0.094 0.096 0.100 0.104 0.108 0.110 0.105 0.000 0.101
Abs2      0     0     0     0     0     0     0     0     0     0     0
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 0.075 0.075 0.075 0.077 0.082 0.099 0.143 0.253 0.506 1.000 0.136
Rbsol 0.075 0.075 0.075 0.077 0.082 0.099 0.143 0.253 0.506 1.000 0.136
Tvis  0.899 0.899 0.898 0.896 0.889 0.870 0.822 0.705 0.441 0.000 0.822
Rfvis 0.083 0.083 0.083 0.085 0.091 0.109 0.156 0.272 0.536 1.000 0.148
Rbvis 0.083 0.083 0.083 0.085 0.091 0.109 0.156 0.272 0.536 1.000 0.148
SHGC  0.858 0.858 0.857 0.853 0.844 0.825 0.778 0.667 0.418 0.000 0.780
SC: 0.91



Layer ID#          102        0        0        0        0        0
Tir              0.000        0        0        0        0        0
Emis F           0.840        0        0        0        0        0
Emis B           0.840        0        0        0        0        0
Thickness(mm)      3.0        0        0        0        0        0
Cond(W/m2-K     )328.1        0        0        0        0        0
Spectral File  CLEAR_3.DAT         None         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  3.54  2.76  3.63 3.63  3.67 3.67  3.75 3.75  4.11 4.11
   0        6.71  30.84  3.30  3.11  5.87 5.87  5.51 5.51  5.52 5.52  6.21 6.21
 783        0.00   4.00  3.64  2.58  3.63 3.63  3.67 3.67  3.75 3.75  4.11 4.11
 783        6.71  30.84  3.33  3.07  5.87 5.87  5.51 5.51  5.52 5.52  6.21 6.21
```

Figure G.1 WINDOW-5 output file for single pane clear glazing type (SPC); Window ID: 1000

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

Unit System : SI
Name        : DOE-2 WINDOW LIB
Desc        : Double Clear IG
Window ID   : 2000
Tilt        : 90.0
Glazings    : 2
Frame       :  3 Al flush              3.970
Spacer      :  1 Class1                2.330  -0.010   0.138
Total Height: 1524.0 mm
Total Width : 4724.4 mm
Glass Height: 1409.7 mm
Glass Width : 4610.1 mm
Mullion     : None
Gap        Thick    Cond  dCond    Vis   dVis   Dens   dDens     Pr     dPr
1 Air        6.3 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  0.703 0.702 0.699 0.692 0.678 0.646 0.577 0.438 0.208 0.000 0.601
Abs1  0.096 0.097 0.099 0.102 0.106 0.112 0.119 0.127 0.130 0.000 0.110
Abs2  0.072 0.073 0.074 0.075 0.077 0.078 0.077 0.070 0.050 0.000 0.073
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 0.128 0.128 0.128 0.130 0.139 0.164 0.227 0.365 0.612 1.000 0.206
Rbsol 0.128 0.128 0.128 0.130 0.139 0.164 0.227 0.365 0.612 1.000 0.206
Tvis  0.814 0.814 0.813 0.809 0.797 0.766 0.693 0.537 0.273 0.000 0.712
Rfvis 0.150 0.150 0.150 0.153 0.164 0.193 0.264 0.418 0.682 1.000 0.238
Rbvis 0.150 0.150 0.150 0.153 0.164 0.193 0.264 0.418 0.682 1.000 0.238
SHGC  0.759 0.759 0.756 0.751 0.738 0.708 0.640 0.498 0.257 0.000 0.660
SC: 0.81



Layer ID#          102      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           0.840    0.840        0        0        0        0
Thickness(mm)      3.0      3.0        0        0        0        0
Cond(W/m2-K     )328.1    328.1        0        0        0        0
Spectral File  CLEAR_3.DAT  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  3.41  2.49  2.37 2.37  2.48 2.48  2.56 2.56  2.75 2.75
   0        6.71  30.84  3.24  2.66  3.11 3.11  3.19 3.19  3.26 3.26  3.53 3.53
 783        0.00   4.00  3.60  1.95  2.37 2.37  2.48 2.48  2.56 2.56  2.75 2.75
 783        6.71  30.84  3.29  2.43  3.11 3.11  3.19 3.19  3.26 3.26  3.53 3.53
```

Figure G.2 WINDOW-5 output file for double pane clear glazing type (DPC); Window ID: 2000

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

Unit System : SI
Name        : DOE-2 WINDOW LIB
Desc        : Double pane Low
Window ID   : 2661
Tilt        : 90.0
Glazings    : 2
Frame       :  3 Al flush              3.970
Spacer      :  1 Class1                2.330  -0.010   0.138
Total Height: 1524.0 mm
Total Width : 4724.4 mm
Glass Height: 1409.7 mm
Glass Width : 4610.1 mm
Mullion     : None
Gap        Thick    Cond  dCond    Vis   dVis   Dens   dDens     Pr     dPr
1 Air       12.7 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  0.346 0.348 0.343 0.336 0.326 0.308 0.269 0.195 0.089 0.000 0.287
Abs1  0.259 0.262 0.269 0.273 0.274 0.276 0.287 0.296 0.244 0.001 0.273
Abs2  0.039 0.039 0.039 0.040 0.041 0.041 0.040 0.035 0.025 0.000 0.038
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 0.356 0.351 0.349 0.351 0.360 0.375 0.404 0.475 0.642 0.999 0.392
Rbsol 0.293 0.289 0.286 0.285 0.287 0.298 0.329 0.413 0.595 1.000 0.325
Tvis  0.691 0.695 0.685 0.672 0.655 0.619 0.541 0.391 0.180 0.000 0.575
Rfvis 0.094 0.087 0.084 0.087 0.100 0.124 0.171 0.277 0.513 0.999 0.154
Rbvis 0.109 0.103 0.102 0.106 0.120 0.150 0.215 0.361 0.631 1.000 0.191
SHGC  0.397 0.400 0.395 0.389 0.380 0.362 0.323 0.245 0.128 0.000 0.338
SC: 0.43



Layer ID#          960      103        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           0.041    0.840        0        0        0        0
Thickness(mm)      3.0      5.7        0        0        0        0
Cond(W/m2-K     )330.8    175.0        0        0        0        0
Spectral File TiAC40_3.afg  CLEAR_6.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  3.31  2.19  1.38 1.38  1.36 1.36  1.40 1.40  1.46 1.46
   0        6.71  30.84  3.21  2.29  1.67 1.67  1.55 1.55  1.58 1.58  1.65 1.65
 783        0.00   4.00  3.76  1.34  1.38 1.38  1.36 1.36  1.40 1.40  1.46 1.46
 783        6.71  30.84  3.32  1.91  1.67 1.67  1.55 1.55  1.58 1.58  1.65 1.65
```

Figure G.3   WINDOW-5 output file for low-E glazing type (CODE) as per IECC specifications; Window ID: 2661

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

Unit System : SI
Name        : DOE-2 WINDOW LIB
Desc        : Picture
Window ID   : 8004
Tilt        : 90.0
Glazings    : 2
Frame       :  5 Vinyl                 1.700
Spacer      :  1 Class1                2.330  -0.010   0.138
Total Height: 1500.0 mm
Total Width :  600.0 mm
Glass Height: 1360.3 mm
Glass Width :  460.3 mm
Mullion     : None
Gap        Thick    Cond  dCond    Vis   dVis   Dens   dDens      Pr     dPr
1 Air       12.7 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  0.226 0.227 0.224 0.219 0.213 0.201 0.176 0.127 0.058 0.000 0.187
Abs1  0.665 0.671 0.676 0.677 0.672 0.664 0.654 0.613 0.452 0.001 0.642
Abs2  0.016 0.017 0.017 0.017 0.017 0.018 0.017 0.015 0.011 0.000 0.016
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 0.093 0.086 0.084 0.087 0.098 0.117 0.153 0.245 0.479 0.999 0.144
Rbsol 0.308 0.304 0.301 0.299 0.301 0.311 0.340 0.421 0.599 1.000 0.336
Tvis  0.573 0.577 0.569 0.558 0.543 0.514 0.449 0.324 0.149 0.000 0.477
Rfvis 0.085 0.078 0.075 0.078 0.090 0.112 0.155 0.257 0.494 0.999 0.141
Rbvis 0.106 0.100 0.098 0.103 0.117 0.147 0.212 0.359 0.630 1.000 0.188
SHGC  0.293 0.295 0.293 0.289 0.282 0.270 0.243 0.189 0.104 0.000 0.253
SC: 0.26



Layer ID#          936      103        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           0.031    0.840        0        0        0        0
Thickness(mm)      5.7      5.7        0        0        0        0
Cond(W/m2-K     )176.5    175.0        0        0        0        0
Spectral File  ES272_6.AFG  CLEAR_6.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  3.31  2.19  1.36 1.36  1.34 1.34  1.37 1.37  1.43 1.43
   0        6.71  30.84  3.21  2.29  1.64 1.64  1.52 1.52  1.55 1.55  1.61 1.61
 783        0.00   4.00  4.43  2.08  1.36 1.36  1.34 1.34  1.37 1.37  1.43 1.43
 783        6.71  30.84  3.49  1.82  1.64 1.64  1.52 1.52  1.55 1.55  1.61 1.61
```

Figure G.4 WINDOW-5 output file for low-E low solar glazing type (LELS); Window ID: 8004

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

Unit System : SI
Name        : DOE-2 WINDOW LIB
Desc        : Picture
Window ID   : 8002
Tilt        : 90.0
Glazings    : 3
Frame       :  5 Vinyl                 1.700
Spacer      :  1 Class1                2.330  -0.010   0.138
Total Height: 1500.0 mm
Total Width :  600.0 mm
Glass Height: 1360.3 mm
Glass Width :  460.3 mm
Mullion     : None
Gap        Thick    Cond  dCond    Vis   dVis   Dens   dDens      Pr     dPr
1 Krypton    6.3 0.00866  2.826  2.346  7.777  3.738 -0.0132  0.672 0.00003
2 Krypton    6.3 0.00866  2.826  2.346  7.777  3.738 -0.0132  0.672 0.00003
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  0.218 0.151 0.148 0.145 0.140 0.130 0.109 0.072 0.027 0.000 0.120
Abs1  0.353 0.404 0.412 0.416 0.415 0.415 0.420 0.411 0.317 0.001 0.404
Abs2  0.076 0.026 0.026 0.026 0.026 0.027 0.026 0.024 0.018 0.000 0.025
Abs3  0.017 0.006 0.006 0.006 0.006 0.006 0.006 0.005 0.003 0.000 0.006
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 0.337 0.413 0.408 0.407 0.413 0.423 0.439 0.488 0.635 0.999 0.435
Rbsol 0.333 0.509 0.505 0.500 0.496 0.497 0.511 0.557 0.665 1.000 0.513
Tvis  0.521 0.482 0.474 0.463 0.447 0.416 0.349 0.231 0.086 0.000 0.384
Rfvis 0.152 0.187 0.182 0.182 0.192 0.212 0.249 0.334 0.536 0.999 0.235
Rbvis 0.183 0.259 0.258 0.261 0.272 0.299 0.360 0.490 0.702 1.000 0.333
SHGC  0.283 0.184 0.182 0.179 0.174 0.164 0.143 0.104 0.051 0.000 0.153
SC: 0.25



Layer ID#          963     1510      103        0        0        0
Tir              0.000    0.000    0.000        0        0        0
Emis F           0.840    0.755    0.840        0        0        0
Emis B           0.043    0.055    0.840        0        0        0
Thickness(mm)      5.7      0.1      5.7        0        0        0
Cond(W/m2-K     )176.5    1839.7    175.0        0        0        0
Spectral File TiAC40_6.afg   HMSC75.SWT  CLEAR_6.DAT         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  3.24  1.83  0.65 0.65  0.68 0.68  0.70 0.70  0.73 0.73
   0        6.71  30.84  3.19  1.87  0.70 0.70  0.73 0.73  0.75 0.75  0.77 0.77
 783        0.00   4.00  3.97  2.01  0.65 0.65  0.68 0.68  0.70 0.70  0.73 0.73
 783        6.71  30.84  3.36  1.66  0.70 0.70  0.73 0.73  0.75 0.75  0.77 0.77
```

Figure G.5 WINDOW-5 output file for super low-E low solar glazing type (SULLS); Window ID: 8002

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

Unit System : SI
Name        : DOE-2 WINDOW LIB
Desc        : Picture
Window ID   : 8003
Tilt        : 90.0
Glazings    : 3
Frame       :  5 Vinyl                 1.700
Spacer      :  1 Class1                2.330  -0.010   0.138
Total Height: 1500.0 mm
Total Width :  600.0 mm
Glass Height: 1360.3 mm
Glass Width :  460.3 mm
Mullion     : None
Gap        Thick    Cond  dCond    Vis   dVis   Dens   dDens      Pr     dPr
1 Krypton    6.3 0.00866  2.826  2.346  7.777  3.738 -0.0132  0.672 0.00003
2 Krypton    6.3 0.00866  2.826  2.346  7.777  3.738 -0.0132  0.672 0.00003
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  0.384 0.385 0.379 0.370 0.357 0.331 0.276 0.181 0.066 0.000 0.306
Abs1  0.039 0.040 0.041 0.042 0.044 0.046 0.049 0.051 0.052 0.000 0.045
Abs2  0.217 0.219 0.227 0.231 0.232 0.232 0.238 0.232 0.160 0.000 0.225
Abs3  0.057 0.057 0.058 0.058 0.059 0.058 0.054 0.043 0.024 0.000 0.053
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 0.303 0.298 0.296 0.299 0.309 0.333 0.383 0.494 0.698 1.000 0.361
Rbsol 0.228 0.223 0.221 0.221 0.227 0.245 0.288 0.387 0.587 1.000 0.275
Tvis  0.647 0.650 0.640 0.627 0.607 0.564 0.472 0.308 0.113 0.000 0.519
Rfvis 0.138 0.132 0.130 0.134 0.150 0.186 0.261 0.416 0.679 1.000 0.227
Rbvis 0.139 0.133 0.131 0.135 0.150 0.183 0.254 0.401 0.653 1.000 0.223
SHGC  0.533 0.536 0.533 0.527 0.514 0.488 0.433 0.324 0.161 0.000 0.455
SC: 0.45



Layer ID#         5004     1511      103        0        0        0
Tir              0.000    0.000    0.000        0        0        0
Emis F           0.840    0.127    0.840        0        0        0
Emis B           0.840    0.109    0.840        0        0        0
Thickness(mm)      5.7      0.1      5.7        0        0        0
Cond(W/m2-K     )176.5   1839.7    175.0        0        0        0
Spectral File  STRPH_6.PPG   HMTC88.SWT  CLEAR_6.DAT         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  3.25  1.90  0.75 0.75  0.80 0.80  0.83 0.83  0.86 0.86
   0        6.71  30.84  3.19  1.93  0.81 0.81  0.86 0.86  0.89 0.89  0.92 0.92
 783        0.00   4.00  3.57  2.44  0.75 0.75  0.80 0.80  0.83 0.83  0.86 0.86
 783        6.71  30.84  3.26  2.35  0.81 0.81  0.86 0.86  0.89 0.89  0.92 0.92
```

Figure G.6 WINDOW-5 output file for high-solar switch option for SULLS glazing type; Window ID: 8003

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

Unit System : SI
Name        : DOE-2 WINDOW LIB
Desc        : Picture
Window ID   : 8001
Tilt        : 90.0
Glazings    : 4
Frame       :  5 Vinyl                  1.700
Spacer      :  1 Class1                 2.330  -0.010   0.138
Total Height: 1500.0 mm
Total Width :  600.0 mm
Glass Height: 1360.3 mm
Glass Width :  460.3 mm
Mullion     : None
Gap        Thick    Cond  dCond    Vis   dVis   Dens   dDens     Pr     dPr
1 Krypton    6.3 0.00866  2.826  2.346  7.777  3.738 -0.0132  0.672 0.00003
2 Krypton    6.3 0.00866  2.826  2.346  7.777  3.738 -0.0132  0.672 0.00003
3 Krypton    6.3 0.00866  2.826  2.346  7.777  3.738 -0.0132  0.672 0.00003
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  0.158 0.117 0.115 0.112 0.107 0.098 0.080 0.049 0.015 0.000 0.091
Abs1  0.358 0.407 0.414 0.419 0.418 0.417 0.423 0.414 0.318 0.001 0.407
Abs2  0.084 0.028 0.028 0.028 0.028 0.029 0.028 0.026 0.020 0.000 0.027
Abs3  0.039 0.020 0.020 0.020 0.020 0.020 0.019 0.016 0.010 0.000 0.019
Abs4  0.010 0.005 0.005 0.005 0.005 0.005 0.004 0.003 0.001 0.000 0.004
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 0.351 0.423 0.418 0.417 0.422 0.431 0.447 0.493 0.636 0.999 0.443
Rbsol 0.350 0.526 0.522 0.516 0.512 0.512 0.525 0.569 0.670 1.000 0.527
Tvis  0.402 0.375 0.368 0.358 0.343 0.313 0.253 0.155 0.047 0.000 0.289
Rfvis 0.185 0.219 0.212 0.211 0.220 0.239 0.272 0.349 0.540 0.999 0.260
Rbvis 0.226 0.310 0.309 0.311 0.320 0.346 0.405 0.526 0.716 1.000 0.378
SHGC  0.230 0.155 0.153 0.150 0.145 0.136 0.116 0.082 0.038 0.000 0.126
SC: 0.21



Layer ID#          963     1510     1510      103        0        0
Tir              0.000    0.000    0.000    0.000        0        0
Emis F           0.840    0.755    0.755    0.840        0        0
Emis B           0.043    0.055    0.055    0.840        0        0
Thickness(mm)      5.7      0.1      0.1      5.7        0        0
Cond(W/m2-K     )176.5    1839.7    1839.7    175.0        0        0
Spectral File TiAC40_6.afg   HMSC75.SWT   HMSC75.SWT  CLEAR_6.DAT         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  3.22  1.69  0.46 0.46  0.49 0.49  0.51 0.51  0.52 0.52
   0        6.71  30.84  3.18  1.71  0.49 0.49  0.51 0.51  0.53 0.53  0.54 0.54
 783        0.00   4.00  4.04  2.12  0.46 0.46  0.49 0.49  0.51 0.51  0.52 0.52
 783        6.71  30.84  3.37  1.92  0.49 0.49  0.51 0.51  0.53 0.53  0.54 0.54
```

Figure G.7 WINDOW-5 output file for ultra low-E low solar glazing type (ULLS); Window ID: 8001

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

Unit System : SI
Name        : DOE-2 WINDOW LIB
Desc        : Picture
Window ID   : 8000
Tilt        : 90.0
Glazings    : 4
Frame       :  5 Vinyl                1.700
Spacer      :  1 Class1               2.330  -0.010   0.138
Total Height: 1500.0 mm
Total Width :  600.0 mm
Glass Height: 1360.3 mm
Glass Width :  460.3 mm
Mullion     : None
Gap         Thick    Cond  dCond    Vis   dVis   Dens   dDens      Pr     dPr
1 Krypton    6.3 0.00866  2.826  2.346  7.777  3.738 -0.0132  0.672 0.00003
2 Krypton    6.3 0.00866  2.826  2.346  7.777  3.738 -0.0132  0.672 0.00003
3 Krypton    6.3 0.00866  2.826  2.346  7.777  3.738 -0.0132  0.672 0.00003
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  0.297 0.300 0.292 0.282 0.269 0.243 0.190 0.108 0.031 0.000 0.224
Abs1  0.024 0.024 0.025 0.025 0.027 0.028 0.029 0.031 0.032 0.000 0.027
Abs2  0.235 0.237 0.244 0.249 0.250 0.251 0.256 0.247 0.169 0.000 0.242
Abs3  0.110 0.112 0.115 0.117 0.116 0.115 0.113 0.098 0.053 0.000 0.108
Abs4  0.003 0.003 0.003 0.003 0.003 0.003 0.003 0.002 0.001 0.000 0.003
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 0.332 0.324 0.321 0.324 0.336 0.360 0.409 0.515 0.714 1.000 0.386
Rbsol 0.341 0.332 0.329 0.332 0.344 0.367 0.415 0.519 0.716 1.000 0.393
Tvis  0.535 0.540 0.526 0.507 0.483 0.436 0.338 0.187 0.051 0.000 0.401
Rfvis 0.132 0.122 0.118 0.123 0.144 0.183 0.260 0.416 0.680 1.000 0.222
Rbvis 0.142 0.130 0.127 0.132 0.152 0.191 0.267 0.420 0.681 1.000 0.229
SHGC  0.439 0.444 0.440 0.433 0.419 0.393 0.340 0.245 0.116 0.000 0.367
SC: 0.38



Layer ID#         5001     1511     1511     5001        0        0
Tir              0.000    0.000    0.000    0.000        0        0
Emis F           0.840    0.127    0.127    0.840        0        0
Emis B           0.840    0.109    0.109    0.840        0        0
Thickness(mm)      3.3      0.1      0.1      3.3        0        0
Cond(W/m2-K     )305.2    1839.7    1839.7    305.2        0        0
Spectral File  STRPH_3.PPG   HMTC88.SWT   HMTC88.SWT  STRPH_3.PPG         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  3.22  1.74  0.52 0.52  0.55 0.55  0.57 0.57  0.59 0.59
   0        6.71  30.84  3.18  1.76  0.54 0.54  0.58 0.58  0.60 0.60  0.62 0.62
 783        0.00   4.00  3.67  2.47  0.52 0.52  0.55 0.55  0.57 0.57  0.59 0.59
 783        6.71  30.84  3.29  2.39  0.54 0.54  0.58 0.58  0.60 0.60  0.62 0.62
```

Figure G.8 WINDOW-5 output file for high-solar switch option for ULLS glazing type; Window ID: 8000

VITA

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