The Pennsylvania State University

The Graduate School

College of Arts and Architecture

OPPORTUNITIES AND LIFE CYCLE ENERGY IMPACTS OF HIGH-PERFORMANCE WINDOWS IN REDUCING ENERGY USE IN RESIDENTIAL BUILDINGS

A Thesis in

Architecture

by

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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

August 2016

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ABSTRACT

Today's energy-efficient windows can dramatically lower heating and cooling costs associated with windows while increasing occupant comfort. However, consumers are often confused about how to select the most efficient window for a residence. Furthermore, how this “efficiency” is defined is another problem that needs to be addressed.

Energy consumption is a scale that is used for defining energy efficiency. In most cases, the amount of energy that is used during the product’s service life (operational energy) will be measured as the total energy consumption of the product. However, the amount of energy that is used for producing a product is also as much important as operational energy, which should be taken into consideration.

In this thesis, it was attempted to provide useful recommendations for selecting the most efficient window glazing systems with regard to their “overall” energy consumption, using a Life-Cycle Energy Analysis (LCEA) method. The effect of using thirteen (13) different commonly used types of glazing systems on the annual energy use for a residential building was compared in various climate conditions across the U.S. Moreover, the amount of energy required for producing these glazing systems were identified. The results obtained from the analyses of these two phases of the study was used to create a simple set of guidelines, which can be utilized to select the most efficient glazing systems in terms of overall energy consumption based on different climate condition.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my advisor Lisa Domenica Iulo for her constant support and inspiration during the writing of this thesis. Without her constructive feedback and insights this research would not have been possible.

I would like to thank my committee members, Dr. R. Allen Kimel and Shadi Nazarian for their constructive criticism, guidance, and support during my proposal and thesis review.

I am grateful to Mehrdad Hadighi, Head of Department of Architecture at Penn State University, for sharing his knowledge during my thesis review.

My special thanks go to my dear friend Mr. Behnoud Kermani for his help, support, and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without him.

For most, my deepest appreciation goes to my beloved parents for their unconditional love and endless support.

CHAPTER 1

1 INTRODUCTION

1.1 Sustainability and Energy Conservation (Problem Statement)

In recent years, the concept of sustainability has become very popular. This concept rose to prominence in the late 1970s and has passed through an intensively discussed process of development during the past 20 years. Sustainable development has been defined in many ways as a result of various approaches and perspectives. However, the most frequently quoted definition of sustainability is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1987). The board on Sustainable Development of the U.S. National Research Council has provided a more comprehensive definition of sustainable development that introduces two separate but related aspects of “what need to be sustained” and “what need to be developed”. It divides each of these main components into three categories. The “need to be sustained” part mostly focuses on the environmental (ecological) point of view while the “need to be developed” category mostly emphasizes addressing social and economic concerns (Kates, 2005). There is no doubt that the building industry is not an exception to this definition. In fact, there are many raw materials and natural resources that need to be sustained. At the same time, there are some new construction methods that need to be developed. In other words, any building must be designed in a way that leads to maximizing resource conservation while creating resources for other structures at the end of its life cycle.

Energy conservation has led to universal efforts and trends towards sustainable development. This can be feasible by efficiently using energy resource (i.e., decreasing energy consumption). Energy conservation would result in improving the quality of the environment and human life as well as increasing financial capital and national security (Gao, 2011). Therefore, energy conservation, which is the main focus of this research, covers all aspects of sustainability, as previously mentioned. This necessitates the importance of energy savings in all fields including the building sector.

The importance of buildings as a significant part of the energy system has been addressed in several studies. As Figure 1 illustrates, buildings are the largest energy consumer in the US. The combined residential and commercial building sectors consume more than 40% (71% of electricity and 54% of natural gas) of the total primary U.S. energy. Over the past three decades, residential energy consumption has significantly grown due to more and larger homes; hence, residential buildings have an important role in total energy consumption in the U.S.

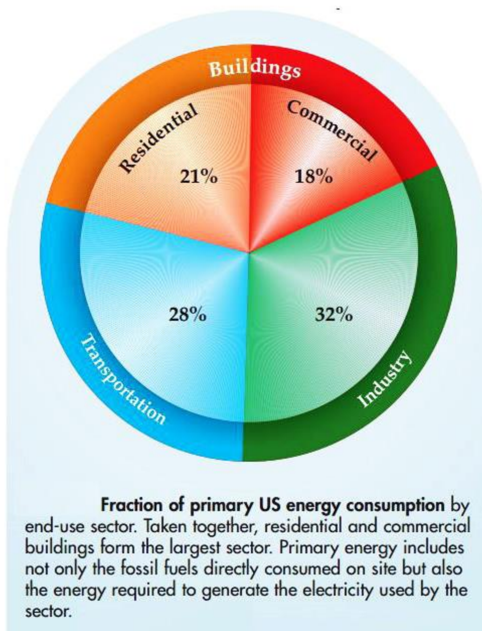


Figure 1. Fraction primary US energy consumption by end-use sector
Source: Glicksman, 2008

According to data from the U.S. Energy Information Administration (EIA) Residential Energy Consumption Survey, space heating, lighting, and air-conditioning account for 40-70% of a building's total energy consumption in single-family buildings. Figure 2 presents average of single-family building end-use energy consumption in the U.S.

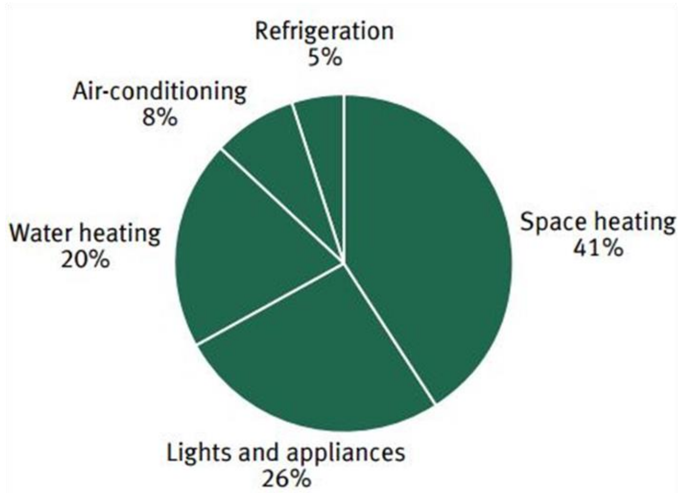


Figure 2. Single family building end-use energy consumption
Source: U.S. Energy Information Administration, 2005

It should be noted that energy consumption portions in different locations depend on the regional climatic condition. For example, as shown in Figure 3, according to EIA's Residential Energy Consumption Survey (2009), energy consumption for space heating or air conditioning in Florida, which is located in a cooling dominated climate zone, is different from Illinois, which is located in a heating dominated climate region.

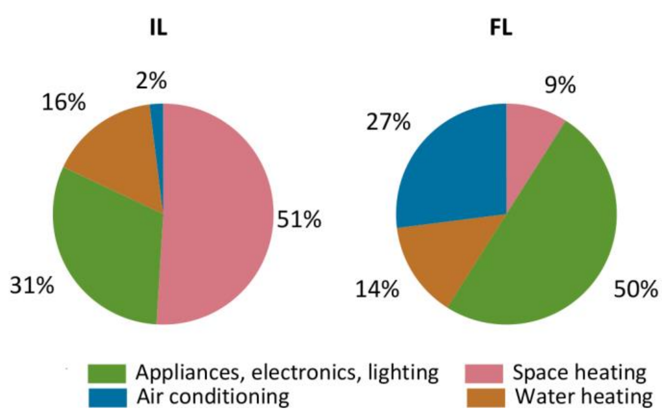


Figure 3.Residential building end-use energy consumption
Source: U.S. Energy Information Administration, 2009

As the weather in Illinois and Midwest is cooler than other areas of the United States, space heating makes up a greater portion of energy use compared to the U.S. average while air conditioning makes up only 2% of energy use. On the other hand, more than a quarter

(27%) of the energy consumed in Florida homes comes from air conditioning, which is more than four times of the U.S. average.

1.1.1 Light control

A good daylighting design can save up to 75 percent of the energy used for electric lighting in a building. The amount of daylight available, the occupancy pattern, and the control strategy can all affect energy savings. In addition, as significant daylight is often available during utility peak demand hours, a good daylighting design can reduce demand charges. Electric lights also generate significant heat in a building. On top of that, so-called soft savings attributable to increase in productivity and health of the building occupants, which can add to the hard savings, researchers say (www.facilitiesnet.com). Since lighting has a significant impact on energy consumption of the building, windows as one of the most important components of the building envelope in terms of light transmission should be taken into consideration.

1.1.2 Heat transfer control

Reducing heat transfer is one way of improving energy efficiency. Electrical energy can be saved if heat entering in summer and heat loss in winter is minimized. It is notable that windows are recognized as the weakest parts of the building's energy systems (Buildings & Construction Initiative, 2007). Therefore, improving the windows thermal performance leads to significant improvement in building's energy efficiency.

1.2 Importance of Windows in Energy Conservation

The U.S. Department of Energy (DOE) indicated that using inefficient windows leads to the loss of approximately 30% of the energy used for heating and cooling all buildings in the U.S. This results in the costs of $42 billion per year (US DOE BT, 2006).

According to Arasteh 2006, "Windows can admit solar heat when it is needed to offset heating energy needs, reject solar gain to reduce cooling loads, significantly mitigate a building's peak electricity demand, and offset much of a building's lighting needs during daylight hours". These benefits can be achieved using windows with better-fixed properties such as relatively lower U-factor compared to today's standards. Moreover, dynamic capability of the windows should be integrated in order to permit reasonable compromise for winter and summer conditions as well as glare and view, and daylight and solar gains. Although today's windows have become more efficient compared to the ones used in prior decades, they are still significant energy liabilities due to energy (heat lost or gained) transmission through them. For example, inefficient windows and doors can cause energy loss of up to 33% in a typical home (Arasteh et al. 2003; Yazdanian et al. 2004). It should be noted that according to US Department of Energy (DOE), "If all the existing windows in the market could be upgraded with efficient windows, savings of more than $300 billion could be realized in the 20 years following these performance improvements".

Following the explanations above, it should be noted that today there are lots of advanced technologies available in the market. As mentioned, the energy performance of the building depends significantly on the location of the building. The impact of using each glazing system on energy consumption of the building also depends on the climatic condition. A glazing system that shows the best performance in one location is not necessarily the best option in another location. Therefore, comparing the impact of different glazing systems on overall energy consumption of the building with respect to its location may be a reasonable solution in order to select the most efficient window in each climatic location.

1.3 Research Question and Objectives

To understand the effects of a special building component (e.g., a window) on overall energy consumption of the building, designers usually use data such as U-Factor, Solar Heat Gain Coefficient (SHGC), and Visible Transmittance (VT) provided by the window manufacturers. These data are then used as an input in some energy simulation software to assist in identifying the most appropriate window selection. However, it should be taken into consideration that the best product that will be chosen with this method is not necessarily the most efficient one. There are other factors such as embodied energy, the durability of a product, and cost, which are important in the overall energy consumption of a building. Until now, there is a considerable amount of literature comparing different types of windows. This research mostly focuses on the amount of energy that could be saved using each of these windows while neglected the amount of energy required for their production. However, there are a few studies conducted regarding the amount of energy consumption over the entire life span of the window. These studies mostly focus on the amount of energy that is required for the production of different types of window frames. Since the glazing part of the window itself has a significant impact on the energy performance of the building and considering the significant amount of energy that is used for producing each type of advanced glazing system, more research is needed on overall energy consumption of different types of windows concerning the glazing part of the window.

With these clarifications, this thesis is intended to provide guidance on the selection of glazing systems for use in buildings (i.e., new residential construction) considering overall energy efficiency during the lifetime of the window.

The aim of this thesis is to answer an important question as follow:
“What are the most efficient window glazing systems for use in different climatic locations in terms of overall energy consumption?”

To answer this question, this research has two main objectives to achieve:

- Compare different types of high-performance glazing systems to find the most effective one in energy-efficient housing with regard to energy consumption.
- Provide criteria for choosing high-performance glazing systems based on their impacts on the overall energy performance of the building.

1.4 Research Approach-Methodology

This research will be conducted analytically using Life-Cycle Energy Analysis (LCEA). LCEA is an easily conducted form of Life-Cycle Assessment (LCA) and one that is particularly relevant to the building industry. LCEA is a practical methodology for decision-making, which mostly focuses on the energy consumption of glazing systems. Both of these methods are explained in more depth in next chapter. LCEA is comprised of two main phases: 1) Production phase, which emphasizes on embodied energy, and 2) Use phase, which focuses on operational energy. The intention of this study is to perform studies on different types of glazing systems that are used in high-performance windows to find the most efficient ones with regards to overall LCEA with respect to climatic location.

In the first part of the research, these windows are broken down into their constituent materials and elements. Based on this information, the embodied energy of each window system is calculated using manufacturing energy data of the building materials from literature and manufacturers data sheets.

For the second part of the study, operational energy use associated with each window's type is analyzed by utilizing glazing system performance indexes, which were gathered from manufacturer data sheets. Afterward, these performance indexes are simulated using energy modeling software to determine the annual energy use in an associated case study residence, which led to a comparison of different high-performance window options. A "new construction, single family, single story building" is considered as the case study. In many cases, some assumptions are made. These assumptions are maintained for each iteration so that the glazing type is the only variable that would change.

Analyzing the overall energy consumption associated with each type of window systems is conducted by comparing embodied energy of each window system during production phase with its operational energy during use phase obtained from energy simulation. It is important to indicate that to be able to compare the energy performance of different glazing systems, the single pane glazing is considered as baseline. Subtracting embodied energy of each type of advanced glazing system from embodied energy of single pane glazing (base line) provides the additional energy required to produce that type of glazing system. On the other hand, subtracting operational energy of each type of advanced glazing system from the operational energy of single pane glazing (base line) provides the amount of energy that can be saved using that type of glazing system.

It should be noted that the energy performance analyses are conducted by assuming buildings located in several different locations throughout the United States. This is performed to represent each climate type in the U.S. These results are used to develop conclusions on the type of systems that are most appropriate for each climate zone.

1.5 Research Organization

The body of this thesis is organized into the following chapters:

- **Chapter 2. Literature review and background**

Chapter 2 provides a general description of the energy simulation methods, LCA method, and LCEA method. Following that, the overall background of LCA studies on windows is explained in this section. The gap in knowledge in this field of study is then discussed. Finally, more explanation about the research objectives and methodology is provided.

- **Chapter 3. Windows**

Chapter 3 provides a description of general background on windows with a goal of identifying high-performance windows of interest for this study. This thorough and comprehensive review includes explanations of window physics and components and different performance criteria for glazing systems.

- **Chapter 4. High-performance windows**

Chapter 4 identifies the concept of high-performance windows and their overall impacts on building energy performance. It also introduces different technological improvements in the glazing systems. Finally, it focuses on advanced Glazing Technologies and their inherent properties used in residential buildings.

- **Chapter 5. Life Cycle Analysis of glazing systems**

Chapter 5 introduces a practical method for modeling the window's LCEA. As mentioned LCEA is comprised of two main phases: 1) Production phase, which emphasizes on embodied energy, and 2) Use phase, which focuses on operational energy.

Determining production energy of each window type was made using the data collected in chapter 4 about the properties of the components of different high-performance windows. Each window is broken down into their constituent materials and elements. Subsequently, the total embodied energy of each window system is calculated by using the embodied energy of each of windows material's component. As previously noted, the existing studies mostly compared LCA of different windows with regard to the impact of using different materials for their window frame. This study specifically focused on the glazing part of the window and considered it as the main variable.

For the next phase (i.e., use phase), building energy simulation is used for determining the operational energy of the building associated with different glazing systems. An overview of energy modeling program RESFEN, which has been used in this study, is provided. Afterward, with the application of this software, Chapter 5 compares the effect of different glazing types and technologies on the annual energy consumption of typical building in different locations across the United States. These glazing systems were single pane window, double pane window and triple pane window. It should be noted that various technologies including low-e coatings (low solar gain, medium solar gain, and high solar gain), chromogenic coating, etc. have been examined on each glazing system. This was carried out to select the best glazing system with the most appropriate technology with respect to overall energy saving for each climatic condition in the US.

- **Chapter 6. Results and discussion**

Chapter 6 presents and discusses the results of the LCEA in order to suggest the most appropriate window in terms of overall energy consumption. For this purpose the operational energy consumed in residential buildings during the operation of the glazing system and the embodied energy during production of the glazing are compared. Also, potential limitations of the glazing systems and how they could be addressed in further research are discussed.

- **Chapter 7. Summary, conclusions, and recommendations**

Upon completion of the study, Chapter 7 summarizes findings and provides the important conclusions of the research. The advantages and limitations of using selected glazing systems are discussed. Finally, a framework/guideline is provided to inform the designers about the appropriate glazing for a specific location, based on the LCEA approach established by this research.

CHAPTER 2

2 BACKGROUND AND LITERATURE REVIEW

Several studies have confirmed that health, comfort, and productivity are improved through well-ventilated indoor environments and access to natural light. Windows have been used in the building industry mainly for the purposes of daylighting and ventilation for many years. However, at the same time windows are considered a major source of heat loss and discomfort in the building.

This section provides a comprehensive background and literature review of research that has been conducted on windows frames, windows glazing, and related factors in terms of their energy consumption and potential energy saving using Life Cycle Analysis (LCA) method. The gap in knowledge will be discussed subsequently, which in turn, will help to better provide the rationale behind the objectives of this research.

Recent developments in windows technology have led to significant improvement in the performance of windows. There are several high-performance glazing systems available on the market that can dramatically cut down the energy consumption of the building. These high-performance windows use a combination of double or triple glazing in addition to improved low-e and solar control coatings, insulating gas sandwiched between panes, and improved frames. All of these features result in producing different types of advanced windows, which have different optical and thermal properties. As a result, heat transfer through the windows is reduced significantly, which leads to cutting the energy lost through windows (www.wbdg.org/resources/windows.php).

Selecting the right window for a specific home always requires tradeoffs between different energy performance features. Moreover, some non-energy related issues should be taken into consideration when selecting appropriate windows; the use of energy simulation is one of the most common and best methods for comparing the impacts of different types of windows on a building’s overall energy consumption.

2.1 Energy Simulation Method

Building energy simulation, also called building energy modeling, is the use of software to simulate the energy use of a building throughout an entire length (years) of operation. A typical energy model has inputs for climate, envelope, heating, cooling, and ventilation systems, schedules of occupants, equipment, and lighting. As an output, energy models can provide building energy use predictions in typical end-use categories: heating, cooling, lighting, fan, plug, process. In addition to energy units, most of the frequently used software packages include utility rates input, which can predict energy costs (Rosenbaum, 2003).

In 2011, Rallapalli pointed out that energy performance simulation tools have several features for designers, including:

- Predict thermal behavior of buildings toward their outdoor environment.
- Predict the impact of daylight and artificial light inside buildings.
- Model the impact of wind pattern and ventilation.
- Estimate the size/capacity of equipment required for thermal and visual comfort.
- Calculate the effect of various building components on each other and predict resulting conditions.
- Check for compliance with building codes.

Also, Building energy simulation can help facility managers and engineers to identify energy saving abilities of the project, and evaluate the energy performance and cost effectiveness of energy saving actions that can be applied.

As previously mentioned, energy simulation method only measures the amount of energy consumed during the operation of the building, while a considerable amount of energy is used for producing each specific window. To have a more reliable study, a comprehensive method such as life-cycle assessment (LCA), which considers the amount of energy consumption over the entire life span of the window (i.e., production phase and use phase), should be used.

2.2 Life Cycle Assessment (LCA) Method

Life Cycle Analysis (LCA) is a quantitative technique for evaluating the resource use and associated environmental impacts of a product from ‘‘cradle to grave’’. It considers entire life stages of a product from resource extraction and commodity manufacturing, to secondary manufacturing, use, maintenance, and end of life (LeVan, 1996). LCA consists of four main phases according to ISO 14040 standard. Figure 4 presents these main phases:

- Goal and scope definition
- Inventory Analysis
- Life cycle impact assessment
- Interpretation

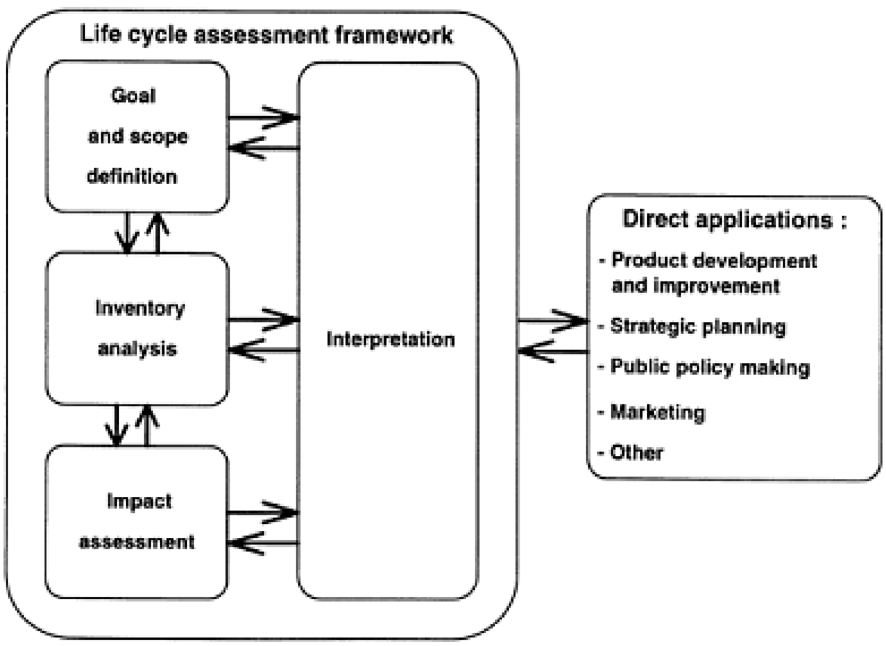


Figure 4. LCA framework
Source: ISO 14040

As shown in Figure 4, the first stage of an LCA study is to identify the purpose of the project (goal and scope definition). According to the scope of the study, some types of data should then be collected as inputs and outputs (Inventory Analysis), as shown in Figure 5. Some of the inputs include:

- Raw materials, such as minerals or ores

- Energy sources, such as gas, electricity, and petroleum
- Water withdrawals and consumption

The outputs include:

- Greenhouse gas emissions
- Toxic pollutants
- Hazardous and nonhazardous waste

The next step is to analyze the collected data and determine how the product affects the environment (Impact assessment). The final step is providing a conclusion and some recommendations (Interpretation).

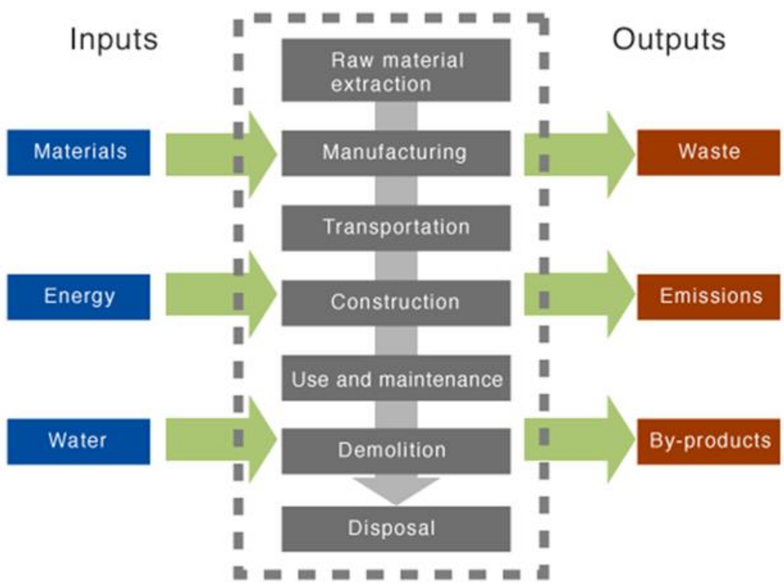


Figure 5. Inventory Analysis
Source: http://www.greenspec.co.uk/life-cycle-assessment-lca/

According to these explanations, it should be noted that researchers are dealing with some challenges regarding the comprehensive approach of a full LCA including uncertainty in results due to inaccurate data for resource/energy inputs and uncertain amount of emissions. Also, there are some questions about how designers are supposed to deal with these numbers. For example, how CO2 (carbon dioxide) and SOx (sulfur oxides) emissions are to be balanced against energy consumption, cost, and other resource depletion. Based upon these challenges, this study attempts to narrow down the LCA to a more specific approach (energy consumption) and uses Life-Cycle Energy Analysis (LCEA) to provide more accurate results.

2.2.1 Life Cycle Energy Analysis (LCEA)

Life-Cycle Energy analysis (LCEA) is a form of life cycle assessment (LCA) that is particularly relevant to the building industry. In LCEA, energy is the only parameter that is measured. Using LCEA, more detailed analyses of the energy attributable to buildings is possible. Compared to a full LCA, LCEA simplifies decision-making concerning energy efficiency- providing the necessary information to reduce energy consumption in buildings (Kofoworola, 2009).

LCEA is comprised of three main parts as follow:

- Embodied energy: The total energy required for the extraction, processing, manufacturing, and delivering of building materials to the building's site (Ramesh et al., 2010).
- Operating energy: Energy required for maintaining comfort conditions and day-to-day maintenance of the buildings. Energy for HVAC (heating, ventilation, and air conditioning), domestic hot water, lighting, appliances, etc. (Ramesh et al., 2010).
- Demolition energy: The required energy at the end of the building's service life for demolition and transportation of the material to landfill sites and recycling plants (Ramesh et al., 2010).

To perform an LCEA, the amount of energy for each part should be calculated. Table 1 provides some possible sources for collecting data for each phase of LCEA.

Table 1. Data sources for LCEA
Source: Ramesh et al., 2010

LIFE CYCLE PHASE	ACTIVITY	POSSIBLE SOURCES OF DATA
	Building Material Production	Manufacturing energy data of the building materials from literature, economic input

(a) Manufacturing phase	Transport Building construction including refurbishment	and output tables, process analysis, hybrid analysis. Quantities estimated from building drawings, bill of materials and interviews with building designer, contractor/owner. Average distances for material transport. Energy data for transport operations. Energy uses from site visit
(b) Use phase	Use of electricity and fuels for heating, sanitary water and lighting	Simulation software-ENERGY-PLUS, VISUAL DOE, E-QUEST, DESIGN BUILDER, ENORM, TRNSYS, ECOTECT, SUNCODE, etc., annual electricity bills, house hold a survey on energy use. Inventory data for fuel production. Electricity mixes data
(c) Demolition phase	Building demolition Transport Recycling	Demolition operations and quantities from specific measured data. Use of equipment and explosives from data base Average distances for material transport energy data for transport operations Specific measured data
(d) Life cycle energy	Total energy use of the building in its life cycle	Phase a+b+c
(e) Life cycle assessment	Life cycle material and energy flow estimation. Impact assessment that building makes on the environment.	Phase a+b+c Greenhouse effect or global warming, ozone depletion, acidification, eutrophication, photochemical smog, etc. estimated using software – SIMAPRO, ECOBAT, LEGEP, BEES, ATHENA, etc.

2.3 Background of Life Cycle Analysis of Windows

A number of studies have been conducted on Life-Cycle Analysis (LCA) of different types of windows. In 1998, Weir and Muneer published the first LCA on double-glazed windows, in which an aluminum window frame was considered with different fill gas (argon, krypton, and xenon) and in a glazing system (clear /Low-e double pane). The embodied energy of each of these components was calculated. Also, the operational energy was simulated for the whole window system. The study showed that the amount of energy that Low-e double pane saved during the use phase was outweighed by its higher required production energy.

Furthermore, several studies have attempted to compare different window framing materials using an LCA method. In 2000, Citherlet et al. performed an LCA on different types of advanced glazing systems. The variable of that study was defined to be the number and types of panes, the gas used between panes, spacers between panes, and frame material. The study was conducted by simulating an office, a classroom, and a residential building in three different cities. Moreover, the environmental impacts (e.g., nonrenewable energy requirements, global warming potential, acidification potential, and photochemical ozone creation) of each of these products were considered in the production and disposal of materials. The windows were evaluated according to their possible energy saving during their use phase. Considering the energy loss through each window unit, the study concluded that improving thermal insulation could outweigh increased production energy requirements. Also, the study confirmed that windows caused the least environmental impact when they are made of insulative materials such as wood and multiple panes used with inert gas.

Entec (2000) published a comparative LCA on wood and PVC window frames. The study indicated that during the production of raw materials, the PVC windows consumed three times more energy than wood frame windows. Moreover, the PVC windows produced seven times more CO_2 compared to wood frame windows during the production phase.

Asif et al., 2000 studied the life cycle assessment (LCA) of the materials normally used for window frames, highlighting their respective benefits and weaknesses. The study compared four different framing materials including aluminum, PVC, Al-clad timber, and timber. The investigation revealed that aluminum frames have the highest amounts of environmental impacts due to the dangerous pollutants release and high-energy consumption during its production. It was observed that PVC contributes large amounts of poisonous pollutants throughout its life cycle, while timber window frames have the least environmental impacts. The study also concluded that regarding embodied energy, aluminum windows have the highest embodied energy compared to the other three framing materials, which is approximately 6 GJ. PVC, Al-clad timber, and timber windows have embodied energy of 2980 MJ, 1460 MJ, and 995 MJ respectively.

In 2005, Recio et al. investigated several window systems commonly used in Spain. For that study, three different window frames (i.e., PVC, aluminum, and wood) and two different glazing systems (i.e., single pane, double pane) were considered. The embodied energy of the wooden window was found to be the least, followed by PVC and aluminum. The study concluded that, while the wood frame was shown to have the lowest embodied energy in comparison with other examined materials, its greater thermal conductivity outweighed the benefits in the production phase. Furthermore, aluminum frames were found to have the highest production energy and the highest conductivity (and subsequent energy use) during the use phase.

Abeysundra et al. (2007) compared the environmental (embodied energy, and global warming), economic (market prices and affordability) and social (thermal comfort, aesthetics, ability to construct fast, and durability) impacts of two types of door and window frames (wood and aluminum), which were widely used for the buildings in Sri Lanka. It was recognized that wooden elements were superior to aluminum elements in terms of environmental impacts. For economic aspects, wooden elements also worked better. However, regarding the social impacts, aluminum elements worked better than wood.

Salazar and Sowlati (2008) provided an LCA on window frame materials and compared three common window types used in North American residential buildings (PVC, fiberglass, and wood covered with an aluminum cladding). The study revealed that, although PVC frame needed less production energy vs. fiberglass, it used the most nonrenewable energy and caused the most damage due to the window's shorter service life (18 years for PVC vs. 25 years for fiberglass and aluminum clad wood).

As explained above, in all LCAs that considered frame materials, wood had a lower embodied energy than PVC or aluminum. It was observed that numerous toxic chemicals are required in the manufacturing of PVC, which may be released at the end of its life (Asif et al. 2002). However, interestingly, Wolf (2012) pointed out that although aluminum has a high embodied energy, unlike PVC, it is easily recyclable and up to 93-95% of its embodied energy can be recouped. In its first incarnation, aluminum is a comparatively expensive material, partly because of the large amounts of energy consumed in smelting the alumina into aluminum. However, aluminum can repeatedly be recycled without any deterioration in quality. The more often the metal is recycled, the more competitive its lifetime cost becomes (Wolf, 2012).

In addition to the LCAs on window frame materials, in recent years there are also some studies conducted that focused on other window components such as glazing materials, spacer materials, and infill gas. For instance, Menzies (2005) compared different high-performance windows using technologies for improved thermal insulation (e.g., low-e coatings, gas-filling, and multiple panes of glazing) in four office buildings in Edinburgh, Scotland. For this study six different types of glazing units were selected including clear air-filled double-glazing, Low-e air-filled double glazing, low-e Argon-filled double glazing, low-e Krypton-filled double glazing, low-e Argon-filled triple glazing, and low-e Krypton-filled triple glazing. Comparisons were made between the additional embodied energy and associated emissions, the financial cost required to install higher performance windows, and the potential savings in life-cycle energy and running costs. The results showed that in all cases, all Krypton-filled windows had a considerably longer payback period than air or argon-filled windows. The study also revealed that the use of low-e coatings (versus uncoated IG) would reduce CO2 emissions from electricity production by around 10%; the financial cost of the low-e coating would be paid back in less than five years, and in terms of energy, in only one month.

Gustavsen et al. (2011) studied the impact of different spacer materials on the total thermal performance of five types of window frame including: thermally insulated wood, solid wood, PVC, and two thermally broken aluminum frames. The study analyzed the effects of spacer conductivity on the U-values of different frame configurations with triple glazing, argon filled cavities, and two low-e coatings. The results of this study showed that U-value of the frame decreased with decreasing spacer's conductivity.

Van Den Bergh et al. (2013) published a report, in which different windows spacers were compared. Two main categories of windows spacer systems were identified in the report including: 1) metal spacers and 2) non-metal spacers. They subdivided the metal spacer category according to the type of metal as: aluminum, galvanized steel, and stainless steel. The non-metal spacer category was further divided into three subgroups: composite, structural foam, and thermoplastic (TPS). The "THERM" software was used in this study for determining the spacer's thermal conductivity. The study concluded that stainless steel and non-metal spacers have better energy performance due to having considerably lower thermal conductivity than aluminum and galvanized steel spacers.

In 2014 Azari examined the life cycle energy and environmental performance (air and water emissions, waste fossil fuel consumption, global warming, acidification, ozone depletion, smog formation) of building envelopes by using LCA. The study had different variables including insulation materials, window-to-wall ratio (WWR), window frame materials, and cavity gas in double-glazings. The results of this LCA confirmed that fiberglass-framed argon-filled low-e window has the lowest environmental impact. On the other hand, aluminum-framed argon-filled low-e window causes the highest environmental impacts.

Minne et al. (2015) provided an LCA and life cycle cost (LCC) on different types of windows to justify their energy payback. The study was conducted on a basic single-pane window as a baseline, two basic double-pane windows, and four energy-efficient windows in a single-family home over seventeen cities in the U.S. For comparing the energy payback, the operational energy was calculated using energy simulation. At the beginning of the energy simulation process, different types of windows were considered with different sizes, shadings, and orientations. However, the sensitivity analysis proved that choosing more energy-efficient windows makes a more significant impact than changing shading, orientation, or window area options. Therefore, for the rest of the study these factors were kept constant. The study concluded that, in terms of energy efficiency during the use phase of the building, low-solar gain windows always performed best due to the reduction in electricity needs. From an economic perspective, however, low-solar gain windows only performed best in warmer climates while moderate-solar gain windows performed best in cooler climates condition.

Table 2 provides a summary of previous LCA related studies on windows.

Table 2. Published studies on LCA of windows

STUDY	GOAL	FUNCTIONAL UNIT	CONCLUSION
Weir and Muneer 1998	Consider relative impacts of frame materials, glazing systems, and infill gas	Double glazed wood window	The amount of energy that Low-e double pane saved during the use phase was outweighed by its higher production energy.
Citherlet et al. 2000	Compare frame materials and justify energy payback	Numerous window systems	Improving thermal insulation could outweigh increased EE. More insulation caused less environmental impact.
Entec. 2000	Compare frame materials	Wood and PVC window frames	EE of PVC frame is three times more than wood frame windows. It also produced seven times more CO_2 compared to wood frame windows during the production phase.
Asif et al. 2002	Compare frame materials	Aluminum, PVC, wood, and clad frames	PVC frame had the highest environmental impact and timber window frames have

			the lowest environmental impacts. Aluminum frame has the highest EE and timber frame have the lowest EE.
Kiani et al. 2004	Justify energy payback	Fully glazed commercial building envelope	Glass manufacturing, assembling and transportation EE is accounted for 35% of the overall life cycle EE of the window. Operational energy will drop up to 53% by using high performance glazed units. Recycling of glass has to be carefully planned otherwise there might be just 2% saving energy by recycling of glass as cullet. There will be no benefit by recycling of glass for transportation distances over 100 km.
Recio et al. 2005	Compare frame materials and justify energy payback	Five window types	Wood frames have the lowest EE, while its greater thermal conductivity outweighed the benefits in the production phase. Moreover, aluminum frames were found to have the highest production energy and the highest conductivity (and subsequent energy use) during the use phase.
Syrrakou et al. 2005	Justify energy payback	Electrochromic device	

Abeysundra et al. 2007	Compare materials	Doors and windows	Wooden elements were superior to aluminum elements regarding environmental impacts and economic aspects. However, regarding social impacts, aluminum elements worked better than wood.
Salazar and Sowlati. 2008	Compare frame materials	Windows and window systems	Although PVC frame needed less production energy vs. fiberglass, it used the most nonrenewable energy and caused the most damage due to the window's shorter service life.
Azari. 2014	Compare frame material, and infill gas	Office building envelopes	The fiberglass-framed argon-filled low-e window has the lowest environmental impact, while aluminum-framed argon-filled low-e window causes the highest environmental impacts.
Minne et al.2015	Justify energy payback	Seven window types	Regarding energy efficiency during the use phase of the building, low-solar gain windows always performed best. From an economic perspective, low-solar gain windows only performed best in warmer climates while moderate-solar gain windows performed best in cooler climates condition.

2.4 Gap in Knowledge

As illustrated in Figure 6, windows are comprised of different components such as glass panes, coatings, structural frames, and spacers. Each of these components can affect windows energy performance.

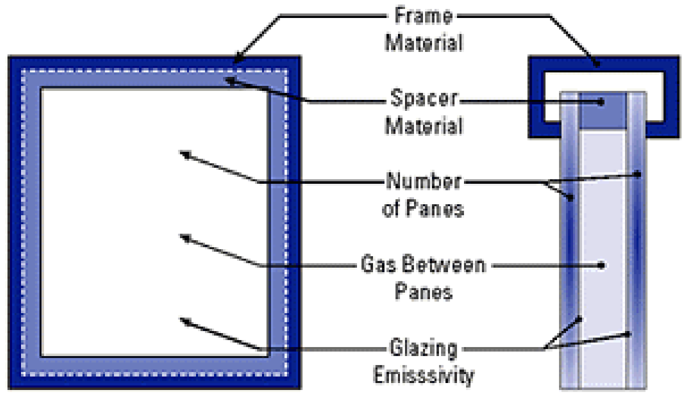


Figure 6. Factors affecting window performance
Source: www.wbdg.org/resources/windows.php

Table 3 provides the best possible option in terms of energy performance for each of these components according to the aforementioned literature review.

Table 3. Best possible window component in terms of energy efficiency base on the literature.

<table>
<tr><th colspan="2">FACTORS AFFECTING WINDOW ENERGY PERFORMANCE</th><th>OPTIONS THAT HAVE BEEN CONSIDERED IN DIFFERENT STUDIES</th><th>BEST OPTION</th></tr>
<tr><td colspan="2">Frame Material</td><td>Aluminum, wood, PVC, Al-clad timber, timber, fiberglass</td><td>Recycled Al-clad timber, fiberglass</td></tr>
<tr><td colspan="2">Spacer Material</td><td>Metal spacers: aluminum, galvanized steel, stainless steel; Non-metal spacers: composite, structural foam, thermoplastic</td><td>Stainless steel and non-metal spacers (These materials have lower conductivity than other options which is very important point with regard to energy).</td></tr>
<tr><td>Number of panes</td><td rowspan="3">Glazing System</td><td>Single pane, Double pane windows, Triple pane</td><td rowspan="3">(?)
Will be investigated in this study</td></tr>
<tr><td>Infill Gas Glazing</td><td>Argon, krypton, xenon</td></tr>
<tr><td>Glazing Emissivity</td><td>Clear glass, Low-e coating,</td></tr>
</table>

As previously explained and as shown in Table 2, most of the studies in this field of interest have been carried out to compare different framing materials, spacer materials, infill gas, or justifying the energy payback. However, there are only handful of studies that deal with the glazing systems. In addition, even among these few studies, no research has been found that covers all of the most frequently used glazing systems in the residential building industry simultaneously and provides a comprehensive result using different glazing systems. Considering the vital impacts of different glazing systems on the operational energy as well the as embodied energy of the windows, this study aims to provide specifically an LCA on glazing part of the window. Moreover, since the amount of operational energy associated with each type of glazing systems significantly depends on the climatic condition, in this study the location of the building was taken into consideration. It should be noted that this variable was not comprehensively considered in previous studies. As a result, the best type of glazing systems in terms of energy saving that can be used in different climatic location would be introduced.

It should be noted that even the most energy-efficient windows must be properly installed, insulated and sealed to ensure energy efficiency. Window installation varies depending on several factors including type of window, type of construction (wood, masonry, etc.), type of framing, exterior cladding (wood siding, stucco, brick, etc.), climatic location (heating dominated climate or cooling dominated climate), type of weather (humid, arid, etc.), etc. Windows should be installed according to the manufacturer's recommendations and be properly air sealed during installation to perform satisfactorily, as expected. In order to air seal the window, caulking the frame and weatherstripping can be used. Caulk is a flexible material used to seal air leaks through cracks, gaps, or joints. DOE provided an instruction for choosing different caulking compounds and weatherstripping types in its website that can be used after making a decision about the appropriate energy-efficient windows to be used in buildings (www.energy.gov/energysaver/energy-efficient-windows).

2.5 Significance of the Study

As discussed in Chapter 1, the primary goal of this thesis is to provide a comprehensive guideline that provides criteria for choosing best possible glazing systems in terms of overall energy consumption considering the location of the building. With the results of such a study, architects, designers, or even consumers can select the most appropriate glazing system for their building based on the localized climatic condition. LCEA method is used for comparing different glazing systems, hence, a thorough guideline that can specifically point out the best possible glazing systems in terms of overall energy consumption/saving for each climatic location is provided.

The LCEA in this study is comprised of two main phases: the production phase and the operational phase. The production phase emphasizes the embodied energy of each of the glazing systems while the operational phase emphasizes the amount of energy consumption of the building over its entire lifetime associated with each of the glazing systems. The operational energy is calculated using energy simulation methods. Comparing the results of embodied energy with operational energy projections for each specific glazing system is used to inform the most energy efficient glazing system for each climatic condition. A detailed discussion of window performance and “high-performance” windows is covered in the subsequent two chapters. The LCAE method used in this thesis to calculate embodied energy and operational energy is provided in chapter 5.

CHAPTER 3

3 WINDOWS

Oxford dictionary defines a window as “an opening in the wall or roof of a building or vehicle that is fitted with glass or other transparent material in a frame to admit light or air and allows people to see out”. The origin of the word window comes from Norwegian “vindauga”, from ‘vind - wind’ and ‘auga - eye’. Moreover, the word “fenestra”, which refers to modern windows is borrowed from a Latin word for windows.

Modern windows are multi-function elements; In addition to letting light come inside a building and providing an outside view, they can act as heat and sound insulation. Furthermore, they may serve as part of the ventilation system of a building. As previously mentioned, windows are part of enclosure system of buildings, which are exposed to heat and light transmission. Therefore, these elements are important in energy conservation of the building.

3.1 History of Glass and Windows

Early “windows” were just holes in walls, which eventually were covered with cloth, wood, or animal hide. Date back to 5000 BC, before glass was used in windows, early humans utilized natural glass as a cutting tool. It is thought that the oldest man-made glass objects were made around 3500 BC.

The discovery of glassblowing was a major innovation that helped people to shape the glass in the first century. Around this time, Romans discovered clear glass, which led them to begin using glass for architectural purposes. However, sheets of glass had not been used until the end of 11^{th} century. The process of making glass sheets was different at that time. The glass sheet was first produced in Germany by hollow glass sphere, which was blown and then hung vertically. Due to the gravity, the glass was pulled and changed into a pod form. The ends of the pod were cut off and the resulting cylinder laid flat. In 1688, a new method was discovered for the production of flat glass sheets. The glass was heated to be melted. Before cooling, molten glass was poured on a table and a roller ran over that to flatten. After cooling, the glass sheet was polished using specific abrasive sands to increase the optical properties (GlassOnline, 2009).

During the Industrial Revolution, an automatic bottle blowing machine was invented for mass production of the glass sheets. After that, scientist studied the possibilities of using different chemicals to increase the glass optical quality. In 1905, a technique was developed to produce large scale glass sheets (GlassOnline, 2009). Since then several attempts have been made to improve the glass/windows properties, hence, improving the performance of the buildings that used those types of glass/windows. For instance, in the 1950s Sir Alastair Pilkington produced reflective glass by floating a molten glass on a molten tin. Relative low cost and appropriate optical property were two major advantages of these types of glasses. Moreover, single pane windows were gradually replaced with double pane windows because of their better insulating value. Nowadays three pane windows have also become popular in some parts of the world to reduce heat transfer across a building enclosure. It is noteworthy that since the 1950s the process of glass manufacturing has not been dramatically changed. However, developing various coating techniques has resulted in producing different types of advanced windows, which have different optical and thermal properties. Chromogenic windows, Low-e windows, and solar control windows are three examples of using coating techniques on windows. These advancements in window's optical and thermal properties play a significant role in the energy performance of buildings, which will be discussed in following chapters.

3.2 Window's Component

Typically windows consist of three major parts; The glazing part, which is made of a transparent insulating material, the coatings for controlling solar gain, and window frame with various materials such as wood, aluminum, etc. The performance of window systems depend on the performance of each of these components (Ariosto, 2013). As mentioned, the focus of this study is only the glazing part of the window.

3.3 Windows Physics

There are several factors related to window's physics that are significantly important in its functionality such as durability and heat and sound insulation. The most important aspect that has a major role in the energy performance of a window in a building is its thermal and optical properties. Since the current study mainly focuses on the energy aspects and behavior of windows towards daylight, it is necessary to introduce a few fundamental parameters such as thermal and solar radiation properties to be able to compare different glazing systems.

3.3.1 Solar spectrum

All types of radiations are transmitted as waves with different wavelengths. Electromagnetic spectrum refers to all possible frequencies of electromagnetic radiations, which is comprised of three major parts; UV radiation, visible radiation (daylight), and infrared radiation. The solar radiation reaching the building occupant can be divided into two further subgroups including diffuse and direct solar radiation. Diffuse radiation reaches the surface of the earth by being scattered throughout the atmosphere. Figure 7 shows the relative position of each type of radiation in the electromagnetic spectrum.

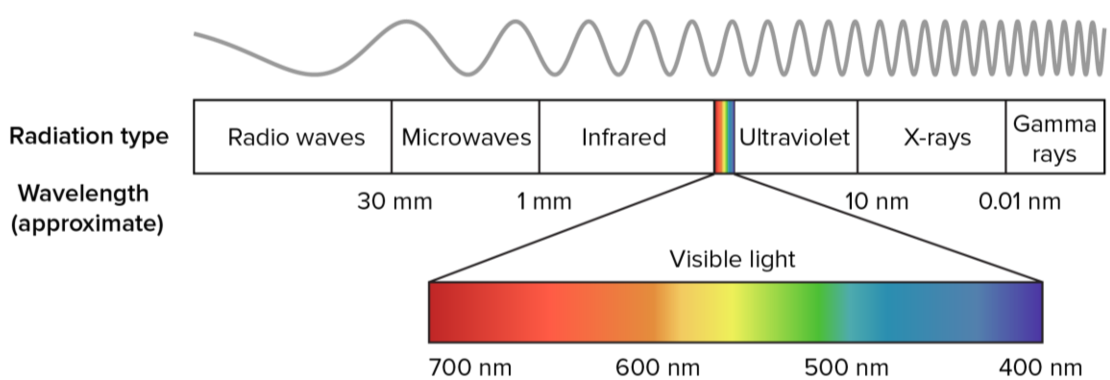


Figure 7. Electromagnetic spectrum showing wavelengths for various types of radiation
Source: www.ka-perseus-images.s3.amazonaws.com

Controlling the amount of daylight in a building is one of the basics of energy-efficient design. In architecture, Daylight Factor (DF) is a ratio used to describe the relationship between indoor and outdoor illuminances (light level).

$$DF = (E_{in} * E_{out}) * 100 \qquad (Eq. 1)$$

Where, E_{in} is the internal daylight illuminance at specific point and E_{out} is the external daylight illuminance. Since the amount of DF depends on the position (DF is position specific), there will be a range of daylight factors in any given space. Early versions of the LEED rating system provided by USGBC originally required a DF of 2 for at least 75% of all regularly occupied areas, not including, storage areas, mechanical, laundry, and other low-occupancy support areas to achieve indoor environment credit.

Windows are one of the most important parts of the buildings facing the solar radiation. The size and location of the windows and visible transmittance (VT) of glazing systems used in the building have a direct impact on the daylight factor experienced at a given point in a particular building space (Kwok & Grondzik, 2007). Furthermore, there are several ways for using solar radiation entering the building through the windows for heating or cooling. For example, it can be used in the floor heating system for decreasing the demand for heating (Jonsson, 2009).

3.3.2 Optical properties

The optical properties of a window determine how the glazing system interacts with the electromagnetic radiation. It also specifies the amount of sunlight that is reflected, transmitted, and absorbed in different panes. The optical properties of a window are commonly summarized in transmittance of daylight or visible transmittance (VT), and the g-value or solar heat gain coefficient (SHGC). The VT indicates the fraction of visible light transmitted through a window. The value of VT varies from 0 (window does not transmit any visible light) to 1 (no visible light is prevented from transmitting), which is desirable to maximize daylight. One of the features of modern windows is to allow selectively in the amounts of visible, infrared, and ultraviolet light with benefiting from using different coatings (Rosencrantz, 2005). According to the ASHRAE by the National Institute of Building Sciences, in general, more than 70% of VT is desired, especially for daylighting applications.

Solar heat gain coefficient (SHGC) is a measure of the total radiation from the sun (both directly and absorbed) entering through the window as heat. SHGC is expressed as a number between 0 (no solar gain transmitted as heat) and 1(solar gain completely transmitted as heat). The SHGC is of concern in cooling dominated climates, where it is desired to limit heat gain. It is also of concern in heating dominated climates where passive solar heating is desirable. According to WBDG, in climates with significant air conditioning loads, glazing systems with SHGC of less than 0.40 are desired. Methods of SHGC reduction typically involve utilizing tinted glass or the application of a coating or film. These methods limit the transmittance of solar energy through the glazing system. Regardless of which option is used, consideration must be given to whether additional lighting will be needed to account for the reduction in daylighting, which may negate reductions in cooling costs (Jonsson, 2009).

3.3.3 Thermal properties

Another windows property, which does not depend on optical properties is window's thermal property. The thermal property of a window can be summarized in a single parameter called U-factor (also called U-value) or thermal transmittance co-efficient. U-factor is a measure of heat loss and shows the amount of heat passed through one square meter of a material when the temperature on either side of that differs by 1^{o}C. The lower the U-factor is, the greater a window's resistance to heat flow and the better its insulating properties (Heath, et al., 2013). The unit for the U-factor is $Btu/\,(hr \times ft2 \times °F)$, although the values are usually shown without a unit attached. In addition, the relationship between heat flow and the U-factor is linear. Therefore, a U-factor of 0.2 is twice as effective at limiting heat transfer as a U-value of 0.4. Based on WBDG, in general cases U-factor of less than 0.4 is preferred for residential applications. Even lower values may be desired in extreme heating climates. Controlling heat flow in glazing systems is important in order to reduce heating and cooling loads in the buildings. This goal is also accomplished through the use of spectrally selective coatings, tints, and intelligent coatings.

The schematic chart provided in Figure 8 explains the difference between the function of glazing systems having high solar gain and Low solar gain. The comparison between glazing systems with high U- factor and low U-factor is also illustrated in Figure 8.

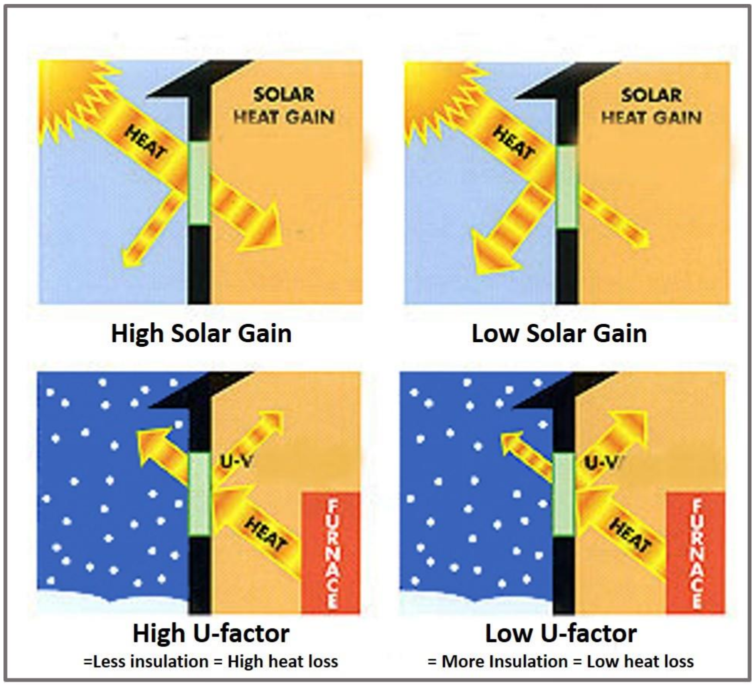


Figure 8. Relation between glazing system properties (U-factor and SHGC) and Heat flow
Source: http://lowestormwindows.com/wp-content/uploads/2010/07/low_e_chart.jpg

3.4 Performance Criteria for Glazing Systems

3.4.1 NFRC

The national fenestration rating council (NFRC) is an independent agency that provides a uniform rating system for windows and other fenestration products. In this program windows and other fenestration products are independently tested, certified, and labeled. The NFRC label would not recommend any product. However, it provides information on how the product will perform, so that the users can decide whether it is a right choice to use. Figure 9 shows a typical NFRC label. The label provides five different performance values for consideration including U-factor, SHGC, VT, Air Leakage (AL), and Condensation Resistance (CR). The only parameters that are related to glazing part of the window, which is the intention of this study are U-factor, SHGC, and VT.

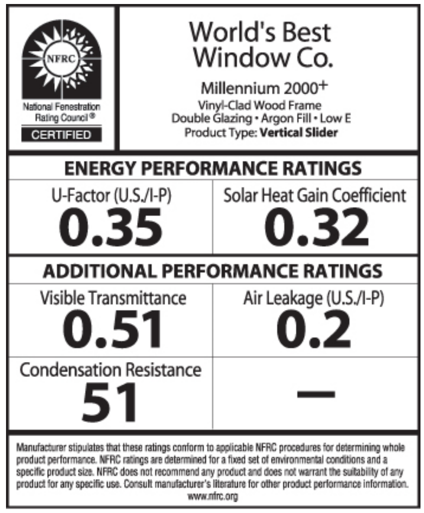


Figure 9. Example of a NFRC rating label
Source: www.nfrc.org/WindowRatings/

3.4.2 ENERGY STAR

ENERGY STAR, which is operated jointly by the US Environmental Protection Agency (EPA) and the US Department of Energy (DOE), is a voluntary program that provides criteria to promote products meeting certain energy-efficiency and performance. In addition, it provides standards for determining “high-performance” homes. ENERGY STAR’s certified homes are independently verified to meet strict guidelines for energy efficiency set by DOE. These homes save money on utility bills, provide a more comfortable living environment with better indoor air quality, and help to protect the environment. ENERGY STAR’s certified homes mainly focus on four major features including efficient walls and windows, efficient air ducts, efficient equipment, and efficient lighting and appliances.

In this regard, ENERGY STAR specifically developed some qualification criteria for residential windows, doors, and skylights. A climate zone map with four different categories is defined for this qualification as shown in Figure 10. Each of these climate zones has specific requirements in terms of the window’s physical properties (i.e. U-factor, SHGC) that are presented in Table 4.

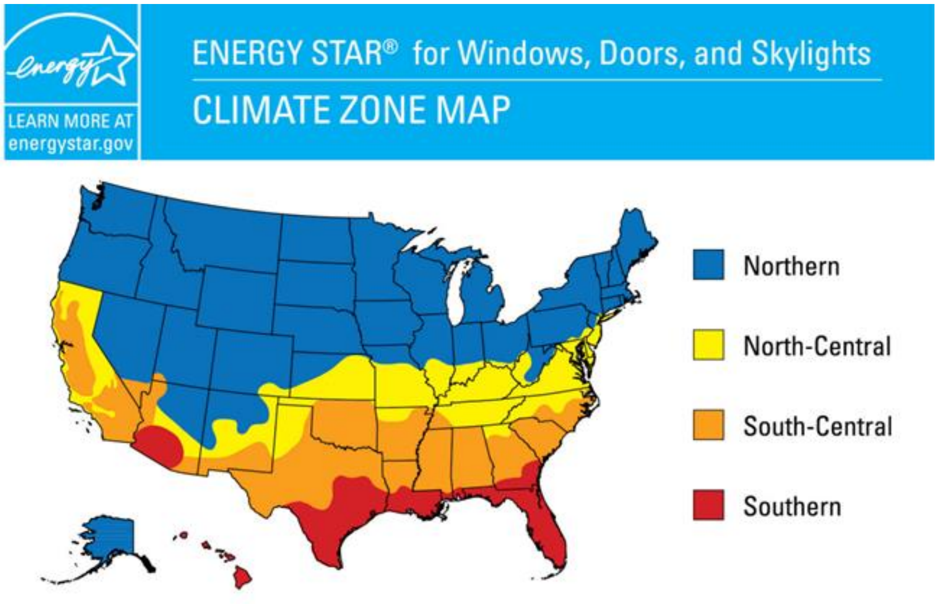


Figure 10. Energy Star climate zone map

Source: https://www.energystar.gov/ia/products/windows_doors/Promotional_Map.pdf?a892-8f62

Table 4. ENERGY STAR requirements for residential windows

Energy Efficiency Requirements for Windows		
Climate Zone	**U-Factor**	**SHGC**
Northern	≤ 0.27	≥ 0.32
North-Central	≤ 0.30	≤ 0.40
South-Central	≤ 0.30	≤ 0.25
Southern	≤ 0.40	≤ 0.25

It is notable that customers can select an appropriate type of window by comparing and matching the window properties provided in NFRC labels with ENERGY STAR requirements.

3.5 Summary of Findings

As mentioned, controlling the heat (U-factor) and light transmission (VT & SHGC) through the glazing area of windows are some of the most effective courses of actions regarding optimization of windows systems. There is currently a broad range of different technologies that may be implemented into window systems to improve their energy performance. Some of these technologies and their application in residential construction will be discussed in chapter 4.

CHAPTER 4

4. HIGH-PERFORMANCE WINDOWS

Considering the substantial impact of windows on the overall energy performance of the house, the building industry has worked to improve the energy efficiency of the windows since the last century. In recent years, a number of technological advancements such as improved framing materials, improved low-e and solar control coatings, manifestation of dynamic glass technologies, and new insulated glass unit (IGU) have significantly improved the performance of the windows.

To determine the effects of using high-performance windows on the energy performance of buildings, the first step is to define clearly what the high-performance windows are. Grondzik and Kwok (2011) defined three main categories of advanced glazing products in *The Green Studio Handbook*; "High-Performance" glazing deals with the traditional performance characteristics of static fenestration components: U-factor, SHGC, and visible transmittance. "Dynamic Glazing" has modifiable transmission properties either across the full solar radiation spectrum or within one portion of the spectrum (such as the visible portion). "Glazing Integrated Photovoltaics" are another type of advanced windows. The U.S. Environmental Protection Agency (EPA) pointed out that high-performance windows are referred to windows with advanced insulating quality, which will be obtained by different methods including:

- Improved Glazing Materials

Advancements in window technology such as double glazing and Low-e coatings, which substantially reduce heat loss and gains.

Carmody et al., (2000) indicated that the main advancements in the performance of the windows are based upon technological developments in glass coatings and insulated glazing assemblies (Glazing Materials). As discussed in chapter 2, the thermal performance of a window is mostly established according to the used glazing material and its properties.

In addition, the way that a building behaves toward the solar radiation and daylight largely depends on glazing's optical properties.

- Improved Framing Materials

Low conductance materials such as wood, vinyl, and fiberglass perform better compared to aluminum. Insulated frames including insulating spacers between glazing systems also perform better than uninsulated frames.

- Air Tightness

High-performance windows need to be sealed around framing and other gaps that may exist. Using materials such as caulks, foams, and weather-stripping would work well to keep drafts out.

Although the overall impact of other windows assemblies such as frames is not negligible, due to the significant impact of glazing materials on the energy performance of the buildings this study only focuses on energy-efficient technologies for glazing products and does not include high-performance solutions for framing or insulating glass components.

According to the explanations above and considering the objective of this research, which is reducing energy consumption, it can be concluded that any kind of advanced windows (static or dynamic) that can improve the energy performance of the houses and reduce the energy consumption of the residential unit can be considered a high-performance window. As shown in Figure 11, improved technologies can lead to a change in basic house design assumptions.

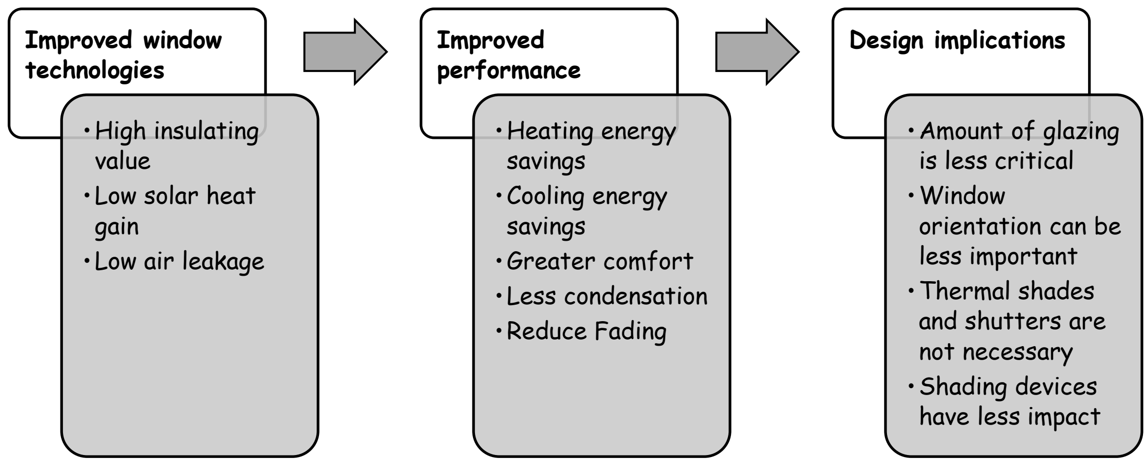


Figure 11. Impacts of improved window technologies
Source: Carmody et al., 2000

4.1 Technological Improvements in Glazing System

Carmody et al., (2000) lists three fundamental approaches to improve the energy performance of glazing system as follow:

4.1.1 Modification of glazing materials

The glazing material can be modified by changing its chemical composition or physical characteristics. Tinted glazing is considered as an example of this approach.

4.1.2 Application of coatings

Different coatings can be applied to the glazing material surface to improve the energy performance of the glazing system. For instance, reflective coatings and films were developed to reduce heat gain and glare. Recently, low-emittance coatings have been developed to improve both heating and cooling season performance. Low-e coatings have a high reflectance to long-wavelength infrared radiation, which leads to a reduction in the heat transfer between glazing layers. Using the low-e coatings within the air gap of a double pane window has a direct impact on the solar heat gain coefficient (SHGC) of the glazing system. The placement of the low-e coatings on different surfaces of the glazing system results in different behavior toward solar heat gain. For example, as shown in Figure 12, placing a low-e coating on “surface 3” results in the maximization of winter passive solar gain, which is ideal for heating-dominated climates. On the other hand, applying a coating on “surface 2” decreases the solar heat gain and is recommended in cooling dominated climates.

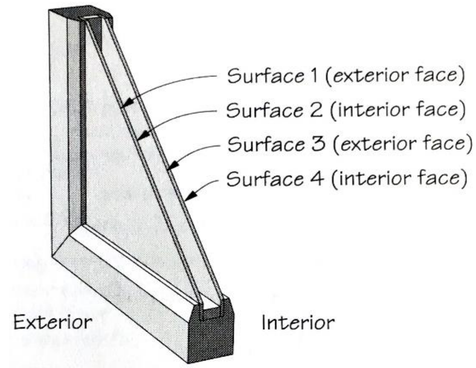


Figure 12. Possible placement of Low-e coating in double pane window

Source: Carmody et al., 2000

Typical low-e coating available on the market today can be placed into three categories:

4.1.2.1 High-Solar-Gain Low-e Coatings

These windows are designed to reduce heat loss but admit solar gain. They are best suited to buildings located in heating-dominated climates.

4.1.2.2 Moderate-Solar-Gain Low-e Coatings

These coatings reduce heat loss and allow a reasonable amount of solar gain. They are suitable for climates with both heating and cooling concerns.

4.1.2.3 Low-Solar-Gain Low-e Coatings

This type of low-e products, also called "spectrally selective" low-e glass, reduces heat loss in winter but at the same time is able to reduce heat gain in both summer and winter. Thus, low-solar-gain low-e glazing systems are ideal for buildings located in cooling-dominated climates.

4.1.3 Solar control glazings and coatings

To reduce cooling loads new types of tinted glass and new coatings can be specified that reduce the impact of the sun's heat without sacrificing the view. Spectrally selective glazing systems and coatings absorb and reflect the infrared portion of sunlight while transmitting visible daylight, thus reducing SHGC and the resulting cooling loads. These solar control coatings can also have Low-emittance characteristics.

4.1.4 Application of multiple layers glazing unit

Assembling various layers of glass (clear or coated with plastic films) and controlling the properties of space between the layers would lead to increase thermal resistance and reduce the heat loss between windows layers (Lower U-factor). Using extra layers would also provide more surfaces for placement of coatings (Carmody et al., 2000). Two or more of mentioned approaches can be combined and added to the glazing systems. Each of the additional layers that are added to the basic glazing system can lead to the change in energy performance of the window significantly.

4.1.5 Low-conductance gas filled glazings

Heat transfers through windows in three different ways including conduction, convection, and radiation. With the use of a low-emittance coating, heat transfer across a gap is dominated by conduction. The low-conductivity inert gas is used instead of air in window glazing cavities to reduce heat transmission through the window. While air is a relatively good insulator, there are other gases (such as argon, krypton, and xenon) with lower thermal conductivities. Using one of these nontoxic gases in an insulating glass unit can reduce heat transfer between the glazing layers significantly. Table 5 provides the thermal conductivity of some of the common infill gases. It should be noted that the lower the thermal conductivity it is, the better insulating values it provides, which results in the lower U-factor of the glazing system.

Table 5. Thermal conductivity of common infill gases

Source: Engineering Toolbox

Infill Gas	Thermal Conductivity W/(m·K)
Air	0.024
Argon	0.016
Krypton	9.43×10^{-3}
Xenon	5.65×10^{-3}

4.2 Summary of Findings

The concept of the high-performance window and the possible solutions for improving the glazing systems were discussed in this chapter. Also, the most commonly used glazing systems in residential buildings and their properties were provided. As mentioned, each of these glazing systems has a special feature or combination of features that is best suited for the special climatic condition. In the next chapter the best possible selection of the glazing systems in different locations with regard to overall energy saving will be elaborated on.

CHAPTER 5

5. LIFE CYCLE ANALYSIS OF GLAZING SYSTEMS

As mentioned, the intention of this research is to compare different types of glazing systems in various climatic conditions to find the most efficient ones considering their impact on energy consumption in residential buildings applications. A considerable amount of literature has been published on the comparison of the different types of windows. These studies mostly focused on the amount of energy that could be saved using each of these windows while neglecting the amount of energy required for their production. However, there are a few studies conducted regarding the amount of energy consumption over the entire life span of the window, which are mostly focused on different types of the window frames. The current research attempts to assess the overall energy consumption of different types of windows with regard to the glazing part of the window. Life Cycle Energy Analysis (LCEA) is used to compare different types of glazing systems over their entire lifetime.

5.1 LCEA of Glazing System

As mentioned, this research has studied the life cycle energy of glass and all of the components associated with an advanced glazing system. LCEA focuses on overall energies consumed over the life cycle of a glazing system including production energy and operational energy. The term “energy consumed” is interpreted as the energy used in the manufacturing of glass, assembling of the glazed unit, the effect of the glazed unit on operational energy, demolition and recycling of glass as well as transportation involved in different stages (Kiani, 2005). However, according to the study conducted on 2001 by Adalberth on total energy consumption of different single-unit dwellings, it was reported that in life cycle energy analysis, operating energy has a major share (80–90%), followed by embodied energy (10–20%), whereas demolition and other energy-related processes have negligible or little share (1%). The following equation shows a breakdown of the LCEA of a glazing system.

LCEA of glazing system=Embodied Energy+ Operational Energy

Figure 13 provides a framework for LCEA of glazing systems based on ISO 14040 standards.

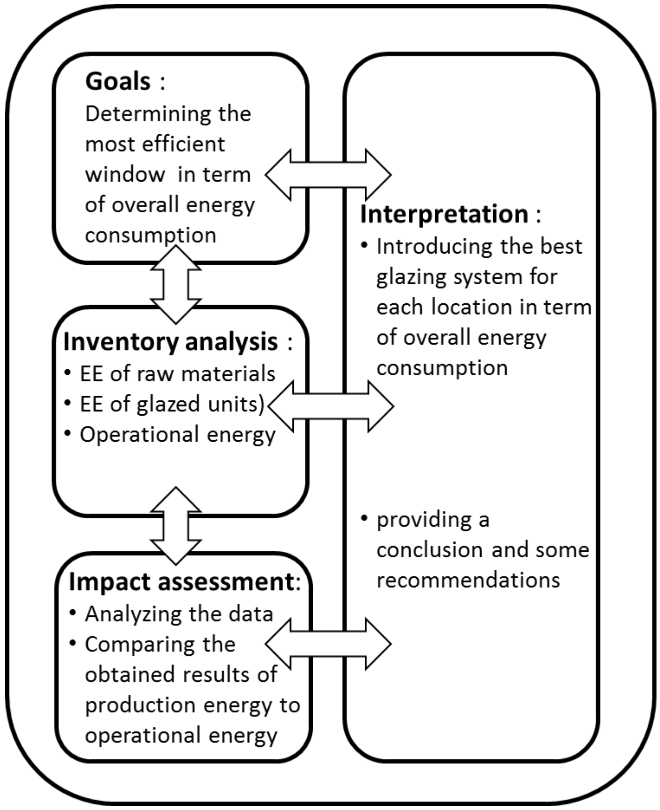
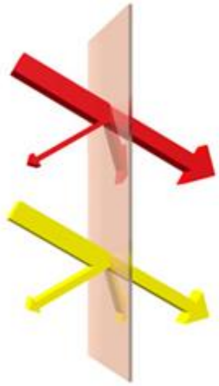
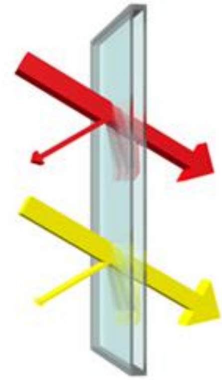
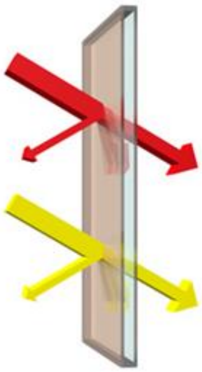
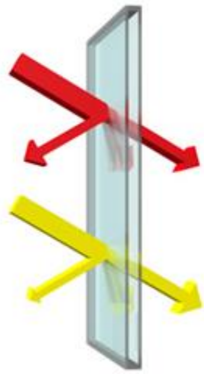
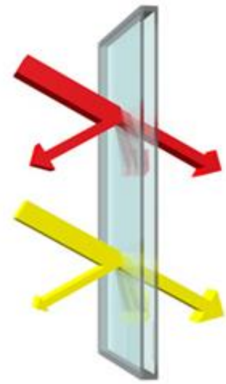
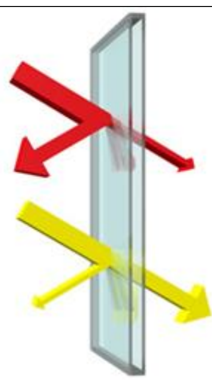
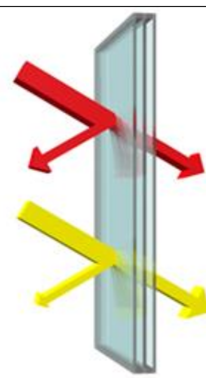
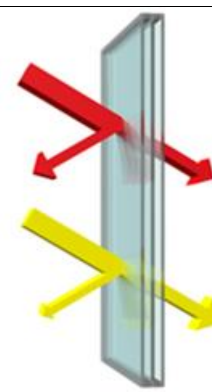


Figure 13. LCEA framework for glazing systems

5.1.1 Glazing systems used in this study

The possible approaches to improve the energy performance of the glazing systems were discussed in chapter 4. In this section, thirteen different glazing systems that are used in this study are introduced. These glazing systems are known as the most commonly used types of advanced windows in residential buildings. Figure 14 presents the glazing systems used in this study along with their properties.

 **Single-Glazed, Clear Glass** U-factor=1.11,SHGC=86,VT=0.90	 **Single-Glazed, Tinted Glass** U-factor=1.11, SHGC=0.73,VT=0.68	 **Double-Glazed, Clear Glass** U-factor=0.49,SHGC=0.76,VT=0.81
 **Double-Glazed, Tinted Glass** U-factor=0.49,SHGC=0.62,VT=0.62	 **Double-Glazed,** **High-solar-gain Low-e Glass** U-factor=0.30,SHGC=0.71,VT=0.75	 **Double-Glazed** **Moderate-solar-gain Low-e Glass** U-factor=0.26,SHGC=0.53,VT=0.75
 **Double-Glazed** **Low-solar-gain Low-e Glass** U-factor=0.25,SHGC=0.39,VT=0.70	 **Triple-Glazed** **Moderate-solar-gain Low-e Glass (with Krypthon gas)** U-factor=0.15, SHGC=0.38,VT=0.65	 **Triple-Glazed** **Low-solar-gain Low-e Glass (with Krypthon gas)** U-factor=0.13, SHGC=0.24,VT=0.56

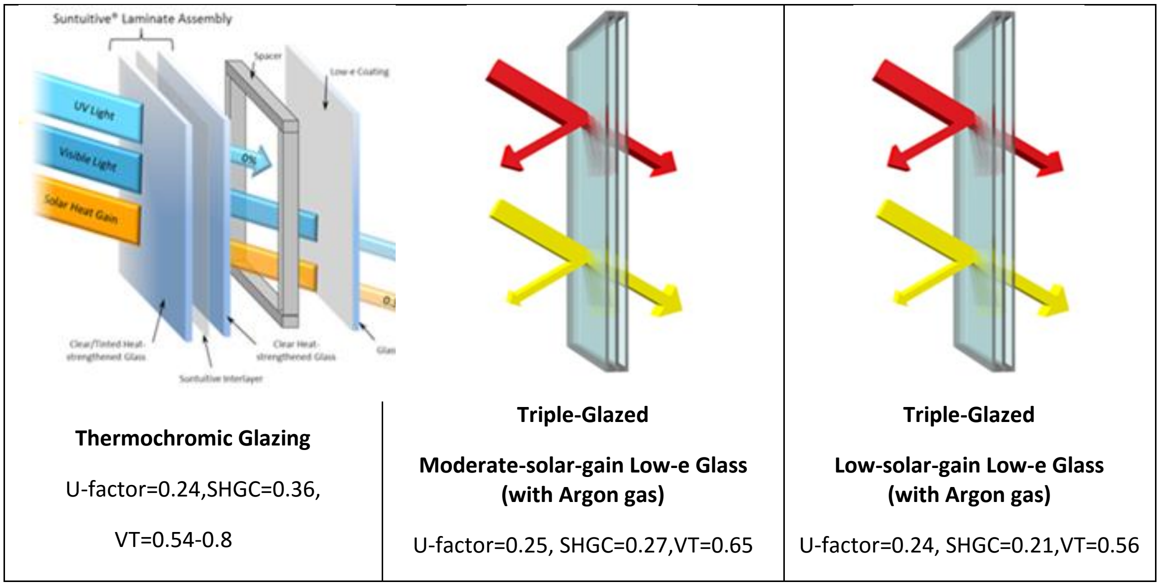


Figure 14. Common glazing systems used in residential buildings
Source: /www.efficientwindows.org

- Clear single glazing

As shown in Figure 15, according to the U.S. Department of Energy (2011), despite all of the innovations in the glass industry, current U.S. window stock still has a large number of clear single glazed windows. Clear single glazing is a central core of all other glazing systems. Due to its high U-factor (U-factor for clear single glazing is equal to 1.11), it allows the highest transfer of energy (i.e. highest rate of heat loss and gain). Also, because of the high VT (VT for clear single glazing is equal 0.90), it permits the highest amount of daylight transmission compared to other types of glazing systems.

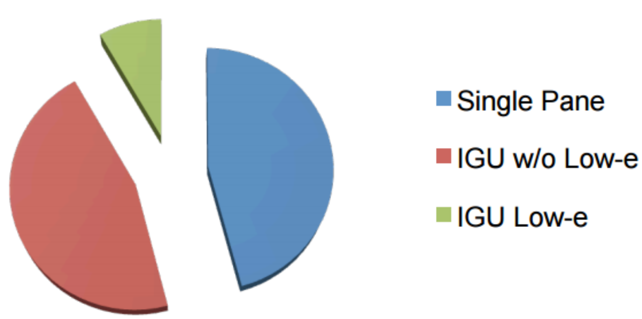


Figure 15. Existing window glazing distribution for residential market
Source: U.S. Department of Energy, 2011

- Tinted single glazing

Tinted glass is used with the goal of decreasing the solar heat gain and controlling the glare. However, they may decrease the visible transmission (VT for tinted single glazing is equal to 0.68) compared to clear glass (VT for clear single glazing is equal to 0.90). The tint has no effect on the U-factor (U-factor for tinted single glazing is equal to 1.11) but reduces solar heat gain (SHGC for tinted single glazing is equal to 0.73), which may be a benefit in the summer in cooling dominated climates and a disadvantage in the winter in heating dominated climates (Carmody, 2015).

- Double clear glazing

A common clear double pane glazing is comprised of two panes of clear glass separated by an air gap used for insulating. Due to the insulating air space between the glass layers and lower U-factor (U-factor for clear double glazing is equal to 0.49), double glazing cuts heat loss in half compared to single glazing (U-factor for clear single glazing is equal to 1.04). In addition to reducing the heat transmission, a double-glazed unit with clear glass would allow the transmission of high visible light (VT for clear double glazing is equal to 0.81) and high solar heat gain (SHGC for clear double glazing is equal to 0.76) (Carmody, 2015).

- Double glazing with a bronze or gray tint

A double-glazed unit with bronze or gray tinted glass is similar to a simple double pane glazing. The only difference is in the outer layer of glasses, which has bronze or gray tint (with using tinted films). Similar to the clear double pane glazing, it cuts heat loss in half due to the insulating air space between the glass layers and also lowers U-factor (U-factor for tinted double glazing is equal to 0.49). In addition, due to the bronze or gray tint, it decreases the solar heat gain (SHGC for tinted double glazing is equal to 0.48). However, it reduces the visible transmission (VT for tinted double glazing is equal to 0.69), which considered as a problem (Carmody, 2015).

- Double glazing with high-solar-gain low-e coatings (with argon infill gas)

These glazing systems are designed to reduce heat loss due to their lower U-factor (U-factor=0.30) but admit solar gain (SHGC=0.71). As mentioned, these products are best suited for buildings located in heating-dominated climates (Carmody, 2015).

- Double glazing with Moderate-solar-gain low-e coatings (with argon infill gas)

These glazing systems are also called spectrally selective low-e glasses due to their ability to reduce solar heat gain (SHGC=0.53) while retaining high visible transmittance (VT=0.75). Benefitting from their low U-factor (U-factor=0.26), such coatings reduce heat loss and a reduced amount of solar gain making them suitable for climates with both heating and cooling demands.

- Double glazing with low-solar-gain low-e coatings (with argon infill gas)

Due to the ability to reduce solar heat gain (SHGC=0.39) while retaining high visible transmittance (VT=0.70), these glazing systems also referred to as spectrally selective low-e glass. This type of low-e product reduces heat loss in winter because of their low U-factor (U-factor=0.25) and considerably reduces solar heat gain both in winter and in summer. Thus, low-solar-gain low-e glazing systems are ideal for buildings located in cooling-dominated climates.

- Triple glazing with moderate-solar-gain low-e coatings (with argon infill gas)

Adding a second layer of glass using argon gas, which is low-conductivity inert gas, and low-e coating will improve the insulating value of the window (U-factor= 0.25). These windows have significantly low heat loss. Also, due to using moderate-solar-gain coating, which is ideal for passive solar design, using these windows are recommended for the building located in cold climate region (Carmody, 2015).

- Triple glazing with low-solar-gain low-e coatings (with argon infill gas)

Due to the application of spectrally selective low-e coatings and its significant low U-factor (U- factor=0.24), this glazing system has low heat loss. Also, due to the reduction of solar heat gain (SHGC=0.21), these windows are recommended in climates with both significant heating and cooling loads (Carmody, 2015).

- Triple glazing with moderate-solar-gain low-e coatings (with Krypton infill gas)

Krypton has better thermal performance (U-factor= 0.15) than argon and is more expensive to produce. The optimal spacing for an argon-filled unit is the same as for air, about ½ inch. Krypton is particularly useful when the space between glazings must be thinner than normally desired, for example, ¼ inch (Carmody, 2015).

- Triple glazing with low-solar-gain low-e coatings (with Krypton infill gas)

Because of the application of spectrally selective low-e coatings and krypton infill gas, this glazing system has significantly low heat loss (U- factor=0.13). Also, due to the reduction of solar heat gain (SHGC=0.56), these windows are recommended in climates with both significant heating and cooling loads (Carmody, 2015).

- Thermochromic glazing

Thermochromic windows are one of the newest advancements in glass industry, which are becoming frequently used in both commercial and residential buildings in recent years. Thermochromic glazing systems are dynamic windows with the ability of using the heat from direct sunlight to change the color of windows when it is necessary. Preferably the thermochromic layers in the glazing system change transmission continuously over a range of temperatures, so they not only reduce heat loads (U-factor=0.24) at times of peak demand, but they maximize daylighting. Thermochromic windows do not require wires, power supplies, or control equipment and can be installed by glazing contractors, just like conventional windows. These features along with lower cost make thermochromic windows very attractive as compared to electrochromic and other dynamic glazing (www.commercialwindows.org).

5.1.2 Modeling the LCEA

At the first stage of LCEA, the embodied energy for each type of glazing system should be calculated. In this regard, the selected glazing systems have been separated into their main glass unit components as shown in Table 6 and Figure 16.

Table 6. Glass unit components

NAME	TYPE	Components
Glazing A	Clear Single Pane	Clear glass
Glazing B	Tinted Single Pane	Clear glass+ thin film
Glazing C	Clear Double Pane	2X Clear glass + Air fill
Glazing D	Tinted Double Pane	2X Clear glass+ thin film+ Air fill
Glazing E	Double Pane/High- performance tint	2X Clear glass+ thin film +Argon fill
Glazing F	Double Pane/High- Solar-gain low-e	
Glazing G	Double Pane/Moderate- Solar-gain low-e	
Glazing H	Double Pane/Low- Solar-gain low-e	3X Clear glass+ 2X thin film + Krypton fill
Glazing I	Triple Pane/Moderate- Solar-gain low-e	
Glazing J	Triple Pane/Low- Solar-gain low-e	
Glazing K	Thermochromic	
Glazing L	Triple Pane/Moderate- Solar-gain low-e	3X Clear glass+ 2X thin film + Argon fill
Glazing M	Triple Pane/Low- Solar-gain low-e	

Considering the breakdown of all of the glazing systems shown in Table 12, they have been classified into seven main categories. This is due to the fact that the glazing systems that fall into the same category have similar components, however, the order of the layers causes their different functionality. As an example, all of the glazings E, F, G, and H consist of two layers of clear glass, one layer of the thin film, and argon gas fill. The abilities and the location of the thin film lead them to provide different functions. For instance, in double pane glazing the placement of low-e coationg on outside surface of the inner pane maximizes passive solar gain (high- solar-gain low-e). However, placment of low-e coating on inside surface of the outer pane would reduce solar heat gain (low- solar-gain low-e).

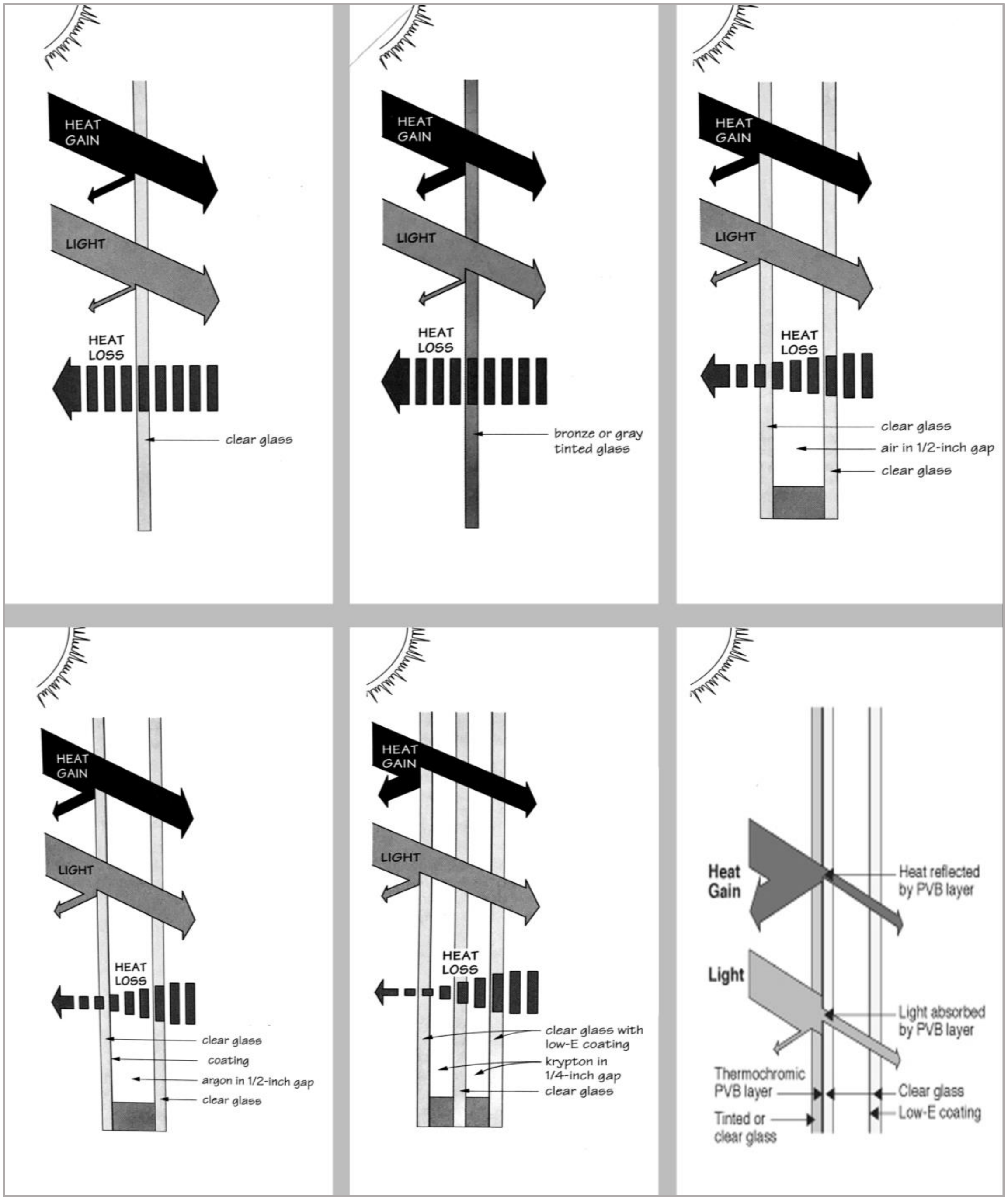


Figure 16. Glass unit components
Source: Carmody et al., 2007

5.1.3 Definition of glazed unit

In LCA, functional unit defines what precisely is being studied, and provides a reference to which the inputs and outputs can be related (Rebitzer et al., 2004). Similar to LCA, LCEA is only applicable when a functional unit represents results. For each LCEA, one or more functional unit/s may be defined. The functional unit in this study represents a range of single to the triple glazed units. There are different sizes of glazed units currently available in the market. Table 7 provides detailed information of the glazed unit used in this study.

Table 7. Detail of used glazed unit in this study

Detail of functional unit	Thickness of glass/ mm	Area of glass	Density of Glass
	6 mm (1/4")	1 ft^2	2480 kg/m^3

The glazing systems may also contain different layers of glass and cavity in the middle. The cavity may be filled with different infill gases such as argon and krypton, based on the required thermal performance for the glazed units.

5.1.4 Inventory analysis

As far as this study is concerned, the LCEA of the glazing system contains three different stages including:

- From excavation of raw materials to manufacturing of glass
- Glass to a multiple glazed unit
- Operational period of the building

The data collected for each of the stages are presented hereafter:

5.1.4.1 From excavation of raw material to manufacturing of glass

There are various sources of published data about the embodied energy (EE) of different types of glass from clear and tinted to more advanced ones such as reflective glass. Each of these sources has a different method for defining the amount of embodied energy. For this study soda lime glass was selected as the base material for the different glazing systems. Soda-lime glass is the most common type of glass used in windows as well as bottles and light bulbs and consists of 13-17% NaO (the “soda”), 5-10% CaO (the “lime”), and 70-75% SiO2 (the “glass”) (Kiani, 2005). Soda lime glass is an inexpensive material with a low melting point. It is also easy to blow and mold, which is preferable for producing glass sheets (Ashby, 2012). Table 8 presents a range of embodied energy used in this study.

Table 8. Max, min and mean of glass manufacturing embodied energy
Source: Ashby, 2012

Glass manufacturing embodied energy MJ/kg	Minimum	Mean	Maximum
	10	10.5	11

5.1.4.2 Glass to a multiple glazed unit

In this stage embodied energy of glass was combined with other components and activities (e.g., assembling, etc.) to produce a glazed unit. The following equation shows a breakdown of embodied energy in this stage.

$$EE_{\text{Glazed unit}} = EE_{\text{infill gas}} + EE_{\text{Glass}} + EE_{\text{assembling of unit}}$$

According to the provided glass area (1 ft^2), embodied energies of the whole glazing systems with respect to different types of glass and infill gas are shown in Table 9.

Table 9. Embodied energy of different glazing systems

COMPONENT		EMBODIED ENERGY (EE) (MJ/ glazed-unit)	SOURCE
Glass (MJ/ft^2)		15.36	Ashby, 2012
Infill Gas	Air	0	Kiani,2005- Weir & Muneer, 1998
	Argon	0.01	
	Krypton	508.2	
Thin film (MJ/ft^2) (average)		122	Hammond, & Jones,2008
Assembling of glazed unit		170	Weir,1998; Syrrakou, 2004
NAME	**TYPE OF GLAZING SYSTEM**	**COMPONENTS**	**TOTAL EE FOR 1 FT^2 GLAZING SYSTEM** (MJ)
Glazing A	Clear Single Pane	Clear glass	186
Glazing B	Tinted Single Pane	Clear glass+ thin film	308

Glazing C	Clear Double Pane	2X Clear glass + Air	201
Glazing D	Tinted Double Pane	2X Clear glass+ thin film+ Air	323
Glazing E	Double Pane/High- performance tint	2X Clear glass+ thin film +Argon fill	323
Glazing F	Double Pane/High- Solar-gain low-e		
Glazing G	Double Pane/Moderate- Solar-gain low-e		
Glazing H	Double Pane/Low- Solar-gain low-e		
Glazing I	Triple Pane/Moderate- Solar-gain low-e with Krypton infill	3X Clear glass+ 2X thin film + Krypton fill	1477
Glazing J	Triple Pane/Low- Solar-gain low-e with Krypton infill		
Glazing K	Thermochromic		
Glazing L	Triple Pane/Moderate- Solar-gain low-e with Argon infill	3X Clear glass+ 2X thin film + Argon fill	460
Glazing M	Triple Pane/Low- Solar-gain low-e with Argon infill		

For calculating the overall embodied energy of each glazing system, the embodied energy of one squre foot of glass (multiplied by number of layers in case of having multiple panes), embodied energy of the infill gas (in multiple glazing systems), embodied energy of one square foot of the thin film (multiplied by number of thin films in case having more than one layer coating), and embodied energy of assembling of one squre foot of the glazed unit were added up together. The value for embodied energy of each section can be obtained from different sources as referenced above.

As it was shown in Table 9, infill gas is highly responsible for increasing the EE of a glazed unit. However, using argon and krypton as an infill gas will result in higher thermal performance of the glazed unit with lower U-value.

5.1.4.3 Operational period of the building

The operational period of a building is the highest energy consuming phase over the life span of the building in terms of the energy used for heating and cooling. As mentioned, to evaluate the effect of the different glazing system on operational energy consumption, energy simulation method was used that will be explained subsequently.

5.2 Building Energy Simulation

To compare the impact of using selected glazing systems in a residential building, the energy consumption of the building associated with each glazing system should be measured during its use phase (i.e., operational energy). "Operational energy" is a term, which refers to "the amount of energy that is consumed by building to satisfy the demand for heating, cooling, ventilation, lighting, equipment, and appliances" (Brebbia & Chon, 2012). The effects of using different glazing systems on the annual operational energy of a typical residential building will be compared in different locations across the United States by using an energy simulation tool (RESFEN). Based on the results, the best possible selection of the glazing systems for different locations in terms of energy saving will be introduced.

5.2.1 Verification and model validation

Verification of a model is known as a process of confirming that computer model and simulation software accurately represent assumptions and specifications intended by the user. Following verification process, it is necessary to validate the model to ensure a simulation model and its associated data are an accurate representation of the real world. A variety of methods are used to validate simulation models including: a) comparison to other models and b) use of data generated by the actual system. Since in current study the real building (actual system) is not available, comparison to another model method was used for validating the energy simulation part of the study. In this method the results obtained from the simulation model are compared to results of other valid models (Sargent, 2005). In this study the results of energy simulation were compared to the results of the valid simulated model (i.e. *Window Annual Energy Use in Typical North American Single Family Houses* by Arasteh et al., 2000), discussed in section 4.4.1.

5.2.2 Choosing a suitable tool

Today, many building energy simulation software are available in the market. Some programs are simple energy analysis tools with limited abilities that only provide a quick analysis of annual energy use of buildings while the advanced versions are capable of providing detailed hour-by-hour energy analysis of buildings. Whole building simulation tools are integrated systems that consider all of the parameters and components together (Rallapalli, 2010). Examples of the programs include:

- Advanced programs for hourly simulation of heat, light, and air movement such as DOE-2. DOE-2 predicts the hourly energy use and energy cost of a building with given hourly weather information, a building geometric, HVAC description, and utility rate structure. DOE-2 has been used for more than twenty-five years for building design studies, analysis of retrofit opportunities, and for developing and testing building energy standards in the US and around the world (Crawley, 2008).

- Complex specialist packages for delighting and artificial lighting, computational fluid dynamics (CFD), 2D and 3D conduction calculations, and moisture migration within the building components (Rallapalli, 2010). ECOTECT is an example of these types of programs. ECOTECT is an advanced visual architectural design and analysis tool that can cover a wide range of performance analysis such as thermal, energy, lighting, shading, acoustics and cost aspects (Crawley, 2008).

- Simplified programs for overall energy consumption assessment, peak temperature prediction, heating/cooling loads calculations (Rallapalli, 2010). For example, RESFEN program, which is a simplified version of the DOE-2 program is widely used for calculating the heating and cooling energy use of windows in residential buildings. It also can be used to compare the performance of window and skylight options. This program can help consumers and builders to pick the most energy-efficient and cost-effective window for a given application, whether it is a new home, an addition, or a window replacement (windows.lbl.gov).

As mentioned, there are various simulation tools available in the market. Selection of a suitable tool should be made based on the requirements of the user and desired output information of the project. It should be noted that as the intention of this study was to compare the energy performance of the different type of glazing systems in the residential building, it was decided to use RESFEN.

RESFEN is a simplified tool that deals strictly with fenestration design for residential buildings. This program can calculate the annual heating and cooling energy use and cost due to fenestration system. While the modifications to most of the building systems are minimal, it allows the user to compare the effect of modifying glazing performance parameters for the entire building. As previously mentioned, RESFEN is a simplified version of the DOE-2 program. DOE-2 is a DOS based program that requires the user to input commands line by line. Learning to operate DOE-2 effectively requires substantial experience and is difficult for all but the most advanced energy modelers. However, RESFEN, which is easier to use software but still operates under the DOE-2 "engine" has been developed. RESFEN simplifies the use of the DOE-2 engine to incorporate only those options used for analyzing the effect of various fenestration products for residential scale buildings. As the intention of the energy simulation in this study was to calculate the overall energy consumption associated with the different glazing systems, RESFEN program was considered a suitable choice. A screen shot of the interface of REFSEN program is shown in Figure 17.

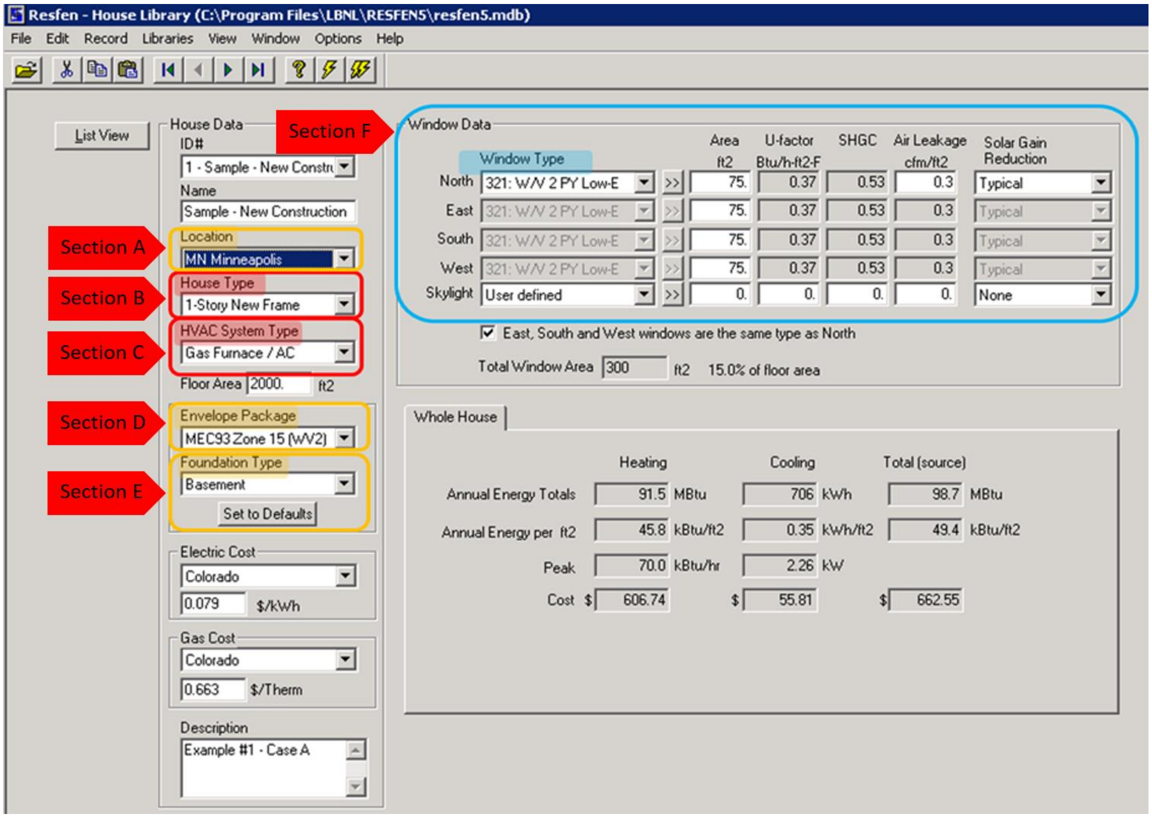


Figure 17. Interface of the RESFEN program
Source: RESFEN Software

5.2.3 Input parameters of REFSEN simulation

This section provides detailed information about the input parameters used in energy simulation by REFSEN.

5.2.3.1 Location parameter

REFSEN software has a location library, which contains data (records) that references weather file for RESFEN to use in the building calculation. The target location to be studied can be selected from "location" tab as shown in section A, Figure 17.

In this study, the energy performance analysis was conducted assuming buildings located in different locations throughout the United States. As shown in Figure 18, in the beginning, four cities including Chicago-IL, Philadelphia-PA, Miami-FL, and Oklahoma-OK, were identified, which represented four climate zones in the US based on ENERGY STAR climate zone classification. The selected cities and their associated climate zones are shown in Table 10. As previously mentioned in Chapter 2, ENERGY STAR specifically developed qualification criteria for residential windows. For this qualification a climate zone is developed with four different categories and specific requirements were defined for each of these categories in terms of the glazing properties.

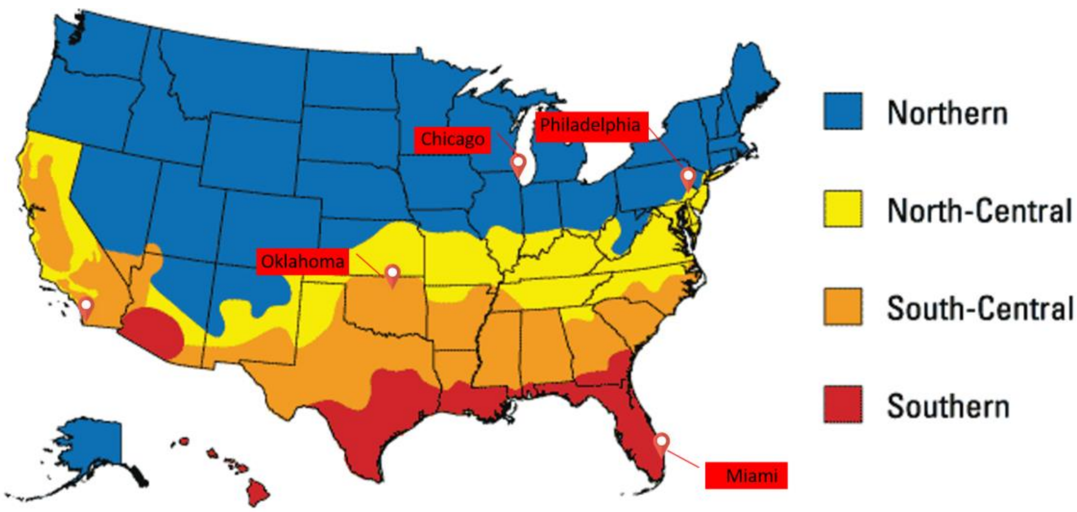


Figure 18. Selected cities based on Energy Star climate zone map

Table 10. Climate Zone Corresponding to Each Location

LOCATION	CLIMATE ZONE
Chicago, IL	Northern
Philadelphia, PA	North-Central
Oklahoma, OK	South-Central
Miami, FL	Southern

It should be noted that since the results of the energy simulation were close in some locations and also the selected cities were near to each other while locating in different climate zones, (e.g. Chicago and Philadelphia located in different climate zone. However, they are relatively close to each other in the U.S scale) there was a concern that the ENERGY STAR climate zone map is not comprehensive enough. As a result, it was also decided to use DOE climate zone map, which has more variety of climate categories, in order to verify the results in each region. As illustrated in Figure 19, DOE climate zone map contains eight climate zones. For reporting purposes, these are further combined into five climate categories including hot-humid, hot-dry/mixed dry, mixed-humid, marine, cold/very cold, and subarctic. Apparently, the ENERGY STAR climate zone map is a simplified form of this classification.

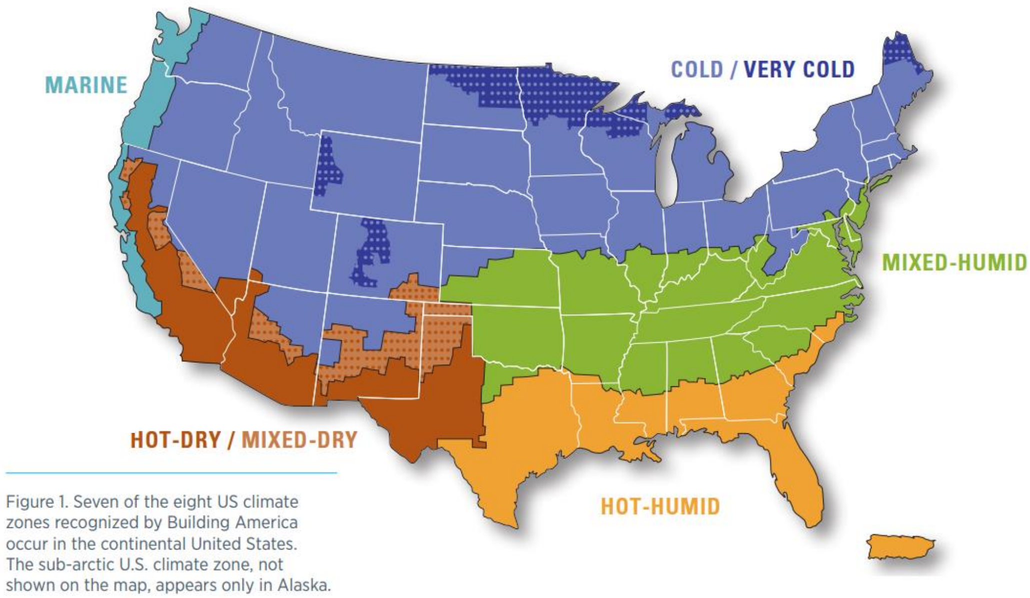


Figure 19. DOE climate zone map

Source: http://energy.gov/sites/prod/files/2015/10/f27/ba_climate_region_guide_7.3.pdf

By combining two maps together as presented in Figure 20, eight cities were selected. As shown in Table 11, these cities were selected such that they represent all four regions in ENERGY STAR while covering each climatic zone in DOE map. As an example, San Diego and Montgomery are located in South Central zone in ENERGY STAR map. However, San Diego is located in hot-dry region while Montgomery is located in hot-humid climate based on DOE map. If only four cities were selected to represent ENERGY STAR climate zone, all climatic zone provided by DOE map would not have been covered.

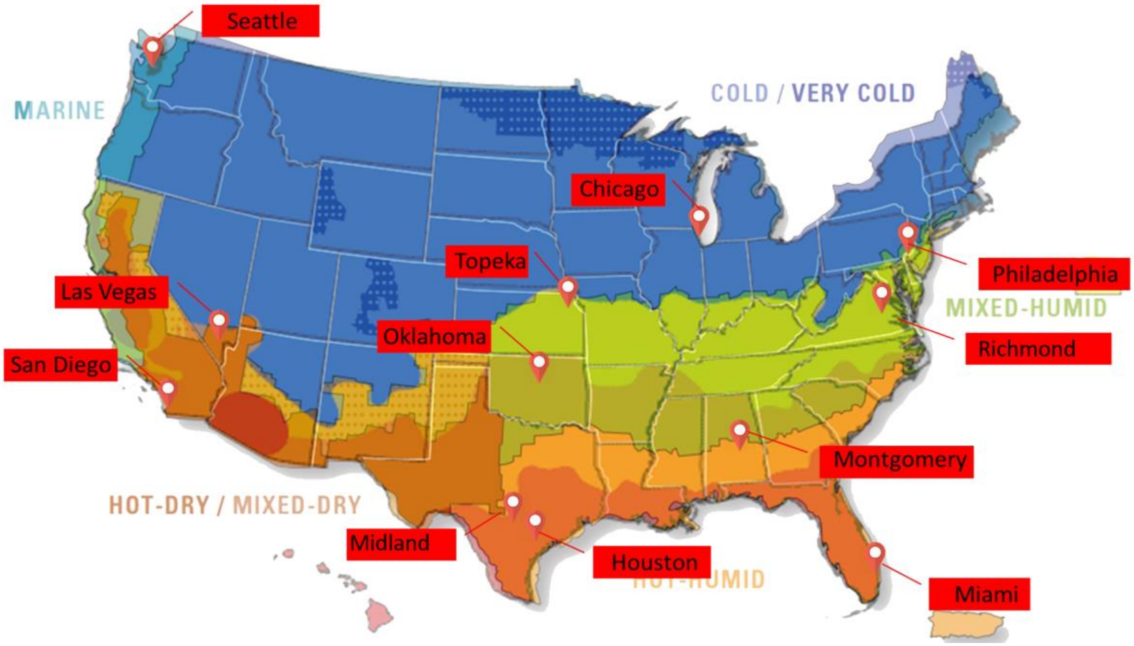


Figure 20. Combination of ENERFY STAR and DOE climate zone map

Table 11. DOE and ENERGY STAR Climate Zone Corresponding to Each Location

LOCATION	DOE CLIMATE ZONE	ENERGY STAT CLIMATE ZONE
Seattle, WA	Cold	Northern
Topeka, KS	Mixed-Humid	North-Central
Richmond, VA	Mixed-Humid	North-Central
San Diego, CA	Hot-Dry	South-Central
Las Vegas, NV	Hot-Dry	South-Central
Midland, TX	Mixed-Dry	South-Central
Montgomery, AL	Hot-Humid	South-Central
Houston, TX	Hot-Humid	Southern

5.2.3.2 Model building

To evaluate the effect of different glazing systems on the energy performance of a building, this study was conducted in one-fixed scale, in which all of the intended glazing systems were examined on one specific model. The scale of the model and all other parameters related to the model were maintained constant for each iteration, so the glazing type was the only variable that changed. To develop the required parameters, some assumptions were made based on the study conducted in 2000 by Arasteh et al., on *Window Annual Energy Use in Typical North American Single Family Houses*. This resource was selected to compare its results with the result obtained in this research, hence, to validate the model predictions of this study.

RESFEN provides several different options that can be specified for building type. These include 1-story or 2-story homes using new or existing wood frame or masonry construction techniques (Figure 17, section B). In this study, 1-story new wood frame construction option was specified. The floor area was assumed to be 2000 sq. ft. house with 300 sq. ft. of window area (15% of the floor area). It was assumed that the windows are equally distributed on all four sides of the house (as shown in Figure 21).

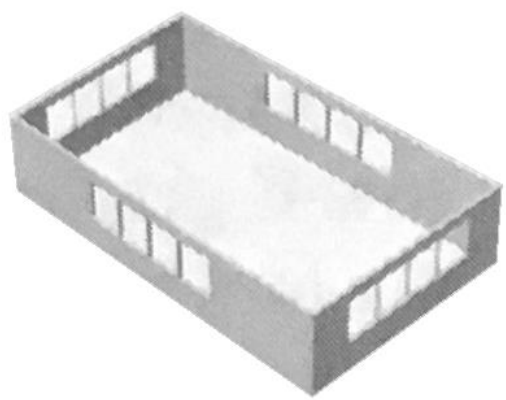


Figure 21. Assumed building type for model simulation
Source: Carmody et al., 2007

5.2.3.3 HVAC system

Another input parameter that needed to be specified was the type of HVAC system (Figure 17, section C) used in the selected building. RESFEN provides two options for this category; Gas Furnace/AC or electric heat pump. In this study, Gas Furnace/AC was assumed and considered as HVAC system (Arasteh et al., 2000; Carmody et al., 2000).

5.2.3.4 Envelope package and foundation type

In order to introduce the level of insulation in different parts of building (walls, floors, ceilings, and foundation), building envelope should be determined in RESFEN. The

“Packages Library” provided in RESFEN is used to construct a set of building envelope insulation definitions. These packages are associated with a location of a building in the “Location Library” to create customized modeling situations. In addition to Envelope Package, REFSEN applies a foundation type to the building to define the properties of the building envelope (Figure 17, section D & E). As mentioned, these options are applied based on established norms for the climate specified in the “location” section.

5.2.3.5 Type of window

Another building component that needs to be specified in RESFEN is the type of windows that will be used (Figure 17, section F). As discussed in Chapter 4, there are several factors and technologies that can be incorporated into window glazing systems (variables of this study). In order to be realistic, this study focuses on the types of technologies that are commonly used in residential buildings.

RESFEN operates by taking the window U-value, SHGC, and air leakage rate into account on each face of the building. Since the air leakage rate is not directly associated with the glazing system and it was assumed that all parameters are equal, the default air leakage rate of RESFEN program was maintained constant (0.3 cfm/ft^2) for all iterations.
The total window U-value can be input using one of the three methods described as follow: 1) RESFEN has a selection of generic window values preloaded in its window library (e.g., low-e IGU, clear IGUs) that may be used for analysis. 2) In addition, new windows may be generated using WINDOW 6 (LBNL, 2011) based on manufacturer specifications. 3) Lastly, the windows can be defined on the spot as a “user defined” window. In this study the last method (method 3) was used, as RESFEN library for glazing types did not contain specifications of all selected glazing types. The summary of properties of each of the glazing systems used in this study, which was input manually in REFSEN program is presented in Table 12.

Table 12. Glazing Performance Properties Used
Source: Carmody et al., 2007

NAME	TYPE	U-FACTOR	SOLAR HEAT GAIN COEFFICIENT	VISIBLE TRANSMITTANCE
Glazing A	Clear Single Pane	1.11	0.86	0.90
Glazing B	Tinted Single Pane	1.11	0.73	0.68
Glazing C	Clear Double Pane with Air infill	0.49	0.76	0.81
Glazing D	Tinted Double Pane with Argon gas	0.49	0.62	0.62
Glazing E	Double Pane/High- performance tint With Argon gas	0.49	0.48	0.69
Glazing F	Double Pane/High- Solar-gain low-e with Argon gas	0.30	0.71	0.75
Glazing G	Double Pane/Moderate- Solar-gain low-e with Argon gas	0.26	0.53	0.75
Glazing H	Double Pane/Low- Solar-gain low-e with Argon gas	0.25	0.39	0.70
Glazing I	Triple Pane/Moderate- Solar-gain low-e with Krypton gas	0.15	0.38	0.65
Glazing J	Triple Pane/Low- Solar-gain low-e With Krypton gas	0.13	0.24	0.56
Glazing K	Thermochromic	0.24	0.36	0.54-0.8
Glazing L	Triple Pane/Moderate- Solar-gain low-e with Argon gas	0.25	0.27	0.65
Glazing M	Triple Pane/Low- Solar-gain low-e With Argon gas	0.24	0.21	0.56

It is important to note that as discussed, the only input parameter that was changed during each simulation was glazing type. All other variables were kept constant during each iteration. With defining the locations (12 selected cities) and using all of the pre-defined input parameters, the total annual energy associated with each type of glazing system was calculated. The main input parameters underlying the simulation are summarized in Table 13.

Table 13. Assumed input parameters
Source: Carmody et al., 2007

PARAMETER	MODELING ASSUMPTION
Floor Area	2,000 sq. ft.
House Type	New construction, single-family, single story
Foundation	Basement
Insulation	Envelope insulation levels are based on location.
Window Area	300 sq. ft. (15% of floor area)
Glazing Type	Variable
Window Distribution	Equal area on north, east south, and west.
HVAC System	Gas furnace & A/C
Weather Data	All TMY (typical metrological year) data
Number of Locations	12 US cities

5.2.4 Output parameters of REFSEN simulation

RESFEN provides simplified results in comparison with other energy simulation tools (e.g., DOE-2, etc.). The results provided by RESFEN are restricted to annual heating, cooling, total energy use, peak values, and estimated costs associated with using the fenestration system. The type of data that was focused on in this study was total annual energy use.

5.2.4.1 Units of the output provided by RESFEN

It should be noted that the unit of output for energy related data obtained from RESFEN is based on “kBtu”. However, since in next chapters the annual energy use values will be compared with Embodied Energy (EE), which are typically computed using units of mega joules (MJ), the values obtained from RESFEN will be presented in MJ in this thesis. Table 14 explains units of the output (annual energy use) provided by REFSEN and its definition.

Table 14. Units of the output provided by RESFEN

Energy Unit	Definition
Btu* (B.T.U)	The heat required increasing the temperature of 1 pound of water 1 ^{o}F.
Mega Joule (MJ)= 10^6 Joule	The heat required raising the temperature of 1 g of water by 0.24 K or the amount of electricity required to light a 1 watt LED for 1 s.

* 1 Btu is equivalent to approximately 1055 joules; 1 kBtu is equivalent to approximately 1.05 MJ

5.2.4.2 RESFEN results and discussion

The values obtained from RESFEN are listed in Table 15. These values show total annual energy use for buildings located in selected twelve cities using thirteen different glazing systems.

Based on the results presented in Table 15, Triple Pane/Moderate-Solar-gain low-e glazing (Glazing I) provides the best performance in terms of annual energy use in cities located in Northern climate zone, i.e., Chicago and Seattle, with 35.77 MJ and 21.21 MJ annual energy use per square foot of area, respectively. The worst performance for this region belongs to Tinted Single Pane glazing (Glazing B) with 58.34 MJ and 37.67 MJ per square foot of area for Chicago and Seattle respectively.

For the North-Central climate zone cities (Philadelphia, Topeka, and Richmond), the best performance was provided by using Triple Pane/Moderate-Solar-gain low-e glazing (Glazing I) and the worst performance was provided by using Tinted Single Pane glazing (Glazing B), which were the same as the result obtained for Northern climate zone cities. This behavior may be explained as follow: Due to the low U-factor (U-factor=0.15) corresponds to Triple Pane/Moderate-Solar-gain low-e glazing (Glazing I), these glazing systems reduce heat loss and allow reasonable amount of solar gain (SHGC=0.50), which can be considered as the best option for heating dominated climate (Northern and North-Central). In contrast, the inefficiency of Tinted Single Pane glazing (Glazing B) may be because of its high inherent U-factor (U-factor=1.11). It should be noted that although the amount of solar gain of glazing B (SHGC=0.73) is more than glazing I, the significant high value of U-factor of Tinted Single Pane glazing may lead to considerable heat loss through windows.

For the cities located in South-central climate zone (Oklahoma, San Diego, Las Vegas, Midland, and Montgomery), Triple Pane/Low- Solar-gain low-e glazing (Glazing J) showed the best performance in terms of annual energy use per square foot of area. The most inefficient glazing in terms of annual energy use in this region was determined to be Clear Single Pane glazing (Glazing A). Meanwhile, for the Southern region cities (Miami and Houston), the best performance was reached by using Triple Pane/Low- Solar-gain low-e glazing (Glazing J) and the worst one was provided by using Clear Single Pane glazing (Glazing A). Similar to the results for North and North-Central, it can be observed that the best and the worst performer for Southern and South-Central cities were similar. This behavior can be explained as follow: Triple Pane/Low- Solar-gain low-e glazing (Glazing J), also called "spectrally selective" low-e glass, reduces heat loss in winter due to its inherent low U-factor (U-factor=0.13), but at the same time is able to reduce heat gain in both summer and winter. Thus, low-solar-gain low-e glazing systems are ideal for buildings located in cooling-dominated climates. On the other hand, the inefficiency of Clear Single Pane glazing (Glazing A) is due to the corresponding U-value (U-value=1.11) and SHGE (SHGE=0.86).

Table 15. Total Annual Energy Use (RESFEN Analysis).
Values measure in MJ/ft2. The best performer in each location is highlighted in yellow while the worst performer is highlighted in green

Location	Glazing A	Glazing B	Glazing C	Glazing D	Glazing E	Glazing F	Glazing G	Glazing H	Glazing I	Glazing J	Glazing K	Glazing L	Glazing M
Chicago, IL	57.5	58.3	43.8	44.6	45.7	38.8	38.9	39.6	35.8	36.3	39.6	40.6	40.9
Seattle, WA	36.4	37.7	26.4	27.5	29.0	22.8	23.5	24.8	21.2	22.5	24.9	26.3	27.0
Philadelphia, PA	46.7	47.5	35.9	36.5	37.2	32.2	31.9	32.4	29.3	29.8	32.3	33.3	33.6
Topeka, KS	51.1	51.5	39.8	40.1	40.5	35.7	35.0	35.2	32.3	32.5	35.1	35.9	36.1
Richmond, VA	35.8	36.0	27.6	27.7	28.0	24.7	23.9	24.2	20.9	22.2	24.1	24.7	24.8
Oklahoma, OK	43.8	43.6	34.5	34.2	34.1	31.1	30.1	30.0	29.6	29.5	29.9	30.1	30.1
San Diego, CA	8.5	8.1	6.6	6.0	5.6	5.9	5.0	4.6	4.5	4.2	4.6	5.0	5.2
Las Vegas, NV	39.7	38.3	32.6	30.9	29.5	29.9	27.2	25.7	25.5	25.3	25.6	24.9	24.6
Midland, TX	34.1	33.1	27.1	26.0	25.2	24.6	22.6	21.6	20.9	19.7	21.4	21.4	21.3
Montgomery, AL	28.7	27.5	23.9	22.7	21.4	22.3	20.2	18.9	19.0	15.7	17.4	18.0	17.8
Miami, FL	41.5	38.3	39.6	36.0	32.3	38.5	34.0	30.2	31.2	26.7	29.4	27.0	27.4

Houston, TX	35.1	33.3	30.8	28.7	26.7	29.0	26.1	23.9	24.9	22.5	23.6	22.6	22.6

It could be therefore concluded that in this study Triple Pane/Moderate-Solar-gain low-e was determined to be the most efficient fenestration system in Chicago, Seattle, Philadelphia, Topeka, and Richmond (i.e., Northern and North-Central region). While in Oklahoma, San Diego, Las Vegas, Midland, Montgomery, Miami, and Houston (i.e., Southern and South-Central region) using the Triple Pane/Low- Solar-gain low-e provided the best performance. However, an important requirement that needs to be satisfied is to verify that the selected glazing types would meet the acceptable performance parameters for high-performance windows. This can be done by comparing the input parameters of the selected glazing systems including U-factor and SHGC with the acceptable criteria for residential windows provided by ENERGY STAR. Table 16 provides the list of best performer glazing systems and their corresponding U-factor and SHGC investigated in this study along with the acceptable values provided by ENERGY STAR. As it can be observed from Table 16, all selected glazing systems (Triple Pane/Moderate- Solar-gain low-e for Northern and North-Central region and Triple Pane/Low- Solar-gain low-e for Southern and South-Central region) meet the requirement of ENERGY STAR criteria.

Table 16. Comparison of best glazing systems properties in each location according to the results of energy simulation with the ENERGY STAR requirement

Climate Zone	Location	Simulation Results			ENERGY STAR REQUIREMENT		Meet the Requirement
		Best Glazing System	U-value	SHGC	U-factor	SHGC	
Northern	Chicago, IL	Triple Pane/Moderate-Solar-gain low-e with Krypton	0.15	0.38	≤ 0.27	≥ 0.32	✓
	Seattle, WA	Triple Pane/Moderate-Solar-gain low-e with Krypton	0.15	0.38			
North-Central	Philadelphia, PA	Triple Pane/Moderate-Solar-gain low-e with Krypton	0.15	0.38	≤ 0.30	≤ 0.40	✓
	Topeka, KS	Triple Pane/Moderate-Solar-gain low-e	0.15	0.38			
	Richmond, VA	Triple Pane/Moderate-Solar-gain low-e	0.15	0.38			

South-Central	Oklahoma, OK	Triple Pane/Low- Solar-gain low-e	0.13	0.24	≤ 0.30	≤ 0.25	✓
	San Diego, CA	Triple Pane/Low- Solar-gain low-e	0.13	0.24			
	Las Vegas, NV	Triple Pane/Low- Solar-gain low-e	0.13	0.24			
	Midland, TX	Triple Pane/Low- Solar-gain low-e	0.13	0.24			
	Montgomery, AL	Triple Pane/Low- Solar-gain low-e	0.13	0.24			
Southern	Miami, FL	Triple Pane/Low- Solar-gain low-e	0.13	0.24	≤ 0.40	≤ 0.25	✓
	Houston, TX	Triple Pane/Low- Solar-gain low-e	0.13	0.24			

5.3 Summary of Findings

The results presented in this chapter provide a good indication of glazing technologies that work best for each specific climate zone. As shown in Table 8, it can be observed that the glazing systems with relatively low U-factor perform well in heating-dominated climates. It should be noted that in cold climate zones, preventing heat loss is more important than passive heating through solar heat gain. On the other hand, in cooling-dominated climates, preventing solar heat gain is the primary objective. For instance, while the triple pane/moderate- solar-gain low-e window provides the best performance in the cold weather locations, it does not perform well enough in cooling-dominated locations. This may be due to the fact that the SHGC is still significantly high for this type of glazing system.

As previously discussed, Life Cycle Energy Analysis (LCEA) consists of two main phases including operational energy and production energy (Embodied Energy). Although according to the results, "Triple pane glazing systems" provides the best performance among other glazing systems in terms of energy use, the amount of energy that is used to produce this type of glazing (embodied energy) is also determinative in selecting the most efficient window.

CHAPTER 6

6. DISCUSSION OF THE RESULTS

This section presents comprehensive results of the analysis conducted in this research. The discussion of the results will be subsequently provided.

6.1 Results

After completing all required inventory analyses, energy impact assessment is the next step of conducting an LCEA. The energy impact assessment in this study consists of comparing the energy consumption (relative to the energy consumption of clear glass, which considered as a baseline, as later discussed in this chapter) of the glazing systems during their production phase and use phase. The energy for producing (embodied energy) 1ft^2 of each of the selected glazing systems (i.e., glazing system A to M) was calculated in Chapter 5. As previously explained, in this study the glass area was assumed to be 300 ft^2, which is 15% of floor area (Carmody et al., 2007). Table 17 provides the overall amount of energy required for producing 300 ft^2 of each of the glazing systems. This was performed by multiplying production energy of 1ft^2 of each selected glazing system by 300 (ft^2).

Table 17. Total embodied energy of different glazing systems

Name	Type Of Glazing System	Components	Total EE For 300 Ft^2 Glazing System (MJ)
Glazing A	Clear Single Pane	Clear glass	55,800
Glazing B	Tinted Single Pane	Clear glass+ thin film	92,400
Glazing C	Clear Double Pane	2X Clear glass + Air	60,300
Glazing D	Tinted Double Pane	2X Clear glass+ thin film +Air	96,900
Glazing E	Double Pane/High- performance tint	2X Clear glass+ thin film +Argon fill	96,900
Glazing F	Double Pane/High- Solar-gain low-e		
Glazing G	Double Pane/Moderate- Solar-gain low-e		

Glazing H	Double Pane/Low- Solar-gain low-e		
Glazing I	Triple Pane/Moderate- Solar-gain low-e with Krypton infill	3X Clear glass+ 2X thin film + Krypton fill	443,100
Glazing J	Triple Pane/Low- Solar-gain low-E with Krypton infill		
Glazing K	Thermochromic		
Glazing L	Triple Pane/Moderate- Solar-gain low-e with Argon infill	3X Clear glass+ 2X thin film + Argon fill	138000
Glazing M	Triple Pane/Low- Solar-gain low-e with Argon infill		

Moreover, Table 18 tabulates the input parameters assumed for conducting the simulation in this study, as discussed in chapter 4.

Table 18. Input parameters assumed for conducting the simulation
Source: Carmody et al., 2007

Parameter	Modeling Assumption
Floor Area	2,000 sq. ft.
House Type	New construction, single-family, single story
Foundation	Basement
Insulation	Envelope insulation levels are based on location.
Window Area	300 sq. ft. (15% of floor area)
Glazing Type	Variable
Window Distribution	Equal area on north, east south, and west.
HVAC System	Gas furnace & A/C
Weather Data	All TMY (typical metrological year) data
Number of Locations	12 US cities

Since the clear single pane (Glazing A) is the fundamental component of all other selected glazing systems and the minimum expected glazing system used in contemporary residential construction, it is considered as the baseline of analyses for energy performance and production energy in this study. Subtracting the energy used during the production phase of each glazing system (Glazing B to M) from the production energy of "Glazing A" provides the additional energy required for producing the advanced glazing systems (with respect to clear single pane glazing, Glazing A, as a baseline). These values are presented in Table 19.

Table 19. Additional energy used for producing 300 ft^2 of each glazing system compared the baseline (glazing A)

<table>
<tr><th>Name</th><th>Type Of Glazing System</th><th>Components</th><th>Additional EE Used For Producing 300 Ft² Of Each Glazing System Compared To Baseline (MJ)</th></tr>
<tr><td>Glazing A</td><td>Clear Single Pane</td><td>Clear glass</td><td>Baseline</td></tr>
<tr><td>Glazing B</td><td>Tinted Single Pane</td><td>Clear glass+ thin film</td><td>36,600</td></tr>
<tr><td>Glazing C</td><td>Clear Double Pane</td><td>2X Clear glass + Air</td><td>4,500</td></tr>
<tr><td>Glazing D</td><td>Tinted Double Pane</td><td>2X Clear glass+ thin film +Air</td><td>41,100</td></tr>
<tr><td>Glazing E</td><td>Double Pane/High- performance tint</td><td rowspan="4">2X Clear glass+ thin film +Argon fill</td><td rowspan="4">41,100</td></tr>
<tr><td>Glazing F</td><td>Double Pane/High- Solar-gain low-e</td></tr>
<tr><td>Glazing G</td><td>Double Pane/Moderate- Solar-gain low-e</td></tr>
<tr><td>Glazing H</td><td>Double Pane/Low- Solar-gain low-e</td></tr>
<tr><td>Glazing I</td><td>Triple Pane/Moderate- Solar-gain low-e with Krypton infill</td><td rowspan="3">3X Clear glass+ 2X thin film + Krypton fill</td><td rowspan="3">387,300</td></tr>
<tr><td>Glazing J</td><td>Triple Pane/Low- Solar-gain low-e with Krypton infill</td></tr>
<tr><td>Glazing K</td><td>Thermochromic</td></tr>
<tr><td>Glazing L</td><td>Triple Pane/Moderate- Solar-gain low-e with Argon infill</td><td rowspan="2">3X Clear glass+ 2X thin film + Argon fill</td><td rowspan="2">82,200</td></tr>
<tr><td>Glazing M</td><td>Triple Pane/Low- Solar-gain low-e with Argon infill</td></tr>
</table>

Similarly, subtracting the annual energy use associated with each of the aforementioned glazing systems (Glazing B to M) from the results of “Glazing A” provides a demonstration of the amount of energy that each glazing system can save per sq. ft. of the area of the building during one year. These values are presented in Table 20. In order to determine the overall amount of energy that can be saved for the entire area of the house using each of these glazing systems (during use phase), the values of Table 20 is multiplied by the total floor area (2000 ft^2). Table 21 presents the total annual energy saving of the whole house using different glazing systems during the use phase.

Table 20. Total annual energy saving with each of the selected glazing systems for 1 sq. ft. of area (Values measure in MJ/ft^2)

	Total Annual Energy Saving (MJ/ ft2)											
	Chicago	Seattle	Philadelphia	Topeka	Richmond	Oklahoma city	San Diego	Las Vegas	Midland	Montgomary	Miami	Houston
Glazing A	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*
Glazing B	-0.84	-1.27	-0.74	-0.42	-0.21	0.21	0.42	1.37	0.95	1.16	3.17	1.79
Glazing C	13.72	10.02	10.87	11.29	8.12	9.28	1.90	7.07	6.96	4.75	1.90	4.33
Glazing D	12.87	8.86	10.23	10.97	8.02	9.60	2.53	8.76	8.12	6.01	5.49	6.44
Glazing E	11.82	7.39	9.50	10.55	7.81	9.71	2.95	10.13	8.86	7.28	9.18	8.44
Glazing F	18.67	13.61	14.56	15.40	11.08	12.66	2.64	9.81	9.50	6.44	2.95	6.12
Glazing G	18.57	12.87	14.88	16.04	11.82	13.72	3.59	12.45	11.50	8.55	7.49	9.07
Glazing H	17.94	11.61	14.35	15.83	11.61	13.82	3.90	13.93	12.45	9.81	11.29	11.18
Glazing I	21.73	15.19	17.41	18.78	14.88	14.14	4.01	14.14	13.19	9.71	10.23	10.23
Glazing J	21.21	13.93	16.99	18.57	13.61	14.24	4.33	14.35	14.35	12.98	14.77	12.66
Glazing K	17.94	11.50	14.45	15.93	11.71	13.93	3.90	14.03	12.66	11.29	12.03	11.50
Glazing L	16.88	10.13	13.40	15.19	11.08	13.72	3.59	14.77	12.66	10.66	14.45	12.56
Glazing M	16.56	9.39	13.19	14.98	10.97	13.72	3.38	15.09	12.77	10.87	14.03	12.50

Table 21. Total annual energy saving with each of the selected glazing systems for the entire house area (Values measured in MJ)

	Total Annual Energy Saving of the Whole House(MJ/ ft2)											
	Chicago	Seattle	Philadelphia	Topeka	Richmond	Oklahoma city	San Diego	Las Vegas	Midland	Montgomary	Miami	Houston
Glazing A	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*
Glazing B	-1688.09	-2532.13	-1477.08	-844.04	-422.02	422.02	844.04	2743.15	1899.10	2321.12	6330.34	3587.19
Glazing C	27431.45	20046.06	21734.15	22578.20	16247.86	18568.98	3798.20	14137.75	13926.74	9495.50	3798.20	8651.46
Glazing D	25743.36	17724.94	20468.08	21945.16	16036.85	19202.02	5064.27	17513.93	16247.86	12027.64	10972.58	12871.68
Glazing E	23633.25	14770.78	18991.01	21101.12	15614.83	19413.03	5908.31	20257.07	17724.94	14559.77	18357.97	16880.89
Glazing F	37348.98	27220.44	29119.54	30807.63	22156.17	25321.34	5275.28	19624.04	18991.01	12871.68	5908.31	12238.65
Glazing G	37137.97	25743.36	29752.58	32073.70	23633.25	27431.45	7174.38	24899.32	23000.22	17091.90	14981.79	18146.96
Glazing H	35871.90	23211.23	28697.52	31651.68	23211.23	27642.46	7807.41	27853.47	24899.32	19624.04	22578.20	22367.18
Glazing I	43468.30	30385.61	34816.84	37559.99	29752.58	28275.50	8018.42	28275.50	26376.40	19413.03	20468.08	20468.08
Glazing J	42413.25	27853.47	33972.80	37137.97	27220.44	28486.51	8651.46	28697.52	28697.52	25954.37	29541.56	25321.34
Glazing K	35871.90	23000.22	28908.53	31862.69	23422.24	27853.47	7807.41	28064.49	25321.34	22578.20	24055.27	23000.22
Glazing L	33761.79	20257.07	26798.42	30385.61	22156.17	27431.45	7174.38	29541.56	25321.34	21312.13	28908.53	25110.33
Glazing M	33128.75	18779.99	26376.40	29963.59	21945.16	27431.45	6752.36	30174.60	25532.35	21734.15	28064.49	25004.82

6.2 Discussion

According to the data provided by American Housing Survey (AHS) in 2008, the average lifespan of an owner-occupied home is twenty-three (23) years. However, relevant to this study more important question that needs to be answered is the typical efficient lifetime of window glazing systems, before maintenance or replacement is required. Howard et al. (2007) indicated that the complete window system typically has a lifetime of fifteen (15) years with no maintenance needed (Howard et al., 2007).

Based on Tables 19 and 21 presented above, this section compares results for the additional embodied energy (production energy) consumed and the total annual energy (operational energy) savings for all thirteen glazing systems in all twelve cities located in four different climatic zones (i.e., Northern North-Central, Southern, and South-Central).. Moreover, the time required for recouping the production energy relevant to the energy savings of the glazing systems located in each of the cities is presented. Following the discussion regarding the typical efficient lifetime of glazing systems, the total energy savings during fifteen years for each type of the glazing system located in different climatic locations are calculated. These values are considered as criteria for selecting the best glazing systems in terms of overall energy saving with respect to the climatic location. In addition, the total energy saving for twenty-three years (i.e., the average lifespan of a residential building) is also presented. This comparison helps to better estimate the total energy saving and consumption of each glazing system during its service life.
The results of using each of the glazing systems in four different climatic locations are presented separately in the following sections.

6.2.1 Cities located in Northern climatic region

Table 22 presents the results of additional embodied energy consumed and total energy saved using each glazing system for Chicago, which is located in the Northern climate. The energy compensation year, net energy savings in fifteen years as well as twenty-three years are also provided in Table 22.

Table 22. Comparison of additional embodied energy used and the total energy saving (operational energy) for Chicago, IL (Northern climatic location)

Glazing Type	EE(MJ)	Total Annual Energy Saving (MJ)	Energy Compensation Year	Net Saving In 15 Years (MJ)	Net Saving In 23 Years (MJ)
Glazing A	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*
Glazing B	36,600	-1,688.09	—*	-61,921.34	-75,426.06
Glazing C	4,500	27,431.45	0.16	406,971.78	626,423.40
Glazing D	41,100	25,743.36	1.60	345,050.44	550,997.34
Glazing E	41,100	23,633.25	1.74	313,398.77	502,464.78
Glazing F	**41,100**	**37,348.98**	**1.10**	**519,134.66**	**817,926.48**
Glazing G	41,100	37,137.97	1.11	515,969.49	813,073.22
Glazing H	41,100	35,871.90	1.15	496,978.48	783,953.68
Glazing I	387,300	43,468.30	8.91	264,724.52	612,470.93
Glazing J	387,300	42,413.25	9.13	248,898.68	588,204.64
Glazing K	387,300	35,871.90	10.80	150,778.48	437,753.68
Glazing L	82,200	33,761.79	2.43	424,226.81	694,321.11
Glazing M	82,200	33,128.75	2.48	414,731.31	679,761.34

* The energy compensation year is not calculated, as no energy could be saved using glazing system B

As it can be observed, glazing “F”, which is Double Pane/High- Solar-gain low-e glazing system provides the best total energy saving by the end of fifteen years compared to other available types of glazing systems used in Chicago. The time required to compensate the embodied energy for this type of glazing system is approximately one year. Therefore, after one year of using this type of glazing system in Chicago, glazing “F” would become the most beneficial glazing system in terms of total energy saving compared to other glazing systems.

Table 23 presents the results of additional embodied energy consumed and total energy saved using each glazing system for Seattle located in the Northern climatic location. The energy compensation year, net energy savings in fifteen years as well as twenty-three years are also provided in Table 23.

Table 23. Comparison of additional embodied energy used and the total energy saving (operational energy) for Seattle, WA (Northern climatic location)

Glazing Type	EE (MJ)	Total Annual Energy Saving (MJ)	Energy Compensation Year	Net Saving In 15 Years (MJ)	Net Saving In 23 Years (MJ)
Glazing A	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*
Glazing B	36,600	-2,532.13	—*	-74,582.01	-94,839.08
Glazing C	4,500	20,046.06	0.22	296,190.92	456,559.41
Glazing D	41,100	17,724.94	2.32	224,774.07	366,573.58
Glazing E	41,100	14,770.78	2.78	180,461.73	298,627.98
Glazing F	**41,100**	**27,220.44**	**1.51**	**367,206.61**	**584,970.14**
Glazing G	41,100	25,743.36	1.60	345,050.44	550,997.34
Glazing H	41,100	23,211.23	1.77	307,068.43	492,758.26
Glazing I	387,300	30,385.61	12.75	68,484.13	311,569.00
Glazing J	387,300	27,853.47	13.90	30,502.12	253,329.91
Glazing K	387,300	23,000.22	16.84	-42,296.74	141,705.00
Glazing L	82,200	20,257.07	4.06	221,656.09	383,712.66
Glazing M	82,200	18,779.99	4.38	199,499.91	349,739.87

* The energy compensation year is not calculated, as no energy could be saved using glazing system B

Based on the data presented in Table 23, the results for Seattle follow similar trends as in Chicago. The time required to compensate the embodied energy of glazing system "F" (Double Pane/High- Solar-gain low-e glazing) is one and a half years. This indicates that considering total energy saving after one and a half years, and compared to other glazing systems, using this type of glazing system is most efficient in Seattle.

As observed, for both cities located in the Northern climatic region, Double Pane/High-Solar-gain low-e glazing system (glazing "F") provides the best total energy saving by the end of fifteen years. These results are reasonable as using Double Pane/High- Solar-gain low-e glazing system (Glazing "F") became beneficial in less than 15 years in the cities located in the extremely heating-dominated climate zone (i.e., Northern). This verifies the fact that glazing systems with high solar gain properties are suitable for heating-dominated climates, as previously discussed in chapter 4.

6.2.2 Cities located in North-Central climatic region

Table 24 presents the results of additional embodied energy consumed and total energy saved using each glazing system for Philadelphia, which is located in North-Central climatic region. The energy compensation year, net energy savings in fifteen years as well as twenty-three years are also provided in Table 24.

Table 24. Comparison of additional embodied energy used and the total energy saving (operational energy) for Philadelphia, PA (North-Central climatic location)

Glazing Type	EE (MJ)	Total Annual Energy Saving (MJ)	Energy Compensation Year	Net Saving In 15 Years (MJ)	Net Saving In 23 Years (MJ)
Glazing A	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*
Glazing B	36,600	-1,477.08	—*	-58,756.17	-70,572.80
Glazing C	4,500	21,734.15	0.21	321,512.26	495,385.46
Glazing D	41,100	20,468.08	2.01	265,921.25	429,665.92
Glazing E	41,100	18,991.01	2.16	243,765.08	395,693.12
Glazing F	41,100	29,119.54	1.41	395,693.12	628,649.46
Glazing G	**41,100**	**29,752.58**	**1.38**	**405,188.63**	**643,209.23**
Glazing H	41,100	28,697.52	1.43	389,362.79	618,942.94
Glazing I	387,300	34,816.84	11.12	134,952.65	413,487.39
Glazing J	387,300	33,972.80	11.40	122,291.98	394,074.36
Glazing K	387,300	28,908.53	13.40	46,327.96	277,596.20
Glazing L	82,200	26,798.42	3.07	319,776.28	534,163.63
Glazing M	82,200	26,376.40	3.12	313,445.94	524,457.12

* The energy compensation year is not calculated, as no energy could be saved using glazing system B

Based on Table 24, in Philadelphia (located in the North-Central climatic zone), glazing "G", which is Double Pane/Medium- Solar-gain low-e glazing system provides the best total energy saving by the end of fifteen years compared to other types of glazing systems. The time needed to compensate the embodied energy of this type of glazing system is approximately one and a half years in Philadelphia. Therefore, glazing "G" in Philadelphia becomes the most beneficial glazing system in terms of total energy saving after approximately one and a half years of being in service compared to other types of glazing systems.

Table 25 presents the results of additional embodied energy consumed and total energy saved using each type of glazing system for Topeka, which is located in North-Central climatic location. The energy compensation year, net energy savings in fifteen years as well as twenty-three years are also provided in Table 25.

Table 25. Comparison of additional embodied energy used and the total energy saving (operational energy) for Topeka, KS (North-Central climatic location)

Glazing Type	EE (MJ)	Total Annual Energy Saving (MJ)	Energy Compensation Year	Net Saving In 15 Years (MJ)	Net Saving In 23 Years (MJ)
Glazing A	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*
Glazing B	36,600	-844.04	—*	-49,260.67	-56,013.03
Glazing C	4,500	22,578.20	0.20	334,172.93	514,798.49
Glazing D	41,100	21,945.16	1.87	288,077.43	463,638.72
Glazing E	41,100	21,101.12	1.95	275,416.76	444,225.69
Glazing F	41,100	30,807.63	1.33	421,014.46	667,475.51
Glazing G	**41,100**	**32,073.70**	**1.28**	**440,005.47**	**696,595.05**
Glazing H	41,100	31,651.68	1.30	433,675.13	686,888.54
Glazing I	387,300	37,559.99	10.31	176,099.83	476,579.73
Glazing J	387,300	37,137.97	10.43	169,769.49	466,873.22
Glazing K	387,300	31,862.69	12.16	90,640.30	345,541.80
Glazing L	82,200	30,385.61	2.71	373,584.13	616,669.00
Glazing M	82,200	29,963.59	2.74	367,253.79	606,962.48

* The energy compensation year is not calculated, as no energy could be saved using glazing system B

The results indicate that for Topeka, Double Pane/Medium- Solar-gain low-e glazing system (glazing "G") also presents the best total energy saving by the end of fifteen years. The time required to compensate the embodied energy of this type of glazing system is approximately one and a half years in Topeka. This means that using glazing "G" in Topeka becomes the most efficient glazing system in terms of total energy saving after one and a half years of being in use compared to other glazing systems.

Table 26 presents the results of additional embodied energy consumed and total energy saved using each glazing system for Richmond located in North-Central climatic location. The energy compensation year, net energy savings in fifteen years as well as twenty-three years are also provided in Table 26.

Table 26. Comparison of additional embodied energy used and the total energy saving (operational energy) for Richmond, VA (North-Central climatic location)

Glazing Type	EE (MJ)	Total Annual Energy Saving (MJ)	Energy Compensation Year	Net Saving In 15 Years (MJ)	Net Saving In 23 Years (MJ)
Glazing A	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*
Glazing B	36,600	-422.02	—*	-42,930.34	-46,306.51
Glazing C	4,500	16,247.86	0.28	239,217.90	369,200.78
Glazing D	41,100	16,036.85	2.56	199,452.73	327,747.53
Glazing E	41,100	15,614.83	2.63	193,122.40	318,041.01
Glazing F	41,100	22,156.17	1.86	291,242.59	468,491.98
Glazing G	**41,100**	**23,633.25**	**1.74**	**313,398.77**	**502,464.78**
Glazing H	41,100	23,211.23	1.77	307,068.43	492,758.26
Glazing I	387,300	29,752.58	13.02	58,988.63	297,009.23
Glazing J	387,300	27,220.44	14.23	21,006.61	238,770.14
Glazing K	387,300	23,422.24	16.54	-35,966.40	151,411.52
Glazing L	82,200	22,156.17	3.71	250,142.59	427,391.98
Glazing M	82,200	21,945.16	3.75	246,977.43	422,538.72

* The energy compensation year is not calculated, as no energy could be saved using glazing system B

The glazing system type that works best for Richmond, located in North-Central region, is the same as the glazing system that worked best for Philadelphia and Topeka, also located in the North-Central climate region. In Richmond, Double Pane/Medium- Solar-gain low-e glazing system (glazing "G") presents the best total energy saving by the end of fifteen years. The time required to compensate the embodied energy of this type of glazing system in Richmond is approximately two years. This indicates that using glazing system "G" in Richmond provides the most efficient performance in terms of total energy saving after two years of service compared to other glazing systems.

It should be noted that the same trend was observed in all three cities located in the North-Central climatic region as Double Pane/Medium- Solar-gain low-e glazing system (glazing "G") provided the best total energy saving by the end of fifteen years. These results are reasonable since using Double Pane/Medium- Solar-gain low-e glazing system (Glazing "G") became beneficial in less than 15 years in the cities located in relatively heating-dominated climate zone (i.e., North-Central). This verifies the fact that glazing systems with medium to high solar gain properties are suitable for relatively heating-dominated climates, as previously described in chapter 4.

6.2.3 Cities located in South-Central climatic region

Table 27 provides the results of additional embodied energy consumed and total energy saved using each glazing system for Oklahoma located in South-Central climatic location. The energy compensation year, net energy savings in fifteen years as well as twenty-three years are also provided in Table 27.

Table 27. Comparison of additional embodied energy used and the total energy saving (operational energy) for Oklahoma, OK (South-Central climatic location)

Glazing Type	EE (MJ)	Total Annual Energy Saving (MJ)	Energy Compensation Year	Net Saving In 15 Years (MJ)	Net Saving In 23 Years (MJ)
Glazing A	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*

Glazing B	36,600	422.02	86.73	-30,269.66	-26,893.49
Glazing C	4,500	18,568.98	0.24	274,034.75	422,586.61
Glazing D	41,100	19,202.02	2.14	246,930.25	400,546.38
Glazing E	41,100	19,413.03	2.12	250,095.42	405,399.64
Glazing F	41,100	25,321.34	1.62	338,720.11	541,290.83
Glazing G	41,100	27,431.45	1.50	370,371.78	589,823.40
Glazing H	**41,100**	**27,642.46**	**1.49**	**373,536.95**	**594,676.66**
Glazing I	387,300	28,275.50	13.70	36,832.45	263,036.43
Glazing J	387,300	28,486.51	13.60	39,997.62	267,889.68
Glazing K	387,300	27,853.47	13.90	30,502.12	253,329.91
Glazing L	82,200	27,431.45	3.00	329,271.78	548,723.40
Glazing M	82,200	27,431.45	3.00	329,271.78	548,723.40

As can be observed, Double Pane/Low- Solar-gain low-e glazing system (glazing "H") provides the best total energy saving by the end of fifteen years in Oklahoma. The time required to compensate the embodied energy of this type of glazing system is one and a half years in this city. This means that using glazing system "H" in Oklahoma becomes the most beneficial glazing system in terms of total energy saving after one and a half years of use compared to other glazing systems.

Table 28 provides the results of additional embodied energy consumed and total energy saved using each glazing system for San Diego located in South-Central climatic region. The energy compensation year, net energy savings in fifteen years as well as twenty-three years are also provided in Table 28.

Table 28. Comparison of additional embodied energy used and the total energy saving (operational energy) for San Diego, CA (South-Central climatic location)

Glazing Type	EE(MJ)	Total Annual Energy Saving (MJ)	Energy Compensation Year	Net Saving In 15 Years (MJ)	Net Saving In 23 Years (MJ)
Glazing A	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*

Glazing B	36,600	844.04	43.36	-23,939.33	-17,186.97
Glazing C	4,500	3,798.20	1.18	52,473.02	82,858.62
Glazing D	41,100	5,064.27	8.12	34,864.02	75,378.17
Glazing E	41,100	5,908.31	6.96	47,524.69	94,791.19
Glazing F	41,100	5,275.28	7.79	38,029.19	80,231.42
Glazing G	41,100	7,174.38	5.73	66,515.70	123,910.74
Glazing H	**41,100**	**7,807.41**	**5.26**	**76,011.20**	**138,470.51**
Glazing I	387,300	8,018.42	48.30	-267,023.63	-202,876.24
Glazing J	387,300	8,651.46	44.77	-257,528.13	-188,316.47
Glazing K	387,300	7,807.41	49.61	-270,188.80	-207,729.49
Glazing L	82,200	7,174.38	11.46	25,415.70	82,810.74
Glazing M	82,200	6,752.36	12.17	19,085.36	73,104.22

Based on Table 28, it is observed that for San Diego, located in the South-Central climatic zone, glazing type “H”, which is Double Pane/Low- Solar-gain low-e glazing system provides the best total energy saving by the end of fifteen years compared to other glazing systems. The time needed to compensate the embodied energy of this type of glazing system is approximately five years in this city. Thus, using glazing system “H” in San Diego becomes the most beneficial one in terms of total energy saving after approximately five years of being in service compared to other glazing systems.

Table 29 presents the results of additional embodied energy consumed and total energy saved using each glazing system for Las Vegas located in South-Central climatic location. The energy compensation year, net energy savings in fifteen years as well as twenty-three years are also provided in Table 29.

Table 29. Comparison of additional embodied energy used and the total energy saving (operational energy) for Las Vegas, NV (South-Central climatic location)

Glazing Type	EE (MJ)	Total Annual Energy Saving (MJ)	Energy Compensation Year	Net Saving In 15 Years (MJ)	Net Saving In 23 Years (MJ)
Glazing A	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*

Glazing B	36,600	2,743.15	13.34	4,547.18	26,492.34
Glazing C	4,500	14,137.75	0.32	207,566.23	320,668.21
Glazing D	41,100	17,513.93	2.35	221,608.91	361,720.32
Glazing E	41,100	20,257.07	2.03	262,756.09	424,812.66
Glazing F	41,100	19,624.04	2.09	253,260.58	410,252.89
Glazing G	41,100	24,899.32	1.65	332,389.77	531,584.32
Glazing H	**41,100**	**27,853.47**	**1.48**	**376,702.12**	**599,529.91**
Glazing I	387,300	28,275.50	13.70	36,832.45	263,036.43
Glazing J	387,300	28,697.52	13.50	43,162.79	272,742.94
Glazing K	387,300	28,064.49	13.80	33,667.29	258,183.17
Glazing L	82,200	29,541.56	2.78	360,923.46	597,255.97
Glazing M	82,200	30,174.60	2.72	370,418.96	611,815.74

Similar to Oklahoma and San Diego, in Las Vegas Double Pane/Low- Solar-gain low-e glazing system (glazing "H") also provides the best total energy saving by the end of fifteen years. The time required to compensate the embodied energy of this type of glazing system is one and a half years in this city. This indicates that using glazing system "H" in Oklahoma becomes the most beneficial glazing system in terms of total energy saving after one and a half years of using compared to other glazing systems.

Table 30 presents the results of additional embodied energy consumed and total energy saved using each glazing system for Midland located in South-Central climate zone. The energy compensation year, net energy savings in fifteen years as well as twenty-three years are also provided in Table 30.

Table 30. Comparison of additional embodied energy used and the total energy saving (operational energy) for Midland, TX (South-Central climatic location)

Glazing Type	EE (MJ)	Total Annual Energy Saving (MJ)	Energy Compensation Year	Net Saving In 15 Years (MJ)	Net Saving In 23 Years (MJ)
Glazing A	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*
Glazing B	36,600	1,899.10	19.27	-8,113.49	7,079.31

Glazing C	4,500	13,926.74	0.32	204,401.06	315,814.96
Glazing D	41,100	16,247.86	2.53	202,617.90	332,600.78
Glazing E	41,100	17,724.94	2.32	224,774.07	366,573.58
Glazing F	41,100	18,991.01	2.16	243,765.08	395,693.12
Glazing G	41,100	23,000.22	1.79	303,903.26	487,905.00
Glazing H	**41,100**	**24,899.32**	**1.65**	**332,389.77**	**531,584.32**
Glazing I	387,300	26,376.40	14.68	8,345.94	219,357.12
Glazing J	387,300	28,697.52	13.50	43,162.79	272,742.94
Glazing K	387,300	25,321.34	15.30	-7,479.89	195,090.83
Glazing L	82,200	25,321.34	3.25	297,620.11	500,190.83
Glazing M	82,200	25,532.35	3.22	300,785.27	505,044.09

Again, same as the other cities located in the South-Central region, in Midland, Double Pane/Low- Solar-gain low-e glazing system (glazing "H") presents the best total energy saving at the end of fifteen years. The time needed to compensate the embodied energy of this type of glazing system is approximately one and a half years in Midland. Therefore, approximately one and a half years after using glazing "H" in Midland, this type of glazing system becomes the most beneficial one in terms of total energy saving compared to other glazing systems.

Table 31 presents the results of additional embodied energy consumed and total energy saved using each glazing system for Montgomery located in South-Central climatic region. The energy compensation year, net energy savings in fifteen years as well as twenty-three years are also provided in Table 31.

Table 31. Comparison of additional embodied energy used and the total energy saving (operational energy) for Montgomery, AL (South-Central climatic location)

Glazing Type	EE (MJ)	Total Annual Energy Saving (MJ)	Energy Compensation Year	Net Saving In 15 Years (MJ)	Net Saving In 23 Years (MJ)
Glazing A	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*

Glazing B	36,600	2,321.12	15.77	-1,783.16	16,785.83
Glazing C	4,500	9,495.50	0.47	137,932.54	213,896.56
Glazing D	41,100	12,027.64	3.42	139,314.55	235,535.64
Glazing E	41,100	14,559.77	2.82	177,296.56	293,774.73
Glazing F	41,100	12,871.68	3.19	151,975.22	254,948.67
Glazing G	41,100	17,091.90	2.40	215,278.57	352,013.81
Glazing H	**41,100**	**19,624.04**	**2.09**	**253,260.58**	**410,252.89**
Glazing I	387,300	19,413.03	19.95	-96,104.58	59,199.64
Glazing J	387,300	25,954.37	14.92	2,015.61	209,650.60
Glazing K	387,300	22,578.20	17.15	-48,627.07	131,998.49
Glazing L	82,200	21,312.13	3.86	237,481.92	407,978.95
Glazing M	82,200	21,734.15	3.78	243,812.26	417,685.46

Similarly, it can be observed that glazing “H”, which is Double Pane/Low- Solar-gain low-e glazing system provides the best total energy saving at the end of fifteen years compared to other available types of glazing systems used in Montgomery. The time required to compensate the embodied energy of this type of glazing system is two years in this city. Thus, after two years of using glazing system “H” in Montgomery, this glazing system would become the most beneficial one in terms of total energy saving compared to other glazing systems.

As it can be conceived for all five cities located in South-Central Climatic location, Double Pane/Low- Solar-gain low-e glazing system (glazing “H”) provides the best performance in terms of total energy saving by the end of fifteen years. These results are reasonable as using Double Pane/Low- Solar-gain low-e glazing system (Glazing “H”) became efficient in less than 15 years in the cities located in relatively cooling-dominated climate zone (i.e., South-Central). This confirms the fact that glazing systems with low solar gain are suitable for cooling-dominated climates, as previously discussed in chapter 4.

6.2.4 Cities located in Southern climatic region

Table 32 provides the results of additional embodied energy consumed and total energy saved using each glazing system for Miami, which is located in Southern climatic region.

The energy compensation year, net energy savings in fifteen years as well as twenty-three years are also provided in Table 32.

Table 32. Comparison of additional embodied energy used and the total energy saving (operational energy) for Miami, FL (Southern climatic location)

Glazing Type	EE(MJ)	Total Annual Energy Saving (MJ)	Energy Compensation Year	Net Saving In 15 Years (MJ)	Net Saving In 23 Years (MJ)
Glazing A	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*
Glazing B	36,600	6330.34	5.78	58,355.03	108,997.71
Glazing C	4,500	3798.20	1.18	52,473.02	82,858.62
Glazing D	41,100	10972.58	3.75	123,488.71	211,269.36
Glazing E	41,100	18357.97	2.24	234,269.58	381,133.35
Glazing F	41,100	5908.31	6.96	47,524.69	94,791.19
Glazing G	41,100	14981.79	2.74	183,626.90	303,481.24
Glazing H	41,100	22578.20	1.82	297,572.93	478,198.49
Glazing I	387,300	20468.08	18.92	-80,278.75	83,465.92
Glazing J	387,300	29541.56	13.11	55,823.46	292,155.97
Glazing K	387,300	24055.27	16.10	-26,470.90	165,971.29
Glazing L	**82,200**	**28908.53**	**2.84**	**351,427.96**	**582,696.20**
Glazing M	82,200	28064.49	2.93	338,767.29	563,283.17

It can be realized that Triple Pane/Moderate- Solar-gain low-e with argon gas infilled (glazing “L”) provides the best total energy saving by the end of fifteen years compared to other types of glazing systems used in Miami. The time required to compensate the embodied energy of this type of glazing system is approximately three years in this city. This indicates that using glazing system “L” in Miami becomes the most efficient glazing system in terms of total energy saving after approximately three years of being in use compared to other glazing systems.

Table 33 provides the results of additional embodied energy consumed and total energy saved using each glazing system for Houston, which is located in Southern climatic region.

The energy compensation year, net energy savings in fifteen years as well as twenty three years are also provided in Table 33.

Table 33. Comparison of additional embodied energy used and the total energy saving (operational energy) for Houston, TX (Southern climatic location)

Glazing Type	EE (MJ)	Total Annual Energy Saving (MJ)	Energy Compensation Year	Net Saving In 15 Years (MJ)	Net Saving In 23 Years (MJ)
Glazing A	*Baseline*	*Baseline*	*Baseline*	*Baseline*	*Baseline*
Glazing B	36,600	3587.19	10.20	17,207.85	45,905.37
Glazing C	4,500	8651.46	0.52	125,271.87	194,483.53
Glazing D	41,100	12871.68	3.19	151,975.22	254,948.67
Glazing E	41,100	16880.89	2.43	212,113.40	347,160.55
Glazing F	41,100	12238.65	3.36	142,479.72	240,388.90
Glazing G	41,100	18146.96	2.26	231,104.41	376,280.10
Glazing H	41,100	22367.18	1.84	294,407.76	473,345.23
Glazing I	387,300	20468.08	18.92	-80,278.75	83,465.92
Glazing J	387,300	25321.34	15.30	-7,479.89	195,090.83
Glazing K	387,300	23000.22	16.84	-42,296.74	141,705.00
Glazing L	**82,200**	**25110.33**	**3.27**	**294,454.94**	**495,337.57**
Glazing M	82,200	25004.82	3.29	292,872.36	492,910.95

The results for Houston follows a similar trend as in Miami. This is reasonable as both of the cities are located in the same climatic region (i.e., Southern). As in Miami, for Houston glazing type "L", which is Triple Pane/Moderate- Solar-gain low-e with argon gas infilled, provides the best total energy saving at the end of fifteen years compared to other types of glazing systems. The time required to compensate the embodied energy of glazing system "L" is approximately three years in Houston. Thus, using glazing system "L" in Houston becomes the most beneficial glazing system in terms of total energy saving after approximately three years of service.

It should be stated that for both cities located in the Southern climatic location, Triple Pane/Moderate- Solar-gain low-e with argon gas infilled (glazing “L”) provides the best total energy saving by the end of fifteen years compared to other glazing systems. The results are reasonable as using Triple Pane/Moderate- Solar-gain low-e with argon gas infilled (Glazing “L”) became efficient in less than 15 years in the cities that are located in extremely cooling-dominated climate zone (i.e., Southern). Based on the explanation provided in chapter 4, the results confirm that glazing systems with medium solar gain properties are suitable for using in cooling dominated climate (as well as heating dominated climate). Furthermore, based on the results, it could be hypothesized that Triple Pane glazing works better for cooling dominated climate (i.e., hot weather) compared to heating dominated climate (i.e., cold weather).

As it is realized, for almost all cases that have been studied in this research, the amount of energy used to produce the glazing system is higher than the total energy saved in one year (first year) of using the same type of glazing system. As the number of years increases, however, the amount of energy that is saved using glazing systems can gradually compensate for the embodied energy (EE) of the product. After this point, the glazing system is considered beneficial since the amount of energy savings overcomes production energy. As was observed, each selected glazing system used in each specific location became beneficial before fifteen years of being in service.

The results indicate that using high-solar-gain glazing in heating-dominated climate regions (Northern) acts satisfactory, as the amount of embodied energy used for the production of this type of glazing system can be compensated in the first few years of its service life. Similar behavior was observed for Medium- Solar-gain glazing used in the North-Central climate zone, which is known as a relatively heating dominated climate. In cities located in the Southern-Central region, which is a relatively cooling dominated climate, by using Low- Solar-gain glazing, the amount of energy saved during first few years was high enough to compensate the production energy of the glazing systems. For the cooling dominated climate (Southern region), however, Triple Pane/Moderate- Solar-gain low-e with infilled argon gas can be considered as the most suitable option, as the amount of embodied energy used for its production can be recouped in the first few years of it service life.

6.3 Verification of the Results Using Cost Analysis

In order to verify the results obtained using this LCEA method, a simple cost analysis was performed. For this purpose, the cost of each glazing system that showed the best performance in terms of energy saving in different locations was estimated using a report released by the US Department of Energy (DOE, year of publication), which lists average window prices per square foot in US dollar for a variety of window types. This cost was then divided by total embodied energy (production energy) used for its corresponding glazing system to obtain the price of one unit of energy used for producing that specific glazing system. Afterward, this value was multiplied by the total annual energy saving of the corresponding glazing system to identify the total annual cost saving. The price of each glazing system was divided by the total annual cost saving in order to determine the payback time of each glazing system (in terms of cost). Figure 22 depicts the flowchart of this process. The number of years needed for the selected glazing system to payback the initial costs (money) as well as compensate for the energy used during the production phase of the glazing systems is tabulated in Table 34.

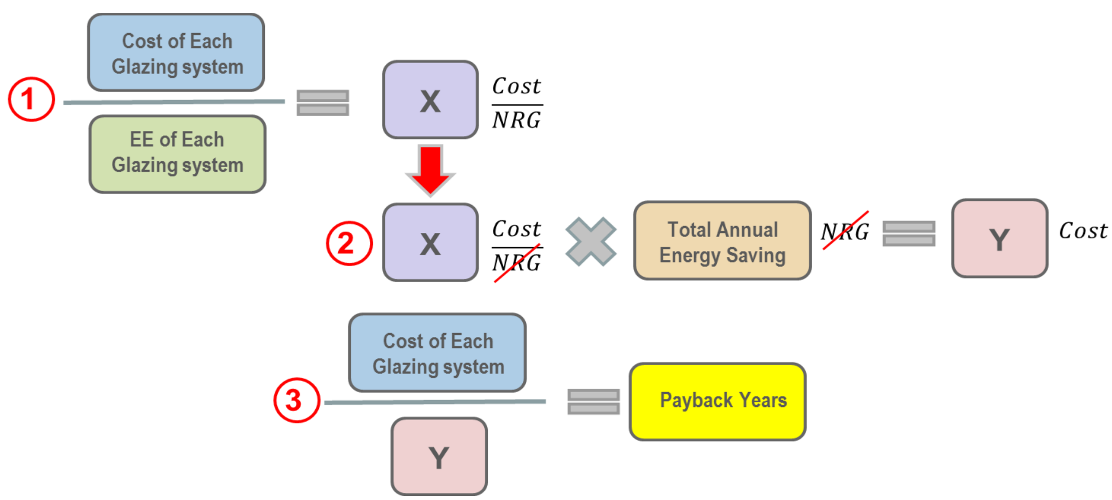


Figure 22. Flowchart of cost analysis

Table 34. Comparison of Energy and Cost Compensation year

Location	Best Option	Best Glazing System	Energy * Compensation length (Year)	Cost ** Compensation length (Year)
Chicago, IL	Glazing F	Double Pane/High-Solar-gain low-e with Argon infilled	1.10	2.61
Seattle, WA	Glazing F	Double Pane/High-Solar-gain low-e with Argon infilled	1.51	3.58
Philadelphia, PA	Glazing G	Double Pane/Medium-Solar-gain low-e with Argon infilled	1.38	3.27
Topeka, KS	Glazing G	Double Pane/Medium-Solar-gain low-e with Argon infilled	1.28	3.03
Richmond, VA	Glazing G	Double Pane/Medium-Solar-gain low-e	1.74	4.12
Oklahoma, OK	Glazing H	Double Pane/Low-Solar-gain low-e with Argon infilled	1.49	3.52
Las Vegas, NV	Glazing H	Double Pane/Low-Solar-gain low-e with Argon infilled	5.26	3.50
Midland, TX	Glazing H	Double Pane/Low-Solar-gain low-e with Argon infilled	1.48	3.91
Montgomery, AL	Glazing H	Double Pane/Low-Solar-gain low-e with Argon infilled	1.65	4.96
San Diego, CA	Glazing H	Double Pane/Low-Solar-gain low-e with Argon infilled	2.09	7.48

Miami, FL	Glazing L	Triple Pane/Moderate-Solar-gain low-e with Argon infilled	2.84	5.36
Houston, TX	Glazing L	Triple Pane/Moderate-Solar-gain low-e with Argon infilled	3.27	6.17

* The metric used for energy calculation was MJ
** The metric used for cost calculation was US dollars

As can be noted from the table above, the number of years needed for glazing systems to payback the amount of production cost is strongly in agreement with the number of years required for recouping the production energy, as previously computed chapter. This verifies the results of energy analysis in this study. The slight difference between payback year (cost) and compensation year (energy) may be due to the fact that the cost of each glazing system provided by vender does not necessarily reflect the cost of energy-related production of the glazing system; some other additional costs such as transportation, interest rate, framing, etc., are also considered in the price of windows at the time of purchase. This simple cost analysis proves and confirms the reliability of the results obtained in this study.

6.4 Summary of Findings

As it can be observed, in order to evaluate the capability of glazing systems in increasing energy efficiency of the building during its entire lifetime, the energy used during the production phase of the glazing products and the amount of energy saved during the service life of the product should be taken into account simultaneously.

Based on the results provided, Double Pane/High- Solar-gain low-e (Glazing “F”) was determined as the best option for the Northern climatic zone. Double Pane/Medium- Solar-gain low-e (Glazing “G”) was determined to be the best choice for the North-Central climatic zone. It was observed that Double Pane/Low- Solar-gain low-e (Glazing “H”) works as the best glazing system in terms of overall energy saving in South-Central climatic location. The best option for the glazing system in Southern climatic location was identified to be Triple Pane/Moderate- Solar-gain low-e with argon gas (Glazing “L”).

CHAPTER 7

7. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Summary

This thesis presents the results of Life-Cycle Energy Analysis (LCEA) on different glazing technologies to find the most efficient glazing systems in terms of energy consumption during different stages of product's life (i.e., production phase and operational phase) for a variety of climatic conditions. The study provides a comparison of the effect of using different glazing systems on the annual energy use for a residential building in various climatic condition zones (based on the ENERGY STAR climate zone map) in the US including Northern, North Central, Southern, and South Central. The performance of thirteen different types of the glazing system was investigated using RESFEN software. Moreover, the amount of energy required for producing the glazing systems (embodied energy) were computed and studied in this research. The primary goal of this study was to provide a comprehensive guideline that can provide criteria for choosing the best possible glazing systems in terms of overall energy consumption considering the location of the buildings. Architects, designers, or consumers can use the results of this study to select the most appropriate glazing system for their building based on the local climatic condition.

7.2 Conclusions and Recommendations

The basis of this research was sustainability (sustainable design). This study attempted to address some sustainability-related issues in window's industry. Therefore, the focus of the research was on both overall energy that is used during production phase and energy that can be saved using different glazing systems during operational phase.

Most of the energy resources currently used such as fossil fuels are exhaustible and are not renewable. Worldwide, windows are responsible for a significant amount of unwanted heat gain and heat loss between buildings and the environment (Ballinger and Lyons, 1996).

This can be translated into the loss of energy resources. Thus, the reduction in the amount of energy used for producing windows and the increase in the amount of energy saved due to the presence of windows in buildings could be considered an important course of action in terms of saving energy resources.

Therefore, the original contribution of this thesis was to introduce the best glazing system -with respect to the climatic condition- that if is used, it would help consumers to save more energy and consequently more cost during the entire lifetime of the glazing system compared to other available glazing systems. The results of this study have shown that the glazing system that has the best performance in terms of energy saving is not necessarily the most efficient one regarding its overall energy consumption. For instance, although a triple-pane glazing system is more effective than a double-pane glazing in terms of energy saving during the operational phase, it has higher embodied energy than a double-pane glazing and would not be able to compensate the amount of energy used for its production in less than fifteen years in most of the locations (different climate conditions).

One question that may be raised is "why should consumers take both production and operational energy into account once the windows have been manufactured?" As previously mentioned, due to the fact that the non-renewable energy resources are being finished, sustainable design (sustainability in general) is becoming more common in every aspect of human life such as building industry. Therefore, in addition to the operational phase, the production phase of any product should be taken into account simultaneously. For example, although the triple glazing system can save more energy (or money) during its operation (after purchase) in all climatic conditions, most of the times it is not the best glazing system option for buildings. This is due to the fact that it needs more energy (and money) for its production, which cannot be quickly compensated by the energy saving during the operational phase. It should be noted that the most expensive option is not necessarily the best option in terms of overall cost or energy savings (although it may be the best one in terms of energy or cost savings during operational phase). This is due to the fact that the correlation between production energy and cost of the windows (production cost) are directly related to each other; the more the embodied energy (EE) of a window, the more the cost of that window. Windows that can save people more money and energy (more advanced glazing systems) during the time that they own the window (operational phase) are definitely more costly (and need more energy for production) compared to less advanced windows at the time of purchase (production phase). For example, triple-pane-Low -E windows cost approximately $32 per square foot, or a total of $9600 for the purpose of this project (300 ft2), while Double pane- Low-e windows cost about $26 per square foot or a total of $7800 for this project (Carmody & Haglund, 2012). Among those windows that are currently available, there is a specific type of glazing system for each climatic location that if used would result in saving more overall energy and cost at the end of its lifespan. As mentioned, this specific type of glazing system is not necessarily the glazing system that has the best energy saving capability when considering the operational phase alone.

Summary of the main findings of this study are categorized as follow:

In terms of energy saving:

- Manufacturers define the performance of their glazing systems based on their thermal transmittance coefficient (U-Factor), Visible Transmittance (VT), and Solar Heat Gain Coefficient (SHGC). Owners and designers should consider the effect of the interaction of these three variables when selecting glazing products.
- Using an extra layer of glass results in improving the thermal resistance of the glazing system and reducing the U-factor. However, it does not affect the SHGC.
- Applying low-e coating to glass affects SHGC without compromising the amount of VT.
- Triple-pane glazing has the best performance in terms of energy saving in all selected locations due to their inherent lower U-factor as well as providing more surfaces for placement of coatings.
- High-solar-gain low-e coatings are best suited for buildings located in heating dominated climate (Northern zone). These coatings reduce heat loss significantly and allow a reasonable amount of solar gain.

- Moderate-solar-gain low-e coatings are best suited for buildings in a relatively heating dominated climate (North-Central zone). These coatings reduce heat loss and allow a reasonable amount of solar gain.
- Glazing systems with low-solar-gain low-e coating are suitable for relatively cooling dominated climates (South-Central zone). These coatings reduce heat loss in winter due to having low U-factor, but at the same time are able to reduce solar heat gain due to having low SHGC in both summer and winter, which is ideal for a building located in heating dominated climates.
- Triple glazing works considerably better in buildings located in cooling dominated climate compared to those in heating dominated climate.

Table 35 provides the list of the best glazing systems investigated in this study with respect to the overall energy saving during the use phase.

Table 35. Best glazing systems in each location according to the results of energy simulation

	Best Glazing System	U-value	SHGC
Chicago, IL	Triple Pane/Moderate- Solar-gain low-e with Krypton gas infilled	0.15	0.38
Seattle, WA	Triple Pane/Moderate- Solar-gain low-e with Krypton gas infilled	0.15	0.38
Philadelphia, PA	Triple Pane/Moderate- Solar-gain low-e with Krypton gas infilled	0.15	0.38
Topeka, KS	Triple Pane/Moderate- Solar-gain low-e with Krypton gas infilled	0.15	0.38
Richmond, VA	Triple Pane/Moderate- Solar-gain low-e with Krypton gas infilled	0.15	0.38
Oklahoma, OK	Triple Pane/Low- Solar-gain low-e with Krypton gas infilled	0.13	0.24
San Diego, CA	Triple Pane/Low- Solar-gain low-e with Krypton gas infilled	0.13	0.24
Las Vegas, NV	Triple Pane/Low- Solar-gain low-e with Krypton gas infilled	0.13	0.24
Midland, TX	Triple Pane/Low- Solar-gain low-e with Krypton gas infilled	0.13	0.24
Montgomery, AL	Triple Pane/Low- Solar-gain low-e with Krypton gas infilled	0.13	0.24
Miami, FL	Triple Pane/Low- Solar-gain low-e with Krypton gas infilled	0.13	0.24
Houston, TX	Triple Pane/Low- Solar-gain low-e with Krypton gas infilled	0.13	0.24

As mentioned, Table 33 presents the list of the best glazing systems in terms of energy saving during the use phase. However, it is important to note that glazing system that has the best performance in terms of energy saving is not necessarily the most efficient glazing system with respect to its overall energy consumption.

In terms of production energy:

- Triple-pane glazing systems require the highest amount of energy during the production phase compared to other types of the glazing system studied in this research (about four times more than double pane and eight times more than single pane glazing system). This would lead to a decrease in the overall energy saving of triple glazing system during its service life compared to double pane glazing system.
- Infill gas plays a significant role in the amount of embodied energy (EE) of a glazed unit. In all cases, krypton-filled glazing systems have shown to have a considerably higher EE than argon-filled glazing systems. However, using krypton as an infill gas would result in better thermal performance due to having lower U-value.

Based on the results provided, the concluding remarks of this research can be summarized as follows:

There has always been a tradeoff between energy used during the production phase of the glazing products and the amount of energy that can be saved during the service life of the product. If the embodied energy of glazing systems (production energy) is compensated by the amount of energy saved as the product is being used, the glazing system is considered beneficial and efficient. The time required for glazing systems to compensate the energy used during their production phase is governed by the type of glazing systems as well as the location of the building (climate condition). Thus, if the objective is to choose a product with higher energy efficiency (lower energy consumption), the energy consumption during the entire life cycle of the product should be taken into consideration; the objective that has not been paid attention by designers/owner who consider the operational phase of the advanced glazing system solely.

Table 36 tabulates the best option for the glazing systems that can be used in each city studied in this research based upon the comparison of embodied energy and the total energy consumed during the use phase of glazing systems.

Table 36. Best glazing systems in each location based on the comparison of embodied energy and the total energy

	Best Option	Best Glazing System	U-value	SHGC
Chicago, IL	Glazing F	Double Pane/High- Solar-gain low-e with Argon infilled	0.30	0.71
Seattle, WA	Glazing F	Double Pane/High- Solar-gain low-e with Argon infilled	0.30	0.71
Philadelphia, PA	Glazing G	Double Pane/Medium- Solar-gain low-e with Argon infilled	0.26	0.53
Topeka, KS	Glazing G	Double Pane/Medium- Solar-gain low-e with Argon infilled	0.26	0.53
Richmond, VA	Glazing G	Double Pane/Medium- Solar-gain low-e	0.26	0.53
Oklahoma, OK	Glazing H	Double Pane/Low- Solar-gain low-e with Argon infilled	0.25	0.39
San Diego, CA	Glazing H	Double Pane/Low- Solar-gain low-e with Argon infilled	0.25	0.39
Las Vegas, NV	Glazing H	Double Pane/Low- Solar-gain low-e with Argon infilled	0.25	0.39
Midland, TX	Glazing H	Double Pane/Low- Solar-gain low-e with Argon infilled	0.25	0.39
Montgomery, AL	Glazing H	Double Pane/Low- Solar-gain low-e with Argon infilled	0.25	0.39
Miami, FL	Glazing L	Triple Pane/Moderate- Solar-gain low-e with Argon infilled	0.25	0.27
Houston, TX	Glazing L	Triple Pane/Moderate- Solar-gain low-e with Argon infilled	0.25	0.27

It should be noted that this selection is based on the minimum amount of time required for embodied energy of the glazing systems to be compensated.

As previously indicated, glazing systems that have the highest amount of energy saving during the operational phase are not necessarily the best glazing systems in terms of overall energy saving. Table 37 provides a comparison of embodied energy (EE) of the glazing systems that perform best during operational phase and the best possible glazing systems in terms of overall energy consumption. Table 37 also presents the difference of the amount of energy that can be saved with each of these glazing systems. The results of this comparison prove that the additional amount of energy that is used for producing (in production phase) the best advance glazing system is significantly high that cannot be recouped by the amount of energy saved using that glazing system before 15 years.

Table 37. Comparison of best glazing systems during operational phase and best possible option in terms of overall energy consumption

City			Embodied Energy (production phase)	Energy saving in 15 years (operational phase)	Overall energy saving in 15 years
Chicago	Best Glazing System in operational phase	**Triple Pane/Moderate-Solar-gain low-e with krypton gas**	443,100	652,024.52	208.924.52
	Best Glazing System in terms of overall energy saving	**Double Pane/High- Solar-gain low-e with argon gas**	96,900	560,234.66	463,334.66
	Difference between production energy and operational energy of the best glazing system in operational phase and the best glazing system overall		346,200	91,789.86	-254,410.14
Seattle	Best Glazing System in operational phase	**Triple Pane/Moderate-Solar-gain low-e with krypton gas**	443,100	455,784.15	12,684.15
	Best Glazing System in terms of overall energy saving	**Double Pane/High-Solar-gain low-e with argon gas**	96900	408,306.60	311,406.60
	Difference between production energy and operational energy of the best glazing system in operational phase and the best glazing system in overall		346,200	47,477.55	-298,722.45
Philadelphia	Best Glazing System in operational phase	**Triple Pane/Moderate-Solar-gain low-e with krypton gas**	443,100	522,252.60	79,152.60
	Best Glazing System in terms of overall energy saving	**Double Pane/Medium-Solar-gain low-e with Argon infilled**	96,900	446,288.70	349,388.70

	Difference between production energy and operational energy of the best glazing system in operational phase and the best glazing system in overall		346,200	75,963.90	-270,236.10
Topeka	Best Glazing System in operational phase	**Triple Pane/Moderate-Solar-gain low-e with krypton gas**	443,100	563,399.85	120,299.85
	Best Glazing System in terms of overall energy saving	**Double Pane/Medium-Solar-gain low-e with Argon infilled**	96,900	481,105.50	384,205.50
	Difference between production energy and operational energy of the best glazing system in operational phase and the best glazing system in overall		346,200	82,294.35	-263,905.65
Richmond	Best Glazing System in operational phase	**Triple Pane/Moderate-Solar-gain low-e with krypton gas**	443,100	446,288.70	3,188.70
	Best Glazing System in terms of overall energy saving	**Double Pane/Medium-Solar-gain low-e with Argon infilled**	96,900	354,498.75	257,598.75
	Difference between production energy and operational energy of the best glazing system in operational phase and the best glazing system in overall		346,200	91,789.95	-254,410.05
Oklahoma	Best Glazing System in operational phase	**Triple Pane/Low-Solar-gain low-e with krypton gas**	443,100	427,297.65	-15,802.35
	Best Glazing System in terms of overall energy saving	**Double Pane/Low-Solar-gain low-e with Argon infilled**	96,900	414,636.90	317,736.90
	Difference between production energy and operational energy of the best glazing system in operational phase and the best glazing system in overall		346,200	12,660.75	-333,539.25

San Diego	Best Glazing System in operational phase	**Triple Pane/Low-Solar-gain low-e with krypton gas**	443,100	129,771.90	-313,328.10
	Best Glazing System in terms of overall energy saving	**Double Pane/Low-Solar-gain low-e with Argon infilled**	96,900	117,111.15	20,211.15
	Difference between production energy and operational energy of the best glazing system in operational phase and the best glazing system in overall		346,200	12,660.75	-333,539.25
Las Vegas	Best Glazing System in operational phase	**Triple Pane/Low-Solar-gain low-e with krypton gas**	443,100	430,462.80	-12,637.20
	Best Glazing System in terms of overall energy saving	**Double Pane/Low-Solar-gain low-e with Argon infilled**	96,900	417,802.05	320,902.05
	Difference between production energy and operational energy of the best glazing system in operational phase and the best glazing system in overall		346,200	12,660.75	-333,539.25
Midland	Best Glazing System in operational phase	**Triple Pane/Low-Solar-gain low-e with krypton gas**	443,100	430,462.80	-12,637.20
	Best Glazing System in terms of overall energy saving	**Double Pane/Low-Solar-gain low-e with Argon infilled**	96900	373,489.80	276,589.80
	Difference between production energy and operational energy of the best glazing system in operational phase and the best glazing system in overall		346,200	56,973.00	-289,227.00
Montgomery	Best Glazing System in operational phase	**Triple Pane/Low-Solar-gain low-e with krypton gas**	443,100	389,315.55	-53,784.45
	Best Glazing System in terms	**Double Pane/Low-Solar-gain low-e**	96900	294,360.60	197,460.60

	of overall energy saving	**with Argon infilled**			
	Difference between production energy and operational energy of the best glazing system in operational phase and the best glazing system in overall		346,200	94,954.95	-251,245.05
Miami	Best Glazing System in operational phase	**Triple Pane/Low-Solar-gain low-e with krypton gas**	443,100	443,123.40	23.40
	Best Glazing System in terms of overall energy saving	**Triple Pane/Moderate-Solar-gain low-e with Argon infilled**	138000	433,627.95	295,627.95
	Difference between production energy and operational energy of the best glazing system in operational phase and the best glazing system in overall		305,100	9,495.45	-295,604.55
Houston	Best Glazing System in operational phase	**Triple Pane/Low-Solar-gain low-e with krypton gas**	443,100	379,820.10	-63,279.90
	Best Glazing System in terms of overall energy saving	**Triple Pane/Moderate-Solar-gain low-e with Argon infilled**	138000	376,654.95	238,654.95
	Difference between production energy and operational energy of the best glazing system in operational phase and the best glazing system in overall		305,100	3,165.15	-301,934.85

Note: To observe the difference of production energy and operational energy between the best glazing system in operational phase and the best glazing system in terms of overall energy saving, in all cases the energy corresponds to best glazing system in operational phase subtracted from the energy corresponds to the best glazing system in overall energy saving

As stated in the objective of the research and since sustainability and sustainable design have been taken into account in this study, this thesis focused on the energy use of the glazing systems, not cost. However, to ensure that the results of the analysis are reliable and also reasonable, a simple cost analysis was performed as well. The results of energy analysis and cost analysis were strongly in agreement, as shown in chapter 6.

7.3 Guideline

As previously discussed, the two main objectives of this study included 1) Compare different types of high-performance glazing systems to find the most effective ones in sustainable housing with regard to overall energy consumption, and 2) Provide criteria for choosing high-performance windows based on their impacts on the overall energy performance of the building.

No previous study has evaluated different types of glazing systems in different cities in the US to introduce the best one in terms of overall energy consumption for the specific city (climatic condition). Therefore, the original contribution of this thesis was to introduce the best glazing system with respect to the climatic condition that if is used, it would help consumers to save more energy and consequently more cost during the entire lifetime of the glazing system, compared to other available glazing systems. This research will help to motivate consumers to use the most reasonable glazing system option with respect to the location of the building. It should be noted that selecting the best performing window that people can afford does not save them the largest amount of money during the time that they own the window. For example, triple glazing systems with krypton gas infill is the most expensive glazing system in the market. Compared to double glazing, it can save more money and energy during the lifetime of the window. However, in terms of overall cost and energy, it is not the best option since the cost or energy that can be saved during operation will not pay back the cost or energy of production any sooner than other types of glazing systems. The point is that being able to afford the best performing glazing system in the market does not mean that type of glazing system should be used, since, based on the results provided in this research, the best performing glazing system in terms of energy saving during operation phase is not necessarily the best glazing system in terms of overall energy saving.

In this section, a comprehensive guideline that specifically points out the best possible glazing systems in terms of overall energy consumption/saving for each climatic location is provided. This guideline can be used by designer, architects, or even consumers in order to be able to choose the most appropriate glazing system in terms of overall energy saving with respect to the climatic location of a building. Table 38 presents the best option of glazing system for using in different ENERGY STAR climatic locations.

Table 38. Best glazing systems in each climatic location with respect to overall energy consumption/saving

Climatic location	Best option for glazing System
Northern	Double Pane/High- Solar-gain low-e with Argon infilled
North-Central	Double Pane/Medium- Solar-gain low-e with Argon infilled
South-Central	Double Pane/Low- Solar-gain low-e with Argon infilled
Southern	Triple Pane/Moderate- Solar-gain low-e with Argon infilled

It can be observed that double pane/high-solar-gain low-e (Glazing "F") was determined to be the best choice for the Northern climatic zone. Double pane/medium-solar-gain low-e (Glazing "G") was evaluated to be the best option in the North-Central climatic zone. It was observed that double pane/low-solar-gain low-e (Glazing "H") works as the best glazing system in terms of overall energy saving in South-Central climatic location. The best glazing system option for the Southern climatic location was identified to be triple pane/moderate-solar-gain low-e with argon gas infilled (Glazing "L").

In addition, the following findings can be taken into consideration while choosing glazing systems for a building:

- It was observed that for typical lifetime of the windows argon gas infill would work better than krypton gas when overall energy saving is considered. This is due to the fact that the embodied energy of krypton is significantly higher than argon. It should be noted that as the number of year increases, gradually glazing systems with krypton gas infilled would become more suitable and beneficial. Therefore, if windows industries aim to provide a window with a much longer lifetime in the future, krypton gas would be a better option to be used compared to argon.
- Basically, except in the case of an extremely cooling dominated climate (Southern region), double pane windows are more suitable options in comparison with Triple pane windows.

- Generally, triple pane glazing systems are better suited and can save more energy in cooling dominated climate compared to heating dominated climate.

7.4 Future Work

Energy efficiency in glazing systems depends on different factors, some of which such as the location of the building, the variety of glazing systems, etc. were examined in this thesis, while some other factors were not considered in this study. This section presents some possible ideas and recommendations for the future work, which will likely help to improve the applicability and reliability of the research.

This study may be expanded in three areas in order to increase the precision of results, as discussed below:

1. Based on the results of this study, energy simulation can be considered a strong tool in order to choose the most appropriate glazing system in terms of energy saving based on the climatic location of a building. In each one of the iterations of the energy simulation in this research only one type of glazing system was examined. However, in reality it is possible to use different types of glazing system in a house, depending on the condition/requirements. A combination of glazing systems can be used in future studies, which in turn may lead to improving the efficiency of the house.
2. For this research an ideal condition of heating, ventilation, and air conditioning system was assumed (100% efficiency). Examining different conditions may result in obtaining more realistic results.
3. As mentioned in Chapter 6, the amount of energy used for producing a glazing system depends on the embodied energy of each of its component. The main problem with triple-pane glazing systems was that their production energy is significantly higher compared to other types of glazing systems. Thus, it may be possible to increase the efficiency of the system by proposing some other materials with lower embodied energy. In future studies other applicable and appropriate materials can be identified and their production energy and operational energy can be compared.

It should be concluded that the process of selecting an efficient window involves many considerations in terms of energy consumption. Energy consumption is an important issue that should be taken into account during the entire lifetime of a product from production to service life (production phase and operational phase). Making decisions based upon one attribute may not always lead to a completely balanced conclusion.

Having a sustainable approach is a fact that takes place in every simple measure for ones life. For example, although choosing a suitable window for our house may initially seem irrelevant to “Sustainable Development”, it completely covers all of the important aspects of triple-bottom-line (i.e., environmental, economic, and social). The environmental impact of selected windows was the main concern of this study, and consequently best energy efficient windows in a variety of geographical locations were identified. As the fossil fuel is one of the main sources of energy in the U.S., energy conservation will lead to the reduction in fossil fuel consumption. At the same time, energy efficiency concerns have real life consequences on economic issues; which means that choosing a proper window will have a great impact on energy bills. Besides, energy efficient windows not only make up for their cost premium by savings on energy bills, but their improved thermal comfort is also an immediate benefit. A window with good energy performance will generally provide greater thermal comfort and consequently a better quality of life (social impact). It could be therefore stated that the connection between environment, society, and economy is inevitable in every energy related matters that deal with sustainability issues such as using suitable glazing systems for buildings.

GLOSSARY

Air leakage (air infiltration): The amount of air that will leak through a window.

Air leakage rate: A measure of the rate of air leakage around a window, door or skylight in the presence of a specific pressure difference. It expressed in units of cubic feet of air transport through a square foot of window area. This value generally lies between 0.1 and 0.3 ft3/ft2. The lower a window air leakage rating, the better its air tightness.

Ambient temperature: The temperature of the surrounding environment; technically, the temperature of the air surrounding a power supply or cooling medium; abbreviated ABM. Ambient room temperature ranges from 68 to 77 degrees Fahrenheit.

American Housing Survey (AHS): A statistical survey funded by the United States Department of Housing and Urban Development (HUD). It is the largest regular national housing sample survey in the United States and contains information on the number and characteristics of U.S. housing units as well as the households that occupy those units.

Argon: An inert, nontoxic gas used in insulating glass unit to reduce heat transfer.

ASHRAE: American Society of Heating, Refrigerating, and Air Conditioning Engineers; an organization that publishes standards for thermal design in buildings

Black body: The ideal perfect emitter and absorber of thermal radiation. It emits radiant energy at each wavelength at the maximum rate possible as a consequence of its temperature, and absorbs all incident radiance.

Btu (B.T.U): An abbreviation for British Thermal Unit- the heat required to increase the temperature of one pound of water one degree Fahrenheit.

Condensation: The deposit of water vapor from air on any cold surface whose temperature is below the dew point, such as a cold window glass or frame that is exposed to humid indoor air.

Conduction: The transfer of heat between substances, which are in direct contact with each other. Conduction occurs when heat flows through a solid.

Convection: The movement of gases and liquids caused by heat transfer. As a gas or liquid is heated, it warms, expands and rises because it is less dense resulting in natural convection.

Daylight factor: In architecture, a daylight factor is the ratio of the light level inside a structure to the light level outside the structure. It is defined as: DF = (Ei / Eo) x 100%

Daylight: Visible light, or daylight, is the range of wavelengths of the electromagnetic spectrum between 0.38 µm and 0.78 µm.

Day lighting: Is the practice of placing windows or other openings and reflective surfaces so that during the day natural light provides effective internal lighting.

Dew point: the temperature at which water vapor in air will condense at a given state of humidity and pressure.

DOE-2: A building simulation computer program to calculate total annual energy use.

DOS: Abbreviation for disk operating system is an acronym for several computer operating systems that are operated by using the command line.

Double-glazing: A type of windows essentially with two panes of glass with a vacuum between them. The trapped air creates insulation that prevents heat loss or gain through the window because the air temperature cannot penetrate the vacuum and therefore bounces back

Electrochromic window: Glazing with optical properties that can be varied continuously from clear to dark with a low voltage signal. Ions are reversibly injected or removed from an electrochromic material, causing the optical density to change.

Embodied energy: Embodied energy is the energy consumed by all of the processes associated with the production of a building, from the mining and processing of natural resources to manufacturing, transport and product delivery.

Emittance: The ratio of the radiant flux emitted by a specimen to that emitted by a blackbody at the same temperature and under the same condition.

Fenestration: The arrangement of windows and other openings in a building.

Fiberglass: A type of fiber-reinforced plastic where the reinforcement fiber is specifically glass fiber. The glass fiber may be randomly arranged, flattened into a sheet (called a chopped strand mat), or woven into fabric.

Float glass: Glass formed by the process of floating the material on a bed of molten metal. It produces a high-optical-quality glass with the parallel surface, without polishing and grinding.

Frame: the fixed frame of a window, which holds the sash or casement as well as hardware.

Functional unit: In LCA functional unit defines what precisely is being studied and quantifies the service delivered by the product system, providing a reference to which the inputs and outputs can be related.

Gas fill: A gas other than air, usually argon or Krypton placed between window or skylight glazing panes to reduce the U-factor by suppressing conduction and convection.

Glass: An inorganic transparent material composed of silica (sand), soda (sodium carbonate), with small quantities of alumina, boric, or magnesia oxides.

Glazing system: The glazing specifications and configurations for a building.

Glazing: The combination of glass, framing, and other materials that fill openings in a building's skin

Heat gain: The transfer of heat from outside to inside by means of conduction, convection and radiation through all surfaces of a house.

Heat loss: The transfer of heat from inside to outside by means of conduction, convection and radiation through all surfaces of a house.

Humidity: The amount of water vapor in the air.

HVAC: Heating, ventilation, and air conditioning; an umbrella term for all thermal regulation systems in a building

Infrared radiation: Invisible, electromagnetic radiation beyond red light on the spectrum, with wavelengths greater than 0.7 of microns.

Insulating glass (IG): more commonly known as double glazing or triple glazing/pane is double or triple glass window panes separated by a vacuum or gas filled space to reduce heat transfer across a part of the building envelope

Insulating value: see U-value

Krypton: An inert, nontoxic gas used in insulating glass unit to reduce heat transfer.

LEED: Leadership in Energy and Environmental Design; a rating system to recognize buildings that achieve certain environmental standards

Life Cycle Assessment (LCA): Is a tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle. LCA provides an adequate instrument for environmental decision support

Life-Cycle Energy analysis (LCEA): A form of life cycle assessment (LCA) that is particularly relevant to the building industry. In LCEA, energy is the only parameter that is measured.

Low-e: low-emissivity; transmitting less thermal energy that normal, as with a coating on construction glass.

Mega joule (MJ): 1 MJ is equal to one million (10^6) joules. The joule is the standard unit of energy in general scientific applications. One joule is defined as the amount of energy exerted when a force of one newton is applied over a displacement of one meter. Also, one joule is equivalent to the heat required to raise the temperature of 1 g of water by 0.24 K or the amount of electricity required to light a 1-watt LED for 1 s. In some applications, the British thermal unit (Btu) is used to express energy. One Btu is equivalent to approximately 1055 joules.

NFRC: The National Fenestration Rating Council is a non-profit organization, which sponsors an energy efficiency certification and labeling program for windows, doors, and skylights.

Operational energy: The amount of energy that is consumed by building to satisfy the demand for heating, cooling, ventilation, lighting, equipment, and appliances”

Pane: One of the compartments of a door or window consisting of a single sheet of glass in a frame; also a sheet of glass.

Payback period, energy: The amount of time it takes an object to recoup its embodied energy through energy savings

Polyvinyl chloride (PVC): An extruded or molded plastic material used for window framing and as a thermal barrier for the aluminum window.

Radiation: When electromagnetic waves travel through space, it is called radiation. When these waves (from the sun, for example) hit an object, they transfer their heat to that object.

Reflectance: the ratio of reflected radiant energy to incident radiant energy.

Reflective glass: Window glass coated to reflect radiation striking the surface of the glass.

Refraction: The deflection of the light ray from a straight path when it passes at an oblique angle one medium (such air) to another (such as glass),

RESFEN: A computer program used to calculate energy use based on window selection in a residential building.

Sash: The portion of a window that indicates the glass and the framing sections directly attached to the glass, not to be confused with the complete frame into which the sash sections are fitted.

Sensitivity Analysis: A method of validation consists of changing the values of the input and internal parameters of a model to determine the effect on the model's behavior of output.

Sheet glass: A transparent, flat glass found in older windows, now largely replaced by float glass.

Single glazing: single thickness of glass in a window or door.

Skylight: a roof window that gives light and ventilation.

Smart window: Generic term for windows with a switchable coating to control solar gain.

Solar control coatings: Thin film coatings on glass or plastic that absorbs or reflects solar energy, thereby reducing solar gain.

Solar Heat Gain Coefficient (SHGC): The fraction of solar radiation admitted through a window or skylight, both directly transmitted, and absorbed and subsequently released inward. SHGC is expressed as a number between 0 and 1. The lower a window's SHGC, the less solar heat it transmits, the greater it's shading ability. It can be expressed in terms of the glass alone or can refer to the entire window assembly.

Solar radiation: the total radiant energy from the sun, including ultraviolet and infrared wavelength as well as visible lights.

Solar spectrum: The intensity variation of sun light across its spectral range.

Specific heat: The specific heat is the amount of heat per unit mass required to raise the temperature by one degree Celsius. The relationship between heat and temperature change is usually expressed in the form shown below where c is the specific heat.

Spectrally selective glazing: A coated or tinted glazing with optical properties that are transparent to wavelengths of energy and reflective to others. Typically spectrally selective coatings are transparent to visible light and reflect short-wave and long-wave infrared radiation.

Sunshade: A component on the exterior side of a window that blocks direct light from high sun angles, reducing glare

Sustainable design: A method of building that aims to give future generations the same resources available today

Thermochromic window: Glazing with optical properties that can change in response to temperature changes.

Tinted glass: Glass colored by incorporation of a mineral admixture or tinted coating. Any tinting reduces boat visual and radiant transmittance.

Transmittance: The percentage of incident light that passes through a material

Triple glazing: Three panes of glass or plastic with two air spaces between.

U.S. Department of Energy (DOE): A Cabinet-level department of the United States Government concerned with the United States' policies regarding energy and safety in handling nuclear material.

U.S. Energy Information Administration (EIA): a principal agency of the U.S. Federal Statistical System responsible for collecting, analyzing, and disseminating energy information to promote sound policymaking, efficient markets, and public understanding of energy and its interaction with the economy and the environment. EIA programs cover data on coal, petroleum, natural gas, electric, renewable and nuclear energy. EIA is part of the U.S. Department of Energy.

U-factor: The percent of thermal energy lost through a material or assembly. It is expressed in units of Btu/hr-sq-ft-°F. Values are normally given for NFRC/ASHRAE winter condition of 0 °F outdoor temperature, 70 °F in door temperature, 15 Mph wind, and no solar load. The U-factor may be expressed for the glass alone or the entire window, which includes the effect of the frame and the spacer materials. The lower the U-factor, the greater the window's resistance to heat flow and the better its insulating value.

USGBC: United States Green Building Council, a nonprofit organization that promotes sustainable design in construction, most notably through the development of the LEED system.

Validation: The process of determining the degree to which a simulation model and its associated data are an accurate representation of the real world from the perspective of the intended uses of the model.

Verification: The process of determining that a model implementation and its associated data accurately represent the developer's conceptual description and specifications.

Visible Transmittance (VT): The portion of incident light on a surface that is transmitted

Whole Building Design Guide (WBDG): A complete internet resource for a wide range of building-related design guidance, criteria and technology managed by the National Institute of Building Sciences

WINDOW-6 program: A program that calculates thermal performance of fenestration products.

REFERENCES

Adalberth, K. (1997). Energy use during the life cycle of buildings: a method. Building and Environment, 32(4), 317-320.

Aksamija, A., Abdullah, A., & Cross, B. (2014). Whole building energy analysis: A comparative study of different simulation tools and applications in architectural design. Proceedings of the 2014 ACEEE Summer Study on Energy Efficiency in Buildings.

Andrew, Ella (2015) “Futuristic Materials That Will Change Building Forever” GREEN WIZARD Web. April.24.2015.https://www.greenwizard.com/2015/04/futuristic-materials-that-will-change-building-forever/#sthash.HzvjY4Xj.dpu

Arasteh, D., Huang, J., Mitchell, R., Clear, B., & Kohler, C. (1999). A database of window annual energy use in typical North American single family houses. ASHRAE Transactions, 106(1).

Arasteh, D., Selkowitz, S., Apte, J., & LaFrance, M. (2006). Zero energy windows. Lawrence Berkeley National Laboratory.

Ashby, M. F. (2012). Materials and the environment: eco-informed material choice. Elsevier.

Asif, M., Davidson, A., & Muneer, T. (2002). Life cycle of window materials, a comparative assessment. Millenium Fellow School of Engineering, Napier University, Edinburgh http://www. cibse. org/pdfs/Masif. pdf.

Azari, R. (2014). Integrated energy and environmental life cycle assessment of office building envelopes. Energy and Buildings, 82, 156-162.

Ballinger, J. A., & Lyons, P. R. (1996). Advanced glazing technology for Australia-research and application. Renewable energy, 8(1), 61-65.

Brebbia, C. A., & Chon, T. S. (2012). Environmental Impact (Vol. 162). Wit Press.

Buildings, U. S., & Construction Initiative. (2007). Buildings and climate change: status, challenges and opportunities.

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable and sustainable energy reviews, 29, 394-416.

Carmody, J. (2007). Residential windows: A guide to new technologies and energy performance. WW Norton & Company.

Carmody, J., & Haglund, K. L. (2012). Measure Guideline: Energy-Efficient Window Performance and Selection. US Department of Energy, Energy Efficiency & Renewable Energy, Building Technologies Program.

Citherlet, S., Di Guglielmo, F., & Gay, J. B. (2000). Window and advanced glazing systems life cycle assessment. Energy and Buildings, 32(3), 225-234.

Crawley, D. B., Hand, J. W., Kummert, M., & Griffith, B. T. (2008). Contrasting the capabilities of building energy performance simulation programs. Building and environment, 43(4), 661-673.

Devlin, K. (2014, October 13). A Guide to Energy-Efficient Glass, a Look at the Past, Present and Future of High-Performance Glass Solutions. Glass magazine.

Entec. 2000. Life cycle assessment of polyvinyl chloride and alternatives, final report. www.defra.gov.uk/ENVIRONMENT/consult/pvc/. Accessed July 6, 2007.

Fay, R., Treloar, G., & Iyer-Raniga, U. (2000). Life-cycle energy analysis of buildings: a case study. Building Research & Information, 28(1), 31-41.

Gao, Y., Luo, H., Zhang, Z., Kang, L., Chen, Z., Du, J., & Cao, C. (2012). Nanoceramic VO 2 thermochromic smart glass: a review on progress in solution processing. Nano Energy, 1(2), 221-246.

GlassOnline.com. Glassonline.com - a brief history of glass, 2009

Glicksman, L. R. (2008). Energy efficiency in the built environment. Physics Today, 61(7), 35.

Griffiths, P. W., Eames, P. C., Lo, S. N. G., & Norton, B. (1996). Energy and environmental life-cycle analysis of advanced windows. Renewable Energy, 8(1), 219-222.

Grondzik, W. (2011). The Green Studio Handbook. Elsevier Science.

Hammond, G., & Jones, C. (2008). Inventory of carbon & energy: ICE. Bath, UK: Sustainable Energy Research Team, Department of Mechanical Engineering, University of Bath.

Heath, N., Baker, P. H., & Menzies, G. (2013). Slim-profile double glazing—thermal performance and embodied energy, Historic Scotland technical paper 9, technical conservation group, Historic Scotland.

Howard, N. P., Burgess, J., & Lim, C. (2007). Comparative service life assessment of window systems. Forest & Wood Products Research & Development Corporation.

Jonsson, A. (2009). Optical Characterization and Energy Simulation of Glazing for High-Performance Windows.

Kates, R. W., Parris, T. M., and Leiserowitz, A. A., (2005). What is sustainable development? Environment: Science and Policy for Sustainable Development, 47(3), 8-21.

Kiani, M., Ip, K., & Miller, A. (2005). Evaluate the whole life environmental impact of glass in a fully glazed commercial building. In World Sustainable Building Conf., Tokyo.

Kofoworola, O. F., & Gheewala, S. H. (2009). Life cycle energy assessment of a typical office building in Thailand. Energy and Buildings, 41(10), 1076-1083.

Kwok, A. G., & Grondzik, W. T. (2007). The green studio handbook: environmental strategies for schematic design. Enquiry: A Journal for Architectural Research, 4(2).

Mandil, C. (2004, November). International Energy Agency," World Energy Outlook 2004. In International Energy Symposium, IEEJ, Tokyo (Vol. 16).

Menzies, G. F., & Wherrett, J. R. (2005). Multiglazed windows: potential for savings in energy, emissions and cost. Building Services Engineering Research and Technology, 26(3), 249-258.

Minne, E., Wingrove, K., & Crittenden, J. C. (2015). Influence of climate on the environmental and economic life cycle assessments of window options in the United States. Energy and Buildings, 102, 293-306.

Rallapalli, H. S. (2010). A comparison of EnergyPlus and eQUEST whole building energy simulation results for a medium sized office building (Doctoral dissertation, Arizona State University).

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. Energy and Buildings, 42(10), 1592-1600.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., & Pennington, D. W. (2004). Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environment international, 30(5), 701-720.

Recio, J. M. B., Narváez, R. P., & Guerrero, P. J. (2005). Estimate of energy consumption and CO2 emission associated with the production, use and final disposal of PVC, aluminium, and wooden windows. Départment de Projectes d'Engineyeria, Universitat Politecnica de Catalunya, Environmental Modelling Lab, Barcelona, Spain.

Rosenbaum, M. (2003). Understanding the Energy Modeling Process: Simulation Literacy 101. The Pittsburgh Papers: Best of Green-Build 2003, 99-108.

Rosencrantz, T., Bülow-Hübe, H., Karlsson, B., & Roos, A. (2005). Increased solar energy and daylight utilization using anti-reflective coatings in energy-efficient windows. Solar energy materials and solar cells, 89(2), 249-260.

Salazar, J., & Sowlati, T. (2008). Life cycle assessment of windows for the North American residential market: case study. Scandinavian Journal of Forest Research, 23(2), 121-132.

Sargent, R. G. (2005, December). Verification and validation of simulation models. In Proceedings of the 37th conference on winter simulation (pp. 130-143). Winter simulation conference.

Van Den Bergh, S., Hart, R., Jelle, B. P., & Gustavsen, A. (2013). Window spacers and edge seals in insulating glass units: A state-of-the-art review and future perspectives. Energy and Buildings, 58, 263-280.

Weir, G., & Muneer, T. (1998). Energy and environmental impact analysis of double-glazed windows. Energy Conversion and Management, 39(3), 243-256.

Wolf, A. T. (2012). Sustainability driven trends and Innovation in Glass and Glazing [J/OL].

www.arpa-e.energy.gov/sites/default/files/03%20-%20Selkowitz%20-%20ARPA%20E_selk_final.pdf

www.facilitiesnet.com/energyefficiency/article/Harnessing-Daylight-For-Energy-Savings-Facilities-Management-Energy-Efficiency-Feature--4267

www.mnre.gov.in/solar-energy/ch4.pdf

www.ravenwindow.com

www.smartenergy.arch.uiuc.edu/pdf/Archive/HighPerformanceWindows.pdf

www.sustainabilityworkshop.autodesk.com

www.windows.lbl.gov/software/resfen/resfen.html