Analysis of Energy Efficient Curtain Wall Design Considerations in Highrise Buildings

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A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirements for the degree of

Master of Science

Department of Civil, Environmental, and Architectural Engineering

2017

This thesis entitled:
Analysis of Energy Efficient Curtain Wall Design Considerations in Highrise Buildings
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Analysis of Energy Efficient Curtain Wall Design Considerations in Highrise Buildings

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Today's built environment is responsible for 40% of the annual energy consumption in the United States. There is great potential for improvements in building design to reduce the contribution of the built environment to the national energy consumption. In order for widespread change to take place, architects and engineers must be provided with the tools necessary to understand the energy implications of their design decisions.

The iconic skyscrapers that form our nation's skylines represent a large sector of buildings that is in need of improvements in energy efficiency. The curtain wall façades in highrise buildings provide a powerful aesthetic, but when not designed properly, the façade can be a major weakness in terms of energy efficiency. A building energy model representative of a "typical" highrise building within the U.S. was used to identify the potential weaknesses in the façade of a highrise building and to characterize the general energy consumption of a highrise building design. The model was then used to provide quantification for the energy consumption savings and annual energy cost savings that can be achieved with an optimized curtain wall design.

Based upon the findings, a set of climate-specific recommendations were made that identify the variables that have the most potential within a given climate to provide annual energy savings. The ranges of values for each variable in the analysis were based on products currently on the market. The results of this analysis present an argument for increased evaluation of the performance characteristics of curtain walls in highrise buildings, and offer useful design guidance to help architects and engineers to make informed decisions towards a more energy efficient curtain wall and therefore building.

Acknowledgements

I would like to thank the people that guided me and supported me through this process. I thank Dr. Zhai for acting as my advisor throughout this process, for all the insight and direction he provided. I would also like to thank my other committee members, Dr. Krarti and Dr. Beamers for being willing to hear my ideas and offer their insight as well.

I would like to thank my employers at MKK Consulting Engineers for allowing me to learn more about the commercial building design industry, for affording me the flexibility to work and perform my research, and for supporting me through the process.

I owe a huge thanks to my friends and family who supported me and encouraged me through the process, and to my fellow “Bat Cave” members for helping keep the sanity intact. I hope that I am able to return the kindness and encouragement that was afforded me by so many throughout this process.

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Chapter 1: Introduction

1.1 Introduction

Global fuel consumption at its current level is not sustainable for centuries to come, especially if consumption rates continue to increase as they have been for the last century. Growing awareness of the issues of climate change and finite fuel resources have led to new developments in energy efficiency, but there is still much improvement that needs to be made. There have been many efforts to develop alternative energy production that either comes from a more sustainable source or is cleaner for the environment. However, more attention needs to be paid to reducing consumption rather than simply increasing the capacity. One area that is in need of focused attention is reducing the energy needs of the built environment. Worldwide the built environment accounts for roughly 40 percent of annual energy consumption [1]. In the United States it is responsible for 41 percent of the 94.6 Quadrillion Btu of total energy consumption annually [2]. The built environment represents a vast, relatively untapped potential for reduced fuel consumption. Many technologies have been, or are currently being developed to assist in creating more energy efficient buildings. Research and development have resulted in the ability to implement energy efficient building envelopes, construction materials, and heating and cooling strategies. However, in many cases, these resources have not yet been utilized to their full potential. One sector that would benefit from the implementation of available energy efficiency measures is highrise buildings. However, in order for widespread implementation to occur, the impacts of these various building technologies on building energy consumption must be thoroughly understood. When implementation can be justified, the design community will turn to these technologies. Tools and guides must be developed that make it easier for the design community to understand and justify energy efficiency strategies to business owners. When the technology is available, implementation is simple, and the energy and cost benefits are indisputable only then will widespread change occur.

Chapter 2: Literature Review

2.1 History of the Highrise Building

The highrise building has always been a symbol of strength, industry, and achievement. “Highrise” buildings are loosely defined, but the Council on Tall Buildnigs and Urban Habitat defines a “tall building” as “one in which the height strongly influences planning, design, or use” [3]. The International Building Code defines a highrise building as one that has “occupied floors located more than 75 feet above the lowest level of fire department vehicle access” because of the special consideration required for fire and occupant safety at that height [3]. The highrise as it is known today is drastically different from the earliest highrise buildings. The construction of the Home Insurance Building in Chicago in 1855 is generally marked as the beginning of the modern highrise [4]. The highrise emerged as a result of two separate technological developments: steel frame construction and the elevator. Frame construction allowed for taller structures without increased wall thickness, and elevators made it feasible for tenants to occupy spaces above the 4th or 5th floor. The first generation of highrise buildings were heavily clad with masonry. The buildings’ exterior thermal mass mitigated heat loss in the winter, and heat gains in the summer months. Windows only made up 20-40% of the façade, compared to the modern highrise trend of 50-75% glazed façade [5]. However, because of the lack of effective lighting technology, these early highrise buildings relied heavily on daylighting. Even though 20-40% glazing was high for the time, it was not sufficient for daylighting by today's standards. Lighting levels of 22-40 lux were typical of office buildings in the early 1900s, compared to the 250-500 lux that is common today.

Highrise design was forced to change course because of the enforcement of the Zoning Law of 1916 in New York City. The new regulation was in response to the growing skyline. Not only was there growth in the number of highrise buildings, but there also emerged a race to hold the record for the tallest building. The Zoning Law required the incorporation of façade setbacks, (illustrated in Figure 1) based on overall building height to enable light and air to reach the streets and buildings below [4]. As a result, buildings had a much higher surface-to-volume ratio, which increased the heating and cooling losses through the envelope. Artificial lighting requirements were also more demanding than before. In the 1930s buildings began relying on air conditioning to provide cooling, rather than natural ventilation. Between the added air-conditioning, increase in artificial lighting, and less efficient envelope design, highrise buildings began to trend towards increased energy consumption. The Empire State Building is a prime example of this generation of highrise architecture. The traditional high

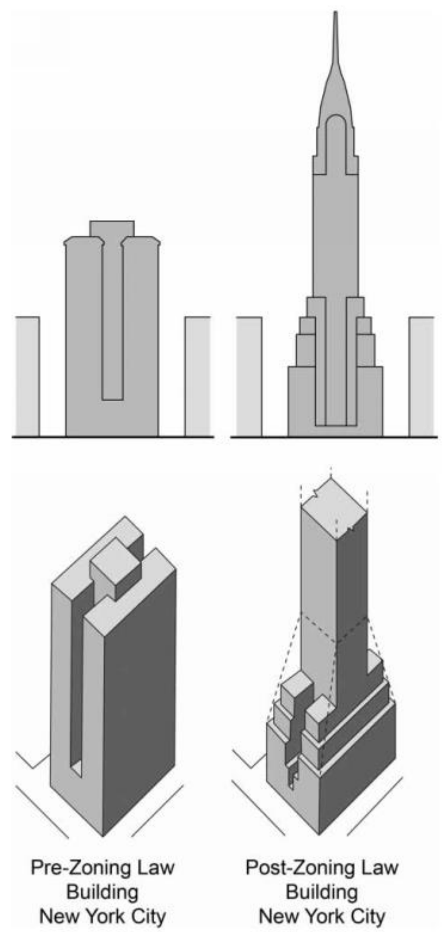

Figure 1: Zoning Law of 1916 [5]

thermal mass materials were maintained in the façade, had a relatively low window-to-wall ratio, and it reflects the setback architecture of the time. It was also the largest building constructed during this time period, and remained the tallest in the world for over forty years [5].

After World War II, new building technologies, a modernist movement, and economic prosperity sparked a new wave of skyscraper construction in the United States. These new buildings, such as the Lake Shore Drive Apartments in Chicago and the Lever House in New York, utilized new, lightweight curtain wall technology to produce impressive towers of highly glazed façades – between 50% and 75% glass [5]. The glazed façades were an attempt to connect the occupants to the outdoors, provide impressive views to entice new tenants, and stand as a status symbol for companies. A new Zoning Law was established that allowed buildings a 20% density bonus if they incorporated public plazas to the building plot [5]. The Zoning Law of 1916 required highrise buildings to be much more slender and less compact than their predecessors. The "density bonus" allowed for deeper floor plans, while allowing for preservation of views and light penetration, which was the original concern of the zoning laws. This resulted in structures that had building surface area-to-volume ratios that were reminiscent of the earliest highrise buildings. However, the energy saving benefits of a lower surface area ratio were offset by the poor thermal qualities of the highly glazed façades. The glazing used was generally tinted grey or bronze to achieve a certain aesthetic, which allowed low amounts of daylight into the space. It became the cultural trend to use black or dark-colored cladding, which only made the heat gains worse. The poor thermal qualities of the envelope coupled with the complete reliance on mechanical ventilation and high artificial light requirements caused drastic increase in energy consumption in highrise buildings built during the 1960s. The buildings built in the late 1960s had nearly double the primary energy requirements of buildings constructed in the early 1950s [5].

In 1973, the energy crisis in the United States caused yet another shift in design paradigm. Much more attention was paid to the energy implications of the façade design. Architects shifted from tinted and reflective glass towards double-glazing, low-emissivity coatings, and argon-filled cavities [5]. The U-values of buildings after the 1970s was nearly three times as effective as the buildings from the 1960s. Daylight was relied on much more heavily, and the dark façade colors were no longer in vogue. Code requirements for office illuminance were lowered to a much more reasonable value, however the development of computers during this time period created larger electricity demands and larger internal loads. New structural technologies allowed for buildings that were taller than ever. The World Trade Center in New York and the Sears Tower in Chicago were both built in the early 1970s. At the same time, interest in highrise construction had grown significantly in Europe and Asia, so the energy efficient measures developed since the 1970s would begin to have a much more widespread impact.

The pursuit of energy efficient façades has remained the trend since the 1970s, and has grown significantly in the last decade. Rising fuel prices and further fossil fuel depletion along with the increasing concern over climate change and carbon emissions have caused architects, engineers, and researchers to focus on energy efficiency measures. Passive heating and cooling strategies, daylight utilization, and integrated energy generation are a few of the approaches that have been explored. Façade design receives much more attention than ever now that the correlation between energy consumption and façade design is evident. The façade design is a core determinant for occupant comfort, heating and cooling loads, and artificial lighting requirements. Some architects have begun to incorporate thermal mass into the façade, others have concentrated on harnessing the full potential of daylight, and others still are developing new concepts such as the double-skin façade to provide natural ventilation for the space.

Highrise buildings are located across a variety of climates, and are used for many different purposes. For this reason there is not a single strategy that can be applied to all designs to provide guaranteed energy savings. Façade design is multifaceted and site-specific, which makes the design process quite complex. However, a successful retrofit or new construction façade design has the potential to provide large energy and equipment cost savings. There is a wide range of products available for architects to choose from, and other products are being modified to make them more widely available on the market. Arguably, all the components are available to consistently create low energy façades in any new construction or retrofit situation. However, there are still significant barriers to widespread adaptation of energy efficient façades. Some glazing technologies are not yet available because of affordability, availability, or reliability. It is difficult to provide accurate, holistic modeling to prove to investors and owners the exact potential for savings that will occur with some additional up-front investment.

The built environment is responsible for 41% of annual energy consumption, and a major contributor to this energy consumption is the highrise building sector. The implementation of energy saving strategies in highrise buildings could potentially dramatically impact annual energy consumption both in the United States and worldwide. However, in order to affect widespread change, architects must become more familiar with available technologies. The design process must also be streamlined, and methods for proving performance to building owners must be more effective.

2.2 Curtain Walls

Developments in steel frame construction in the early 20th century allowed the building structural load to be transferred from the exterior walls to an internal support system. These advancements spurred the development of the curtain wall façade, which is one of the most recognizable features of most modern highrise buildings. The curtain wall is a nonbearing façade system that hangs from the building's structural frame, reminiscent of a curtain on a window frame. Curtain wall systems offer a great amount of flexibility to the architect, and can be as unique as the buildings they occupy. Figure 2 shows examples of some basic curtain wall strategies on the market. Within these glazing systems, there are numerous variables that can be manipulated to produce desired aesthetic, thermal, and functional desires of the client. Curtain wall systems are complex systems, and design decisions can potentially have drastic impacts on the energy and comfort performance of the building.

The modern skyscraper has reached heights that were only achievable through the curtain wall system. Not only are curtain walls lighter than the first generation of highrise façades, but they also streamline the construction process. Systems can be assembled on-site, or they can be fabricated elsewhere and brought to the site and installed as panel systems. Curtain walls can be anchored to the building in a variety of ways. The fastening approach is often selected based on the aesthetic goals of the architects and desired construction characteristics. Curtain wall systems enable architects to design the tallest buildings in the world, and also allow for timely construction.

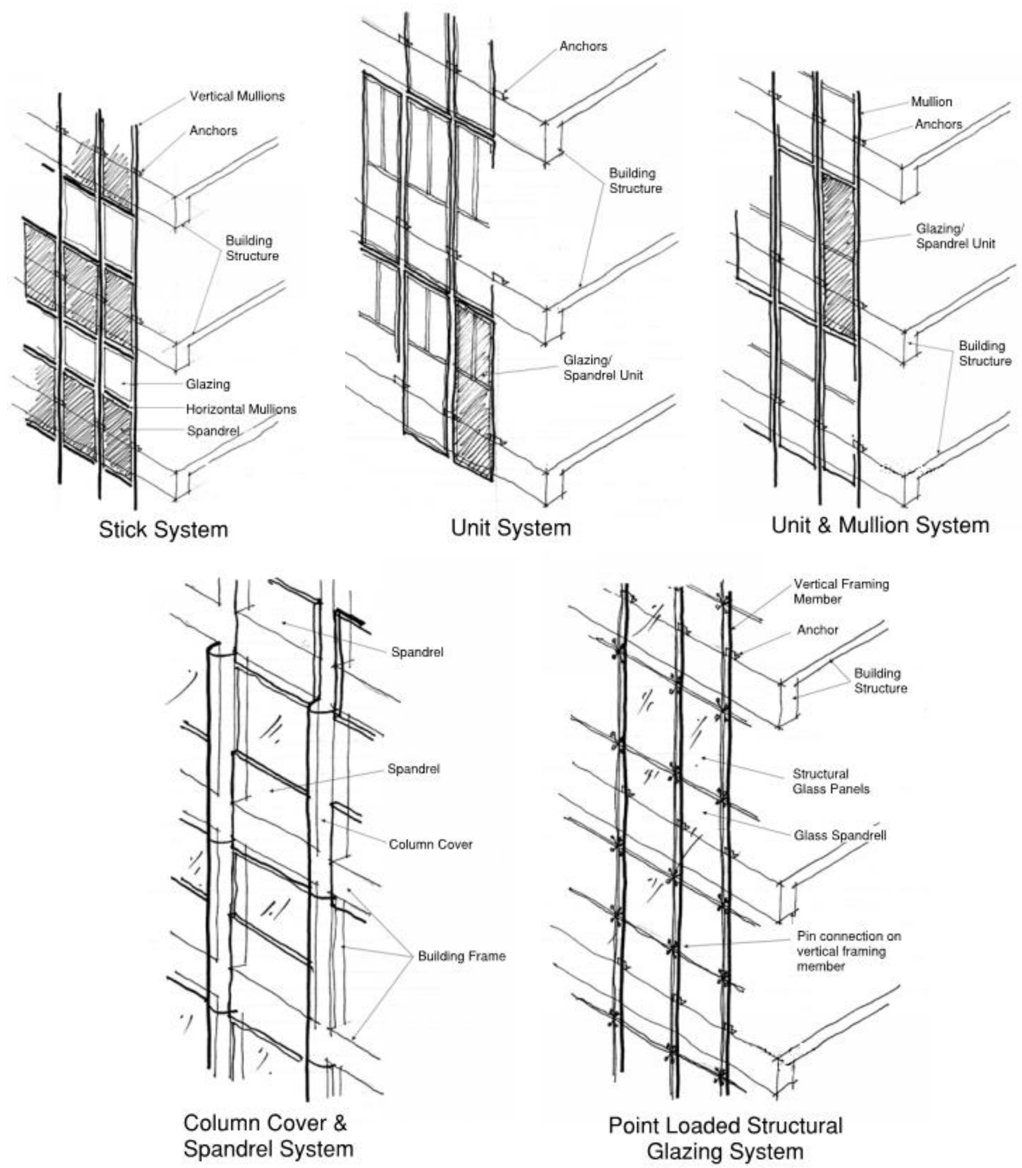

Figure 2: Curtain Wall System Types [6]

Another benefit to curtain walls is the flexibility of building shape and material selection. The eclectic skylines of Chicago and New York City are a testament to the endless potential combinations of shape and cladding materials. Curtain wall systems allow for a wide range of window-to-wall ratios. Opaque materials on the façade can be any combination of masonry, metal, or even opaque glass sections. The glazing on highrise façades can take many forms as well. The growing concern for energy efficiency in buildings has led to many developments in available glazing products and strategies. Current highrise buildings display the evolution of glazing strategies in the different glass tinting, reflectivity, coatings, and fillings utilized throughout the last century of highrise design. The current design trend is to attempt to balance the utilization of daylighting with the thermal gains and losses from the glazed façade. Most current highrise buildings have single-skin façades with different glazing characteristics, but there is also a growing interest in the energy saving potential of double-skin façades. Double skin façades utilize the stack effect to provide natural ventilation through the cavity created between the interior façade and a second, offset façade. Highrise glazing can be operable for increased occupant control or fixed for greater envelope control. Curtain walls also offer the potential of external solar control, which can greatly affect the thermal gains of the envelope especially on the scale of a highrise façade.

Curtain wall construction allows the architects to achieve various aesthetic properties. The highrise has always been a symbol of strength and success. This is largely portrayed through the massive scale of highrise buildings. Ludwig Mies van de Rohe was one of the first architects to begin incorporating large amounts of glazing to showcase what he thought was the most significant aspect of highrise buildings – its structural skeleton [4]. Architects have used the curtain wall to achieve a sleek aesthetic of flat-paneled glass. They create visual interest through reflections of the surrounding buildings. Some architects take advantage the height capability of lightweight curtain walls to create façades that seem to disappear into the sky. Other designs take advantage of the flexibility of shape to produce iconic structures such as the Chrysler Building, the Empire State Building, the Swiss Re Headquarters, or the Bank of China [4]. The possibilities available with curtain walls are endless, and architects are continuing to produce designs that push the limits of shape and visual aesthetics.

Figure 3: Left to right - Empire State Building, Chrysler Building, Swiss Re Headquarters, Bank of China [7]

The popularity of highrise construction has spread from Chicago and New York City to the rest of the United States, and has grown drastically around the world for the last half-century. The diversity of climates in which highrise buildings are now located has created the need for even more flexibility in the highrise envelope. The curtain wall system provides great flexibility, but the wide range of construction options available makes optimization incredibly complicated, especially in terms of energy efficiency. The following is an exploration of curtain wall façade technologies – what is currently used and what may be the future of highrise building construction and retrofit. The technologies are examined with a specific focus on their energy implications.

2.3 Glazing

A crucial decision for each curtain wall design is the glazing characteristics. Because glazing typically occupies a large percentage of the highrise façade, it can have a drastic impact on the occupant comfort, energy consumption, safety, and aesthetic qualities of the building. In the United States, windows account for 30% of building heating and cooling loads [8]. Window views have been known to provide physical and psychological benefits to the occupants, even improving the productivity of workers in the space [9]. The heat transfer characteristics of a given glazing system can have a drastic impact on occupant comfort as well [10]. However, increasing the available views through glazing must be balanced with the energy implications of increased glazing area. There are a variety of glazing types and strategies available on the current market, each with different advantages and disadvantages. Proper selection requires an in-depth understanding of the characteristics of available glazing technologies, and their implications for energy, lighting, and occupant satisfaction. The glazing characteristics can then be taken full advantage of for a given design and climate.

The original skyscrapers utilized simple, singe-pane windows. In the mid-20th century, it became popular to have tinted and reflective glazing to achieve a certain aesthetic. During the energy crisis in the 1970s, it became evident that the poor thermal and radiation properties of the windows used in highrise buildings were a large energy sink. The energy implications of glazing selection were more carefully considered, and a variety of glass types began to penetrate the market. Low-e coatings, double-glazed panels, and a variety of gas-filled cavity glazings became popular solutions to the inefficient façades.

Glazing impacts the heating load, cooling load, and electrical lighting load of the space. Most glazings attempt to incorporate one or two of the following goals: control solar gain in cooling conditions, reduce heat loss in heating conditions, and increase and/or redirect visible transmission in daylighting conditions [11]. Most new glazings achieve control through controlling the spectral properties of the glass, controlling the intensity of transmitted light, or redirecting the light entirely [11]. Today, more is understood about the thermal and transmittance properties of the different glazing systems than ever before. Characterization of the specific performance features of different glazing systems allows architects to make more strategic selection for a given building design.

2.3.1 Tinted Glazing

The goal of tinting glass is to alter the spectral qualities of the glass. Solar radiation strikes the façade at a wide range of wavelengths, from UV to infrared. Visible light is only a small fraction of the incoming radiation. The infrared radiation is largely responsible for the heat gains associated with incident solar radiation. The properties of the glass control what portion of wavelengths are transmitted, reflected, and absorbed by the glazing. The

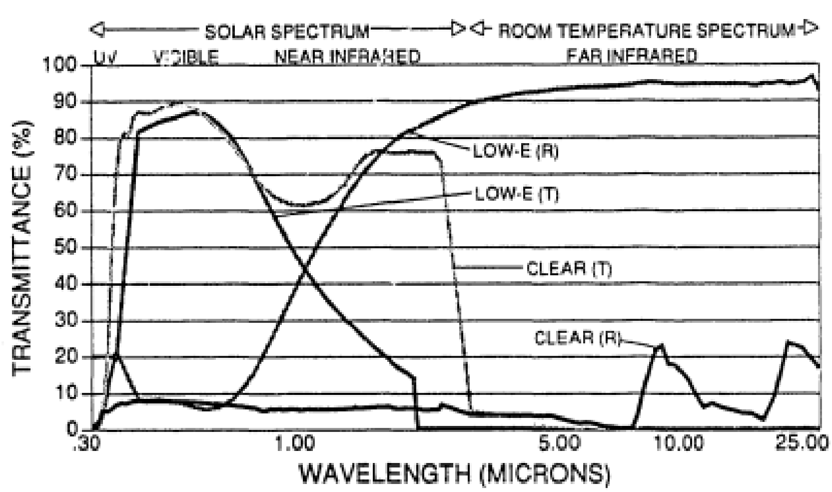

Figure 4: Spectral transmittance of glazing materials [11]

metal oxides added to the base glass during the manufacturing of tinted glass increase the absorption ratio [12]. Transmission is subsequently decreased, but the energy that is absorbed by the tinted glass must be released into the space and to the exterior as heat. The heat that is released into the space can lead to occupant discomfort.

Typical colors on the market include green, pink, blue, bronze, and grey [12]. Each color varies the visible transmittance (VT) through the glazing (as seen in Figure 4). The most widely used color is green, for its low levels of transmittance in the infrared range. Grey is often used to reduce glare [12]. Tinted glass can also be used in conjunction with other coatings to alter transmittance and thermal properties. A study compiled in 1992 by the Lawrence Berkeley Laboratory in California assessed the luminous efficacy of the typical tinted glazings on the market [11]. Figure 5 shows the efficacy of a variety of glazing types. Luminous efficacy refers to the ratio of the visible transmission to shading coefficient [11]. The higher the efficacy, the better; however, there is a limit to efficacy around 2.0 before color neutrality begins to degrade [11]. The goal for a cooling dominated space is to have a higher visible transmittance without sacrificing the solar shading coefficient. Blue and green tints are more effective for these uses. Bronze glass, on the other hand, generally transmits more infrared radiation than visible light.

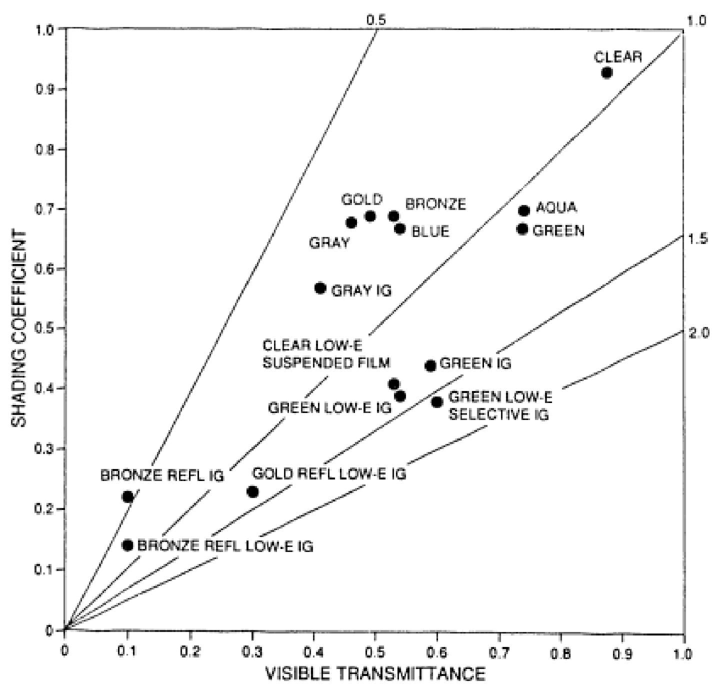

Figure 5: Luminous efficacy of glazing materials [11]

Traditionally, tinted glazing was utilized to achieve an aesthetic quality preferred by the architect. However, tinted glazing can have a large impact on the HVAC loads for any building. If tinted or clear glazing is to be used in a design for its aesthetic qualities, it is important that performance be optimized in order to achieve energy efficiency.

2.3.2 Surface Coatings

Surface coatings originated, similar to tinted glass, were developed as an aesthetic application. One of the most common early coatings was reflective glazing. Architects appreciated the play of light on the façade, and the visual interest of how the glazing reflected the surrounding buildings. Reflective coatings, as well as new types of surface coatings have been developed that now improve thermal and visual characteristics of glazing.

Reflective coatings can be utilized to achieve certain solar control qualities. All incident solar radiation must be transmitted, absorbed, or reflected. An increase in the reflection reduces the amount of absorbed and transmitted radiation, both of which create heat gains in the space. Reflective coatings can be added to clear or tinted glass, and are a relatively common practice. The simplest reflective coatings are achieved by depositing a metallic film to one surface of the glass. Some coatings are applied during the manufacturing process, while others are deposited after the glass has passed through the manufacturing line. Reflective coatings can be useful for reducing solar gains, but care must be taken to ensure that the glare does not adversely affect the surrounding buildings.

Low-emissivity coatings were developed in the 1970s, and are now widely popular for their energy-saving potential. A report by the DOE shows that low-emissivity glazings account for 50% of the market share [8]. The goal of low-e glazing is to have high transmittance values in the visual wavelengths, but to limit the transmission of infrared wavelengths [13]. The spectral quality of low-e glazing allows the advantages of daylighting potential while limiting the heating or cooling costs. The emissivity of typical glass is around 0.87, while typical low-e glass has emissivity values between 0.04 and 0.16 [12]. Low-e coatings can be applied to clear or tinted glass to achieve the desired visual and thermal properties. Low-e coatings were originally designed for heating climates to allow short-wave radiation into the space, but trap the long-wave radiation that is re-radiated by interior surfaces [11]. However, low-e coatings that are spectrally selective can also be used in cooling climates to keep long-wave radiation from penetrating the glass.

Low-emissivity coatings work well in conjunction with double-pane glazing technologies, in which the low-e coating is applied to the inner glass cavity. Radiative transfer is reduced through the glazing. This reduces the discomfort felt by building occupants. Low-e coatings in double, or even triple glazing applications are more typical in the residential market than in the highrise market because of their weight and initial cost [11]. However, application of the simpler low-e glazing systems allows for larger amounts of glazing without the added energy penalty. The energy payback is generally shorter in more extreme climates, but not as beneficial in mild climates [11].

A 2011 study of the effects of Low-e coatings in different climates compares four glazing options: clear glass, clear glass plus a low-e film, double-pane glass with a low-e film in between, and double-pane glass [14]. As can be seen from the heating and cooling load impacts in Figure 6, the performance of a low-e glazing is highly dependent on the local climate. For a cooling dominated climate such as Mexico City, the Double Glass + Film configuration was more effective than the Glass + Film. However, the Double Glass configuration had the best overall performance. For Ottawa, the best overall performance was the Glass + Film. The study also assessed the energy cost implications for the results based on local heating and cooling costs. For Mexico City the double glass remained the most successful design, but for Ottawa the double-glass + film configuration achieved the lowest annual energy cost [14]. Because the cost of heating versus cooling costs for a given location may differ, economic implications may not match the straight energy saving characteristics of the glazing type.

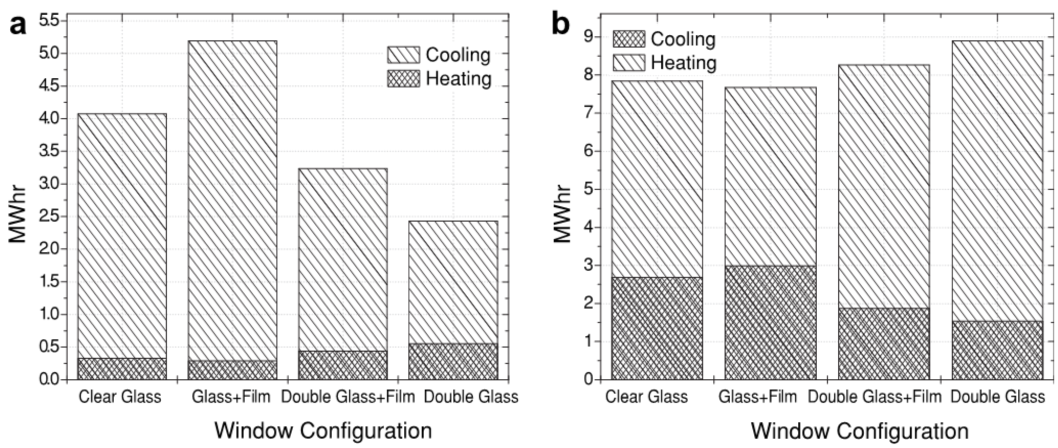

Figure 6: Cooling and heating energy loads for (a) Mexico CIty and (b) Ottowa [14]

This study shows a small sample of the potential energy savings available through low-emissivity coatings. It only explores one specific metal compound, and two distinct climates. The low-e market contains a wide variety of options of metal compounds and glazing configurations. Clearly it is necessary to assess the implications for a given glazing option for the specific climate. Low-e coatings can be extremely cost-effective in certain circumstances.

A 1998 study by Sekhar, S.C. analyzes the energy performance and life cycle cost of a range of types of reflective and low-emissivity coatings in double-pane glass [15]. The study concludes that for a Singapore climate, the energy savings in terms of both HVAC load and lighting energy are significant. The base case was a double pane float glass, and it was compared to double glaze with heat reflecting glass and two kinds of low-e coatings. The HVAC load savings can be seen in Table 1. The values are averages of the various tints also included in the analysis. The study also claims that properly designed window systems can potentially save 50-70% of the lighting energy, and 30-40% of the perimeter zone energy with daylighting. Sekhar also showed the discounted payback period of the low-emissivity glazings for this particular case to be 4 years, which is generally an acceptable payback period for most companies. This again is one case, in a specific climate, with a particular geometry, so savings would not be guaranteed for every case. However, this case does show that savings through these surface coatings are possible.

Table 1: Energy consumption comparison [15]

Glazing	Peak Cooling Load	Total Load	Savings From Baseline
Double Glaze Float Glass	496kW	1790 MWh	
Double Glaze Heat Reflective Glass	405kW	1688 MWh	91kW, 102 MWh
Double Glaze HRG with Low-e	384kW	1643 MWh	112kW, 147 MWh

2.3.3 Insulating Glass

Insulating glass units can reduce heat losses compared to single glazing by at least 50% [12]. The concept behind insulating glass is that a gas pocket is created between sheets of glass, limiting heat conduction, convection, and radiation through the window surface. Radiative heat losses can be reduced from 0.85 to 0.1, or even lower through the application of a low-e coating. A 12mm air cavity has a U-value of 3 W/m^{2}K, while with the addition of a low-e coating that same cavity can reach a U-value of 2 W/m^{2}K [12].

Gas-filled cavities have become standard practice for many residential applications, and are used in limited commercial applications. The gases used to fill the cavity space further reduce heat transfer through the glass. The most popular gas-fill is Argon gas because of its relatively low cost [11]. Also used are krypton and xenon, though they are less readily available and so have a much higher associated cost. The U-value of a 15mm argon-filled double pane window with low-e coating is about 1.1 W/m^2K, while a similar krypton-filled pane yields a U-value around 0.8 W/m^2K [12]. Triple pane windows offer even further reduction in U-values. The lowest U-values can be achieved through evacuated panes, in which a vacuum is created between panes. However, the structural stability of the glass is difficult to achieve with evacuated panes, and the complexity of manufacturing is cost-prohibitive. A vacuum glazing can cost up to 15% more than a standard double-glazing with similar thermal properties [16]. However, evacuated glass can achieve heat transfer rates two to five times less than gas-filled cavities [17]. With all the insulating glass types, it is difficult to obtain a proper, long-lasting seal on the cavity. Manufacturing expenses are high, which drastically limits the use of insulating glass on a large scale such as in a highrise building.

A less common insulating glass category is referred to as transparent insulation materials. The materials can be glass, polycarbonate, quartz foam, or any other type of translucent material that allows for the creation of air spaces between the two external panes of glass. A developing strategy is the use of aerogels, which has microscopic cavity structures that allow for insulation values of R-12 to R-15, and allow visual transmittance of around 90% [18]. Combined with low-e coatings, the aerogel panels could make windows with U-values below 0.6W/m^2K. However, development continues to overcome the barriers to a cost-effective manufacturing process, as well as the production of highly transparent large panels [18]. There are many different configurations for the materials within the cavity of transparent insulating material glazings. However, due to the complex nature of these configurations, transparent insulation materials would likely not be used in highrise buildings to a large extent.

2.3.4 Switchable Glazing

Another emerging technology is chromogenic glass, which responds to the environment to produce advantageous glazing characteristics. The categories of chromogenic materials are photochromics, thermochromics, electrochromics, and liquid crystals [11].

Photochromic materials automatically reduce their transmission capacity in response to an increase of incident UV light. The advantage to photochromic glazing is its durability and capacity to reduce glare. A disadvantage is that it does not discern between times when solar gains may be desirable, such as during the winter. The absorption properties of photochromic materials also create uncomfortable heat gains and radiation. At this time, photochromics are difficult to produce to scale, and are rare in large-scale application, but research in this area is ongoing.

Thermochromic materials change state or properties when heat is applied. There are several approaches to thermochromic glazing. Cloud Gel and TALD, two hydrogel thermochromic products, have recently been developed. Hydrogels can have solar energy transmission values of 0.8 to 0.9 in the low temperature state, while ranging from 0.05 and 0.4 when activated [12]. Care must be taken with hydrogels that freezing does not occur when temperatures reach below freezing. Another approach to thermochromic glazing is to utilize plastics that begin gradually clouding between 25°C and 120°C [12]. Certain metal oxides can also be used between the panes of glass, which can act as a low-e coating as temperature increases [12]. The advantage of thermochromic glazing is that they reduce overall and peak energy loads. They can also reduce glare and improve thermal comfort. The disadvantages are that visible light is limited when the thermochromic glazing is activated, and the life of these glazings is limited. The manufacturing process for thermochromics needs much further development to make them economically feasible [19].

Electrochromic glazing research has received the most attention in recent years. Research to improve marketability and to assess the energy cost savings for electrochromic windows is on-going [20-30]. Electrochromic glazing operates through the transfer of ions to influence the visual and infrared transmission qualities of the material. Figure 7 shows a cross-section of a product being developed by SAGE Electrochromics. Typical of most electrochromic windows, the unit includes an electrochromic layer (EC), an ion conductor layer (IC), and a counter electrode layer (CE) sandwiched between two transparent conductor layers (TC) [20]. When voltage is applied to the transparent conductors, Lithium ions travel through the conductor layer. The electrochromic layer generally contains a tungsten oxide, which reacts with the lithium to form lithium tungstate, a light absorbing material [21]. The amount of change in

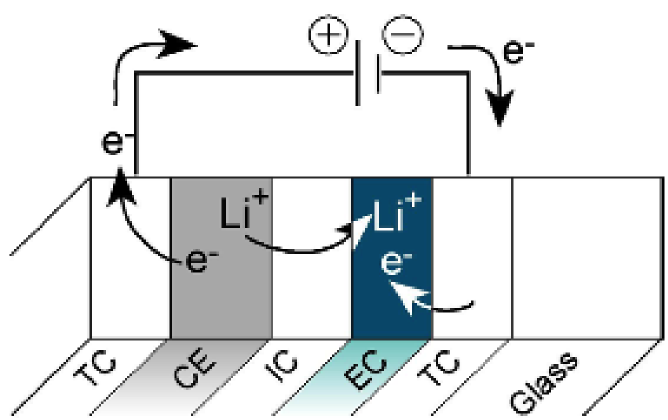

Figure 7: Cross-section of a SAGE Electrochromic window [20]

the absorption is directly dependent on how much voltage is applied. The process is then reversed when voltage is removed, and the window returns to the clear state. Low-emissivity coatings can be used in conjunction with the other layers of the electrochromic glazing to reduce the amount of the absorbed radiation that is emitted into the space. In prototype testing at the Lawrence Berkeley National Laboratory, glazings reached a visible transmittance (VT) range of 0.6-0.05, and solar heat gain coefficients (SHGC) of 0.42-0.09 [22].

Two of the largest advantages to electrochromic windows are that they offer a greater extent of occupant control than other switching technologies, and they maintain window views throughout the shading spectrum. The voltage application can either be occupant controlled, or it can be controlled through a central building automation system, connected to a variety of feedback devices. The initial cost for these systems is substantial, not just for the glazing itself, but for the electrical and monitoring systems as well. Once installed, the operating costs are relatively low. A recent study of electrochromic prototypes by the Lawrence Berkeley Laboratory revealed that the prototypes would switch with an applied voltage of ±3-5 V dc [22]. An ASHRAE study quoted that the electricity needed to power and control 1500ft^2 of electrochromic glazing per day is less than what is needed to power a single 60W light bulb per day [21]. Electrochromic technology also offers significant potential to reduce total and peak energy consumption. The Lawrence Berkeley Laboratory testing predicts potential daylighting energy savings of 44% on average, compared to a case with blinds and no daylighting controls. The total daily cooling loads with lighting heat gains included remained similar to the base case, but the peak loads were reduced by 19-26% with electrochromic windows [22]. The greatest savings were the greatest for façades facing south, east, and west in hot U.S. climates [23].

There are many factors limiting large-scale application of electrochromic glazing. The technology has shown to degrade in performance relatively quickly. Compared to the long-term warranties on many other current glazing technologies, electrochromic glazing does not measure up. The installation costs are still a concern, and companies such as SAGE are continuing product development to make electrochromic glazing a viable option. A 1999 analysis by SAGE estimated that in order for significant market penetration, electrochromic units must be sold at prices below $15/sq.ft, which they have yet to achieve [24]. A cost-benefit study of a highrise residential tower in Hong Kong showed a 6.6% savings on annual energy. However, it showed a benefit/cost ratio of 0.6, which means the investment would not be economically beneficial [25]. The manufacturing process is still quite complicated, which translates to increased cost. It is also still difficult to produce large panel sizes that are dependable, let alone on a scale that would be required for widespread application for highrise buildings. Switching time is a concern with electrochromics; most current technologies require 5-10 minutes to switch from fully colored to bleached states [26]. Current electrochromic technologies also display much more difficulty in switching in low temperatures – on the order of 40-85 minutes [22]. In variable climates, or on partly cloudy days, this switching time can cause problems for system controls, and ultimately will negatively affect occupant comfort. While the colored glass will mitigate some glare, current technology does not adequately intercept enough of the glare, and secondary glare control may be necessary. There are many aspects of electrochromic glazing that require improvement, but because of adaptability of control and potential energy savings, electrochromics are currently receiving the most attention as a potentially feasible switchable glazing technology.

Liquid crystal panels operate similarly to electrochromic layers in that transmission is changed via the application of an electrical charge. Liquid crystals without applied voltage are scattered randomly throughout the cavity. When voltage is applied, the crystals align themselves to permit the transmission of light [12]. There are two main approaches to liquid crystal technology: suspended particle technology and micro-encapsulation. Suspended particle technology is a thin cavity of liquid crystals between two sheets of glass coated with a conduction material. Micro-encapsulation is the same concept, except the liquid crystals are contained in tiny cavities [11]. The advantage to liquid crystal technology is that the switching time is much faster than other switching glazings – 1 to 3 seconds [21]. A disadvantage to liquid crystals is that they are non-transparent when no voltage is applied. This technology is also not stable in larger panels, against ultraviolet radiation, or in extreme temperatures [12]. Currently liquid crystal technology is more commonly used indoors and in automobile applications.

2.3.5 Directional Control

There are many options for external shading in order to control the direction of incident solar radiation. However, a technique that is integrated into the glazing itself is a holographic device. The holographic effect is achieved by 3-D laser etchings on a photographic film, which is laminated between two glass panes [12]. The etchings can have different configurations to achieve a variety of light dispersion and selection. For example, equally spaced parallel lines will redirect the incident sunlight onto the ceiling, while concentric elliptical lines will separate the light into individual spectral colors and concentrates them on different focal points. The elliptical lines make it possible to regulate the transmission of certain wavelengths (stopping infrared may be extremely useful) [12]. Holographic glass is often mounted to tracking louvers because the transmission of the glass is dependent on the angle of incidence. Usually the louvers are programmed to track the zenith angle of the sun [31]. Holographic glazing has been used on a limited scale in only a few cases. The technology is extremely complicated to not only produce the glass, but also to incorporate a low-maintenance, dependable louver system where necessary.

2.4 Shading

Shading devices are available in a wide range of forms – overhangs, side fins, light shelves, blinds, louvers, and screens. Shading devices can be fixed or moveable, translucent or opaque; they can be internal, external, or even between panes of glass.

The advantage to external shading is that it blocks or redirects the incident solar radiation before it enters the building. Internal shades alleviate some glare problems, but once the infrared radiation has passed through the glazing, the majority of it is dissipated into the space, so they can cause problems with heat gain. External shading devices are utilized less for highrise buildings because of the added construction costs, increased maintenance, and aesthetic effects. Because there are generally large amounts of glazing on contemporary highrise buildings, external shading devices could have a large energy savings impact, but they could also drastically alter the view characteristics of the façade. External shade design is a complex process and is heavily influenced by shade design, façade orientation, and glazing type [32]. Architects often prefer to maintain continuity in façade design, but they are now exploring new and creative ways to address the different energy needs of each façade orientation. Some architects have even designed the entire building footprint such that portions of the building provide self-shading [33].

Internal shading devices are common because they are an inexpensive solution for glare control and they are generally manually operable, which increases occupant control. Occupant control can have its drawbacks as well, as blinds or shades may remain drawn when they are not needed, reducing potential daylighting or heating benefits. There are systems available for automated blinds, which reduce the amount of user control, but are much more easily optimized for energy saving practices.

Tzempelikos, A. performed a study in 2007 to determine the energy saving potential of an external roller shade device and lighting control for a south-facing façade in Montreal, Quebec, Canada [34]. The study optimized the window-to-wall ratios for the south façade at 30%. The transmittance of the shade was also optimized as 20%. Results would vary for other façade orientations and window-to-wall ratios. The study analyzed the energy effects of active versus passive lighting controls for the building, and compared passive control versus active control of shades. Passive control was modeled as the worst-case scenario of shades closed during 100% of working hours. Active automatic controls optimized the

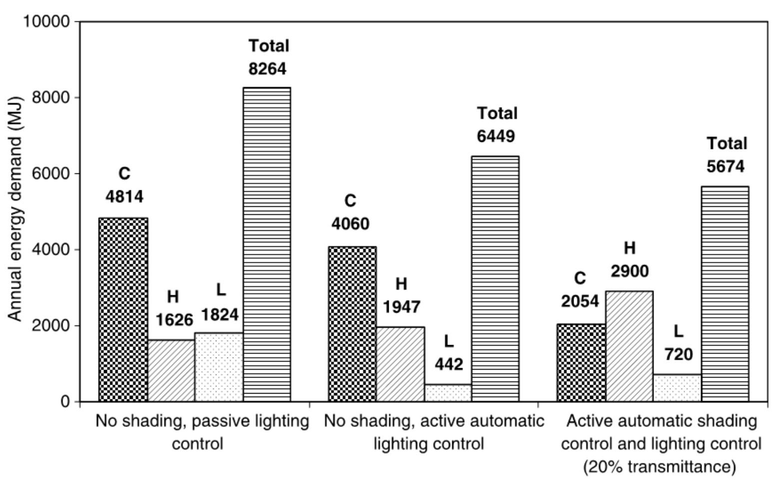

Figure 8: Comparison of energy consumption for shading and lighting control [34]

daylight potential, and remained open unless the incident solar radiation posed a glare risk. Figure 8 shows the potential savings from automatic shading and lighting control. The use of shading control in particular results in a 50% reduction of the cooling load compared to no shading control, and a 12% reduction in total annual energy consumption.

Actual savings would depend on what kind of HVAC systems were utilized in conjunction with the shading device. Alternative glazings were not assessed in this case, which would impact the results. Shading devices are sensitive to orientation, surface area ratio, and climate, so results could be more or less pronounced based on change in any of these variables. A 1998 study by Lee, E. at the Lawrence Berkeley National Laboratory performed a similar analysis for a building in California [35]. This study drew similar conclusions regarding a dynamic automated venetian blind system. They were able to produce 1-22% lighting energy savings, 13-28% cooling load reductions, and 13-28% peak cooling load reductions annually compared to a static blind with the same daylight controls [35]. These studies clearly show that shading devices and their controls combined with lighting controls can potentially have a large impact on the energy consumption of a building.

2.5 Double-Skin Façades

There has been a dramatic increase in research pertaining to double-skin façades in the last decade. A double skin façade (DSF) can take a variety of forms, but the most basic DSFs are made up of two adjacent glazing units with solar control devices in between [36]. The double-skin façade is basically an exaggerated version of double pane glass combined with the building's ventilation and shading systems. The original goal of DSFs was to

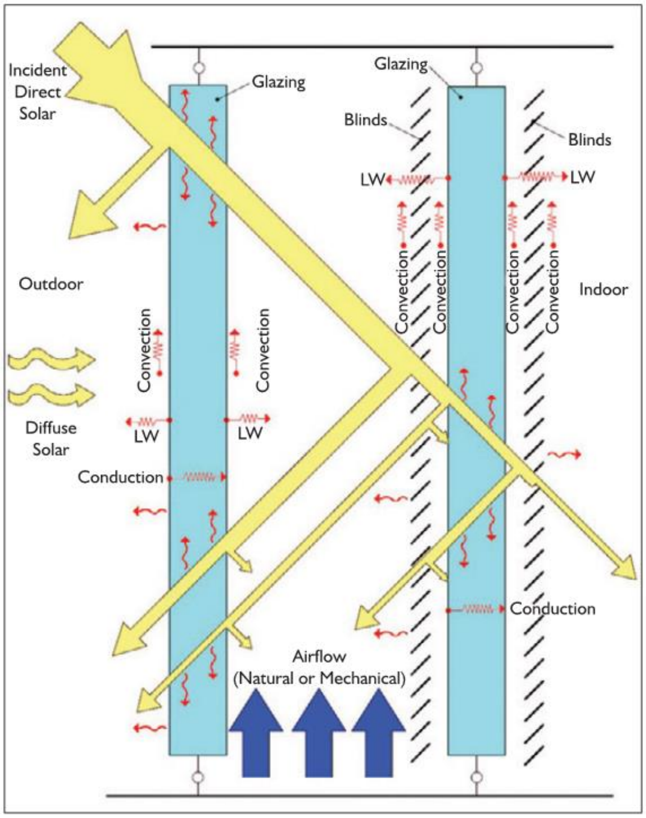

Figure 9: Thermodynamics of a DSF [34]

provide an effective sound barrier, and the technology has been developed to include daylighting and HVAC benefits. The recent growth in attention for DSFs is because of the potential natural ventilation capabilities, and occupant comfort advantages associated with this type of façade. However, most European architects and engineers continue to advise clients that the main benefit is not necessarily energy efficiency, depending on the circumstances [37]. The physics associated with the DSF makes modeling and prediction of this technology extremely difficult (Figure 9). Another difficulty is that DSFs vary widely from one design to the next. DSFs can span multiple floors, or be contained to one floor. The cavities can range from 15-150cm deep, and a variety of glazings and solar shading devices can make up the DSF system [38]. Façades can be naturally ventilated, if design properly and climate The success of DSFs depend on careful control of the integrity of the envelope, which translates to less occupant control and a more extensive sensor and controls system.

Although double-skin façades have already been implemented in several locations, the benefits and performance characteristics of ventilating façades are still widely debated. Double-skin façades have been implemented more often in Europe because of higher expectations on behalf of occupants in terms of view and daylight [36]. DSFs potentially allow for greater perimeter-to-floor ratios with less negative impacts on occupant comfort. DSFs have been used most often in new building construction, but there are increasing cases of retrofit applications [39,40]. Existing double-skin façades have been the focus of performance measurement and modeling verification in order to better understand exactly how the heat transfer occurs. A study by Corgnati, S. for the application of double-skin façades in Torino, Italy monitored an existing DSF for two years. The conclusion was that while the DSF displayed energy performance on par with other glazed façades, but was not competitive with traditional windowed opaque façades [41]. Hamza, N. performed a simulation analysis of DSFs in hot, arid climate. The study showed that a reflective DSF had lower cooling loads than a reflective single-skin façade [42]. Altan, H. et al. performed a similar analysis in Sheffield, England, and recommends DSF designs on the basis of their use of passive solar energy and positive work environment [43]. In 2009, ASHRAE released a study of the Pearl River Tower in Guangzhou, China. The article outlines the impacts of certain design decisions for DSFs. The case study shows that the room conditioning load and cavity ventilation load is lower than the cooling load for a single façade. However, if the cavity air were returned to the HVAC system and recirculated, the load would be higher than that of the single façade [36]. Cetiner, I. compares the energy performance and economic tradeoffs between efficient single-skin façades and efficient double-skin façades in moderate climates, such as Istanbul. The study

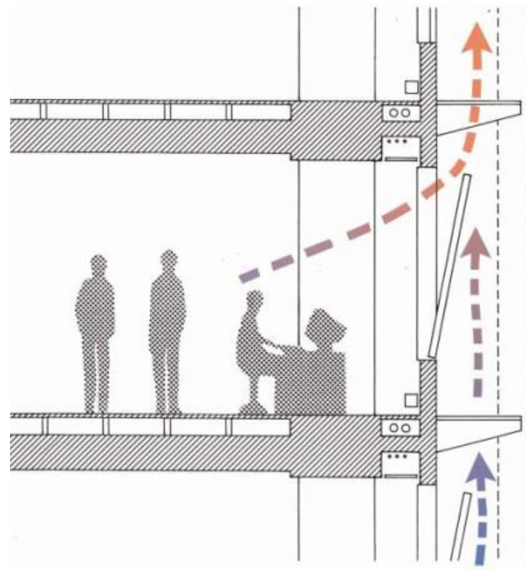
Figure 10: Cross-section of one DSF strategy [5]

concludes that the most efficient DSF design is 22.84% more efficient than the most energy efficient single-skin configuration. However, it also showed that the most cost effective single-skin configuration is 24.68% more cost effective over its lifetime than the most cost effective double-skin configuration [44].

The Cetiner study brings up an important drawback to the ventilating façades, which is the significant initial investment required to produce a highly energy efficient double-skin façade envelope. Other disadvantages to double-skin façades are potential excessive thermal gains and visual discomfort as a result of poor design [36]. Because of the wide variety of design options and the complicated nature of predictive modeling, it is difficult to produce a reliable, energy efficient DSF design. Another drawback is that dust, noise, condensation, odors, and even smoke from potential fires can be problems within the DSF cavity. If the cavity is naturally ventilated, there is increased risk of these potential problems, which leads to the increase in maintenance costs [36].

There are many potential advantages to the double-skin façade, as well as many potential drawbacks. The most important lesson learned from the various studies of DSF performance is that the façades must be tailored for each individual project and climate in order to reach maximum efficiency.

2.6 Thermal Concerns

2.6.1 Thermal Bridging

In highly glazed façades much of the focus is concentrated on the glazing portion in order to reduce the negative thermal impacts. However, even in façades with the highest window-to-wall ratio, there exists the potential for thermal bridging through the opaque section of the façade. Window frames and curtain wall fastenings can be sources of heat loss through thermal bridging. Research is ongoing to determine the extent of the impacts of various glazing fastening strategies on thermal loss [45-47]. Song, S.Y. et al. performed a study in 2007 on the performance of several insulation strategies for aluminum curtain wall fasteners in highrise buildings in Korea [45]. Compared to the existing fastener strategy, they found 8.14% reduction in heat loss by coating the upper part of the fastener with urethane foam and the lower part with insulation paint. A Gustavsen, A. study on various high performance frame systems examined two current curtain wall systems that yielded overall U-values of 0.73 and 0.65 W/m^{2}K [46]. These U-values are still two to three times better than typical U-values of insulating glass, but slightly higher than U-values that can be achieved through opaque, insulated façades (0.2-0.3 W/m^{2}K) [46]. While thermal bridging effects should be considered with highly glazed façades, the thermal bridging of the glazing section are much more significant than through the other façade materials.

2.6.2 Occupant Comfort

A major thermal concern with curtain walls is the implications of large amounts of glazing on occupant comfort. As previously discussed, the increased view and daylighting from highly glazed façades are generally positive in terms of occupant satisfaction. However, the heat gains, glare potential, and draft concerns associated with curtain wall design generally negatively impact occupant satisfaction. Occupant comfort is one of the most difficult standards to quantify, and it is equally difficult to attempt to predict. Occupants will subconsciously be affected by dozens of external factors at once, and preferences for what is "comfortable" can vary significantly from one person to the next.

The most common quantification for thermal comfort is PMV (percent mean vote) and PPD (predicted percentage of dissatisfaction) [10]. Glass surface temperature and incident solar radiation are two of the most common sources of problems of occupant comfort in glazed façades. Several recent studies have examined the occupant comfort associated with glazing, as well as strategies for improving occupant satisfaction.

Singh, M.G. et al. examined 15 different glazing types in order to quantify the impacts of different tinted, insulated, and reflective glazings on occupant comfort [10]. This study mostly examined the thermal effects of incident solar radiation and resulting temperature changes in the space. They tested the glazings in a variety of Indian climates throughout the year. Five different tinted single pane windows were tested, as well as 10 double-pane windows with a variety of configurations (tinted, absorbing, low-e) and U-values. PPD was calculated based on the ISO standard equation 7730, with variables such as mean radiant temperature, air temperature, transmittance, incident radiation, convection coefficients, metabolic rates, and human mechanical efficiency. Figure 11 and Figure 12

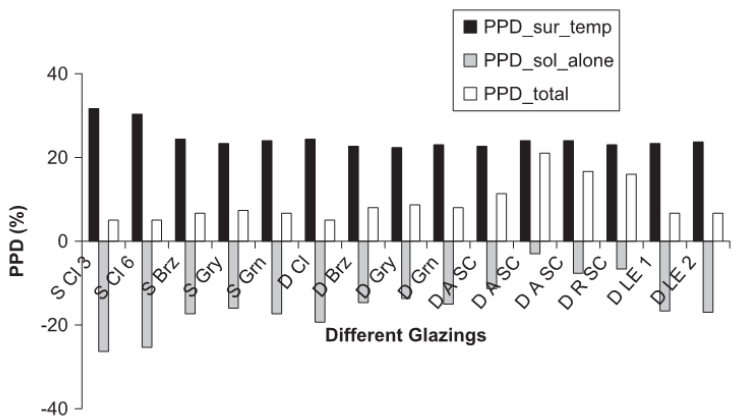

Figure 11: PPD for cold and cloudy climate of Shillong [10]

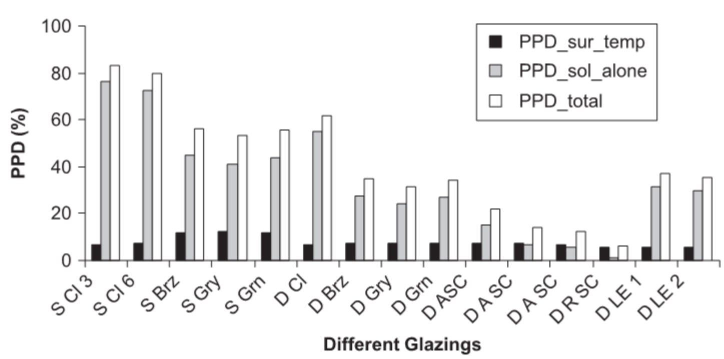

Figure 12: PPD for hot and dry climate of Jodhpur [10]

show the results of two types of climates for the range of glazing types. As is evident, the effectiveness of the glazing is dependent on climate, further enforcing the necessity of climate-specific design choices. For the hot and dry climate, the double pane windows with absorbing film produced the best results, while the single glazing showed up to 80% dissatisfaction. For the cloudy, cold climate, the single panel glazing and low-emissivity double-panel glazings produced the most satisfaction, while the absorptive double glazing produced the most dissatisfaction. The solar PPD for the cold climate was shown as negative because the warming effect from the incident solar radiation is actually a positive attribute. As can be seen from the variety of results of this study, the choice in glazing can dramatically impact the satisfaction of the occupants.

In a 2011 study, Hwang, R.C. and Shu, S.Y. assessed the impact of building envelope regulation on thermal comfort and the energy-saving potential of PMV-based comfort control in glass-façade buildings [48]. The analysis was performed for the climate region of Taiwan. Simulations were performed with a variety of glazing types, overhangs, and glazing areas. For glazing type, it was shown that discomfort increases with higher transmittance because of incident solar radiation to the space. Discomfort also increases as a result of absorption because of the increased surface temperature of the glass. The total radiation varied with the SHGC in a quadratic relationship. It was also shown that discomfort increases with increased window size due to the radiant heat of the surface and the increased solar radiation – the solar radiation accounting for a larger fraction of the total radiation as the window area increases. They concluded that it is possible to achieve energy conservation and satisfactory levels of thermal comfort through careful façade design. It was also concluded that the energy savings through PMV-based control in areas with high cooling loads were limited, but increased in potential as cooling load decreased.

The other common source of occupant discomfort with highly glazed façades is the induced draft from surface temperature of the glass. The occupant discomfort caused by radiation from surface temperature in cooling conditions was discussed previously. However, in heating climates it is often necessary to utilize radiators and convectors below or near the windows to mitigate the effects of cold drafts from the cold glass surface temperatures. Ge, H. et al. studied the effects of the cold drafts created by two types of glazing on occupant comfort [49]. Heiselberg, P. has also performed research in this area [50, 51]. The cold draught is caused because of a temperature differential between the cold glass surface and the warmer room air. A conventional double glazing unit was compared to a high-performance glazing unit. The results showed that occupants closer than 2m from the wall experienced discomfort from drafts [49]. Heiselberg suggests that structural components be used to work as obstacles to break down the convective boundary layer and reduce the draft. Ge suggests the use of an overhead diffuser to break up the boundary layer. The HVAC load impacts of this approach have yet to be determined. He also suggests the use of a better-insulated glass panel. Besides the conduction benefits of a well-insulated window, a study by Larsson, validates the conclusion that improved insulation will increase the surface temperature of the glass, reducing the convective losses [52]. He also suggests that improved thermal performance of the window reduces, or even eliminates the necessity for HVAC systems below the windows. Reduction of the HVAC system not only potentially reduces the load, but also increases the amount of useable floor space.

The influence of shading devices on thermal comfort was discussed previously (2.4 Shading). Solar shading devices act to mitigate glare concerns, but also prevent incident solar radiation from being absorbed by the glazing and/or being transmitted into the room causing uncomfortable solar gains [9,34,53]. Shading devices must be optimized for a given climate, much like most façade characteristics. Other simple strategies such as assigning occupied zones away from the glazed surface can act to improve overall occupant comfort, but this strategy often limits the flexibility of the floor plan, and is simply not possible in other situations.

Optimization of the various façade improvement interventions will result in a more energy efficient building and increased occupant comfort. The bottom line for most building owners is not only to obtain tenants, but also to retain them. Occupant comfort is a large part of that equation.

2.7 Ventilation and HVAC

2.7.1 HVAC loads and Energy Consumption

The quantification of the advantages of these advanced façade technologies is almost always in terms of heating and cooling load impacts. There is concern on behalf of the owners for initial cost, but generally in buildings the operating costs vastly outweigh the initial costs over the building's lifetime. According to a technical journal from the Council on Tall Buildings and Urban Habitat, for a building with a 50-year lifespan, the initial costs account for 12%, maintenance counts for 4%, and operation costs account for 85% of the lifetime costs of the building [54]. The exact amount of the HVAC costs depend on climate and building design, but it does account for a vast majority of the energy consumption by the building [33].

Annual energy savings are crucial for reducing operational costs, but reduction in the peak load conditions can provide dramatic cost savings as well. The HVAC system must be sized for the most extreme heating and cooling requirements. A reduction in the peak energy requirements for the same building will result in initial and annual cost savings on a smaller central heating and cooling plant, as well as smaller ducts, pipes, and other system equipment. For this reason, proper building energy modeling and equipment sizing is crucial to the energy efficiency of the building. There continues to be new research and development in energy efficient HVAC system equipment.

A variety of systems have been used throughout recent history for heating and cooling of highrise buildings. Variable-Air-Volume (VAV) systems are one of the most common systems in highrise buildings. Some buildings will utilize low-temperature VAV systems, in which the supply air is much colder than usual (32-48 degrees Fahrenheit) to allow for lower supply air volumes. Duct sizes can be reduced, however, special measure must be taken to insulate vents and prevent condensation. Because there are many times in highrise buildings where the exterior zones require heating while the interior zones require cooling, many times the VAV systems are supplemented by hot-water or electric baseboards, or by a reheat system [55]. Another VAV strategy is to implement VAV units in the interior zones and supply the heating and cooling needs of the exterior zones with fan-coil units. This allows for reduction of the mechanical systems supporting the VAV system, but does require additional mechanical pumps and heat exchangers for the fan coil units.

However, it is another solution for the issue of highrise buildings requiring heating and cooling simultaneously.

Displacement ventilation has grown in popularity as well, from its energy-saving potential. Usually the air is introduced into the space at the floor level, thereby encouraging stratification. The concept behind displacement ventilation is similar to that of the UFAD systems. The system is configured to condition the occupied space. In most buildings, air is delivered from above. This generally conditions the air from floor to ceiling throughout the building. Because of stratification with the displacement ventilation, the space is only conditioned to about 1.8m above the floor height, which is much a little over half the typical floor-to-ceiling height [37]. The overall volume of conditioned space is reduced, theoretically limiting the HVAC requirements to each space. This system also removes contaminants to the upper region of the room, away from occupants rather than diffused throughout the space. A popular method of displacement ventilation, called under-floor air distribution (UFAD), is under much scrutiny for proof of the benefits assumed to accompany the system. There are benefits to stratification of the room air with UFAD systems, but also potential health and thermal conduction concerns due to the concentration of hot air and contaminants at the ceiling. It is difficult for UFAD systems to control the conditioning of perimeter zones separately from interior zones. There are also maintenance concerns with the cleanliness and limited access to the under floor systems. UFAD systems are climate dependent, and it are still a relatively new technology, so they are not currently widely implemented. They can be more cost intensive to install, but they also require less ductwork, which can limit the expense of the system [55].

Some tall buildings with glazed façades utilize a central atrium with the stack effect to provide some natural ventilation for the space (See Natural Ventilation). Stack effect occurs when outdoor temperatures are lower than the inside temperatures. Cool air flows in the lower floors and rises through the building as it is warmed. In highrise buildings this effect can be more pronounced because of the height of the buildings. Stack effect can be utilized to ventilate, but in highrise buildings it can also cause pressure issues and can make it difficult to keep the building uniformly heated or cooled [55]. Mixed-mode operational systems switch to a mechanically ventilated system during the winter to mitigate heat losses [37]. A mixed-mode trombe wall system could be utilized to provide insulation and heat through a double-skin façade arrangement.

These and other energy-saving HVAC systems have been gaining in popularity in recent years, but further research is necessary to gain a more accurate cost-benefit analysis for implementation in highrise buildings.

2.7.2 Natural Ventilation

The first generation of highrise buildings had much more thermally massive façades, which were naturally ventilated generally through operable windows. As façade design changed, mechanical ventilation became more and more heavily relied on. Because of the fuel consumption and high energy cost associated with mechanical systems, there has been an increasing amount of attention for passive approaches to building HVAC. Natural ventilation has been revived as a potential energy-saving HVAC intervention.

Natural ventilation in highrise buildings harnesses the potential of buoyancy and the stack effect to remove heat from the building envelope [56]. The configuration of each natural ventilation system is unique to the building layout, orientation, thermal mass, and façade design. Climate also plays a large role in the design and success of natural ventilation systems. Because natural ventilation is tied intrinsically to the building design, it is most often carried out in new construction. Yeang, K. provides guidelines for implementation of natural ventilation systems in his book, *The Green Skyscraper: The Basis for Designing Sustainable Intensive Buildings* [40]. He suggests that the building orientation, surface to volume ratio, and footprint must all be tailored for maximum natural ventilation from the beginning of the design process to ensure the greatest success.

Natural ventilation can be integrated into the daytime HVAC strategy, or it can be used separately in a "night-flush" strategy. Daytime natural ventilation under the right climate conditions improves the occupant comfort and satisfies the code ventilation requirements for fresh air. Nighttime ventilation takes advantage of the cooler night temperatures to remove heat loads that have been absorbed by the thermal mass in the space. With this strategy, the thermal mass is then "activated" at night and cooling is released throughout the day. Nighttime ventilation under the right circumstances will reduce the peak and total cooling load, and in certain climates and building designs it can eliminate the need for mechanical air-conditioning [56].

There are several potential configurations for natural ventilation, and the basic concepts can be adapted to individual designs. Natural ventilation can be used in different configurations in isolated floors with cross flow ventilation or in individual rooms with single-sided ventilation (Figure 13). The disadvantage to the isolated approach is that it is usually only effective when the width-to-height ratio is less than 5 for each space [57]. This could limit the complete reliance on natural ventilation for spaces that do not comply. However, individual spaces are typically simpler to model and predict performance. The double-skin façade works well with the concept of natural ventilation because the second façade provides protection from some of the noise, wind, pollutant and thermal concerns associated with single skin façades and natural ventilation. It allows for a more controlled form of natural ventilation. Double-skin façade systems can be isolated to single stories, or they can span multiple stories. Both approaches are adaptable for natural ventilation. The GSW Headquarters in Berlin is an example of the double-skin façade and natural ventilation. This design uses a west-facing DSF as a thermal flue. As the air is heated and rises due to buoyancy, it draws fresh air from the cooler, east façade. The GSW building is naturally ventilated for around 70% of the year [5]. The Commerzbank building in Frankfurt takes a different approach by utilizing an atrium for the thermal flue (Figure 14). The Commerzbank building relies on natural ventilation more than 80% of the year. The disadvantage to this approach is that high pressure differences can be created by the buoyancy effect [25]. To mitigate this effect, the spaces can be divided into separate segments that are individually tied to the outdoors.

Full natural ventilation represents the greatest potential for HVAC operation and equipment savings. However, even the most careful designs may not be able to rely on

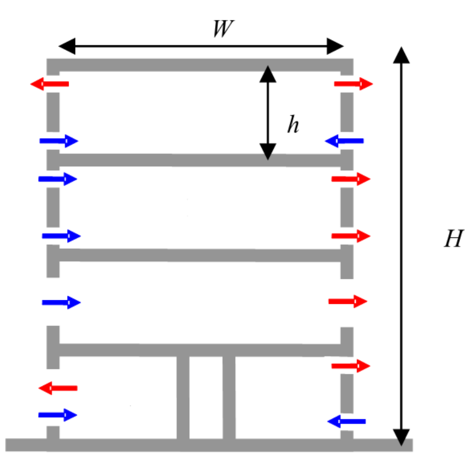

Figure 13: Natural ventilation in isolated spaces [55]

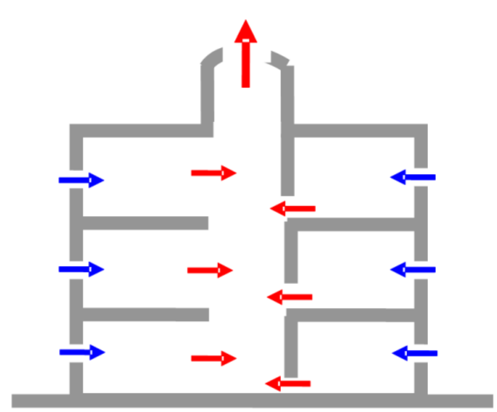

Figure 14: Natural ventilation through an atrium [55]

natural ventilation year round. Mixed-mode ventilation allows for some of the energy saving advantages of natural ventilation, but addresses both heating and cooling loads. Most buildings using natural ventilation would need to utilize a supplemental HVAC system to meet year-round loads. It is hoped that a successful natural ventilation design will allow the HVAC system to be downsized as a result of lower peak loads. Yeang, K. compares energy consumption of a typical air-conditioned office to good practice, open-plan natural ventilation. With a base-case load of 390 kWh/m^2, he expects that natural ventilation could produce the same results with only 136 kWh/m^2, or 65% energy savings per unit area [37]. Similar to the other building components, design of a natural ventilation system requires careful planning and optimization for the particular climate and building use in conjunction with the other building components in order to produce a successful design.

2.8 Integrated Design Process

A common theme with façade design is that everything is climate dependent, and design choices for one component often affects the design of another, seemingly unrelated component. In an effort to produce the most energy efficient building design, integrated design is essential. Façade design is integral to the tangled web of systems within the building design (Figure 15). The performance of the façade and supporting systems are closely tied to the building orientation, floor layout, and location. These are variables that are generally decided very early on in the design process. In order to have the greatest opportunity for energy savings, façade design must be considered in conjunction with the other variables at the beginning design stages. For example, a footprint that is optimized for solar potential will influence the choice of glazing; the glazing that is optimized for both its thermal characteristics will reduce the size and nature of the HVAC needs; the glazing that is further optimized for daylight potential will reduce the electrical lighting load, which will decrease the sensible heat gains, which will further reduce the size of the HVAC system. If the footprint was not addressed early on, the energy consumption savings from the glazing could potentially be drastically reduced, which would in turn affect all the other potential benefits.

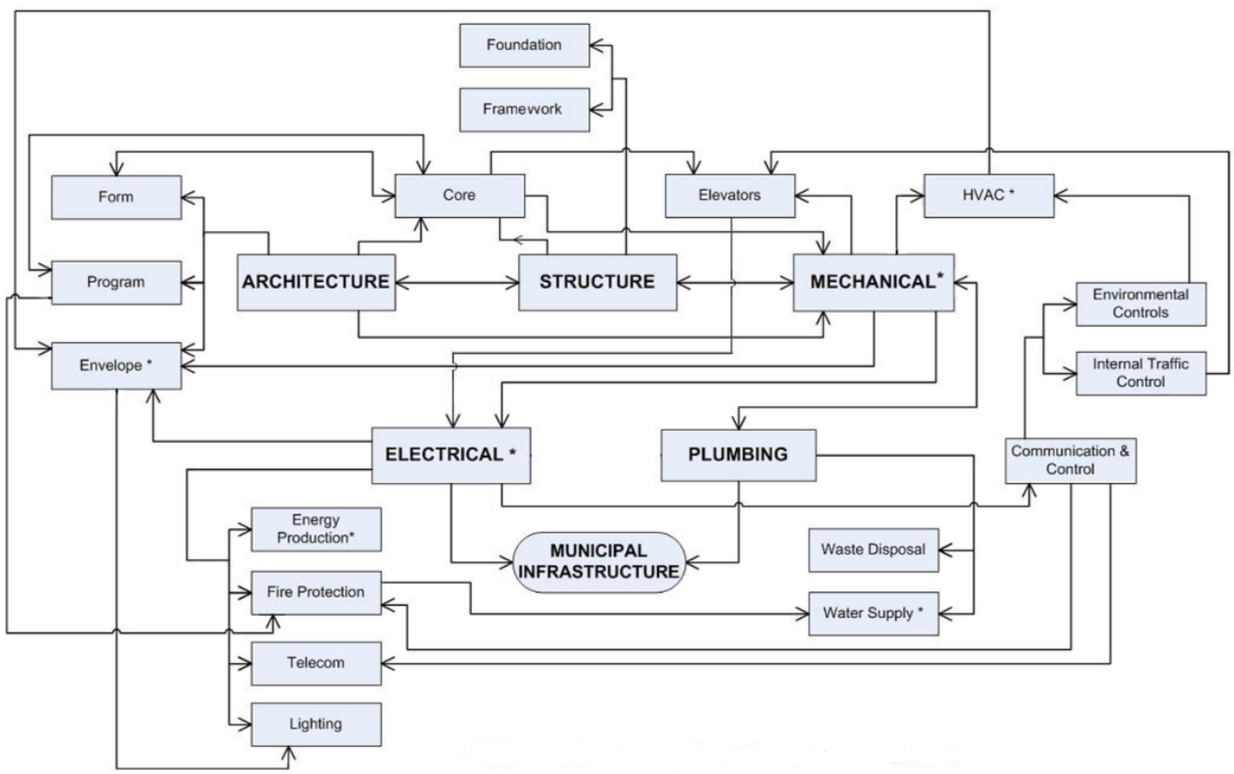

Figure 15: Tall Building System Integration Web [58]

Tzempelikos, A. et al. performed a simulation and optimization of façade design, lighting design and control, and HVAC components for a Montreal institutional building [59]. Because they performed this service in the beginning design phase, they were able to influence factors such as window-to-wall ratio, shading components, and daylight potential rather than simply being able to select the most energy efficient glazing. Because of the compounding nature of effective façade, daylighting, and HVAC design, they were able to reduce the baseline peak cooling load by up to 36%, and eliminate the need for perimeter heating altogether [59].

Effective integrated design first requires a paradigm shift. Most architects and engineers have already acknowledged the benefits of integrated design. It is not always possible because of client constraints, but integrated design from the start makes it easier for the engineer to produce the best results possible. The other major component involved in system design in the conceptual stage is the necessity of simulation and modeling capabilities. Case studies can provide a baseline for many initial design decisions. If there were a more extensive, centralized organization of case studies and simulation research, then case studies could probably be used more extensively farther into the design process. However, because performance characteristics are unique to each design situation, case studies do not produce the hard numbers often required to convince the building owner to pursue an initially costly, yet energy efficient design.

There have been many recent published journals and research papers that assess different façade technologies in a variety of climates, and most of them utilize at least one type of simulation software. There is a large amount of new research coming out of Hong Kong and China because the recent surge in highrise construction in Asia, and the need for energy efficient new construction and retrofits [25, 60-70]. Bojik, M. and Yik, F. from the Hong Kong Polytechnic University have done extensive research and simulation of glazing technologies in the hot, humid climates of Hong Kong and other areas [25, 60, 65, 67]. Lam, J. and Wan, K. have also contributed to the research through the City University of Hong Kong in the simulation and design recommendations for building envelopes in a variety of

Asian climates [61, 62, 65]. Tzempelikos, A. has contributed numerous publications about the relationship between glazing and thermal systems through simulation [34, 53, 59, 71]. Lee, E. out of the Lawrence Berkeley National Laboratory has published many simulation-based reviews of various types of high performance building façades [23, 35, 56, 37, 72]. The Lawrence Berkeley National Laboratory and its associates have published numerous building case studies, technology reviews, market assessments, and a variety of simulation-based research. A variety of façade technologies have been assessed in a variety of climates: the hot and humid of Hong Kong, the temperate climate of California, and the heating dominated climate of Russia [73]. These studies can be utilized as case studies to guide design decisions for similar climates, but design decisions will change based on building orientation, façade materials, and specific building purposes. Building energy simulation is one of the most common ways engineers, architects, and researchers quantify results and justify conclusions.

One of the largest barriers to effective energy-efficient design is that simulation is often time consuming and complicated. Some of the most widely used simulation software for façade simulations is EnergyPlus, BLAST, DOE-2, and HTB2. EnergyPlus is more prominent in the recent simulation-based research. These programs, while powerful, are still quite complicated. This adds time and, consequently, cost to the already complex and extensive design process. Efforts have been made to more seamlessly integrate building energy simulation into the design process, and improve optimization. A 2004 study assessed the advantages of an integrative building simulation program – one that modeled lighting, energy, ventilation, and fire and smoke risks [74]. The extensive modeling would be time consuming, but it would provide comprehensive building monitoring, and improved optimization of systems. Zheng, G. et al. suggest a “grey relational method,” which is a vector analysis method to aid the decision-making process for incomplete or uncertain systems [69]. It is also helpful in situations where alternatives are difficult to quantitatively compare. The study concludes that the improved grey relational projection theory for façade design, but it is currently not commonly used. Tzempelikos, A. presents a methodology for a systematic approach to the selection of glazed facades in conjunction with consideration for the heating and cooling implications [71]. It is intended to be an integrated approach, ideally implemented at the beginning design phase. Design and consulting companies are constantly searching for new ways to improve their processes. However, the research previously referenced shows the invaluable nature of energy simulation in guiding the choice of façade alternatives.

2.9 Code Compliance

Three international organizations have developed the most commonly accepted building codes [75]. The most commonly used code in the United States is the ASHRAE/IES 90.1 is a code for the energy efficient design of new buildings, except for low-rise residential buildings. The code stipulates the heating, ventilation and air conditioning requirements, occupant comfort standards, and energy consumption standards. Standard 90.1 stipulates a maximum window-to-wall ratio for commercial buildings based on the climate, internal loads, and window transmittance. The International Energy Conservation Code is another set of commonly used standards focusing on energy efficiency. The IECC specifies window-to-wall ratio based on climate, R-value, and heating degree-days. It also specifies the SHGC for window systems including framing for different kinds of glazings.

The third set of codes is from the Chartered Institute of Building Services Engineers, or CIBSE. The window-to-wall ratios are determined based on building type. It also sets standards building energy efficiency, lighting, HVAC, fires safety, and sustainability.

The infiltration of a building can have a large impact on the safety and energy consumption of a building. For this reason, building codes have established standards for air tightness for buildings. ASHRAE 90.1-2007, which is cited by many current building codes in the United States requires air leakage for fenestration to be less than 0.4 cfm/ft^2. The IECC 2006 Code specifies requirements for curtain walls in particular. The IECC requires air leakage of less than 0.3 cfm/ft^2 of glazing area. Both documents comment on the necessity of sealing all joints with caulking or other sealants. These standards are helpful for energy efficient design of buildings, but a recent ASHRAE Journal article by Colin Genge comments on the difficulty of actually testing and proving these air tightness values in a highrise building [55]. Typically the standards of the IECC and ASHRAE are based on a standard ASTM (American Society for Testing and Materials) test procedure requiring certain test pressure. For highrise buildings it is difficult to maintain a uniform building pressure throughout the entire building because of stack effects and wind effects that change as heigh increases. In the article, Genge suggests that the testing procedure must be tailored to the needs of a highrise building. This shows that, while there may be air tightness standards in place, highrise buildings likely need more attention in the form of specific tightness requirements and testing procedures.

With regards to other building design criteria specifically relative to highrise buildings, ASHRAE has published a chapter called “Tall Buildings” in the *ASHRAE Handbook – HVAC Applications.* This document outlines a variety of design concerns that are specific to highrise buildings such as stack effect and fire protection. It has rules of thumb for design practices and general guidelines.

The International Building Code has included a portion specifically relating to the regulations placed on "tall buildings." These codes focus mostly on fire and safety requirements of highrise building designs. Much of the code is dedicated to fire resistance measures, evacuation strategies, and fire containment. September 11, 2001 caused these and similar codes to be re-evaluated because of the catastrophic collapse of the World Trade Center. Safety for highrise buildings is a complicated issue, and one that is highly regulated by codes. There are not as many code requirements for HVAC systems and façade types specifically for highrise buildings.

Governments around the world are beginning realize the importance of energy efficiency in the building realm. Because many governments already have a system of requirements in place for building codes, it provides a platform for introducing new programs to encourage energy efficient options. The European Commission has begun to require building energy labels and regular inspection of air conditioning plants to encourage energy efficiency and proper equipment maintenance [76]. The UK has implemented these strategies as part of a plan to reduce the annual carbon footprint. The United States Green Building Council has implemented the Leadership in Energy and Environmental Design (LEED) certification program, which has become a popular incentive program for implementing energy efficient building technologies. The LEED system is a rating system that allows buildings to receive certification on a scale of energy efficiency. The LEED system is not a code standard, but it does help direct the design process toward more energy efficient measures. It has become almost a status symbol for buildings, increasing its appeal to tenants or clients. It has been shown that energy efficient buildings are occupied faster, and can be cost effective if designed properly. It is the intent of the LEED certification system to incentivize design choices towards energy efficiency.

2.10 Case Studies

2.10.1 Energy Efficient Highrise Retrofit: The Empire State Building

The Empire State Building is one of the most recognizable skyscrapers in the United States, and possibly the world. It was recently the subject of a large retrofit design process to improve the energy efficiency of the façade. The building owner was committed to a profitable design, but he was also committed to energy efficiency from the beginning of the retrofit process [77]. The Empire State Building opened in 1931, at 1472 feet tall. It maintained the record for the world's tallest building for over forty years [5]. This office building retrofit was not just intended to improve the energy efficiency of the Empire State Building. The owner was committed to making the retrofit a model for future retrofits of similar, inefficient buildings [77]. Rocky Mountain Institute, Jones Lang LaSalle, Johnson Controls, and the Clinton Climate Initiative were the major organizations that were involved or consulted in the retrofit.

The Empire State Building (ESB) retrofit design team took an integrated approach throughout the process, in what they called a "deep" retrofit [78]. The first step was to assess the existing systems and energy usage of the building using eQUEST. They then generated over 70 potential interventions that could meet the goal of 68% of the existing energy usage. 17 implementable strategies were identified, which were modeled and used for an analysis of net present value for each intervention. The process was extremely collaborative from the building owners, to the research organizations, to the building maintenance staff. Careful planning and strategic assessment of alternatives led to a final design recommendation that was both energy efficient and cost effective.

The planning team attempted to balance the reduction in energy use with financial returns. Eight measures were eventually selected [78]. First the façade was updated. The ESB façade was made up of insulated glass. All 6,500 windows were planned to be removed and updated with a suspended coated film and gas filled. Radiative barriers were installed behind existing perimeter radiator units. The existing window-to-wall ratio is very difficult to alter, especially in more massive exteriors like the ESB. The extent to which daylighting can be effected in retrofits is generally limited. However, control systems for the lighting systems were designed to take maximum advantage of available daylighting, complete with occupancy sensors and task lighting. A new energy efficient demand control ventilation system with VAV units was designed. The existing control system was upgraded to digital and would offer greater control of the new and existing systems. Also a new tenant energy management strategy was planned, which would provide more in depth feedback for tenant energy use, hopefully reinforcing the daily practice of energy efficiency. One of the most significant sources of savings was in the installation of a smaller chiller plant. Because of the integrated design approach, the cooling load was reduced by 1,600 tons, leaving the existing chiller vastly oversized. The ESB owners had been planning to replace the entire system, but they were now able to simply update the system, saving up to $17 million initial equipment costs. The final design plan would cost $13 million initially, and provide a 38% reduction in energy use, and annual energy savings of $4.4 million.

Clearly the retrofit efforts in the Empire State Building yielded not only environmental benefits, but also will provide financial benefits for the building owners for years to come. One of the goals of the ESB project was to form a process and provide the tools necessary for other highrise buildings to follow suit. Since the Empire State Building, interest in highrise retrofits has increased greatly. In 4 years, another U.S. highrise icon will be receiving an extreme renovation of its own. The Willis Tower (formerly the Sears Tower) will be undergoing massive renovations to produce the annual energy savings up to 80% from the baseline [79]. The 16,000 windows on the building's exterior will receive updates to increase the insulation value, saving up to 60% of heating energy. Daylighting capacity will be expanded to allow for savings of up to 40% of the existing lighting energy. Successful, high-profile energy retrofits in highrise buildings will only serve to reinforce the fact that energy efficient measures are affordable and effective for buildings at all stages.

2.10.2 Energy Efficient New Construction

The Commerzbank, built in 1997 in Frankfurt, Germany is one of the first of many in the new generation of ecological highrise designs [4]. The goal in the design of the Commerzbank tower was to build the first high-rise in the world that utilized natural ventilation and at the same time natural lighting. Integrated design was used to ensure that the façade, floor plans, and HVAC strategies work en tandem to produce an energy efficient final product. The tower consists of a triangular ground plan with a segmented atrium that runs the length of the building. The energy-efficient façade reduces the heat gains, making utilization of the natural ventilation more effective. The tower is able to utilize natural ventilation for up to 80% of the year [4].

The Hearst Tower, commissioned in 2006, was the first LEED Gold certified skyscraper in New York City. In order to achieve a design that is 26% more energy efficient than the typical construction methods, the 600-ft tower utilizes a wide range of ecological building design measures [80]. The lightweight, diagonal external structural braces allow for large, unobstructed view glass and an open floor plan. These measures allow for maximum light penetrability into the space. The façade is enclosed by low-emissivity glass that reduces the amount of solar gain into the space. The energy efficient façade combined with a lighting control strategy helps to further reduce the energy consumption of the Hearst Tower.

The Comcast Center in Philadelphia was the tallest LEED certified building in the United States at the time of its 2009 commissioning [81]. This is achieved through a variety of energy efficiency measures, including an energy efficient façade design. The glazing for this building is a high-performance, ultra-clear, low-iron glass [82]. The glazing blocks 60% of solar heat gains, while allowing in 70% of the visible light. This allows for a drastic reduction in heating and cooling equipment and operational costs. The building also incorporates sunscreens and louvers to optimize daylight. Lighting and occupant sensors combined with an energy efficient control strategy take full advantage of the energy saving potential of the façade.

2.11 Application

The built environment in the United States is responsible for 41% of overall fuel consumption, which equates to around 31.8 Quadrillion Btu annually [2]. There is a wide range of available technologies, which could potentially drastically reduce the national annual consumption. Architects and engineers are now more mindful than ever of the energy implications of their design decisions. As a result of the growth of energy consciousness, new designs and retrofits have been introduced to the market that validate the energy efficiency and cost-effectiveness of a variety of interventions. However, a vast majority of buildings in the U.S. and worldwide could benefit from more energy efficient façades. One major barrier to implementation is the complex and time-consuming nature of a proper modeling and design process. While increased efforts at the beginning of the design process often results in a more successful final design, many building owners would be more likely to pursue these measures if the design process were streamlined. Another barrier to implementation, especially with façade design, is the nature of energy efficient design in that it is climate specific, and unique to each specific design. This also increases the design time involved to achieve all the potential energy efficient advantages of façade design.

The purpose of this analysis is to be able to provide some general guidelines based on building energy simulations that quantify the potential savings related to the products mentioned throughout Chapter 2. These guidelines will be able to provide a starting point for architects and engineers to be able to understand which variables impact the energy consumption of a building and how much. The simulations will cover the range of US climate zones to provide climate-specific recommendations.

For highrise buildings, the façade design is crucial to the energy performance of the building. Curtain wall technology has allowed buildings to achieve heights and silhouettes that are more impressive than ever. Glazing technology, natural ventilation strategies, and new HVAC methods have made the energy efficiency potential of these glazed façades higher than ever. The following analysis and recommendations will provide a simple design guide, which will hopefully encourage implementation of these energy conservation measures. Widespread implementation of these measures could result in a large reduction in annual energy consumption worldwide.

Chapter 3: Highrise Building Energy Model

3.1 Building Energy Simulation Tool

There are several whole-building energy simulation tools that would be able to provide energy analysis of a typical highrise building. EnergyPlus is the best-equipped simulation engine for exploring the thermal and energy impacts related to curtain walls in highrise buildings. EnergyPlus is able to model the energy and water consumption of a building, based on user inputs that describe the form and function of the building and its systems [85]. These variables include building dimensions and materials, HVAC systems, and occupancy patterns, along with many other variables that are necessary to quantify the energy consumption of a building.

EnergyPlus is based on the BLAST and DOE-2 calculation engines, and while there are several whole-building simulation tools available to perform annual energy consumption calculations, EnergyPlus is the most robust. EnergyPlus offers integrated simulation of loads, systems, and plants, allowing for more accurate equipment sizing and prediction of building operation.

3.2 Department of Energy Benchmark Building

In order to perform the energy simulations and implement the different products found in Chapter 2, it was necessary to identify a building design that represents the characteristics of a "typical" highrise building. The Department of Energy (DOE) has developed a library of building energy models to represent the "typical" characteristics of sixteen different commercial building types within the national building stock. The purpose of these models is to provide a common starting point for research and development of energy efficiency strategies [84]. The DOE has developed the commercial building models using the whole building energy simulation software EnergyPlus [85]. Sixteen commercial building types were selected in order to represent 70% of the national commercial building stock according to the data regarding the principal building activity of the building stock from the Commercial Buildings Energy Consumption Survey (CBECS) in 2003 [84]. The DOE has provided EnergyPlus building models in each building type for each ASHRAE climate zone. This study will focus on the "new construction" model for "Large Office Buildings." Table 2 shows a summary of the key variables and their sources [84]. Many of the envelope parameters vary depending on the climate type. Because the DOE provides models for all the ASHRAE climate types, each model is tailored to the specific climate requirements according to ASHRAE 90.1-2004. The climate-specific variables include envelope values, weather files used, site to source energy conversion factors, and ground temperatures.

EnergyPlus offers two different methodologies for glazing performance modeling: the Complex Glazing System and the Simple Glazing System. The complex glazing system requires specific layer-by-layer information to be known for a glazing assembly. The benchmark models utilize the simple glazing system, which requires inputs for overall U-value, SHGC, and visible transmittance values. Because this study is assessing general performance characteristics rather than evaluating specific glazing selections, the Simple Glazing system is the most appropriate methodology for this study.

Table 2: DOE Benchmark Building variables and sources

	DOE Benchmark Building Large Office	Source
Occupancy	200 ft²/person	ASHRAE 62.1-2004
Lighting Power Density	1.0 W/sqft	ASHRAE 90.1-2004
Ventilation	20 cfm/person	ASHRAE 62.1-2004
Process Loads	0.7 W/ft² + 18.5kW elevator load	ASHRAE 62.1-2004
Service Hot Water	21.3 gal/hr*floor	Jamagin et al. 2006, ASHRAE 2007
Schedules	~7:00am – 6:00pm	ASHRAE 90.1-1989
Footprint	240’ x 160’	EIA 2005
Height	12 stories: 156’ (47.6m)	EIA 2005
Floor-to-floor height	13’ (3.96m)	EIA 2005
Plenum depth	4’ (1.2m)	EIA 2005
Perimeter Zone Depth	20’ (6.1m)	EIA 2005
Window-to-Wall Ratio	38%	EIA 2005
Roof Construction	Insulation above deck: U-0.048 to 0.063	ASHRAE 90.1-2004
Wall Construction	Steel: U-0.064 to 0.124	ASHRAE 90.1-2004
Wall, Below Grade	C-0.119 to 1.140	ASHRAE 90.1-2004
Slab-on-Grade Floors	F-0.54 to 0.73	ASHRAE 90.1-2004
Vertical Glazing	U-0.35 to 1.22; SHGC 0.25 to 0.49	ASHRAE 90.1-2004
Lighting Power Density	1.0 W/sqft	ASHRAE 90.1-2004
HVAC System Type	Multizone Variable Air Volume	ASHRAE 90.1-2004
Economizer	Included in: 2b, 3c, 4c, 5a, 5b, 6b, 7 (82°F max)	ASHRAE 90.1-2004
Boiler Efficiency	78%	ASHRAE 90.1-2004
Chiller COP	5.5	ASHRAE 90.1-2004

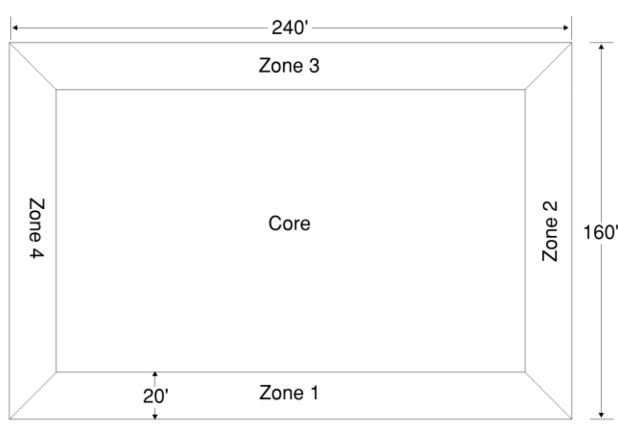

Figure 16: DOE Benchmark Building – Large Office Zoning Plan

3.3 Highrise Baseline Model

3.3.1 Highrise Geometry

The DOE Benchmark Building energy model for a Large Office building is twelve stories tall. As discussed previously, the criteria for the height of a "highrise" building is not clearly defined. In order to assess the energy efficiency implications of the variables surrounding curtain walls in highrise buildings, the height of the reference building model needed to be increased to a height that is "typical" of highrise buildings. The Global Tall Building Database of the Council on Tall Buildings and Urban Habitat (CTBUH) contains statistics for the world's "tall buildings." The CTBUH definition of a tall building is a building that "exhibits some element of 'tallness'" in one or more of the following categories: height relative to context, proportion, or inclusion of tall building technologies (elevator, structural wind bracing, 14 stories or above) [86]. This database includes statistics regarding height, construction material, date of completion, usage type, number of floors, and location. The data was filtered to include completed tall buildings in the United States, and was analyzed to determine reasonable values for representing "typical" height of a highrise building in the United States.

The average height of the highrise buildings in the CTBUH database is 416.67 ft. (128.71 m), and the average number of floors is 32. Figure 17 and Figure 18 show the frequency of building heights, which was used to determine whether any extreme height values were skewing the average values. The averages fall within the range of the majority of building heights, which validates the use of the average values for a "typical" highrise building model. The average floor-to-floor height was also calculated to be 13.12 ft. (4 m), which is very close to the 13 ft. floor-to-floor height used in the DOE Benchmark building.

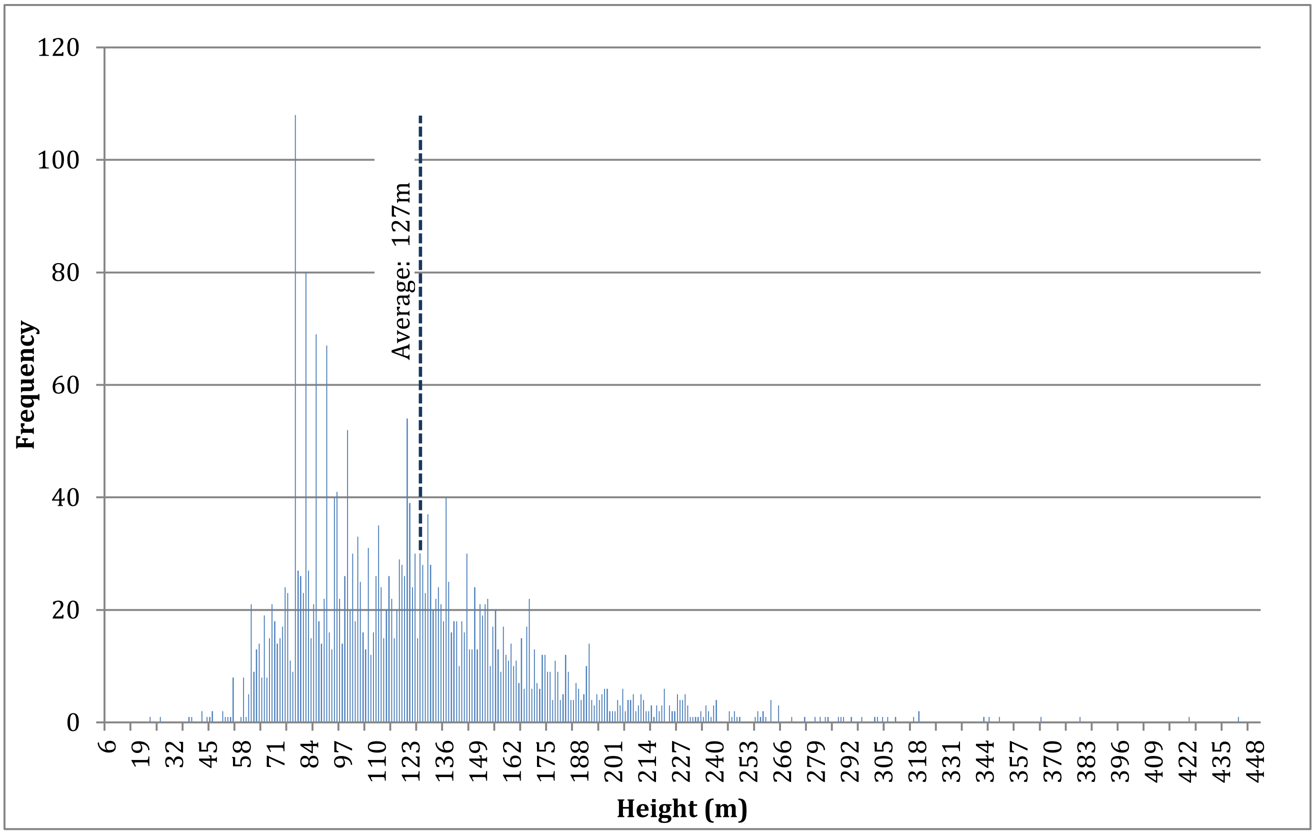

Figure 17: Height of highrise buildings in the United States [86]

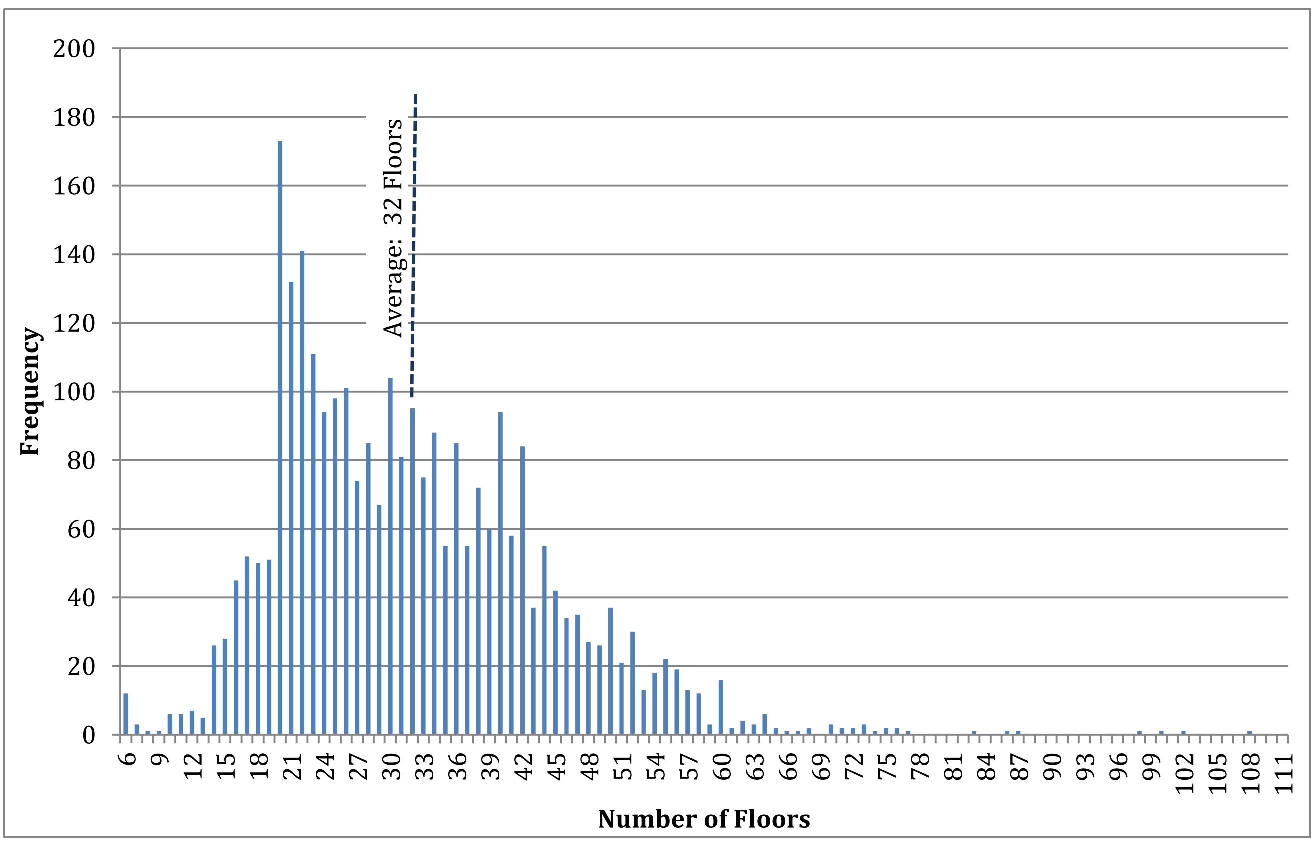

Figure 18: Number of floors in highrise buildings in the United States [86]

3.2.2 Climate Zone Selection

ASHRAE has specified fifteen climate zones: the eight numbered zones characterized by temperature, which are subdivided for moist (A), dry (B), and marine (C) climates. The Department of Energy selected sixteen locations across all the climate zones in cities of concentrated population. From the sixteen representative cities, eleven cities were selected that would serve as a representative sample of climates and cities where construction of highrise buildings is more likely. Figure 19 shows the locations that were selected for this analysis.

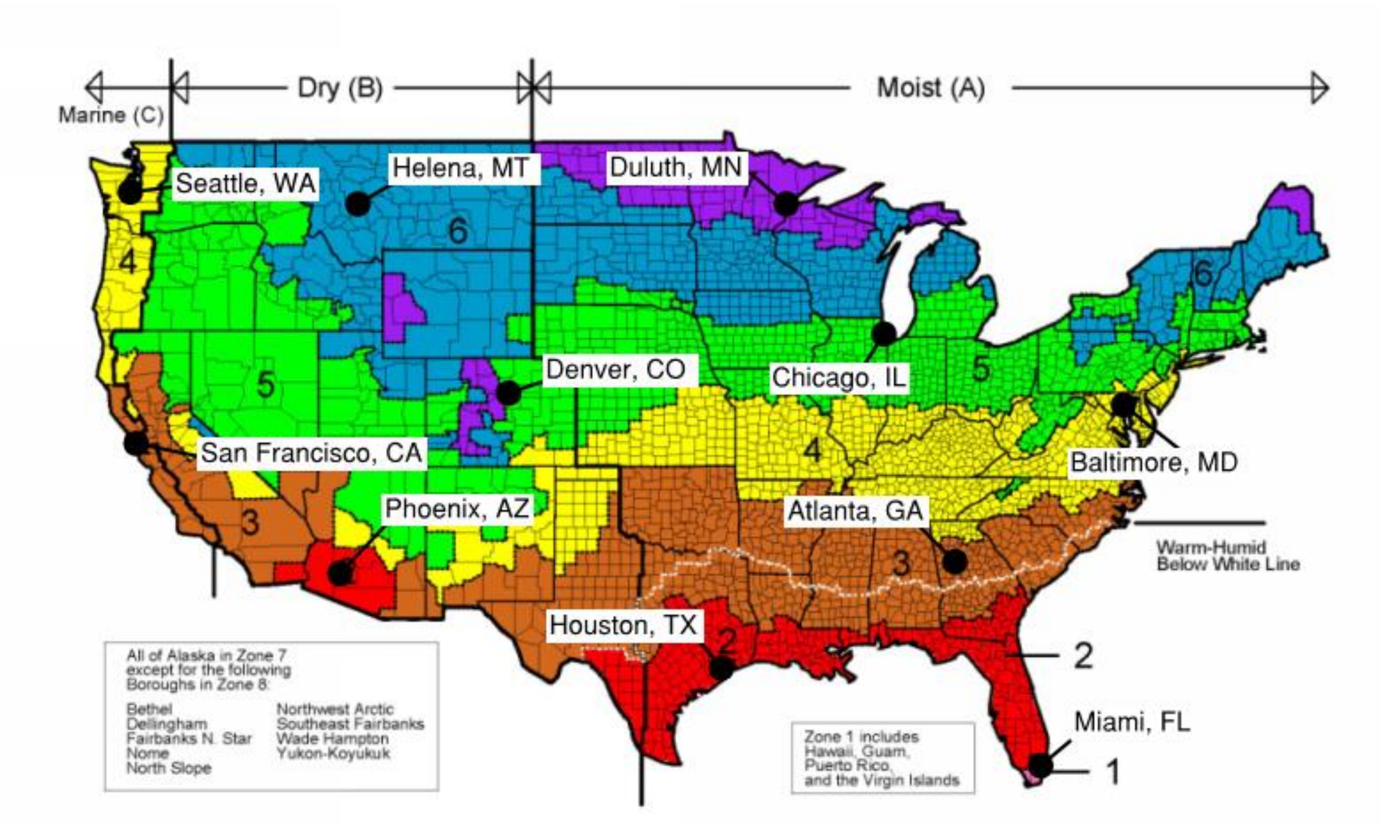

Figure 19: ASHRAE Climate Zone classifications and representative cities [84]

3.2.2 Updated Baseline

The DOE Benchmark building models largely follow ASHRAE Standard requirements from 2004 [87]. The models were updated to the new ASHRAE 2010 Standards in order to be more relevant to current construction practices and requirements [88]. Table 3 highlights the changes that were made between the energy models taken directly from the DOE library and the Highrise Baseline models, which use the increased highrise height and updated ASHRAE Standard values. More detailed envelope values for each climate are listed in Appendix A.

Table 3: DOE Benchmark Building variables updated to Highrise Baseline

Variables	DOE Benchmark	Highrise Baseline
Footprint	240’ x 160’	240’ x 160’
Height	12 stories 156’ (47.6m)	**32 stories 416’ (126.8m)**
Floor-to-floor height	13’ (3.96m)	13’ (3.96m)
Plenum depth	4’ (1.2m)	4’ (1.2m)
Perimeter Zone Depth	20’ (6.1m)	20’ (6.1m)
Window-to-Wall Ratio	38%	38%
Envelope Standard	ASHRAE 90.1-2004	**ASHRAE 90.1-2010**
Roof Construction	Insulation above deck U-0.048 to 0.063	**Insulation above deck U-0.048 to 0.063**
Wall Construction	Steel U-0.064 to 0.124	**Steel U-0.064 to 0.124**
Wall, Below Grade	C-0.119 to 1.140	**C-0.119 to 1.140**
Slab-on-Grade Floors, Unheated	F-0.54 to 0.73	**F-0.52 to 0.73**
Vertical Glazing	U-0.35 to 1.22 SHGC 0.25 to 0.49	**U-0.35 to 1.20 SHGC 0.25 to 0.45**
Lighting Power Density	1.0 W/sqft	1.0 W/sqft
HVAC System Type	Multizone Variable Air Volume	Multizone Variable Air Volume
Economizer	Included in: 2b, 3c, 4c, 5a, 5b, 6b, 7 (82°F max)	**Included in: 2b, 3c, 4c, 5b, 6b, 7 (75°F max); 5a (70°F max)**
Boiler Efficiency	78%	**80%**
Chiller COP	5.5	**5.672**

Chapter 4: Comparison of Highrise Baseline Model

4.1 DOE Benchmark Building updated to DOE Benchmark 32 Stories

The first update that was made was to the DOE Large Office Benchmark Building was to update the geometry so that it reflected the typical height of a highrise as calculated earlier from the CTBUH database. The DOE model is set up with a basement, ground floor, top floor, and middle floor (with a multiplier). There are six thermal zones per floor: one core zone, 4 perimeter zones, and one shared plenum per floor. The eleven building simulations were performed for the original DOE Large Office Benchmark Buildings, and again after the model had been extended to 32 stories. The results are compared in Table 4. As can be seen, the energy use intensity (EUI) is slightly reduced by increasing the height of the building.

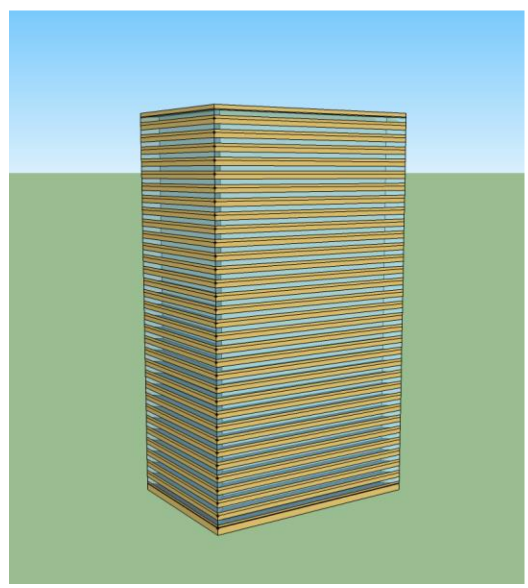

Figure 20: 3D image of Highrise Baseline

Table 4: Energy Use Intensity for 12 stories vs. 32 stories

Energy Use Intensity for 12 stories vs. 32 stories (kBtu/sqft.)				
Location	**DOE Benchmark (12 Stories) (ASHRAE 90.1-1994)**		**DOE Benchmark (32 Stories) (ASHRAE 90.1-1994)**	
	Site Energy	**Source Energy**	**Site Energy**	**Source Energy**
Miami, FL (1A)	56.84	187.57	53.28	175.69
Houston, TX (2A)	55.17	193.44	52.17	181.77
Phoenix, AZ (2B)	54.22	167.58	51.19	157.72
Atlanta, GA (3A)	50.58	163.68	47.73	153.80
San Francisco, CA (3C)	44.50	129.92	41.66	120.70
Baltimore, MD (4A)	52.61	173.05	50.04	163.18
Seattle, WA (4C)	43.15	71.70	40.44	66.82
Chicago, IL (5A)	51.55	157.49	49.07	147.54
Denver, CO (5B)	44.13	133.91	41.36	124.31
Helena, MT (6B)	46.45	139.19	43.67	129.05
Duluth, MN (7)	55.26	149.78	53.11	140.59
Average:	**50.41**	**151.57**	**47.61**	**141.92**

Further analysis of the EnergyPlus outputs revealed that increasing the height of the building made the impacts of the top and bottom floors less pronounced. The middle floors have much lower energy consumption per square foot of area because the heat transfer between adjacent floors is much lower than the heat transfer from the roof to the ambient air or the first floor through the slab on grade. This results in a lower kBtu/sqft for the 32 story building, although the total energy consumption is greater, as expected.

4.2 DOE Benchmark Building updated to Highrise Baseline

The DOE Benchmark Building was not only updated to highrise geometry, but the variables were updated to meet ASHRAE Standards from 2010. Through the process of updating the variables, each variable was assessed to determine how much of an impact the updates had on the overall energy consumption values. Figure 21 shows the percent of site energy savings achieved by changing each variable individually. The magnitude of change in each variable from the ASHRAE 90.1-2004 values to the -2010 values is not consistent across all locations. However, as seen in Figure 21, the energy performance improvements made in the opaque wall construction U-values and the glazing values achieved the greatest energy savings. The average energy savings moving from ASHRAE

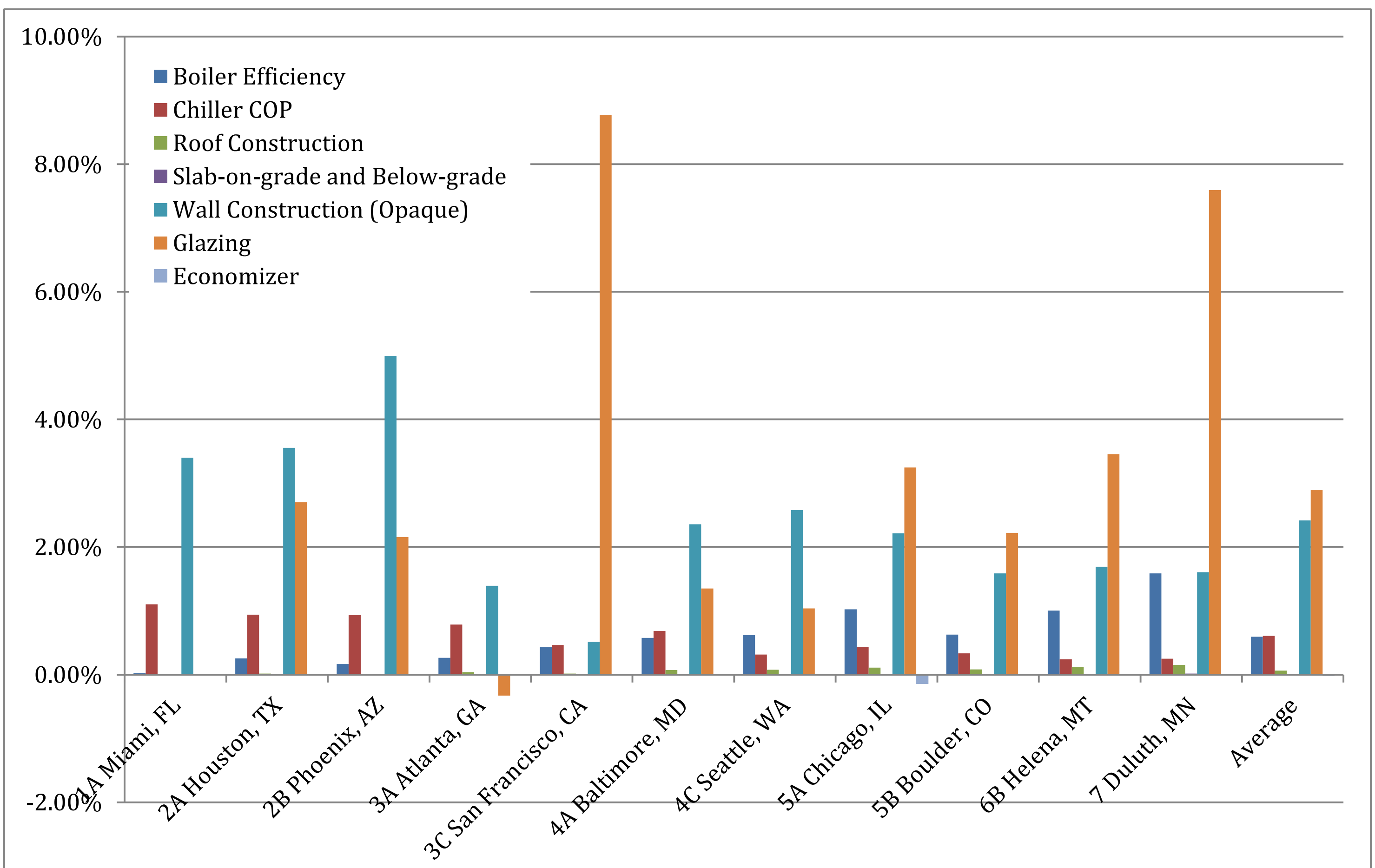

Figure 21: Site Energy Savings through updates to ASHRAE 90.1-2010

90.1-2004 to -2010 for wall U-values is 2.89%, while the average for updating the window U-values and SHGCs is 2.42%. The hot, dry climates of Phoenix and Houston benefit from the significant decrease of window U-value from 1.22 Btu/hr*ft^{2}*°F to 0.7 Btu/hr*ft^{2}*°F. The energy consumption of the highrise in San Francisco improved 8.77% by updating the wall U-value from 0.124 Btu/hr*ft^{2}*°F to 0.084 Btu/hr*ft^{2}*°F. Duluth, Minnesota also improved significantly from the wall U-value update. The other climate regions experienced improvements that hover between 1% and 3% for improvements to the envelope energy performance values. It should also be noted that the roof construction and below grade construction updates had little to no impact on the overall building energy consumption. This is to be expected as the roof and below grade envelope area account for very little of the overall envelope area. The boiler and chiller efficiency improvements affected the overall building energy performance very little – typically less than 1%.

The energy consumption improvements cannot be directly compared across all climate zones, as the updates from ASHRAE 90.1-2004 to -2010 were not necessarily the same for each climate. The chiller and boiler updates were consistent across all climate zones, and as is expected, the improved chiller efficiency has a greater impact in cooling climates, while the improved boiler efficiency has a greater impact on heating dominated climates.

4.3 ASHRAE 90.1-2010 Highrise Baseline Models

The energy models were updated to meet ASHRAE 90.1-2010 standards. With all the variable updates in place, the baseline models showed marked improvement over the ASHRAE 90.1-1994 32 story versions of the DOE Benchmark buildings. Table 5 shows the improvement that was made. In order to validate the models and determine whether the EUI is realistic or not, the results were compared to the EUI of several existing buildings from the BuildingGreen.com case study database [89]. This database shows a variety of existing buildings with an EUI as low as 17kBtu/sqft up to 60 or 70kBtu/sqft. The energy

Table 5: Energy Use Intensity for New Construction by Location

Energy Use Intensity for New Construction by Location (kBtu/sqft.)			
Location	**32 Story Benchmark (ASHRAE 90.1-1994)**	**Highrise Baseline (ASHRAE 90.1-2010)**	**Savings**
Miami, FL (1A)	53.28	50.94	4.40%
Houston, TX (2A)	52.17	48.40	7.24%
Phoenix, AZ (2B)	51.19	46.85	8.48%
Atlanta, GA (3A)	47.73	46.91	1.73%
San Francisco, CA (3C)	41.66	37.63	9.67%
Baltimore, MD (4A)	50.04	47.79	4.50%
Seattle, WA (4C)	40.44	38.81	4.04%
Chicago, IL (5A)	49.07	45.93	6.39%
Denver, CO (5B)	41.36	39.58	4.30%
Helena, MT (6B)	43.67	41.14	5.78%
Duluth, MN (7)	53.11	47.78	10.04%
Average:	**47.61**	**44.70**	**6.11%**

intensity of the building depends highly on the usage rates and schedules, so the range of potential EUIs for a given highrise office building is quite wide. For the purpose of this study, the BuidlingGreen.com database validates that the baseline models has an EUI that is within a realistic range compared to existing large office buildings.

In order to understand how much impact an optimized curtain wall design would have, it is important to understand the origins of the energy losses and gains. Figure 22 shows the breakdown of annual sensible heat gain and loss components for Miami, FL (a cooling dominated climate) and Chicago, IL (a heating dominated climate). The "Opaque and other" sensible gain component includes the thermal impacts of the walls, floors, and roof as well as a time delay associated with the thermal massing of the envelope. As seen below, it is the most significant sensible heat component that the building's HVAC system must overcome. Changes in the building envelope will not only affect the ratio of

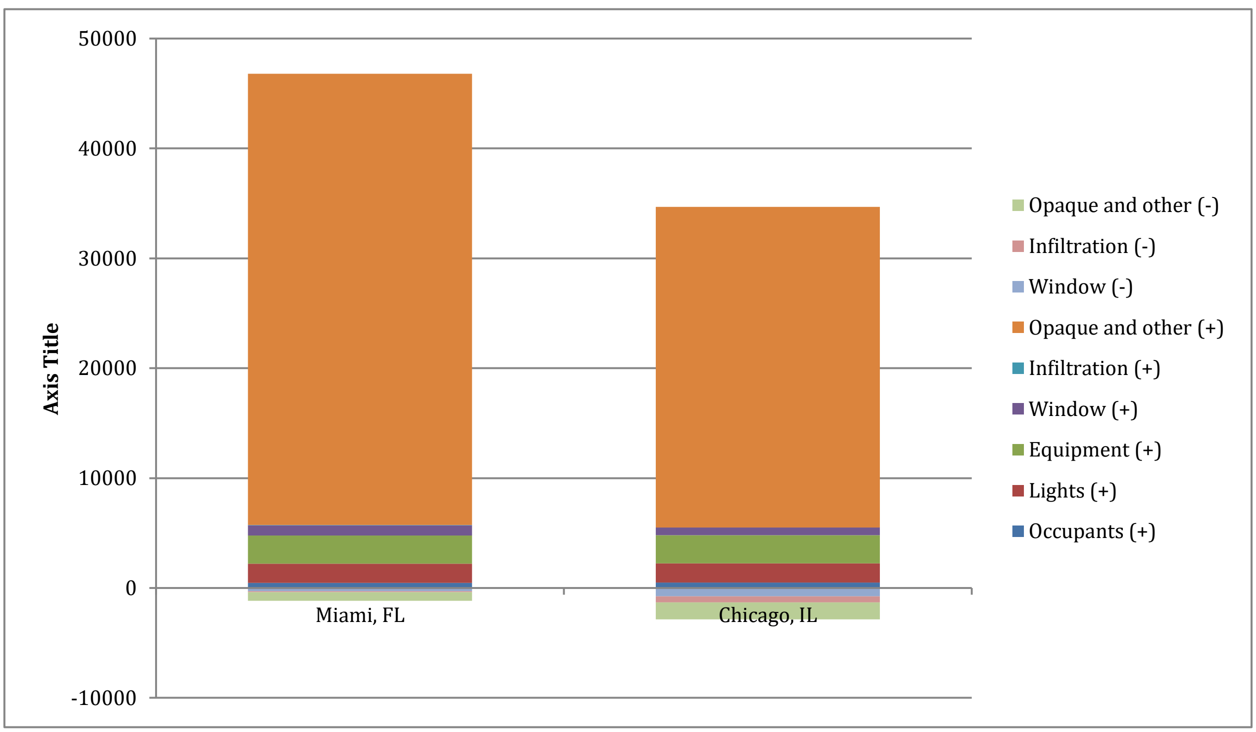

Figure 22: Annual Sensible Heat Gain and Loss Components for Miami and Chicago

conduction through the exterior envelope, they will also alter the thermal massing effects taken into consideration in the energy model. Gains related to "Equipment" (plug loads) and "Occupants" will remain constant, while all the other sensible gain components are subject to change with changes in the envelope properties.

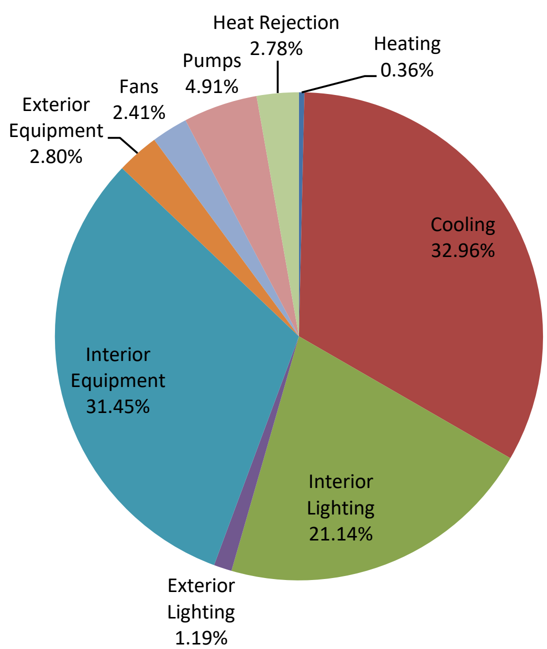

Figure 23: Miami Annual End Use Energy

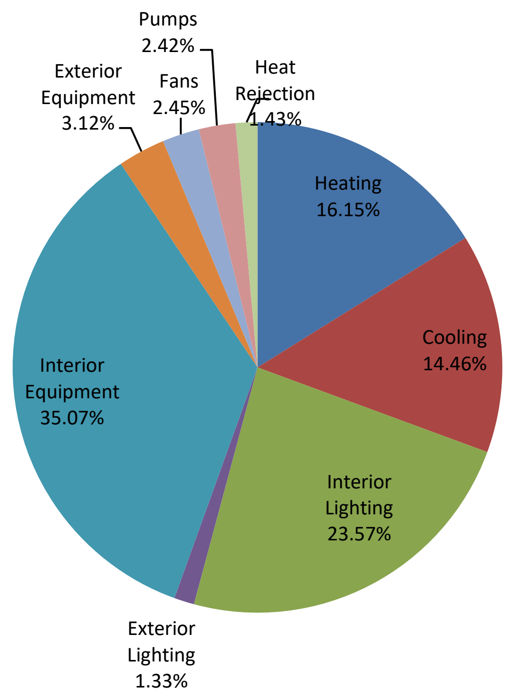

Figure 24: Chicago Annual End Use Energy

Figure 23 and Figure 24 show the breakdown of end use energy for Miami and Chicago baseline models. It is important to note that lighting and equipment loads make up a significant portion of the overall energy consumption. In all the climates, lighting and equipment loads make up between 55% and 75% of the overall end use energy in the building. Unless daylighting is used to reduce the lighting loads, the lighting and equipment loads represent a large percentage of the overall energy consumption that will be unaffected by improving the envelope design for a highrise building.

Heating and cooling-related energy comprises 25-45% of the building energy usage. That usage can be broken down further to determine which zone is consuming the most HVAC energy. Each floor is broken into 6 zones: core, plenum, north, south, east, and west. The depth of the perimeter zones is 20 feet. Below is the energy breakdown by zone for Miami and Chicago. Throughout all the climate zones, the core typically represents 60-65% of the heating and cooling loads. Any envelope improvements would mostly impact the heating and cooling loads for the perimeter zones. The south perimeter zone requires slightly more heating and cooling energy than the other perimeter zones. The difference may be large enough to warrant approaching each façade differently as one strategy may be cost effective on the south side, but not on the other façades. Based on the percentage of building heating and cooling energy related to the perimeter zones, between 5% and 13.5% of the total building energy consumption could potentially be impacted through improved envelope values.

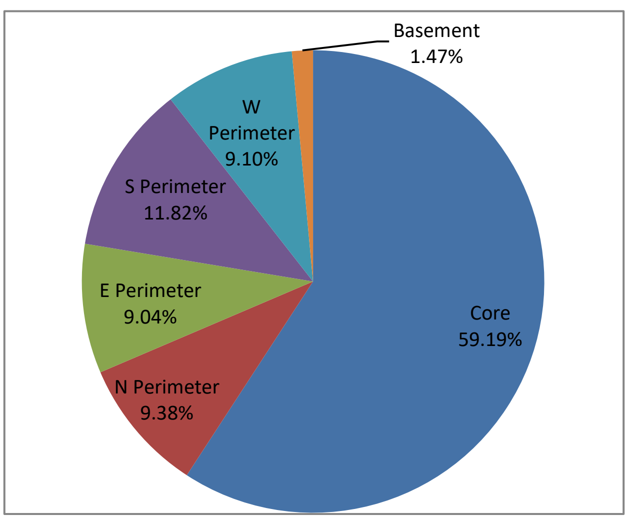

Figure 25: Miami Heating/Cooling Energy by Zone

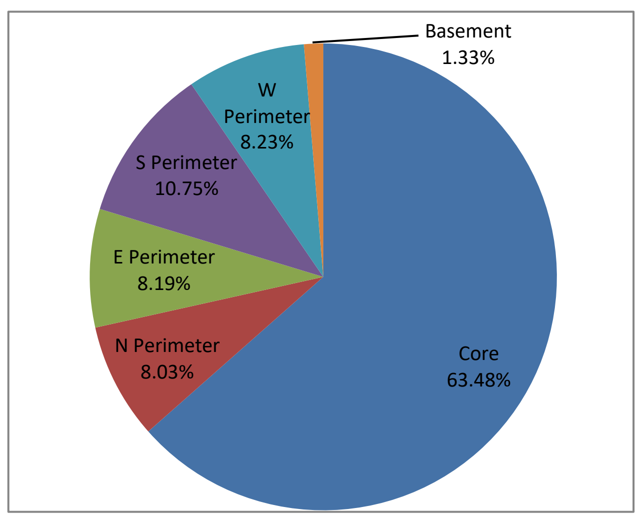

Figure 26: Chicago Heating/Cooling Energy by Zone

Chapter 5: Curtain Wall Envelope Analysis

5.1 Curtain Wall Variables

Each building design is made up of countless variables that impact the energy consumption of the building. For this analysis the scope is focused on variables closely related to the building envelope, particularly the curtain wall itself. The envelope analysis was broken into two major categories. The first is a sensitivity analysis in which one variable was altered in the baseline model to determine which variables had the most significant impact on overall energy consumption. The second is an optimization of glazing properties.

Several variables related to the overall building envelope were chosen for the initial sensitivity analysis to determine their impacts on the energy consumption of the building. These variables include window-to-wall ratio, U-value of both the wall and windows, solar heat gain coefficient (SHGC), visible transmittance (VT), and overhang size. The range of values for each variable is limited to realistic design values and values of real products on the current market, as outlined in Chapter 2. High cost items such as switchable glazing or directional glazing were not evaluated at this time.

Table 6 shows the variables assessed, what ranges were used, and what combinations were simulated. Two main climate zones were focused on for initial variable assessment: Miami, FL and Chicago, IL. These climates are representative of cooling-dominated climates and heating dominated climates, respectively. Each variable was first modeled for Miami and Chicago to determine how significant the impact will be. If the change in cost or energy proved to be significant, then the analysis was extended to include all eleven climate zones.

Many of the minimum and maximum values were selected based on the ASHRAE 90.1 requirements that the envelope meet certain performance standards at minimum. The window-to-wall ratio (WTW ratio) minimum aligns with ASHRAE 90.1, and the maximum of 95% correlates to the maximum possible WTW ratio available from a popular high performance curtain wall assembly manufacturer, Kawneer (www.kawneer.com). Their Curtain Wall 1600 Wall System®3 was used as a representative assembly for the current market. The SHGC and VT values were varied to match values available in the market as discussed in Section 2.3: Glazing. The window and wall U-value maximums were taken from ASHRAE 90.1 requirements, and the minimum values correlate to best-practice market values. The maximum overhang depth of 1.5m was selected as a realistic boundary based on aesthetics and practicality.

Table 6: Simulated Variables and Ranges Used

Baseline:	All 11 Climates						
Group 1:	**WTW Ratio**						
All 11 Climates	40%	50%	60%	70%	80%	90%	95%

Group 2:	Window U-value (Btu/hr*ft2*°F)							
	40% WTW Ratio				**70% WTW Ratio**			
Miami, FL	0.92	0.36	0.64	0.08	0.92	0.36	0.64	0.08
Houston, TX	0.545	0.39	0.235	0.08	0.545	0.39	0.235	0.08
Phoenix, AZ	0.545	0.39	0.235	0.08	0.545	0.39	0.235	0.08
Atlanta, GA	0.47	0.34	0.21	0.08	0.47	0.34	0.21	0.08
San Francisco, CA	0.47	0.34	0.21	0.08	0.47	0.34	0.21	0.08
Baltimore, MD	0.395	0.29	0.185	0.08	0.395	0.29	0.185	0.08
Seattle, WA	0.395	0.29	0.185	0.08	0.395	0.29	0.185	0.08
Chicago, IL	0.3575	0.265	0.1725	0.08	0.3575	0.265	0.1725	0.08
Denver, CO	0.3575	0.265	0.1725	0.08	0.3575	0.265	0.1725	0.08
Helena, MT	0.3575	0.265	0.1725	0.08	0.3575	0.265	0.1725	0.08
Duluth, MN	0.32	0.24	0.16	0.08	0.32	0.24	0.16	0.08

Group 3:	Solar Heat Gain Coefficient									
	40% WTW Ratio					**70% WTW Ratio**				
All 11 Climates	0.2	0.3	0.4	0.5	0.6	0.2	0.3	0.4	0.5	0.6

Group 4:	Overhangs (m) – N/S/E/W, and S/E only											
	40% WTW Ratio						**70% WTW Ratio**					
Miami, FL	0.25	0.5	0.75	1	1.25	1.5	0.25	0.5	0.75	1	125	1.5
Chicago, IL	0.25	0.5	0.75	1	1.25	1.5	0.25	0.5	0.75	1	125	1.5

Group 5:	Opaque Envelope U-value (Btu/hr*ft2*°F)							
	40% WTW Ratio				**70% WTW Ratio**			
Miami, FL	0.098	0.072	0.046	0.02	0.098	0.072	0.046	0.02
Chicago, IL	0.053	0.042	0.031	0.02	0.053	0.042	0.031	0.02

Group 6:	Add Daylight Control						
a:	**WTW Ratio**						
Miami, FL	40	50	60	70	80	90	95
Chicago, IL	40	50	60	70	80	90	95
All Other Climates	40			70			

b:	Overhang Depth (m)											
	40% WTW Ratio						**70% WTW Ratio**					
Miami, FL	0.25	0.5	0.75	1	1.25	1.5	0.25	0.5	0.75	1	1.25	1.5
Chicago, IL	0.25	0.5	0.75	1	1.25	1.5	0.25	0.5	0.75	1	1.25	1.5

c:	Visible Transmittance							
	40% WTW Ratio				**70% WTW Ratio**			
All Climates	0.3	0.5	0.7	0.9	0.3	0.5	0.7	0.9

The combinations of variables were chosen based on engineering judgment for which variables were dependent on others in terms of thermal performance. For instance, the glazing VT will affect the effectiveness of daylight control, so those variables were paired. The energy performance of the façade is highly influenced by WTW ratio, so in order to have simulations that represent current highrise façade design, the variables were simulated with a the 40% baseline WTW ratio as well as the 70% WTW ratio, which is within the range of current practice cited in Chapter 2. Miami, FL and Chicago, IL. were used as representative cities for more extreme climates. If a variable had significant impact in Miami and Chicago, then the simulation runs were expanded to all eleven climate zones. A total of 378 simulations were run for the initial sensitivity analysis.

5.2 Opaque Envelope U-value

The U-value of the opaque wall sections in a highrise building are generally considered of lesser importance as compared to other envelope factors. The weak points in the window itself and the fastening points where the window meets the spandrel sections are the focus of current research because of the concern for thermal bridging in these two areas. Simulations were performed in order to determine the magnitude of improvements of thermal performance in the opaque portions of the assembly.

The impact of U-value on energy consumption and annual cost were evaluated for Miami, FL and Chicago, IL to determine its impacts on a cooling- and heating-dominated climate. The U-value was incrementally reduced from the ASHRAE 90.1-2010 to U-0.02 Btu/hr*ft^{2}*°F, which corresponds to an R-50 insulation value. This analysis shows that even at a 40% WTW ratio, the reduction of the U-value of the opaque section has a much smaller impact on overall energy consumption and cost as compared to the window U-value. Figure 27 shows the difference in energy consumption compared to the baseline, and Figure 28

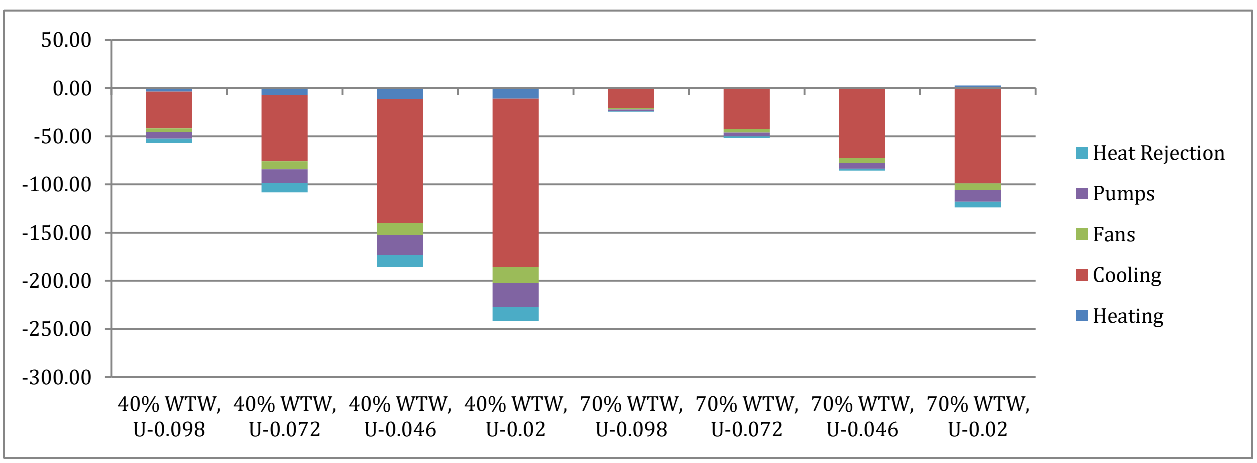

Figure 27: Wall U-value - Annual Energy Consumption Difference from Baseline - Miami, FL

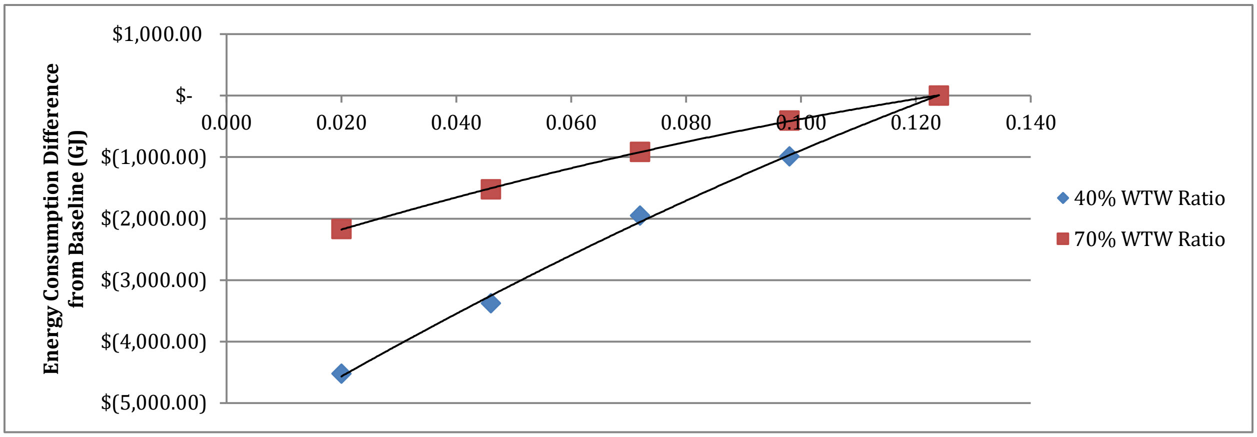

Figure 28: Wall U-value - Annual Energy Cost Difference from Baseline - Miami, FL

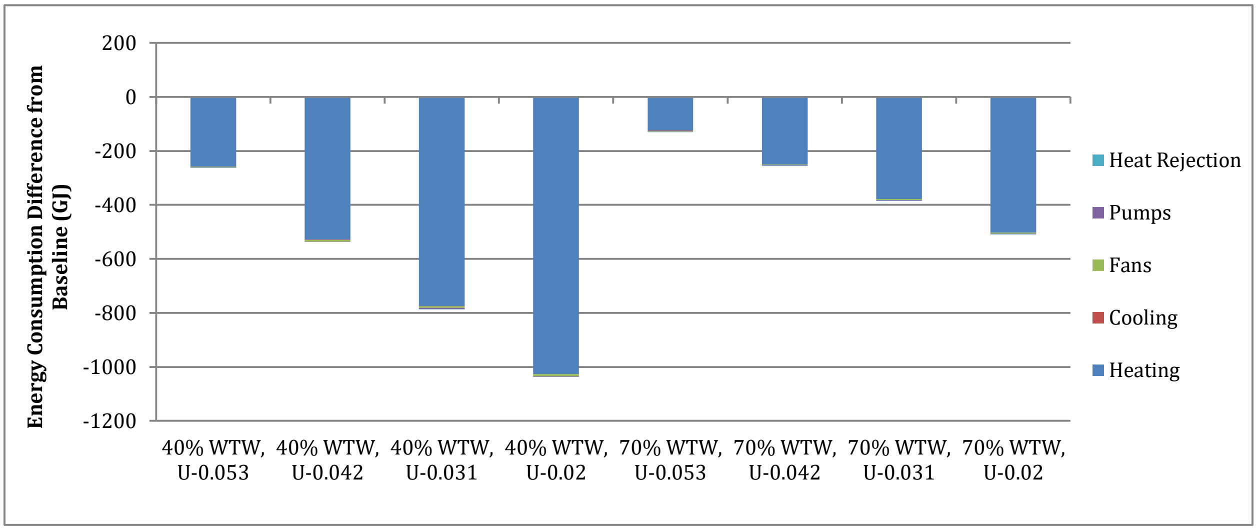

Figure 29: Wall U-value - Annual Energy Consumption Difference from Baseline - Chicago, IL

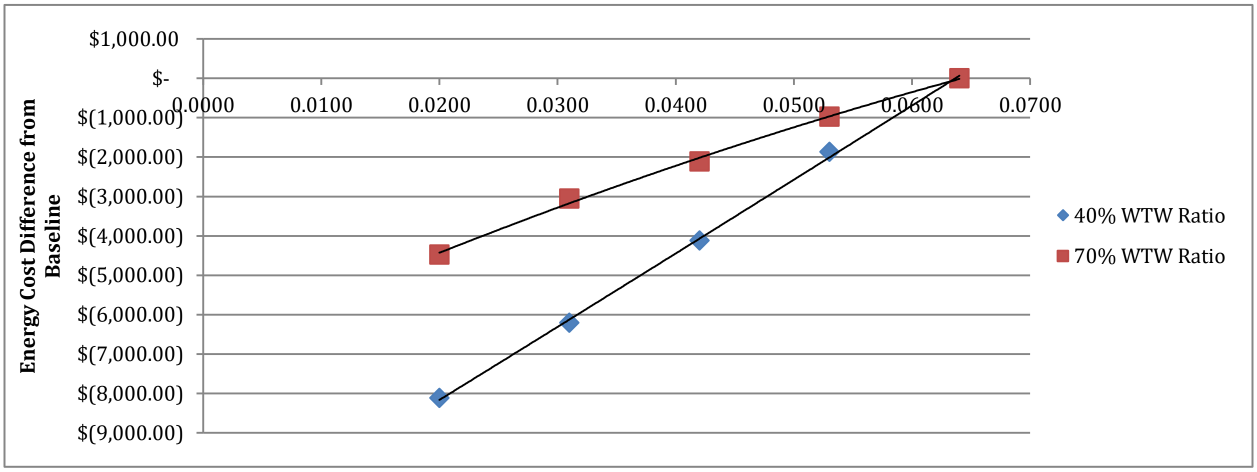

Figure 30: Wall U-value - Annual Energy Cost Difference from Baseline - Chicago, IL

percent cost savings for Miami. Figure 29 and Figure 30 show the impacts in Chicago. Chicago shows more significant energy and cost savings, but even a U-value of 0.02 Btu/hr*ft^{2}*°F only produces $8,117 saved annually, which is a very small savings compared to the overall energy cost of $1,361,080 annually for the baseline.

The energy consumption and cost savings for improving the wall U-value are less than 0.5% from the baseline case each. This is compared to up to 15% savings from baseline for improving the window U-value. In examining a cooling- and heating-dominated climate, it is evident that the improving the thermal performance of the opaque section U-value should not be the main concern for energy or cost savings in any climate zone.

5.3 Window-to-Wall Ratio

The DOE Benchmark model utilizes a 40% window-to-wall ratio (WTW ratio). As explained in Chapter 2, today's highrise buildings have WTW ratios over 60%. A series of simulations were performed to assess how the WTW ratio factors in to the energy consumption of the highrise building model.

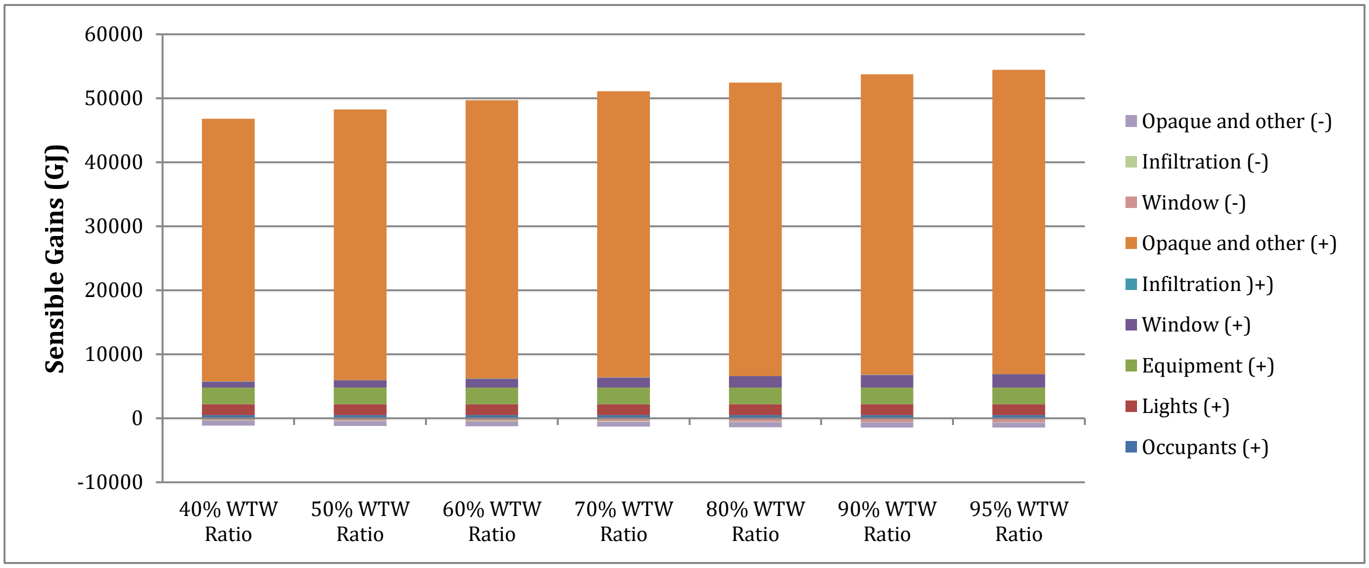

Figure 31: Sensible Gains - Miami, FL

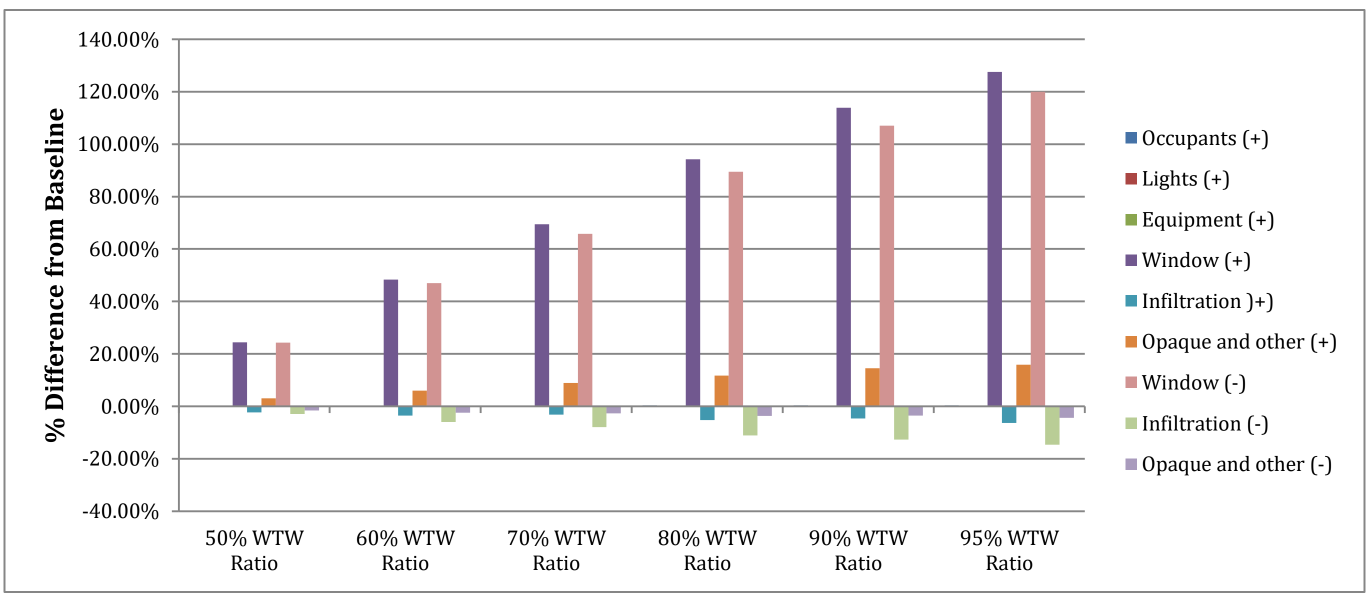

Figure 32: Sensible Gains Percent Difference from Baseline - Miami, FL

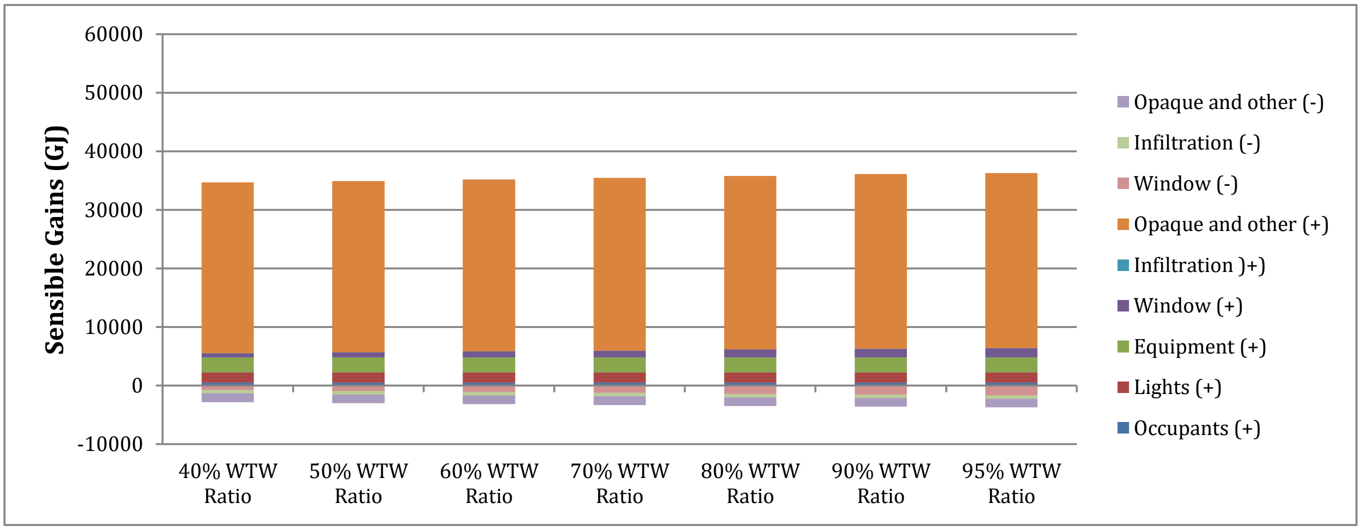

Figure 33: Sensible Gains - Chicago, IL

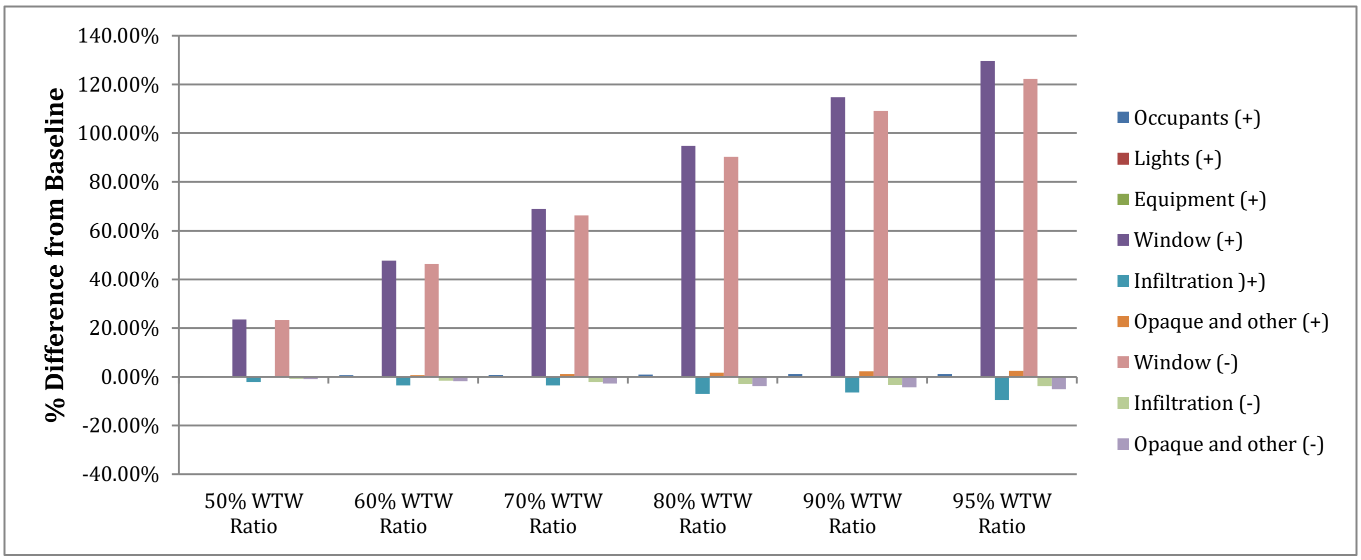

Figure 34: Sensible Gains Percent Difference from Baseline - Chicago, IL

Figure 31 and Figure 33 show magnitude of change in annual sensible heat gains and losses for the building when the WTW ratio is varied for Miami and Chicago, respectively. Figure 32 and Figure 34 show the percent change for each sensible component as the WTW ratio is increased. As can be expected, the gains and losses related to the windows experience the greatest change. The percent change is consistent between heating and cooling dominated climates, however the magnitude of change in annual sensible gains is greater for Miami than for Chicago.

Figure 35 and Figure 36 show the magnitude and percent difference in HVAC energy required for Miami and Chicago as the WTW ratio increases as compared to the 40% WTW ratio baseline. As the WTW ratio increases, and the sensible gains increase, driving the increase in HVAC energy. The figures for all the climate zones can be seen in Appendix B.

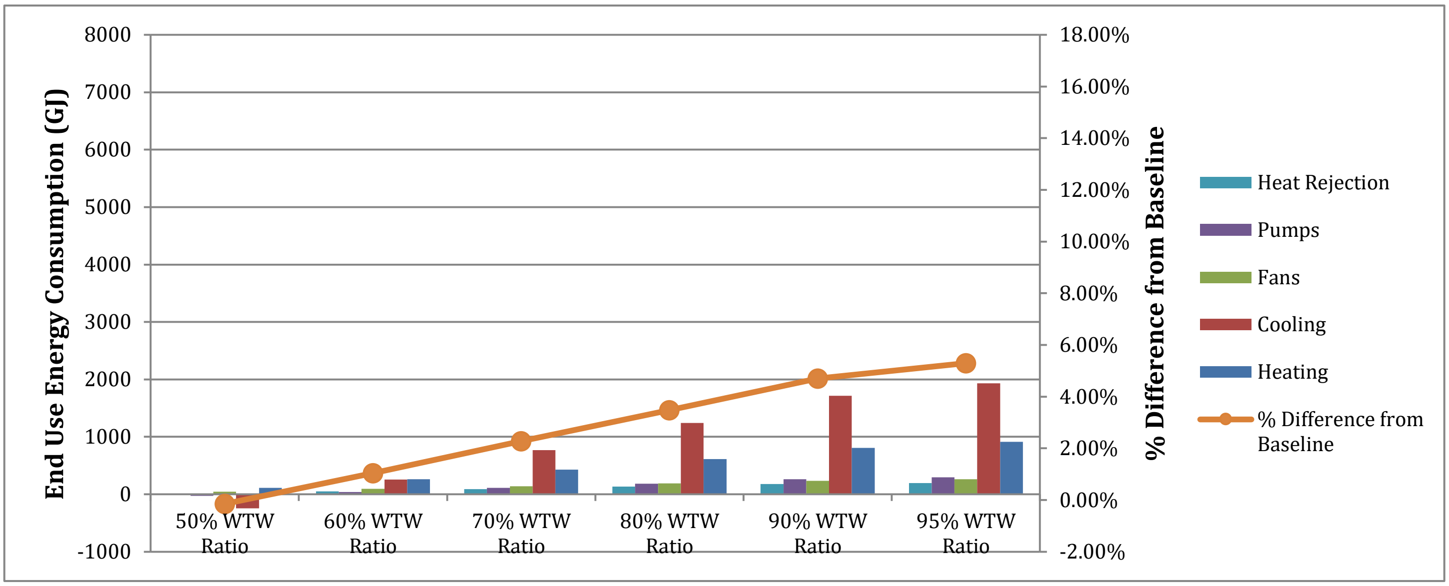

Figure 35: Window-to-wall Ratio –Heating and Cooling Energy Difference from Baseline – Miami, FL

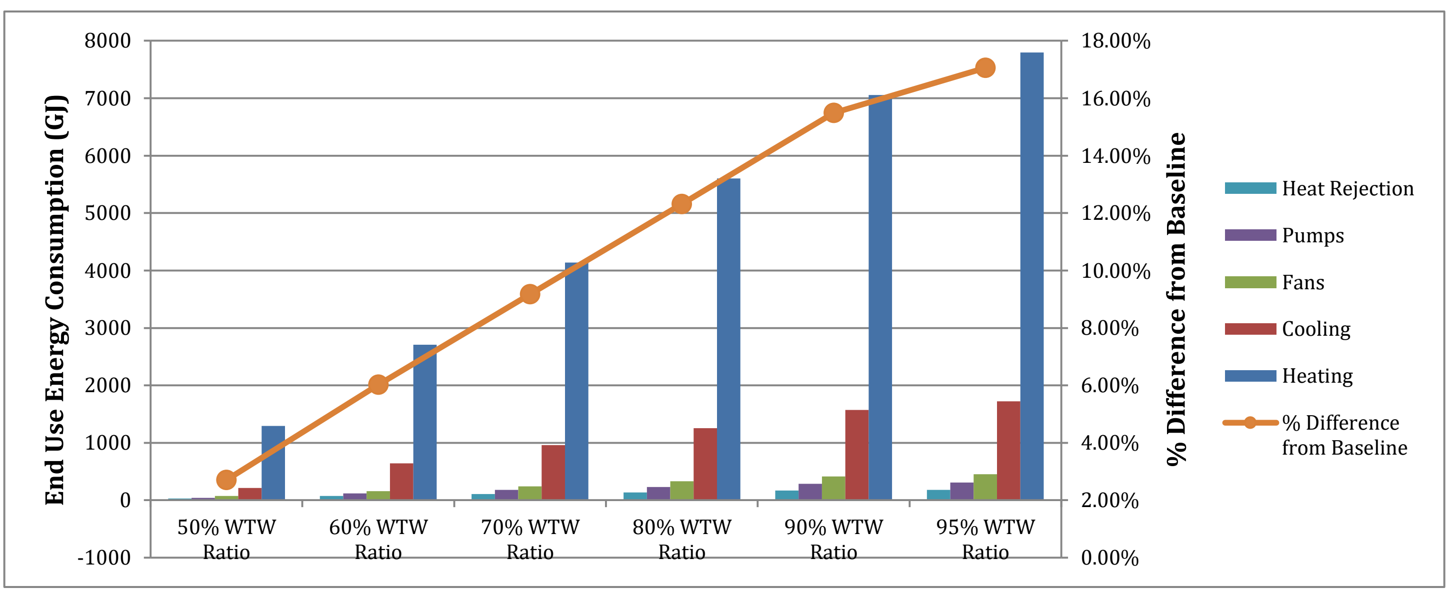

Figure 36: Window-to-wall Ratio – Percent Heating and Cooling Energy Difference from Baseline - Chicago, IL

Both the annual energy consumption and the annual energy cost generally increase linearly with respect to WTW ratio. However, due to different utility costs around the country, the two are not necessarily parallel. Figure 37 shows how the energy consumption increases with WTW ratio. The heating-dominated climates have steeper slopes, meaning the WTW ratio is a more sensitive variable in cooler climates. Miami, Houston, Atlanta, and Baltimore show a slight decrease in energy consumption when the WTW ratio increases to 50%, but then the trend continues upward from there. The savings at the 50% WTW ratio can be traced to a reduction in overall cooling energy.

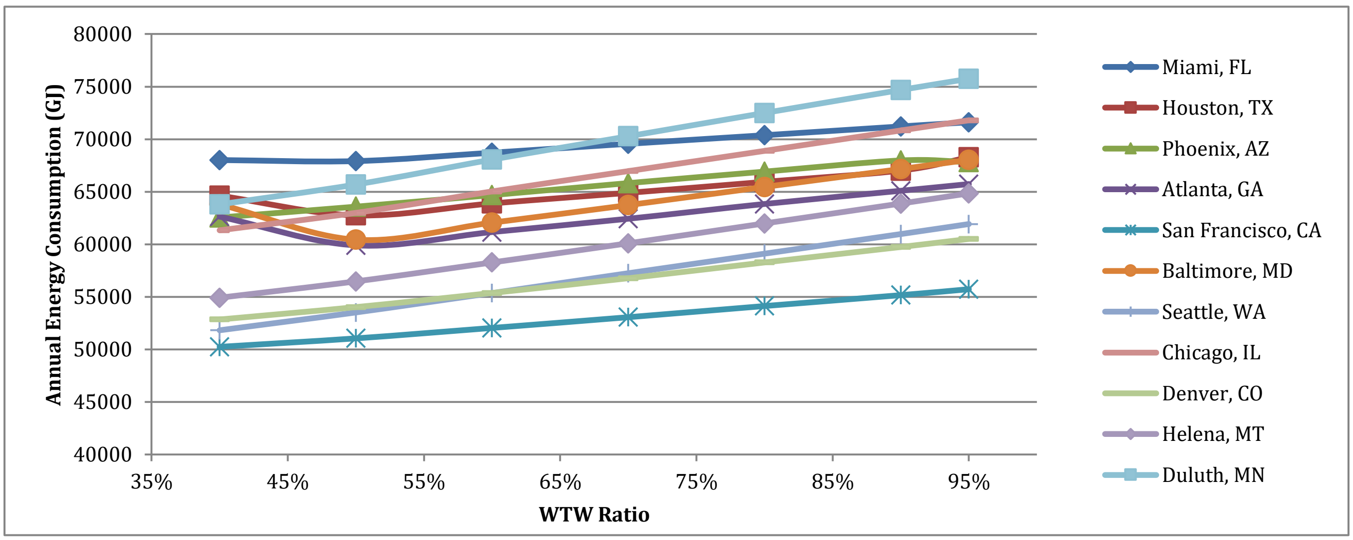

Figure 37: All Climates - Energy consumption vs. Window-to-wall Ratio

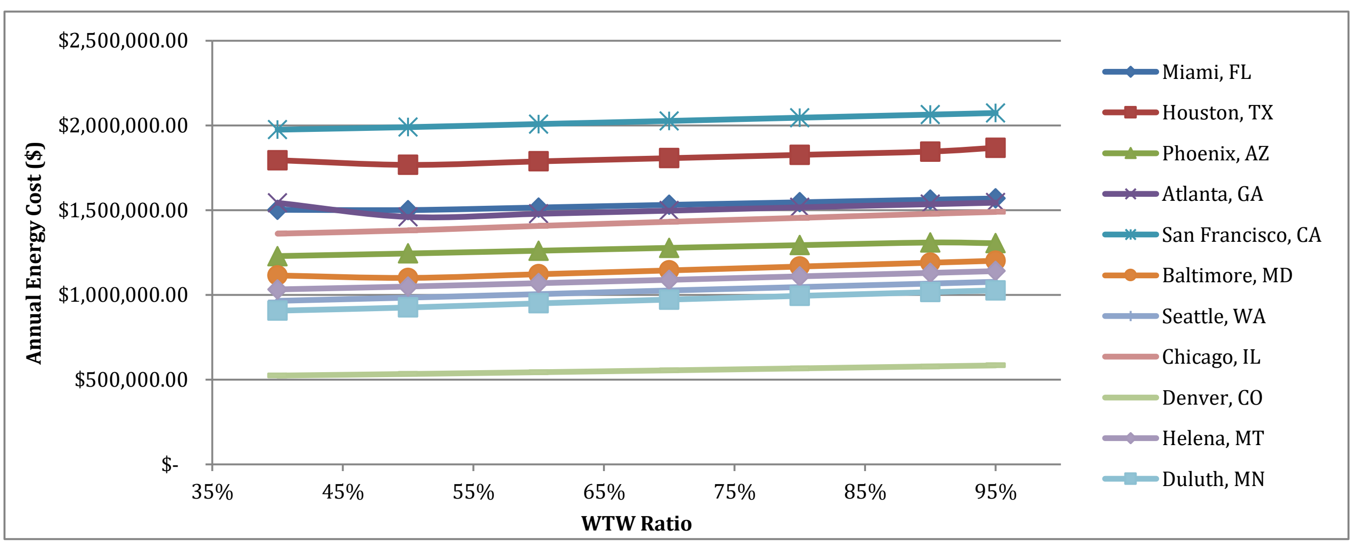

Figure 38: All Climates - Annual Energy Cost vs. Window-to-wall Ratio

The change in annual energy cost also in general varies linearly, but does not exactly mirror the slope of the energy consumption trends. The annual energy cost for the Highrise Baseline in Miami (40% WTW ratio) is $1,501,907 and increases to $1,568,738 (95% WTW ratio). There is a cost outlier at a 50% WTW ratio. The cost per year drops to $1,500,339, a $1,567 savings per year. The 95% WTW ratio case increases in annual energy costs by $66,831, which is a 4.45% annual cost increase. In Miami the cost for each percent increase in WTW ratio is about $1,520 annually, or 0.1%. Chicago's baseline cost is $1,361,080 and increases linearly. At 95% WTW ratio, energy cost is $128,301 more per year than at 40% WTW ratio, which is a 9.43% increase from the baseline. This is an annual increase of $2,332 per percent increase in WTW ratio, or 0.17% for each percent of WTW ratio increased. As seen in Table 7, all climate zones experience between 0.09% and 0.24% cost increase per WTW ratio percentage. If the average highrise building has a WTW ratio of 70%, this translates to a 2.7-7.2% annual utility cost increase.

Table 7: Sensitivity of Annual Energy Consumption and Annual Cost to WTW Ratio

	Annual Energy Change (GJ/% WTW)	% Annual Energy Change (%GJ /% WTW)	Annual Cost Change ($/% WTW)	% Annual Cost Change (%$ /% WTW)
Miami, FL	65.42	0.10%	$ 1,519.97	0.10%
Houston, TX	66.38	0.10%	$ 2,242.16	0.12%
Phoenix, AZ	95.80	0.15%	$ 1,599.98	0.13%
Atlanta, GA	56.34	0.09%	$ 1,869.18	0.12%
San Francisco, CA	99.72	0.20%	$ 1,791.85	0.09%
Baltimore, MD,	76.89	0.12%	$ 1,579.87	0.14%
Seattle, WA	183.72	0.35%	$ 2,043.64	0.21%
Chicago, IL	190.27	0.31%	$ 2,332.75	0.17%
Denver, CO	139.35	0.26%	$ 1,089.56	0.21%
Helena, MT	180.56	0.33%	$ 1,963.67	0.19%
Duluth, MN	217.25	0.34%	$ 2,177.64	0.24%

During the highrise design process, WTW ratio is often selected based on aesthetics and view consideration, and not for its impacts on energy consumption or energy cost. However, in a cool climate like Chicago, an 80% WTW ratio consumes an additional 7,550 GJ of energy per year and costs an extra $93,213 in utility costs per year over a 40% WTW ratio. The National Renewable Energy Lab produced a technical support document that gives cost data for a few specific wall assemblies [91]. The cost for the opaque exterior in a highrise building ranges from $35.75/sqft to $40.75/sqft, depending on the R-value (R-13 to R-28.5). The cost for the fenestration assemblies range from $67.65/sqft to $78.25/sqft. Given the general order of magnitude of the construction costs, the capital costs were calculated for increasing the WTW ratio for the highrise baseline. These costs are shown in Table 8. Between the additional capital costs and the increased energy cost, the consequences of an increased WTW ratio for aesthetic and view purposes must be understood and carefully weighed. These tradeoffs are important in all climate zones, but increase in quantifiable significance in colder climates.

Table 8: Cost of Facade with Increased WTW Ratio

WTW Ratio	Win Cost low	Win Cost high	Opaque Cost Low	Opaque Cost High	Total Low Cost	Total High Cost	Difference from 40% (Low)	Difference from 40% (High)
40	$9,002,529.19	$10,413,125.04	$7,363,993.21	$9,671,034.44	$16,366,522.40	$20,084,159.49	-	-
50	$11,250,685.68	$13,013,542.57	$6,175,943.03	$8,110,783.93	$17,426,628.72	$21,124,326.50	$1,060,106.31	$1,040,167.01
60	$13,504,288.95	$15,620,260.31	$4,985,014.48	$6,546,753.28	$18,489,303.43	$22,167,013.60	$ 2,122,781.02	$2,082,854.11
70	$15,730,651.06	$18,195,468.52	$3,808,481.66	$5,001,628.36	$19,539,132.72	$23,197,096.88	$3,172,610.31	$3,112,937.39
80	$18,006,048.71	$20,827,395.58	$2,606,035.75	$3,422,472.12	$20,612,084.45	$24,249,867.70	$4,245,562.05	$4,165,708.22
90	$20,228,522.34	$23,398,106.03	$1,431,557.81	$1,880,045.85	$21,660,080.15	$25,278,151.88	$5,293,557.75	$5,193,992.40
95	$21,382,350.32	$24,732,725.98	$821,811.32	$1,079,273.88	$22,204,161.64	$25,811,999.86	$5,837,639.23	$5,727,840.37

5.4 Overhang Depth

In certain climates, overhangs can be very useful for blocking detrimental solar thermal gains. The depth of the overhang can be optimized for a given location to block solar gains when they are not needed, yet allow for gains during the winter months when the sun's azimuth angle is lower in the sky. The simulations for overhang depth varied the depth from the baseline case (none) to 1.5m. The energy and cost savings both showed linear responses to increased overhang depth.

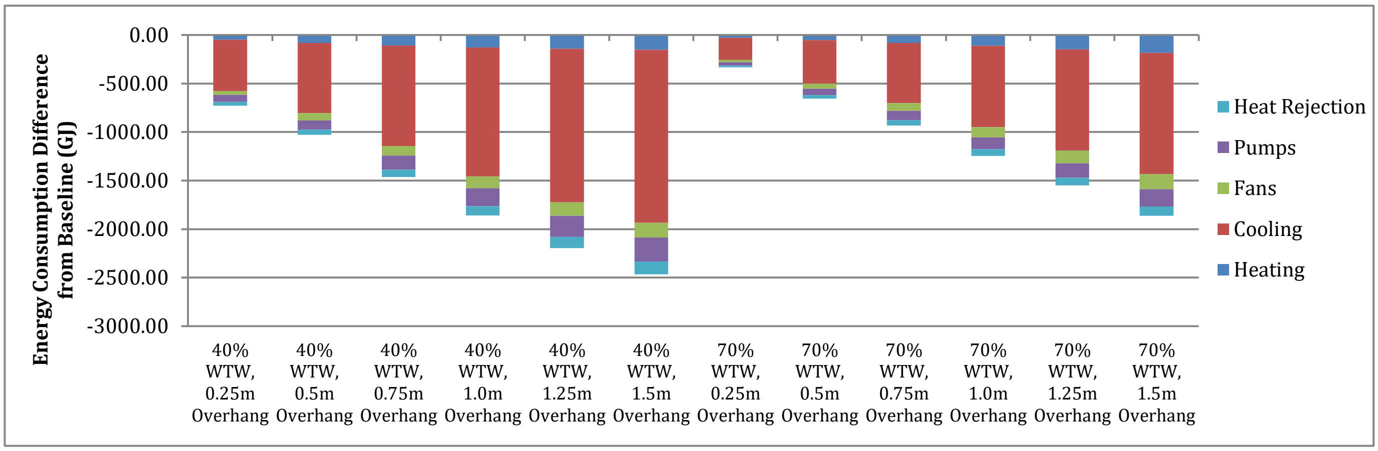

Figure 39: Overhang Depth - Energy Consumption Difference from Baseline - Miami, FL

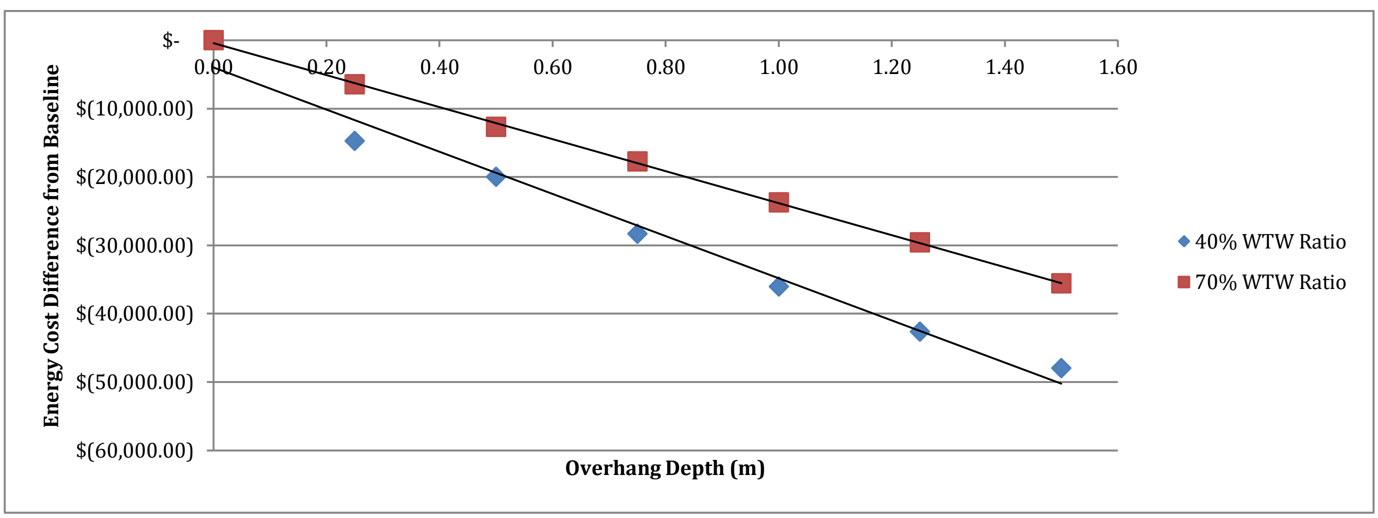

Figure 40: Overhang Depth - Energy Cost Difference from Baseline - Miami, FL

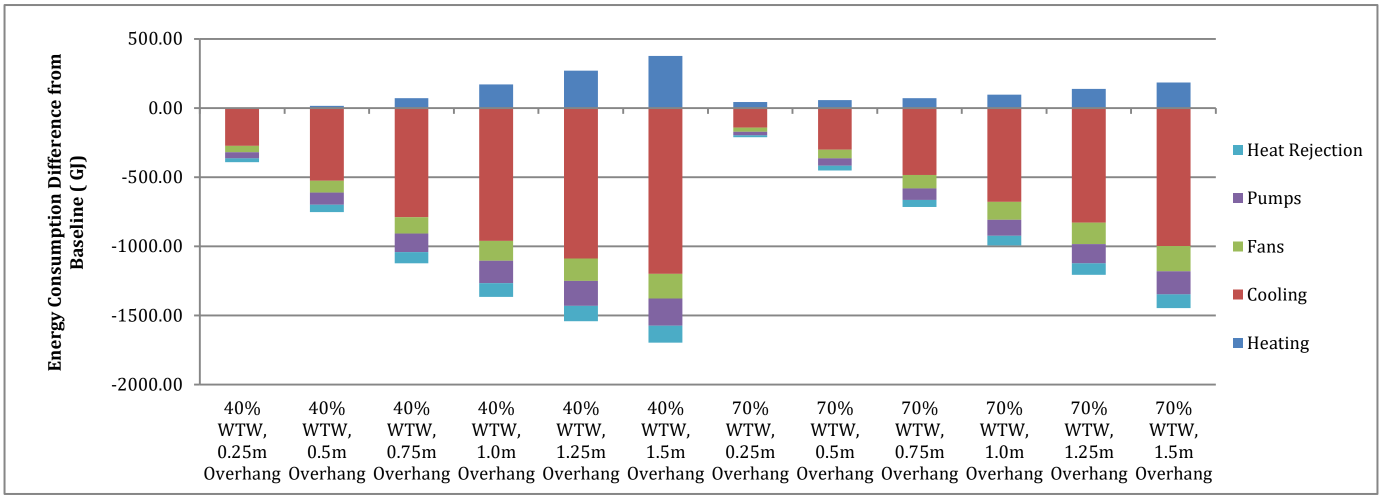

Figure 41: Overhang Depth - Energy Consumption Difference from Baseline - Chicago, IL

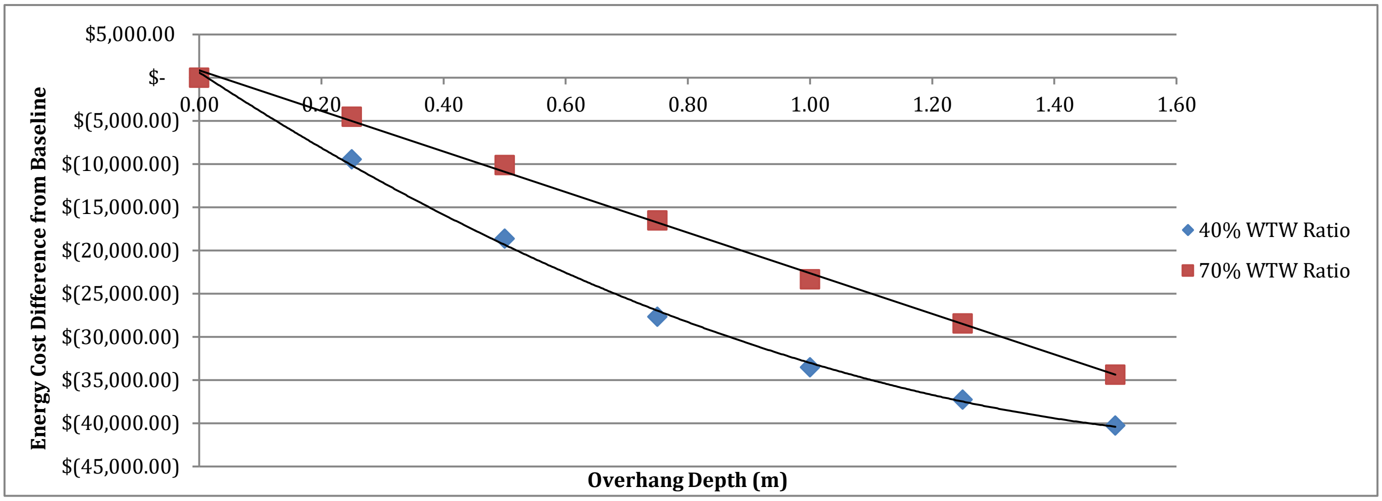

Figure 42: Overhang Depth - Energy Cost Difference from Baseline - Chicago, IL

A Department of Energy and Construction Cost Estimates provides a cost estimate for window overhangs at $12.37/ft for each linear foot of shaded window [92]. The North and South walls are 240 ft in length, and the East and West walls are 160 ft long. Linear length of shaded window for the entire building is 25,600ft. The cost per foot of depth of the overhang is then $316,672/ft depth. The calculations for Miami and Chicago yielded annual utility cost savings for both a 40% WTW ratio and a 70% WTW ratio. As seen in Table 9 the high capital costs associated with implementing overhangs over each window are extremely high, resulting in simple payback periods generally between 25 and 45 years.

The building may outlast the calculated payback period, but most building owners would not agree to implement a strategy with such high payback periods.

When looking at the breakdown of energy consumption by façade, the South and East façades are most affected by the implementation of overhangs. However, while reducing overhangs to these two façades reduces the capital costs, but it also reduces the magnitude of energy cost savings. The payback period is reduced in most climates, but is still 20 to 30 years (Table 10). The results suggest that overhangs in highrise building design are not as cost effective as other strategies may be.

Table 9: Simple Payback Period Calculation for Overhang Depth on All Façades - Miami and Chicago

Depth of Overhang	Miami Annual Cost Savings	Capital Cost	Simple Payback Period	Chicago Annual Cost Savings	Capital Cost	Simple Payback Period
40% WTW Ratio						
0.25m	$ 9,447	$ 259,734	27.49 yrs	$ 14,749	$ 259,734	17.61 yrs
0.5m	$ 18,637	$ 519,469	27.87 yrs	$ 19,991	$ 519,469	25.99 yrs
0.75m	$ 27,661	$ 779,203	28.17 yrs	$ 28,327	$ 779,203	27.51 yrs
1m	$ 33,534	$ 1,038,937	30.98 yrs	$ 36,027	$ 1,038,937	28.84 yrs
1.25m	$ 37,245	$ 1,298,672	34.87 yrs	$ 42,648	$ 1,298,672	30.45 yrs
1.5m	$ 40,252	$ 1,558,406	38.72 yrs	$ 48,001	$ 1,558,406	32.47 yrs
70% WTW Ratio						
0.25m	$ 4,546	$ 259,734	57.13 yrs	$ 6,463	$ 259,734	40.19 yrs
0.5m	$ 10,119	$ 519,469	51.34 yrs	$ 12,701	$ 519,469	40.90 yrs
0.75m	$ 16,533	$ 779,203	47.13 yrs	$ 17,740	$ 779,203	43.92 yrs
1m	$ 23,337	$ 1,038,937	44.52 yrs	$ 23,735	$ 1,038,937	43.77 yrs
1.25m	$ 28,463	$ 1,298,672	45.63 yrs	$ 29,593	$ 1,298,672	43.88 yrs
1.5m	$ 34,386	$ 1,558,406	45.32 yrs	$ 35,573	$ 1,558,406	43.81 yrs

Table 10: Simple Payback Period Calculation for Overhang Depth on South and East Facades – Miami and Chicago

Depth of Overhang	Miami Annual Cost Savings	Capital Cost	Simple Payback Period	Chicago Annual Cost Savings	Capital Cost	Simple Payback Period
40% WTW Ratio						
0.25m	$6,029	$129,867	21.54 yrs	$6,11	$129,867	21.22 yrs
0.5m	$10,995	$259,734	23.62 yrs	$11,831	$259,734	21.95 yrs
0.75m	$15,558	$389,602	25.04 yrs	$17,148	$389,602	22.72 yrs
1m	$19,546	$519,469	26.58 yrs	$19,402	$519,469	26.77 yrs
1.25m	$22,818	$649,336	28.46 yrs	$20,286	$649,336	32.01 yrs
1.5m	$25,162	$779,203	30.97 yrs	$21,306	$779,203	36.57 yrs
70% WTW Ratio						
0.25m	$4,723	$129,867	27.50 yrs	$3,813	$129,867	34.06 yrs
0.5m	$8,280	$259,734	31.37 yrs	$8,330	$259,734	31.18 yrs
0.75m	$12,252	$389,602	31.80 yrs	$13,032	$389,602	29.90 yrs
1m	$15,931	$519,469	32.61 yrs	$18,331	$519,469	28.34 yrs
1.25m	$19,000	$649,336	34.18 yrs	$21,611	$649,336	30.05 yrs
1.5m	$22,334	$779,203	34.89 yrs	$24,709	$779,203	31.54 yrs

5.5 Window U-value

The window U-values for the variable analysis were incrementally reduced from the climate zone-specific ASHRAE 90.1-2010 values down to 0.08 Btu/hr*ft^{2*}°F. The U-value minimum represents the highest thermal performance available from Serious Windows, a company based in Boulder, Colorado that provides products and services related to high performance glazing strategies [90]. The U-value analysis was performed to determine the sensitivity of energy consumption to the window U-value. The effects were considered for a 40% WTW ratio and 70% WTW ratio in order to test how the U-value sensitivity changes at different WTW ratios. The ASHRAE baseline WTW ratio is 40%, and 70% was chosen to represent a WTW ratio that is more typical of current curtain wall design.

The simulation results show that the response of energy consumption to window U-value is not linear. The curves showing percent energy saved from baseline vs. window U-value are more characteristic of second or third order equations, and they are very different across the climate zones. Figure 43 shows a clear point of diminishing returns in terms of energy consumption in Miami around U-0.64 Btu/hr*ft^{2*}°F for a 40% WTW ratio. If the WTW ratio is increased to 70%, the critical point is at U-0.36 Btu/hr*ft^{2*}°F. The

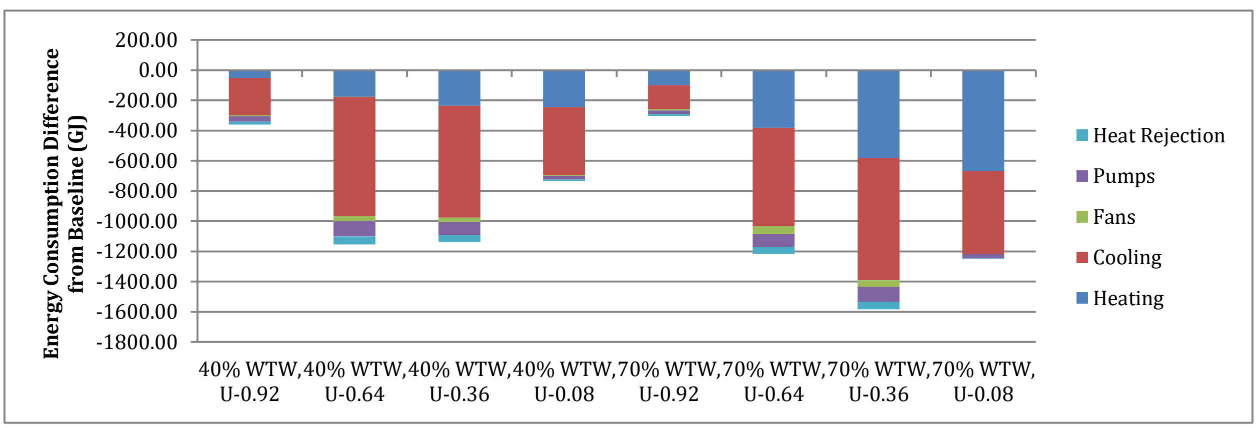

Figure 43: Window U-value - Energy Consumption Change from Baseline – Miami, FL

decrease of U-value reduces both the heat loss and heat gain to the outside environment. Beyond the "critical points" for Miami, any further reduction in U-value acts to trap unwanted internal gains, which increases the need for cooling in the space. The cooling energy required in Miami is much more significant than the heating energy. Figure 44 shows the response of only the cooling energy required in response to window U-value.

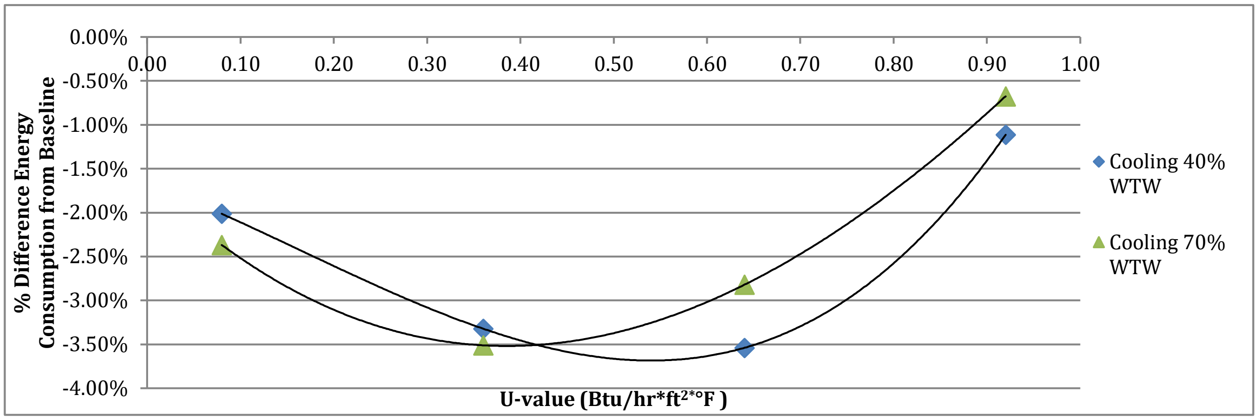

Figure 44: Window U-value – Percent Cooling Energy Savings from Baseline – Miami, FL

The energy relating to heating is more sensitive to changing U-value than the energy related to cooling (Figure 46). For a climate such as Miami where there is little to no heating energy required, even though decreasing the U-value can reduce the heating energy drastically it has very little impact on the overall building energy consumption. For a heating-dominated climate like Chicago, decreasing the window U-value can have a much larger impact on overall building energy consumption. As seen in Figure 45, decreasing the window U-value does increase the required cooling energy, but the decreases in the required heating energy far outweigh the increases in cooling energy.

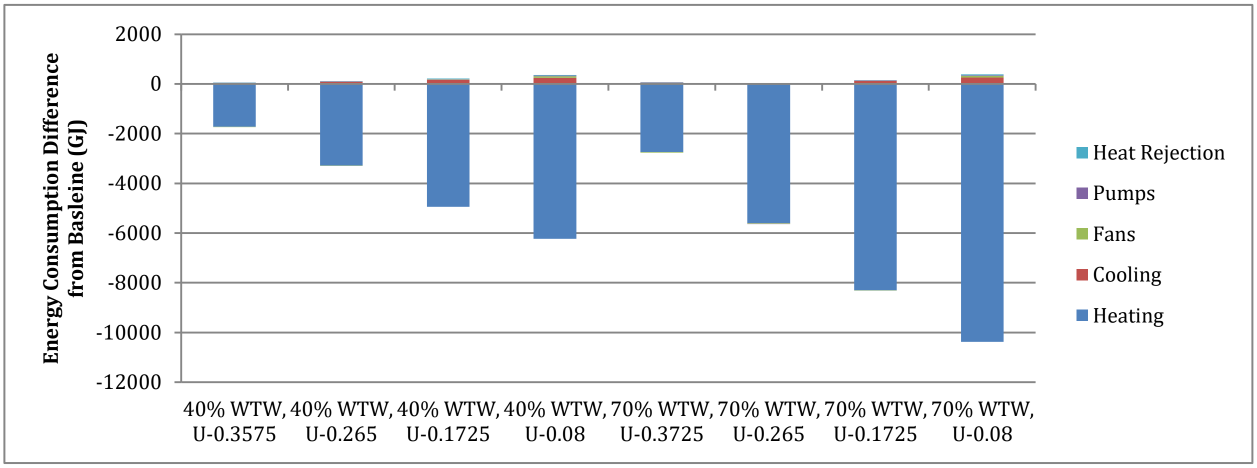

Figure 45: Energy Consumption Change from Baseline - Chicago, IL

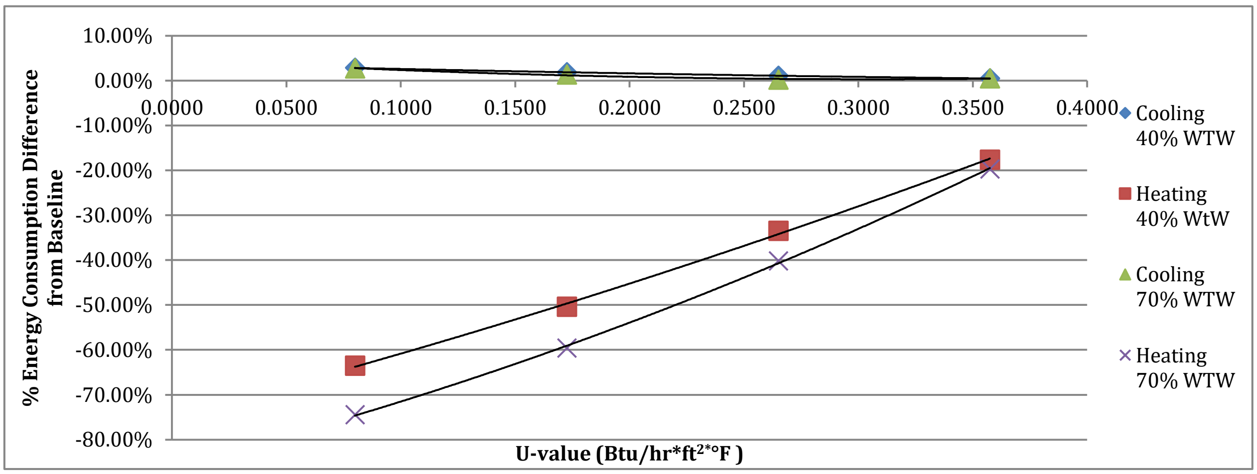

Figure 46: U-value – Percent Heating and Cooling Energy Savings from Baseline - Chicago, IL

Reduction in U-value generally results in substantial cost savings across all the climate zones. The graphs showing cost savings from the baseline for all the climate zones can be seen in Appendix C. The graph of cost savings for Miami (Figure 47) shows two fairly similar, fourth order cost savings trend lines. For both 40% and 70% WTW ratios, the most cost-effective option lies between 0.36 Btu/hr*ft^{2*}°F and 0.64 Btu/hr*ft^{2*}°F. Most of the other cooling-dominated climate zones show a relationship between U-value and energy cost similar to Chicago (Figure 48) that is close to linear, with cost savings increasing as the U-value is decreased. Two outlying climates are Atlanta and San

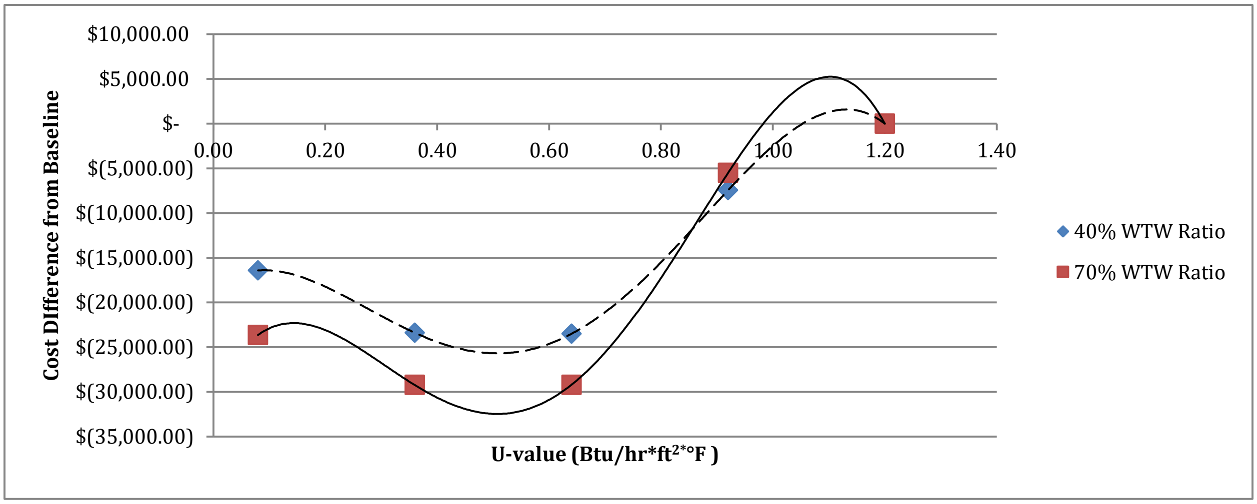

Figure 47: Window U-value - Cost Difference from Baseline - Miami, FL

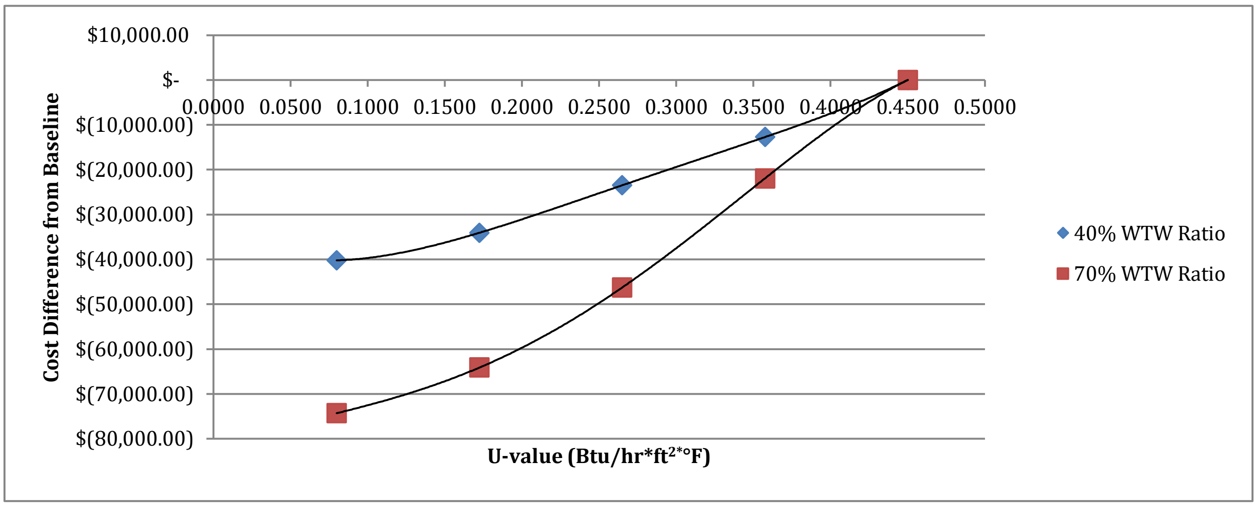

Figure 48: Window U-value - Cost Difference from Baseline - Chicago, IL

Francisco. Atlanta shows similar curves to Miami, in that reducing the U-value to 0.08 Btu/hr*ft^{2}*°F actually increases the cost of energy as compared to a U-0.21 Btu/hr*ft^{2}*°F window. San Francisco is an outlier because as a result of decreasing the U-value, the heat is trapped in the building to the point that the increase in cooling energy costs outweighs the decrease in heating energy reduction. So reduction of U-value is not beneficial in San Francisco in terms of energy cost.

Table 11: Sensitivity of Annual Energy Consumption and Annual Cost to Window U-value

	40% WTW				70% WTW			
Climate	Annual Energy Change $\frac{GJ}{-0.1\ \text{U-value}}$	% Annual Energy Change $\frac{\%GJ}{-0.1\ \text{U-value}}$	Annual Cost Change $\frac{\$}{-0.1\ \text{U-value}}$	% Annual Cost Change $\frac{\%\ \$}{-0.1\ \text{U-value}}$	Annual Energy Change $\frac{GJ}{-0.1\ \text{U-value}}$	% Annual Energy Change $\frac{\%GJ}{-0.1\ \text{U-value}}$	Annual Cost Change $\frac{\$}{-0.1\ \text{U-value}}$	% Annual Cost Change $\frac{\%\ \$}{-0.1\ \text{U-value}}$
Miami, FL	-65.68	-0.10%	-2782.74	-0.19%	-111.43	-0.16%	-3478.81	-0.23%
Houston, TX	-267.64	-0.41%	-4937.74	-0.28%	-506.83	-0.78%	-6335.97	-0.35%
Phoenix, AZ	-372.59	-0.60%	-5069.53	-0.41%	-579.03	-0.88%	-7116.94	-0.56%
Atlanta, GA	-351.89	-0.56%	-3393.08	-0.22%	-837.57	-1.34%	-8351.54	-0.56%
San Francisco, CA	-85.53	-0.17%	4576.92	0.23%	-341.88	-0.64%	5823.27	0.29%
Baltimore, MD	-748.85	-1.17%	-7250.48	-0.65%	-1546.34	-2.43%	-15024.05	-1.31%
Seattle, WA	-770.65	-1.49%	-5268.33	-0.55%	-1446.70	-2.53%	-10318.57	-1.01%
Chicago, IL	-1584.08	-2.58%	-10867.03	-0.80%	-2701.85	-4.03%	-20077.84	-1.40%
Denver, CO	-816.46	-1.54%	-5095.95	-0.97%	-1373.62	-2.42%	-8585.68	-1.55%
Helena, MT	-1097.09	-2.00%	-10499.73	-1.02%	-2497.00	-4.15%	-17363.78	-1.59%
Duluth, MN	-2689.54	-4.22%	-20367.81	-2.25%	-4507.08	-6.41%	-34640.63	-3.56%

Table 11 shows comparison of energy and cost sensitivities across climates. To put the values in useful units, the table shows the change in energy and cost for every 0.1 Btu/hr*ft^{2}*°F that the U-value is decreased. As discussed, San Francisco shows an increase in cost when the U-value is decreased, even though the energy consumption is overall slightly reduced. The cause for this is an increased proportion of cooling energy to heating energy. Energy and cost savings are more sensitive in cooler climates. Increased WTW ratios also increase the generally positive impact of improving the U-value for both overall energy and total utility cost saving potential.

The NREL Technical Support Document provides cost information for a few window assemblies for highrise buildings. The fenestration constructions range from single pane, clear glass to a high performing double pane with low-e and tinted glass. The cost data is associated with specific assemblies, which include a specific SHGC, VT value, and U-value.

The relationships between the U-values and cost are not linear, and there is no database available to provide cost information down to the detail necessary to ascertain the exact cost increase in relation to U-value alone. However, to estimate what potential payback periods may be like for a given climate, two window assemblies with similar SHGC and different U-factors were used to calculate what the change in cost per square foot might be for every 0.1 U-value. A "base" cost of $75.00 was used, and Table shows the results of calculations to determine how much cost would be added per square foot of fenestration to reduce each climate's window U-value to 0.08 Btu/hr*ft^{2*}°F. This was compared with the savings achieved with the same U-value, and a simple payback period was calculated for each climate. As can be seen, some climates achieve very reasonable payback periods under 20 years. Based on a potential life of the window of 20-30 years, some of the cooling-dominated climates would need to replace the windows before any return on investment was made.

Table 12: Estimated Simple Payback Period for Reducing U-value to 0.08 Btu/hr*ft^{2*}°F

Climate	change in U-value	increased cost/sqft	base cost	best U-value cost	Increased cost (40% WTW)	Annual Savings	Payback Period	Increased cost (70% WTW)	Annual Savings	Payback Period
Miami, FL	0.84	6.599	$75.00	$81.60	$878,099	$ 16,410	**53.51**	$1,534349	$23,640	**64.90**
Houston, TX	0.62	4.870	$75.00	$79.87	$648,121	$ 30,614	**21.17**	$1,132,496	$39,283	**28.83**
Phoenix, AZ	0.62	4.870	$75.00	$79.87	$648,121	$ 31,431	**20.62**	$1,132,496	$44,125	**25.67**
Atlanta, GA	0.52	4.085	$75.00	$79.08	$543,585	$ 3,980	**136.58**	$ 949,835	$31,575	**30.08**
San Francisco, CA	0.39	3.064	$75.00	$78.06	$407,688	-	-	$ 712,376	-	-
Baltimore, MD	0.42	3.299	$75.00	$78.30	$439,050	$ 30,452	**14.42**	$ 767,175	$63,101	**12.16**
Seattle, WA	0.42	3.299	$75.00	$78.30	$439,050	$ 22,127	**19.84**	$ 767,175	$43,338	**17.70**
Chicago, IL	0.37	2.906	$75.00	$77.91	$386,782	$ 40,208	**9.62**	$ 675,844	$74,288	**9.10**
Denver, CO	0.37	2.906	$75.00	$77.91	$386,782	$ 18,855	**20.51**	$ 675,844	$31,767	**21.28**
Helena, MT	0.37	2.906	$75.00	$77.91	$386,782	$ 38,849	**9.96**	$ 675,844	$64,246	**10.52**
Duluth, MN	0.4	3.142	$75.00	$78.14	$418,143	$ 65,177	**6.42**	$ 730,643	$110,850	**6.59**

The simple payback periods calculated in this process are estimates. The actual cost of the window assembly would actually be based on a quote from a specific manufacturer and based on the entire curtain wall assembly design. Components impacting the cost include window U-value, window SHGC, VT values, curtain wall assembly type, and labor costs. Labor costs have been built into the cost per square foot values listed in the NREL Technical Support Document. However, in reality, the U-0.08 Btu/hr*ft^{2}*°F fenestration from Serious glass is a multi-pane assembly with a somewhat complex construction process, so that may increase the capital cost of the curtain wall assembly. What Table 12 does show is the order of magnitude of the potential cost increase and payback period for the improved window U-value, as well as how the information from the U-value analysis could be used to help guide future design processes. Through careful design, dependent on reasonable cost quotes from curtain wall suppliers, improving the window U-value appears to be a viable option for many climates, and specifically for heating-dominated climates.

5.6 Window Solar Heat Gain Coefficient

The SHGC is responsible for controlling the amount of solar gains allowed into the space. The range of SHGCs used for the sensitivity analysis was 0.2-0.6. This range is representative of realistic potential SHGCs available on the current market.

Figures 49-52 show how the required heating and cooling energy changes as the SHGC increases. The change in energy consumption is due to the added heat gains through the envelope, and the required HVAC energy to remove those gains from the space. The

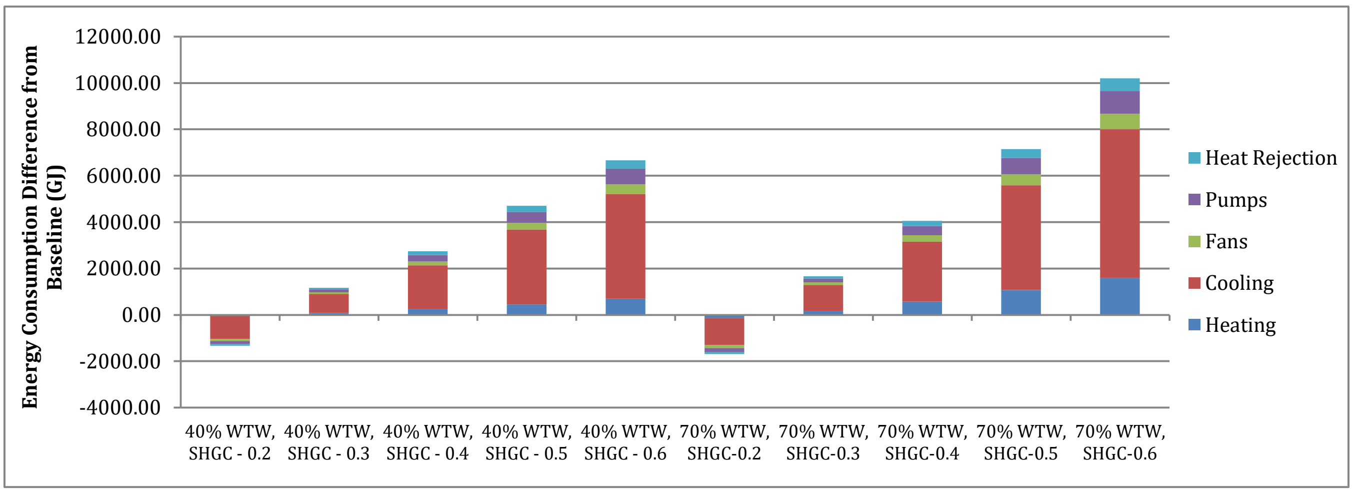

Figure 49: SHGC - Energy Consumption Difference from Baseline - Miami, FL

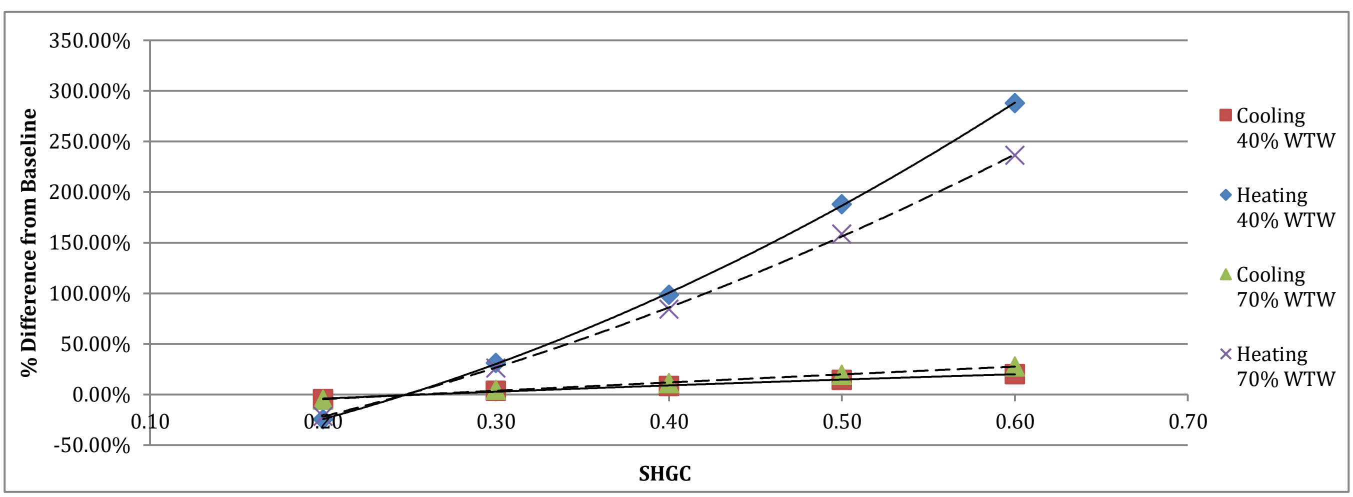

Figure 50: SHGC - Heating and Cooling Energy Consumption Percent Difference from Baseline - Miami

In cooling-dominated climates, the recommended approach is usually to minimize solar heat gains. The linear relationship between energy consumption and SHGC in Figure 49 confirms this strategy is appropriate for highrise buidlings in hot climates such as Miami. Increasing the SHGC in cooling-dominated climates is much more detrimental to the overall energy consumption than in heating-dominated climates. In moderate to more heating-dominated climates the solar gains in the space reduce the heating energy required on colder days. In many cases, the reduced heating energy exceeds the additional cooling energy required when the SHGC is increased.

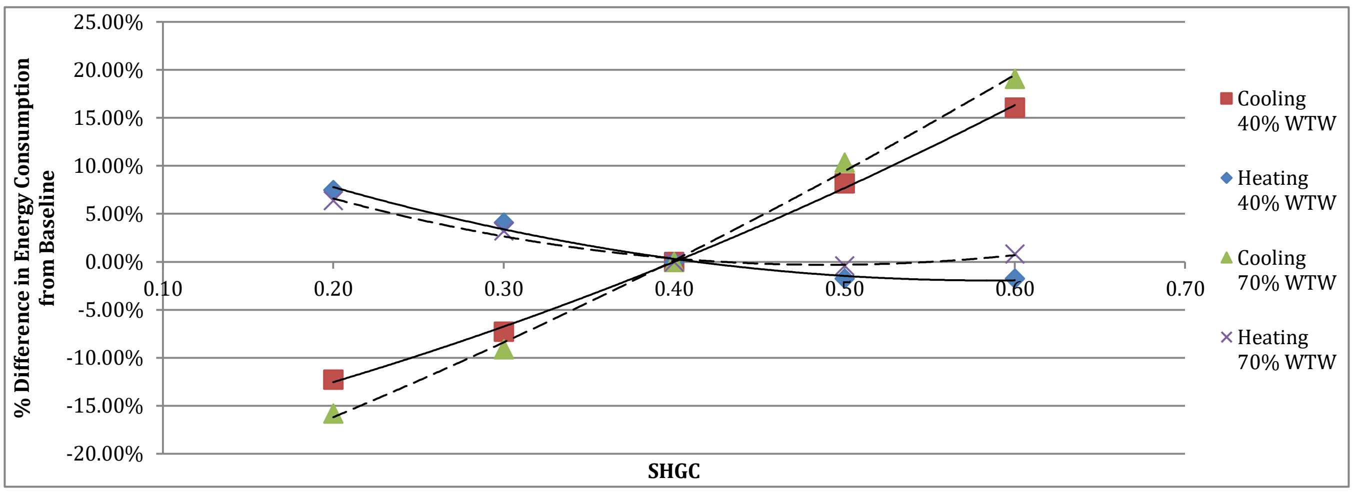

Figure 51: SHGC - Heating and Cooling Energy Consumption Percent Difference from Baseline - Chicago, IL

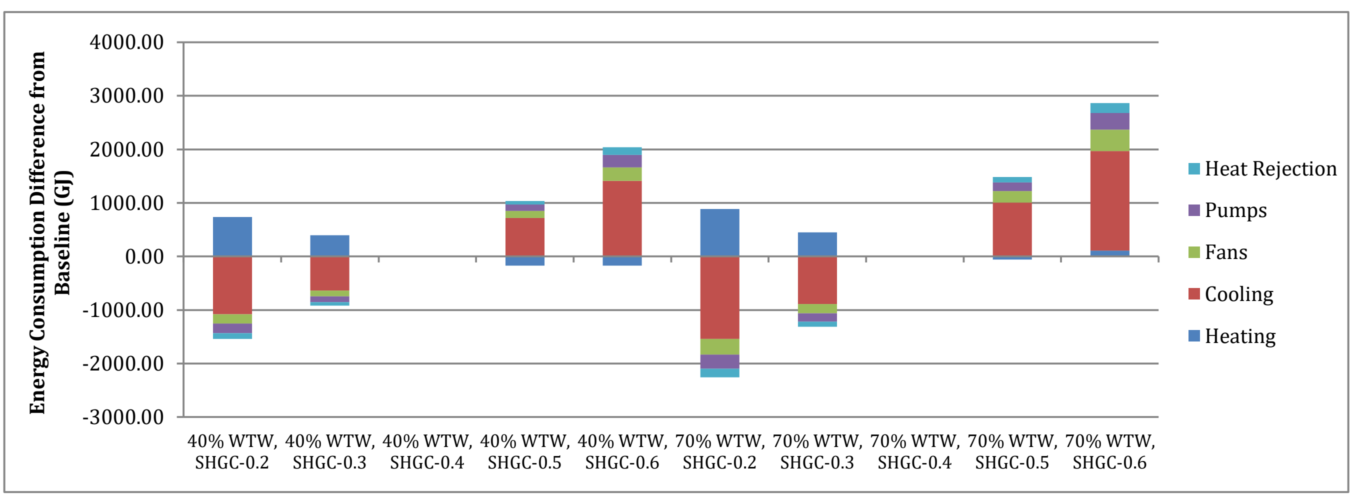

Figure 52: SHGC - Energy Consumption Difference from Baseline - Chicago, IL

The figures for all climate zones can be seen in Appendix D These graphs show that as the graphs move from climate zone 1A to 7, the increased SHGC becomes less detrimental to the cooling energy consumption. In Chicago and Duluth, an increase in SHGC beyond ASHRAE 90.1-2010 requirements results in a decrease in the amount of heating energy required. However, because of the additional cooling energy required, the drawbacks outweigh benefits. ASHRAE 90.1-2010 dictates a prescriptive requirement for a maximum SHGC of 0.25 for Miami's climate. Because not many products on the market have SHGC's much lower than 0.25, the opportunities to improve the energy consumption in a highrise building beyond code requirements are limited when assessing SHGC.

Table 13: Sensitivity of Annual Energy Consumption and Cost with respect to change in SHGC

	40% WTW				70% WTW			
Climate	Annual Energy Change (GJ/0.1SHGC)	% Annual Energy Change (%GJ/0.1SHGC)	Annual Cost Change ($/0.1 SHGC)	% Annual Cost Change (% $/0.1 SHGC)	Annual Energy Change (GJ/0.1SHGC)	% Annual Energy Change (%GJ/0.1SHGC)	Annual Cost Change ($/0.1SHGC)	% Annual Cost Change (% $/0.1 SHGC)
Miami, FL	190.49	0.28%	$ 37,201.14	2.48%	204.34	0.42%	$ 55,818.00	3.65%
Houston, TX	189.71	0.29%	$ 44,256.86	2.47%	169.12	0.37%	$ 59,253.43	3.28%
Phoenix, AZ	164.33	0.26%	$ 23,112.05	1.88%	171.36	0.38%	$ 42,411.71	3.32%
Atlanta, GA	173.01	0.28%	$ 40,396.00	2.62%	127.55	0.31%	$ 42,712.57	2.85%
San Francisco, CA	165.37	0.33%	$ 49,758.57	2.52%	173.53	0.47%	$ 75,115.14	3.71%
Baltimore, MD	197.34	0.31%	$ 30,120.50	2.70%	91.23	0.28%	$ 35,166.50	3.07%
Seattle, WA	168.28	0.32%	$ 24,466.00	2.54%	130.75	0.45%	$ 36,716.50	3.58%
Chicago, IL	93.35	0.15%	$ 23,948.00	1.76%	71.35	0.21%	$ 33,408.00	2.33%
Denver, CO	106.86	0.20%	$ 10,377.50	1.98%	82.80	0.28%	$ 15,610.50	2.81%
Helena, MT	79.39	0.14%	$ 17,560.00	1.70%	63.95	0.22%	$ 27,865.50	2.56%
Duluth, MN	23.19	0.04%	$ 9,736.67	1.07%	18.42	0.08%	$ 16,224.00	1.67%

While the change in energy consumption may not be large, it does have significant implications for utility costs. Because the change of cost and energy consumption are both approximately linear (Figures 53-56), it allows for the calculation of change from the baseline per increase of 0.1 SHGC. The values are shown in Table 13, which shows the sensitivity of energy consumption and cost as they relate to SHGC. As pointed out earlier, energy consumption in cooler climates is less responsive to SHGC. However, because of the different utility rates and because cost of electricity is generally higher than gas, the percent change in annual utility costs is relatively similar across all climates. However, the utility cost savings achieved could justify additional costs incurred by installing a window with a lower SHGC.

Table 14: Estimated Simple Payback Period for Reducing SHGC

Climate	change in SHGC	Increased Cost/sqft	Base Cost	Cost for "Best" SHGC	Increased cost (40% WTW)	Annual Savings	Payback Period	Increased cost (70% WTW)	Annual Savings	Payback Period
Miami, FL	0.05	0.409	$75.00	$75.41	$54,490	$26,871	2.03	$95,212	$32,897	2.89
Houston, TX	0.05	0.409	$75.00	$75.41	$54,490	$25,896	2.10	$95,212	$33,050	2.88
Phoenix, AZ	0.05	0.409	$75.00	$75.41	$54,490	$16,909	3.22	$95,212	$24,190	3.94
Atlanta, GA	0.05	0.409	$75.00	$75.41	$54,490	$26,144	2.08	$95,212	$22,470	4.24
San Francisco, CA	0.05	0.409	$75.00	$75.41	$54,489	$26,359	2.07	$95,212	$41,172	2.31
Baltimore, MD	0.2	1.638	$75.00	$76.64	$217,958	$36,392	5.99	$380,850	$45,705	8.33
Seattle, WA	0.2	1.638	$75.00	$76.64	$217,958	$37,266	5.85	$380,850	$57,553	6.62
Chicago, IL	0.2	1.638	$75.00	$76.64	$217,958	$32,974	6.61	$380,850	$48,903	7.79
Denver, CO	0.2	1.638	$75.00	$76.64	$217,958	$14,035	15.53	$380,850	$18,866	20.19
Helena, MT	0.2	1.638	$75.00	$76.64	$217,958	$20,951	10.40	$380,850	$31,885	11.94
Duluth, MN	0.25	2.047	$75.00	$77.05	$272,448	$15,255	17.86	$476,062	$26,477	17.98

As with the U-value, cost savings and simple payback period were calculated from the cost information available from NREL. There are two window assemblies with the same U-value and different SHGC. Without a detailed database that provides the exact cost of the particular assemblies in the models, the cost must be extrapolated from the NREL data. Simple payback periods were calculated for reducing the SHGC in each climate to 0.2. Not surprisingly, the cooling-dominated climates show payback periods under 10 years. However, if the real cost of decreasing the SHGC as anywhere near the $8.2/SHGC used for this estimation, then initial capital cost will be offset in a reasonable amount of time. In combination with an optimal U-value, the payback period of the envelope improvements would be attractive to any building owner.

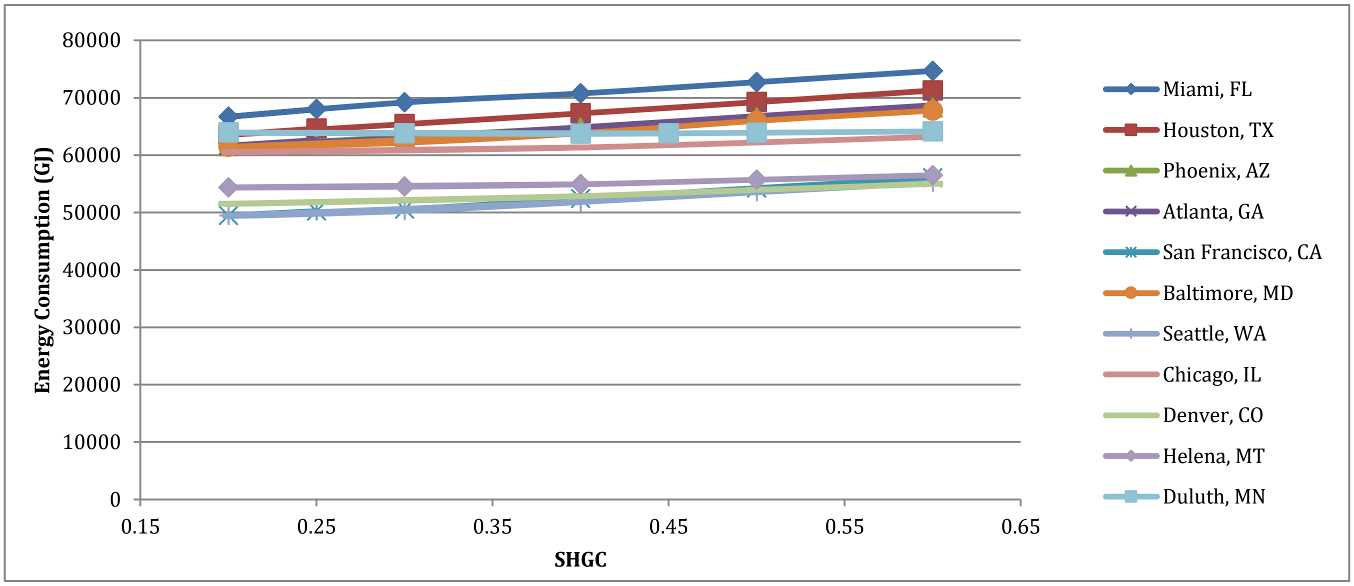

Figure 53: SHGC - Annual Energy Consumption vs. Solar Heat Gain Coefficient - 40% WTW Ratio

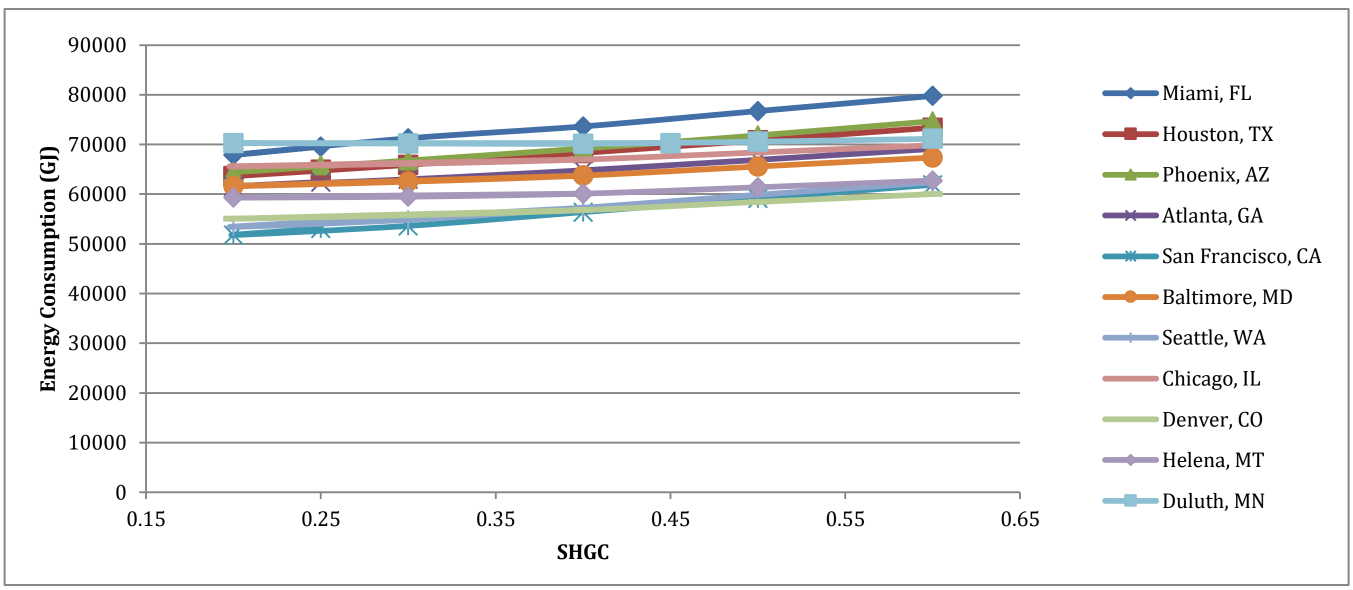

Figure 54: SHGC - Annual Energy Consumption vs. Solar Heat Gain Coefficient - 70% WTW Ratio

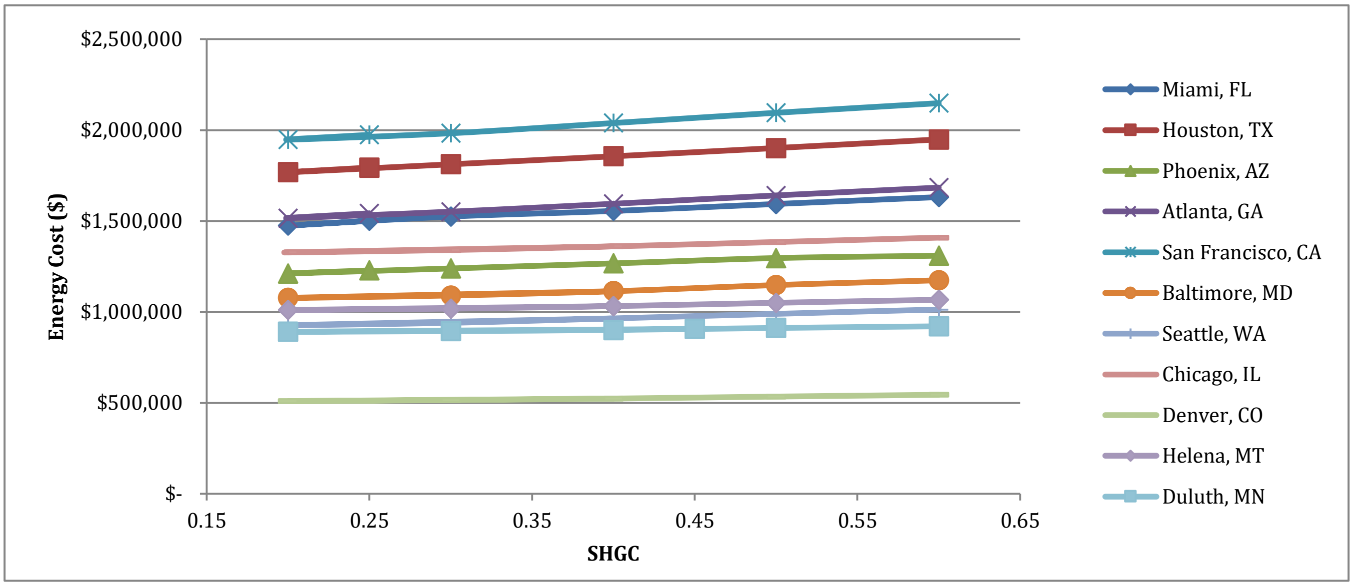

Figure 55: Annual Energy Cost vs. Solar Heat Gain Coefficient - 40% WTW Ratio

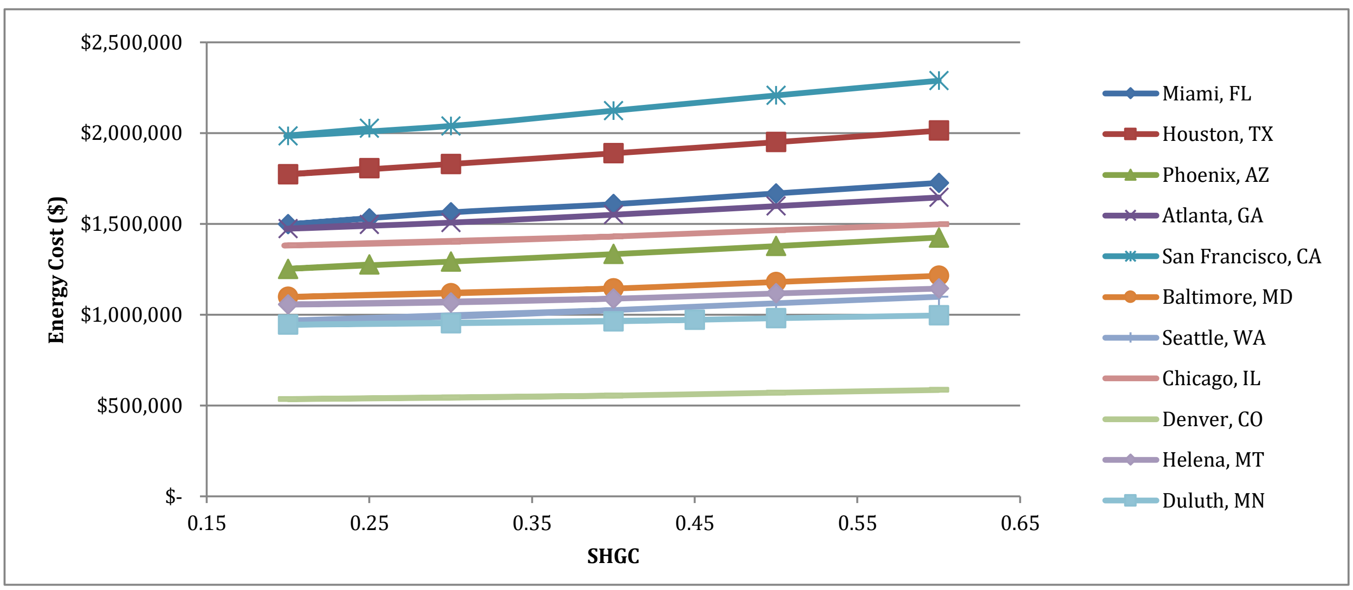

Figure 56: Annual Energy Cost vs. Solar Heat Gain Coefficient - 70% WTW Ratio

5.7 Impacts of Daylight Control

Daylight Control is an often-used energy conservation method that involves the installation of sensors within the space that feed a control system that keeps the illuminance in the space at a set value. For offices a typical value is 500lux. AHSRAE 90.1-2010 [88] now requires photocell daylighting controls when the "primary sightlighted area in an enclosed space equals or exceeds 250ft^2." Most offices would fit this criteria, so daylighting of exterior zones has become standard practice. Daylighting takes advantage of useful light as it penetrates the glazing, and reduces the lighting power to meet the illuminance setpoint of the space. While daylight control is not part of the envelope design, variables such as window-to-wall ratio, SHGC, and overhang depth can have a major influence on the effectiveness of daylight control. Simulations were run with added daylight control to determine whether the addition of daylight control would impact the sensitivity of these variables. Daylighting sensors were assigned to the center of each perimeter façade zone at the height of the work plane, and were assigned a conservative setpoint of 500lux.

EnergyPlus offers two different daylight control calculation methodologies: Detailed and DELight. The main differences between the two methods are that DELight can analyze complex fenestration and shading devices, and that DELight calculates interior refelctions with a radiosity method. There are a few other differences in the calculations, outlined in EnergyPlus documentation. The most critical attribute to assess when selecting a methodology is accuracy of the calcualtion. Todd Gibson performed a validation study of several different daylighting software packages, including EnergyPlus Detailed calculations and EnergyPlus DELight [97]. Gibson compared each software to measured experimental data and found that the Detailed calculations offered a much more realistic approximation for the illuminance on the work plane at different sensor locations, varying exterior illuminance conditions, and did not dramatically increase simulation time. For these reasons, the detailed method was utilized for this analysis.

By just implementing the daylight control in the baseline highrise, immediately Miami and Chicago each experience around $50,000 annual cost savings. The NREL Technical Support Document cites a study performed by RMH Group in 2010 that estimated the cost of implementing daylighting controls at $0.55/ft^2 of daylit area. The capital cost of the daylight control system for this particular model is $195,275. Given the yearly cost savings of implementing the daylighting, the payback period would be around 4 years, and well worth the initial investment.

5.7.1 Daylight Control and Window-to-wall Ratio

The response of energy cost to increased WTW ratio is very similar in the cases with daylight control and without. Adding daylight control reduces the change in cost for each percent of increased WTW ratio by $408/(%WTW). Chicago is even less impacted by the addition of daylight in the WTW ratio cases, with a reduction of only $49/(%WTW).

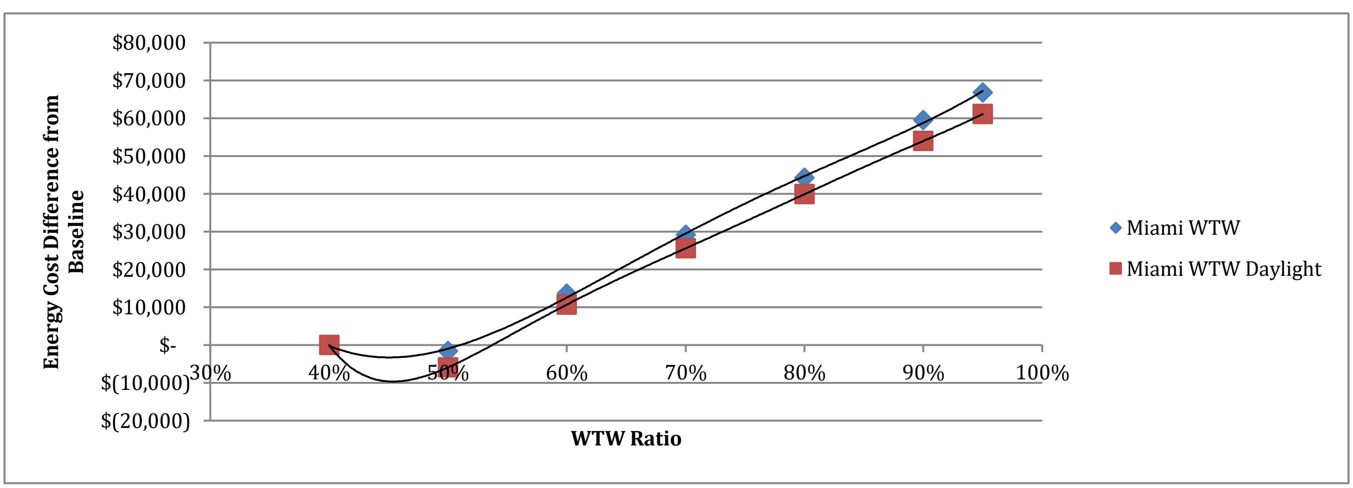

Figure 57: Daylight Comparison - Energy Cost Difference from Baseline - Miami, FL

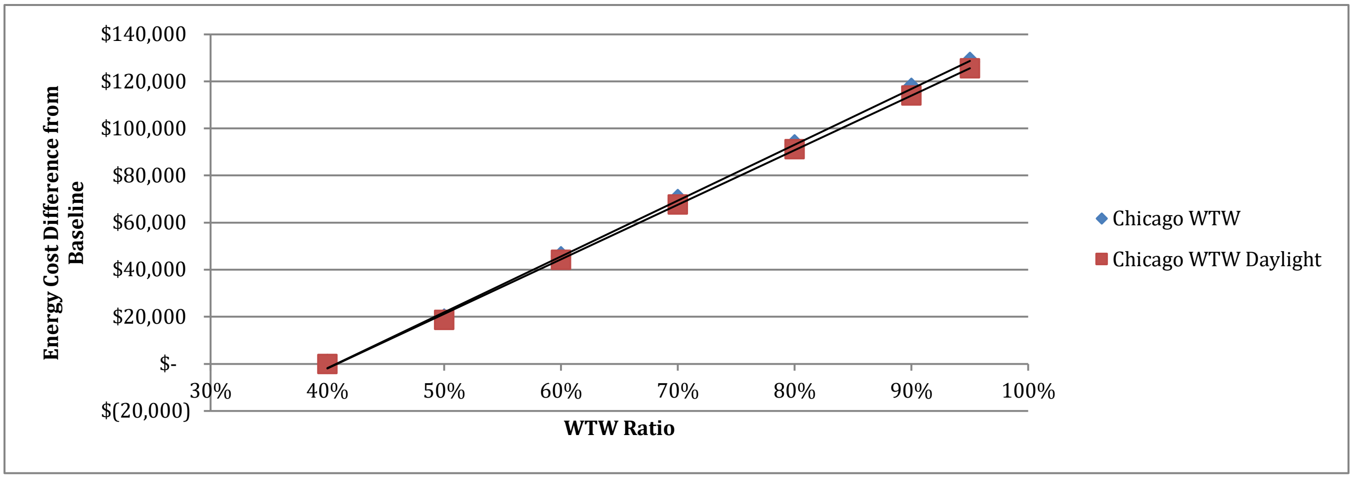

Figure 58: Daylight Control - Energy Cost Difference from Baseline - Chicago, IL

5.7.2 Daylight Control and Overhang Depth

Although overhangs were ruled out earlier because of lack of cost-effectiveness, simulations were performed to be able to understand the impact of overhangs with daylight control strategies. Figure 59 and Figure 60 show the response of annual energy costs to increased overhang depth. The cases with daylight control show an increase in energy cost compared to the simulations without daylight control. In order to compensate for the incident light that is blocked by the overhangs, the lighting power is increased within the space. It is much more beneficial to have daylight control and no overhangs.

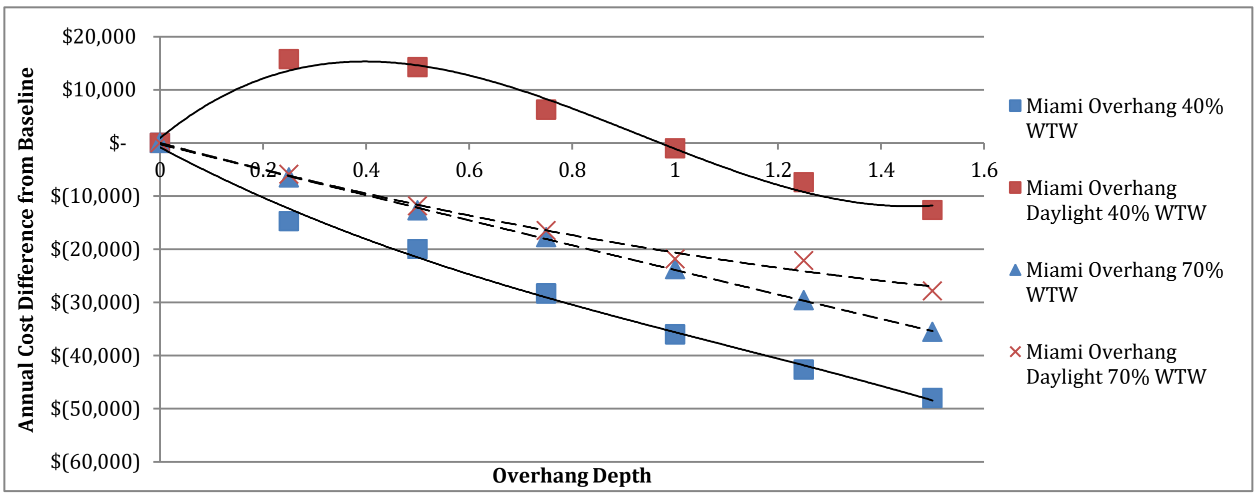

Figure 59: Overhang Depth - Annual Energy Cost Difference from Baseline - Miami

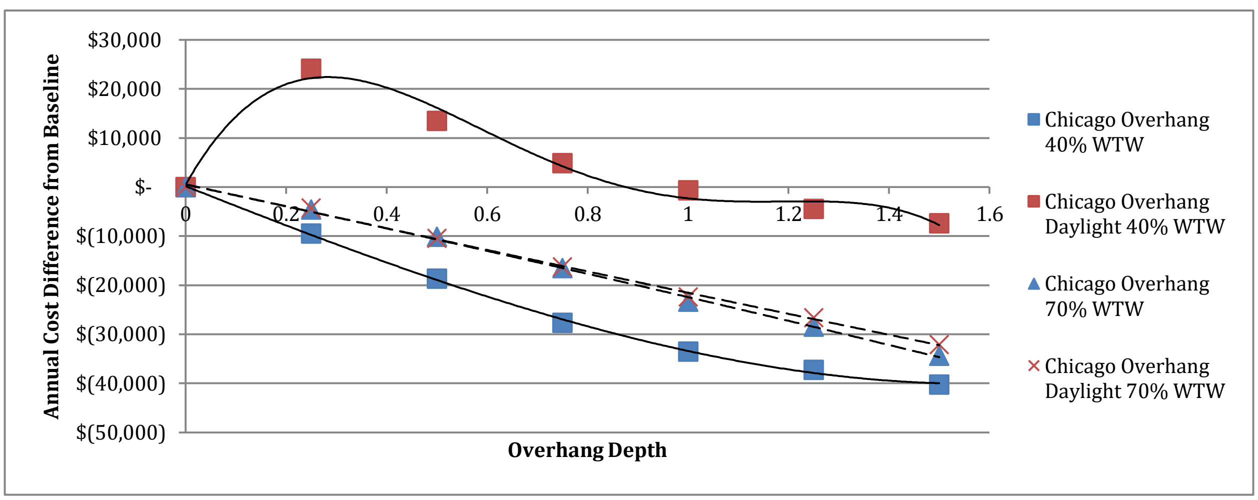

Figure 60: Overhang Depth - Annual Energy Cost Difference from Baseline - Chicago

5.7.3 Daylight Control and Visible Transmittance

The most significant contributor to increasing the savings available with daylight control is the visible transmittance of the glazing. Glazing is selected based on a combination of U-value, SHGC, and VT. Windows higher VT are desirable for their ability to maintain the integrity of the views out of the space, but as discussed in Chapter 2, issues with glare are common in buildings with high window-to-wall ratios. Besides view, another benefit to VT is that it allows (or blocks, depending on what is desired) visible light to enter the space, in proportion to its value. The Miami Highrise Baseline had a visible .transmittance of 0.11, and the Chicago starting value was 0.315. VT values of 0.3-0.9 were

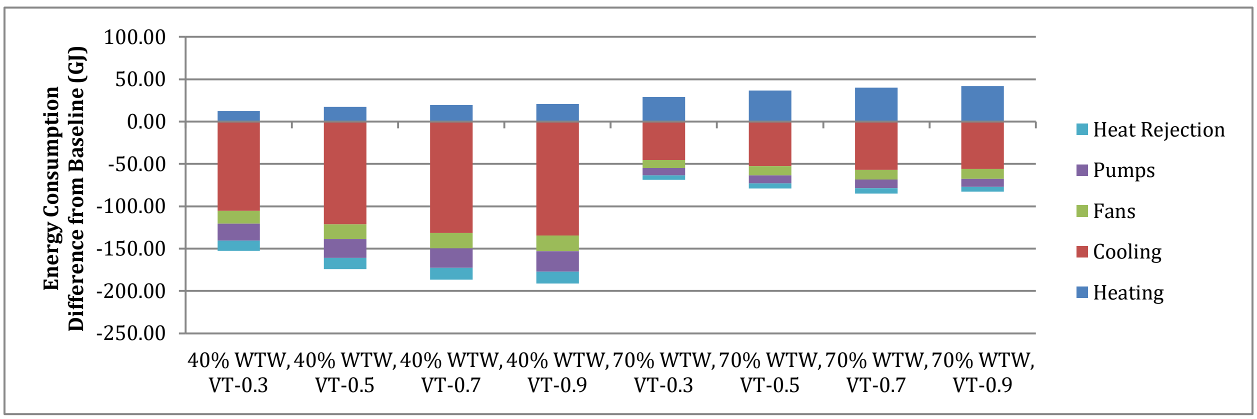

Figure 61: Visible Transmittance – Annual Energy Consumption Difference from Daylight Control Baseline - Miami, FL

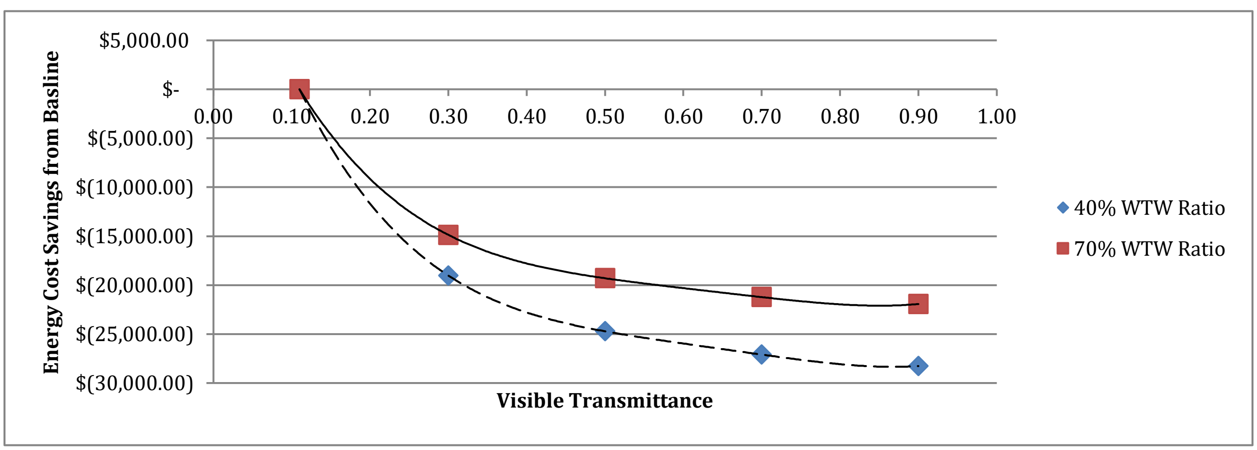

Figure 62: Visible Transmittance - Annual Energy Cost Difference from Daylight Control Baseline - Miami, FL

tested with daylight controls on, and the results showed measureable savings in cooling-dominated climates like Miami, and much less impact in Chicago.

The higher transmittance values allow more usable light into the space, which results in savings in lighting power. The reduced lighting gains to the space reduce the cooling load, and increase the heating load. The "baseline" case for these calculations is the Highrise Baseline model with continuous daylight controls added. The VT levels tested in Miami show that the response of energy consumption energy cost to visible transmittance is not linear. The other cooling-dominated climates (Zones 1-3) show curves similar in shape to that of Miami (Appendix E). As VT values increase beyond 0.5, the benefits of increasing the visible transmittance begin to diminish. The critical area shown on the cost curves between 0.3 and 0.5 transmittance provides a useful range for both energy efficient and cost-effective design. This range also correlates to values that allow for some of the glare drawbacks to be avoided while still taking advantage of the energy savings.

The increased VT in Chicago results in savings, but they are one tenth of the annual cost savings available to a cooling climate like Miami. The other heating-dominated climates share the same magnitude of energy savings and shape of the cost curves. Because there is not a substantial impact of VT on energy consumption or cost, the VT should be selected based on its optical properties to provide for occupant comfort.

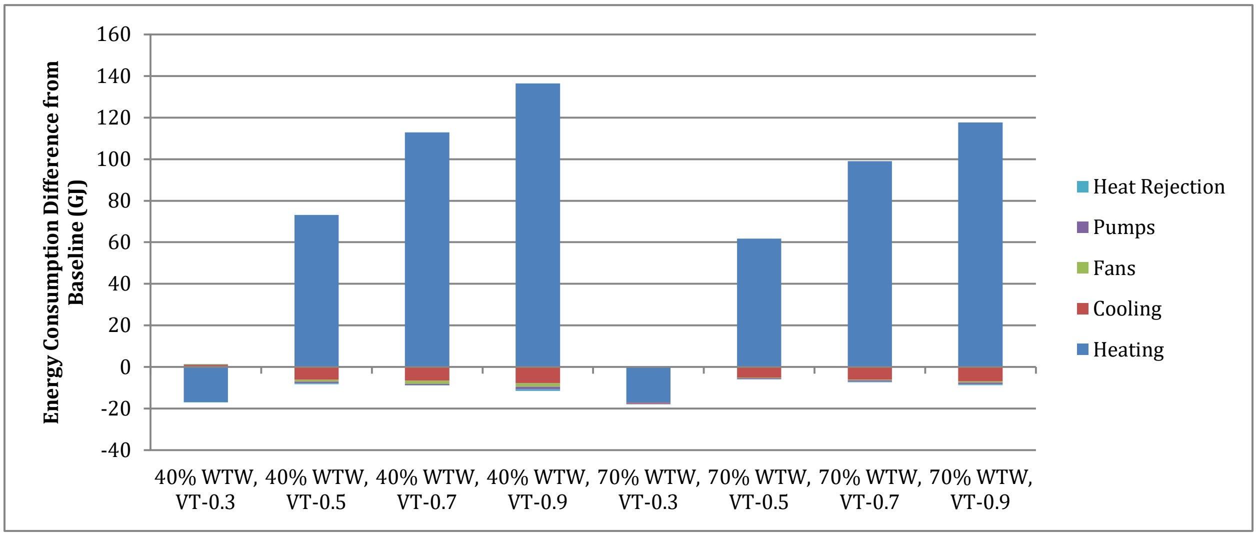

Figure 63: Visible Transmittance - Annual Energy Consumption Difference from Daylight Control Baseline - Chicago, IL

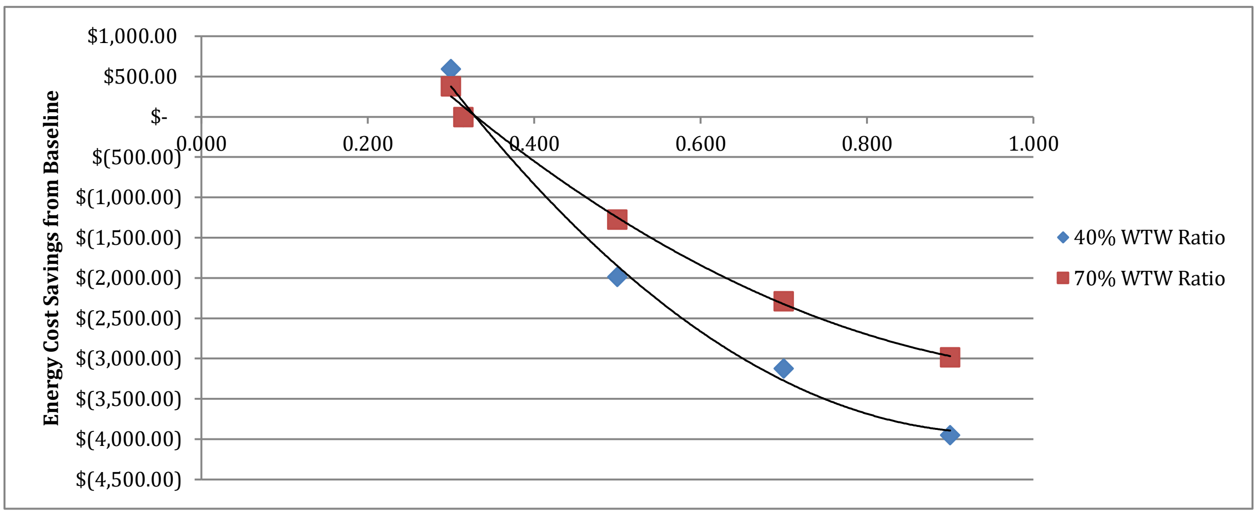

Figure 64: Visible Transmittance - Annual Energy Cost Difference from Daylight Control Baseline - Chicago, IL

There is no cost data available that provides a direct relationship between VT and cost per square foot of glazing, so no payback period can be calculated for VT. It is very difficult to isolate any of the window parameters from the others. However, a visible transmittance value appropriate for the climate and for the occupants clearly can provide energy savings, cost savings, and a comfortable space.

Chapter 6: Parametric Analysis of Window Properties

6.1 Parametric Analysis of Window Properties

The sensitivity analyses in Chapter 5 provide useful insight as to which variables have the most significant impacts on overall building energy consumption. Because of the high window-to-wall ratio and the more critical energy path in the walls of the glazing, annual energy consumption and cost were not very sensitive to changes in the wall U-values for a highrise building with a curtainwall construction. The analysis of the adjustment of WTW ratio showed that setting a maximum WTW ratio of 50% is beneficial for all climates, and limiting it to 40% is beneficial in all climate zones “higher” than climate zone 3A. Although the argument for limiting WTW ratio for the purposes of limiting energy consumption is compelling, there are tradeoffs such as view and aesthetics to consider. These are a few of the driving factors that have led to WTW ratios more typically around 70% in current high-rise buildings. Overhangs are typically cost-prohibitive in highrise building design, although they do result in reduced energy consumption. Window U-value, SHGC, VT, and daylighting controls had the greatest energy consumption impacts, and made the most compelling economic cases as well.

Chapter 5 showed that the critical highrise wall properties are the glazing properties. Therefore, a more thorough analysis of curtainwall performance focused on the glazing properties was performed. When selecting glazing for an assembly, all three window properties must be specified: U-value, SHGC, and VT. While the Chapter 5 analyses held all variables constant except for the variable of interest, in real-world applications all three window properties are subject to change. In order to understand the interaction between the three properties, a parametric analysis was performed.

The WTW ratio for the parametric analysis was held constant at 70% WTW ratio, to represent a typical WTW ratio for current curtainwall designs. Daylighting was modeled (at a 500 lux setpoint) because it has become standard practice, and in many jurisdictions, required by code. Enabling daylighting controls of the interior lighting also allows for a better understanding of all the energy tradeoffs possible via adjusting the window properties. Overhangs were not modeled in light of the high initial cost of incorporating them into the design.

The parametric analysis was performed in all climate zones previously assessed, and the following window properties were analyzed:

Table 15: Window Properties for Parametric Analysis

U-value	SHGC	VT
0.08	0.1	0.3
0.2	0.2	0.5
0.4	0.3	0.7
0.6	0.4	0.9
0.8	0.5	
	0.6	

6.1.1 Sensitivity Analysis

A sensitivity analysis was performed for each of the glazing properties with the expanded results dataset. Figures 65-73 show the results for Miami, FL and Chicago, IL. Figures 65-67 show the annual energy consumption as SHGC, U-value, and VT are varied, respectively, for Miami, FL. As can be seen in the figures, the SHGC is the most crucial glazing property for climate zone 1A. Higher glazing U-values slightly reduce the annual energy consumption, so an optimized glazing selection would minimize SHGC as much as possible, while allowing the U-value to be as high as possible. The VT has relatively low impact on the energy consumption, and should also be maximized for daylighting potential as well as view, aesthetics, and quality of light.

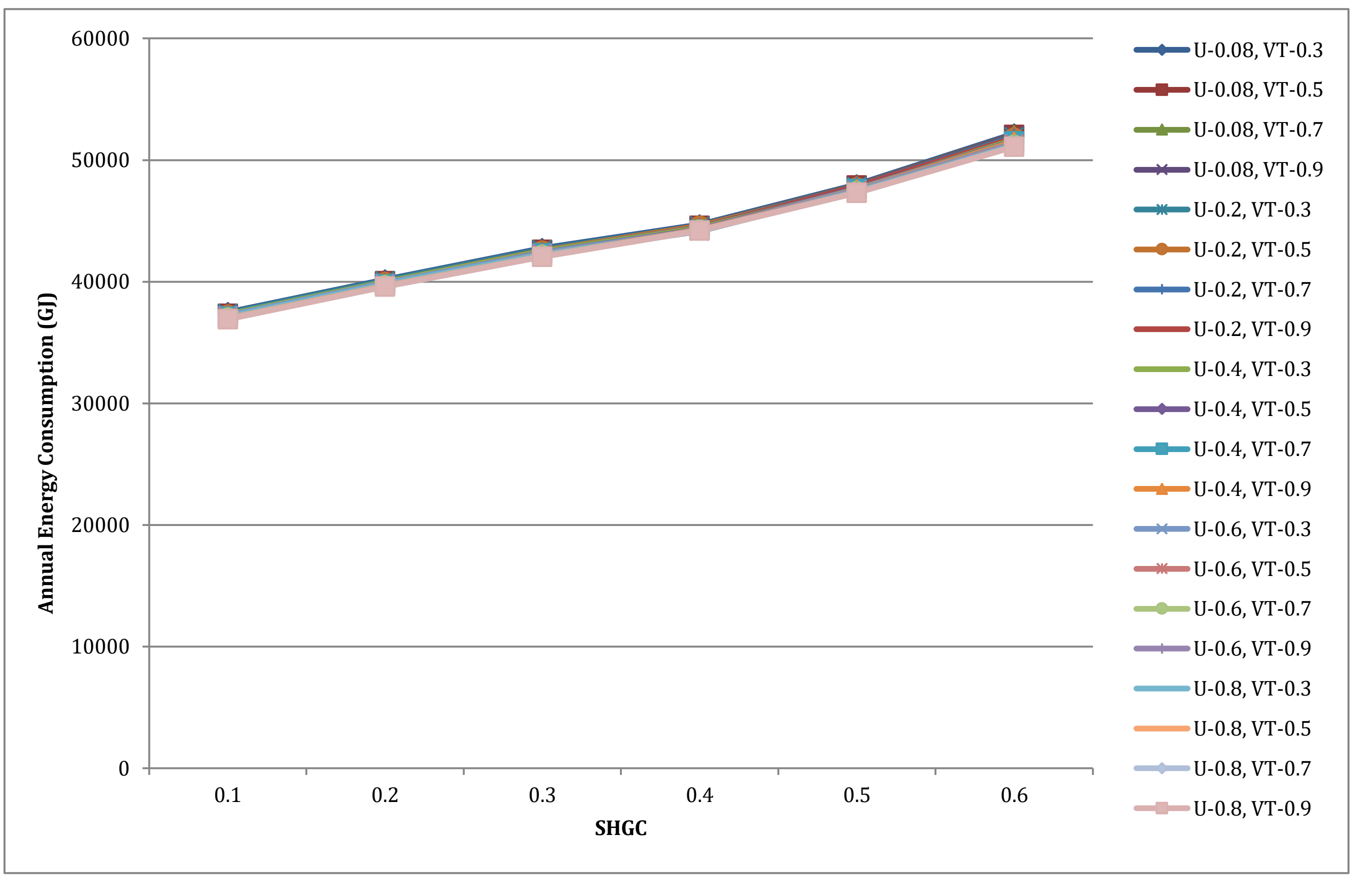

Figure 65: Annual Energy Consumption vs SHGC - Miami, FL

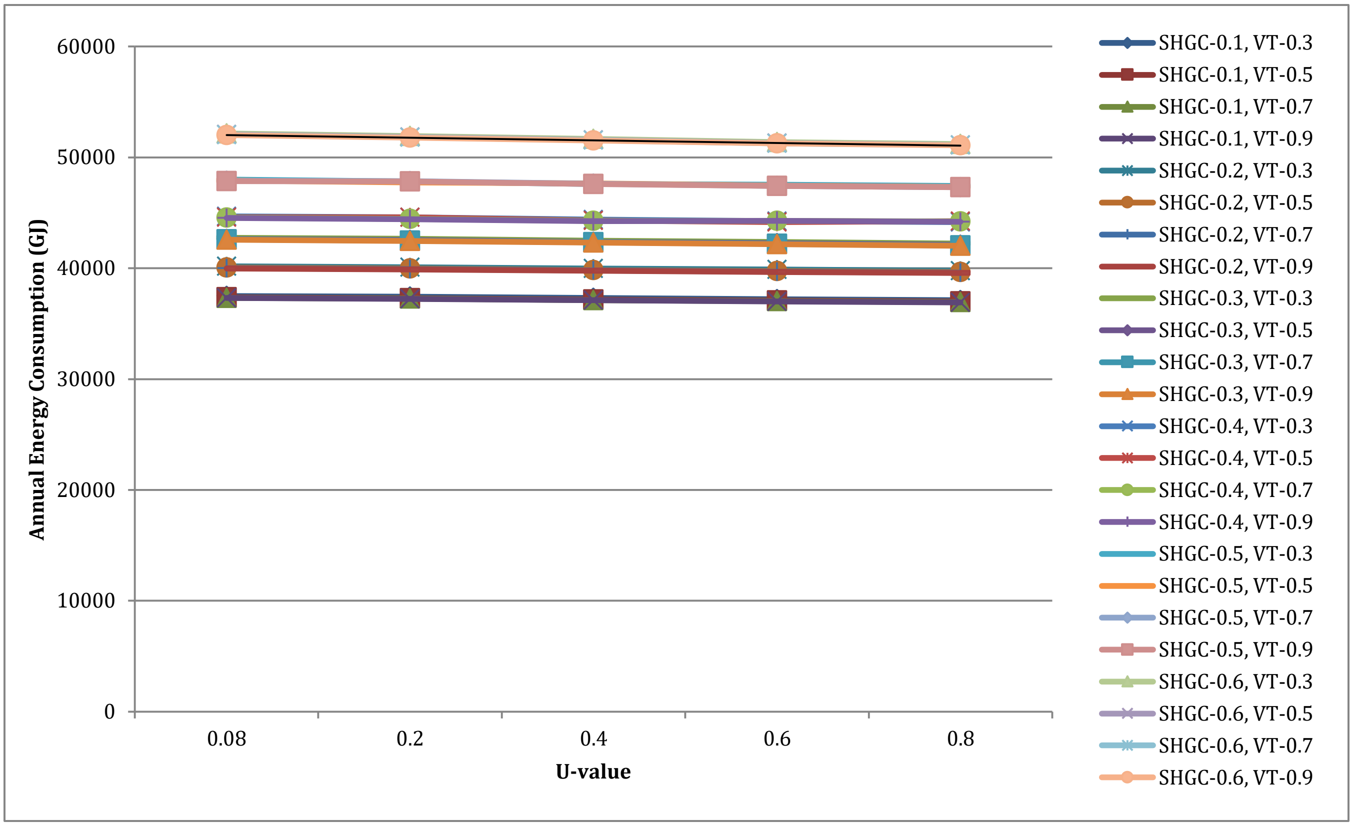

Figure 66: Annual Energy Consumption vs. U-value – Miami,FL

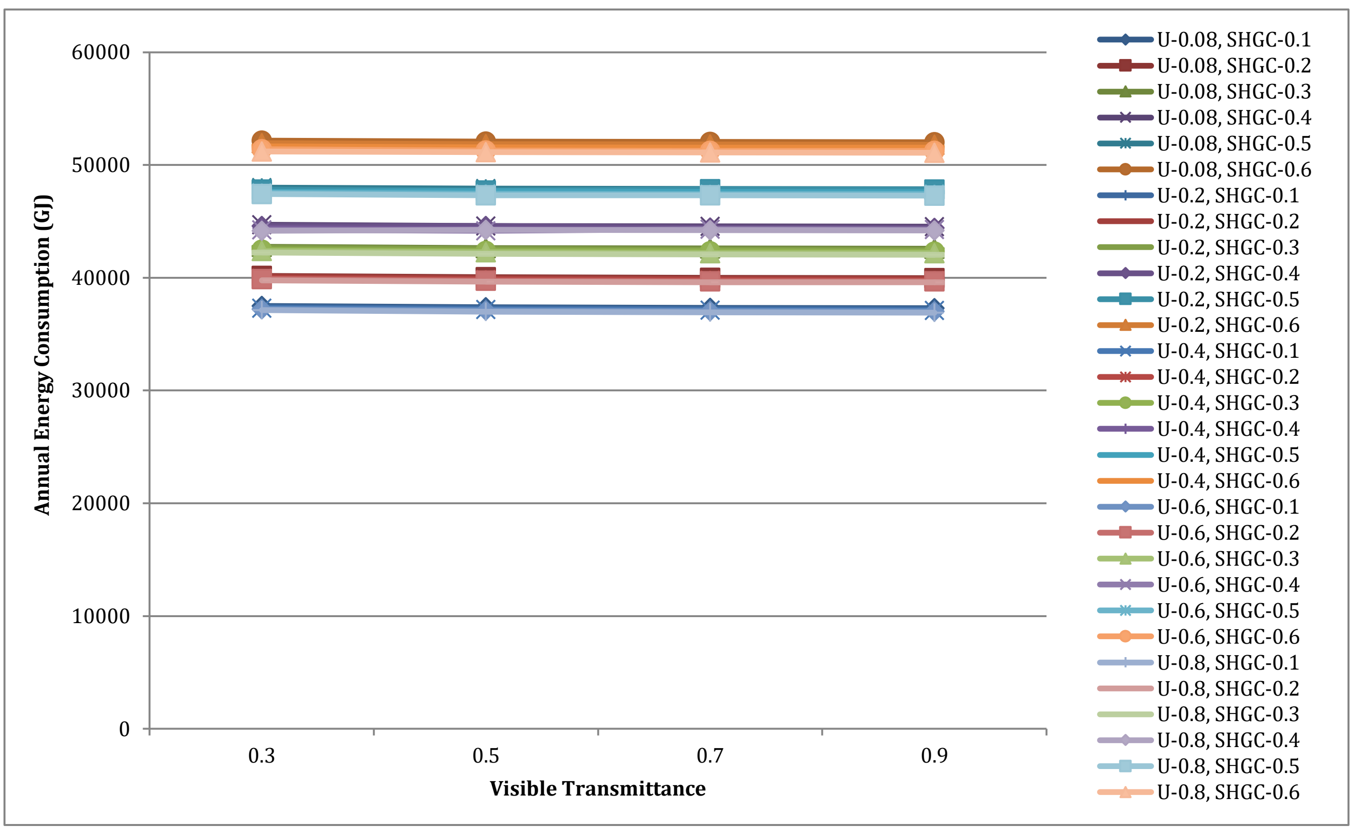

Figure 67: Annual Energy Consumption vs. Visible Transmittance - Miami, FL

Figure 68 shows how the components of HVAC energy are impacted as the SHGC is increased for a U-value of 0.2 and a VT of 50%. The required cooling energy is the HVAC component most heavily impacted by the increase in SHGC. End uses also tied to cooling energy such as heat rejection, pumps, and fans also increase in annual energy consumption as the SHGC is increased. The graphs for other combinations of U-value and VT follow similar trends.

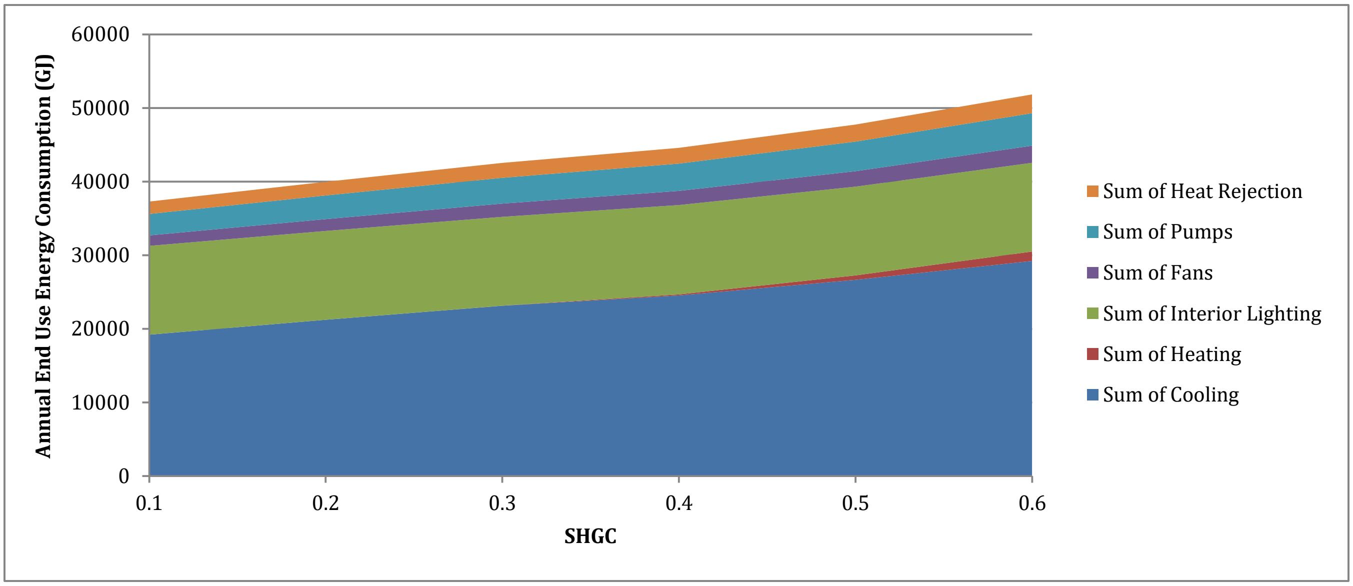

Figure 68: Annual End Use Energy Consumption vs. SHGC - Miami, FL - U-0.2, VT 50%

Figures 69-71 show the same information for Chicago, IL. As the results of the Chapter 5 analyses showed, the building energy consumption for a building in climate zone 5A is much more responsive to changes in U-value than the warmer climate of Miami. The slope of the SHGC graph as compared to the U-value graph shows that the building energy consumption is marginally more sensitive to SHGC than U-value. However, both variables are critical to the optimization of energy consumption for heating-dominated climates. For an optimal glazing selection for Chicago, the U-value and SHGC should both be minimized. The VT also has relatively little impact, and should be maximized.

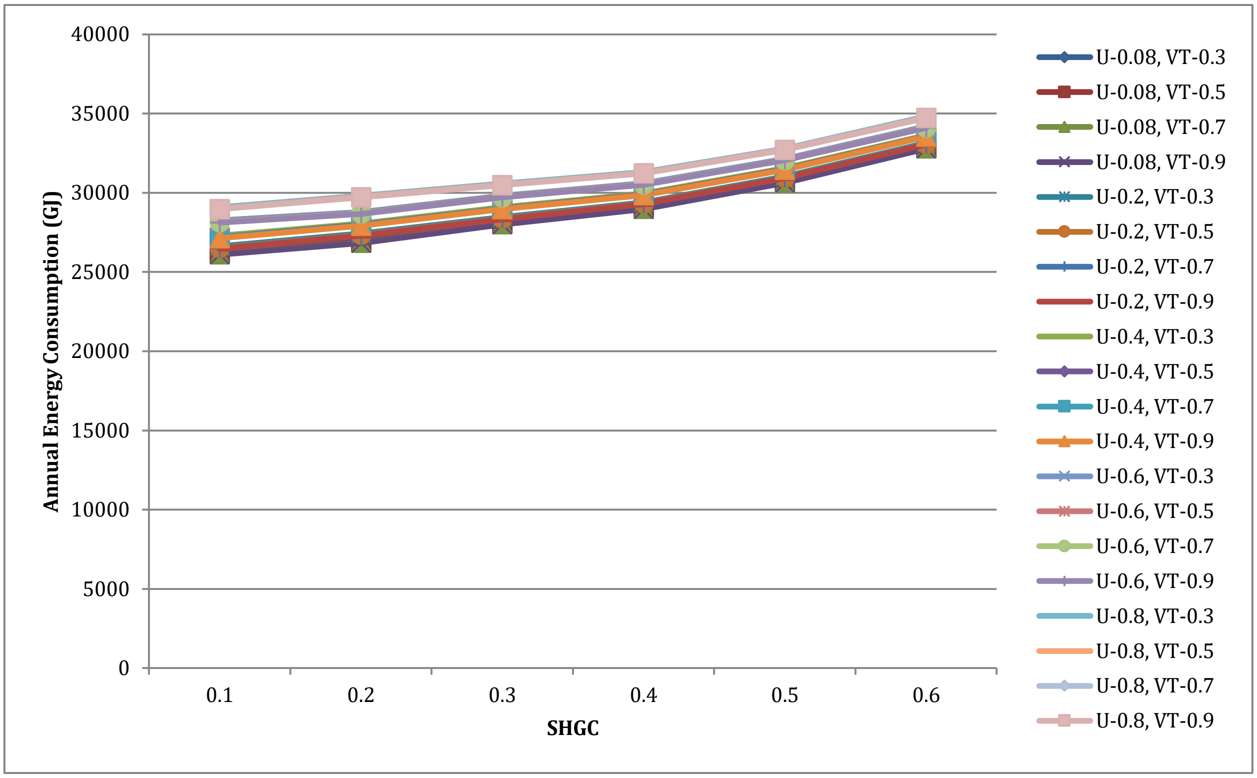

Figure 69: Annual Energy Consumption vs. SHGC – Chicago, IL

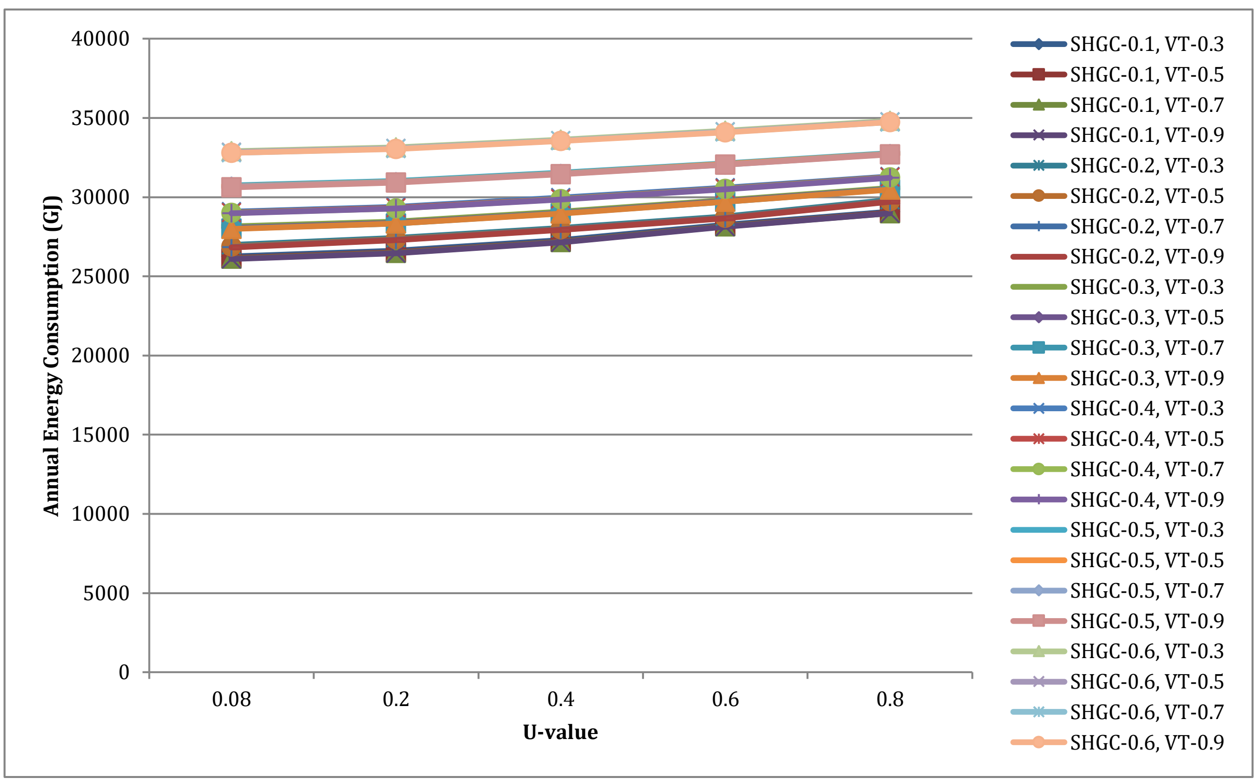

Figure 70: Annual Energy Consumption vs. U-value – Chicago, IL

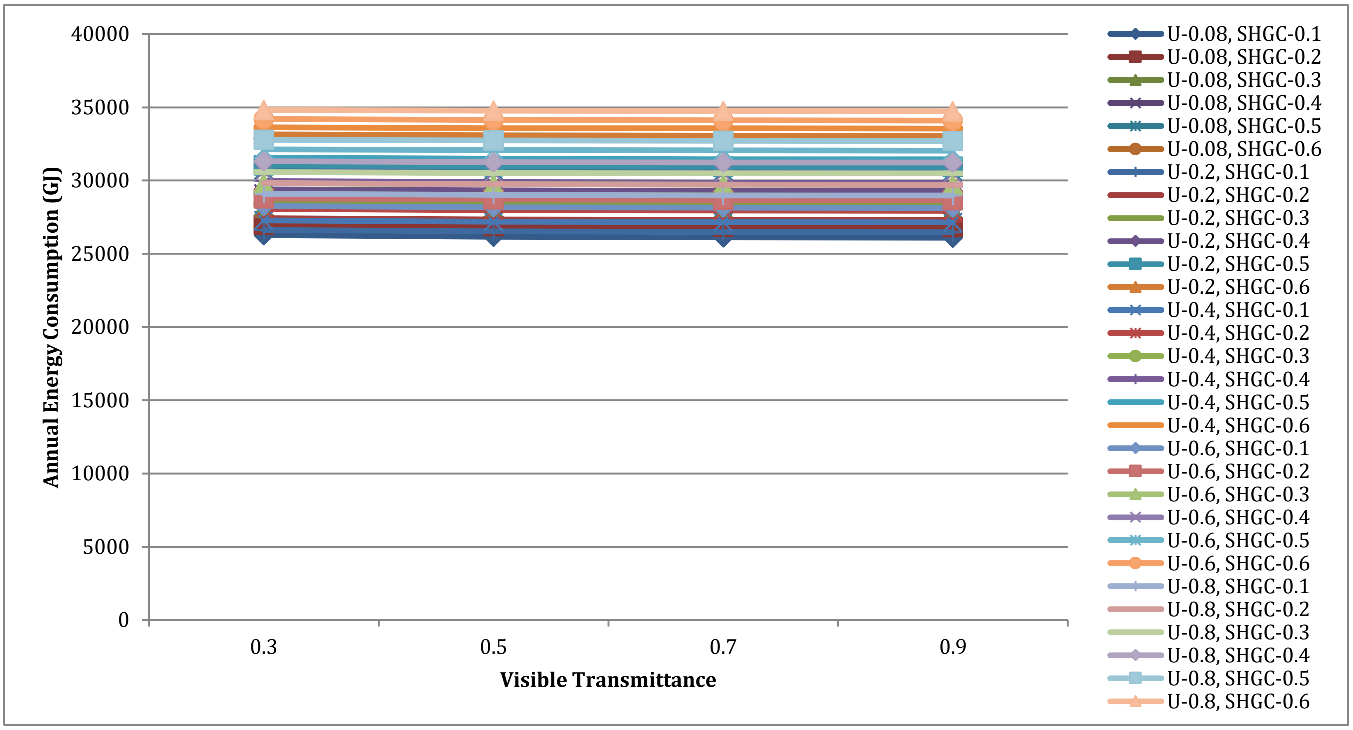

Figure 71: Annual Energy Consumption vs. Visible Transmittance – Chicago, IL

Figure 72 shows how the components of HVAC energy are impacted as the SHGC is increased for a U-value of 0.2 and a VT of 50%. The graphs for other U-value and VT combinations follow similar patterns. As can be seen, the heating energy component reaches a minimum at a SHGC of 0.3, while overall energy consumption is optimized at

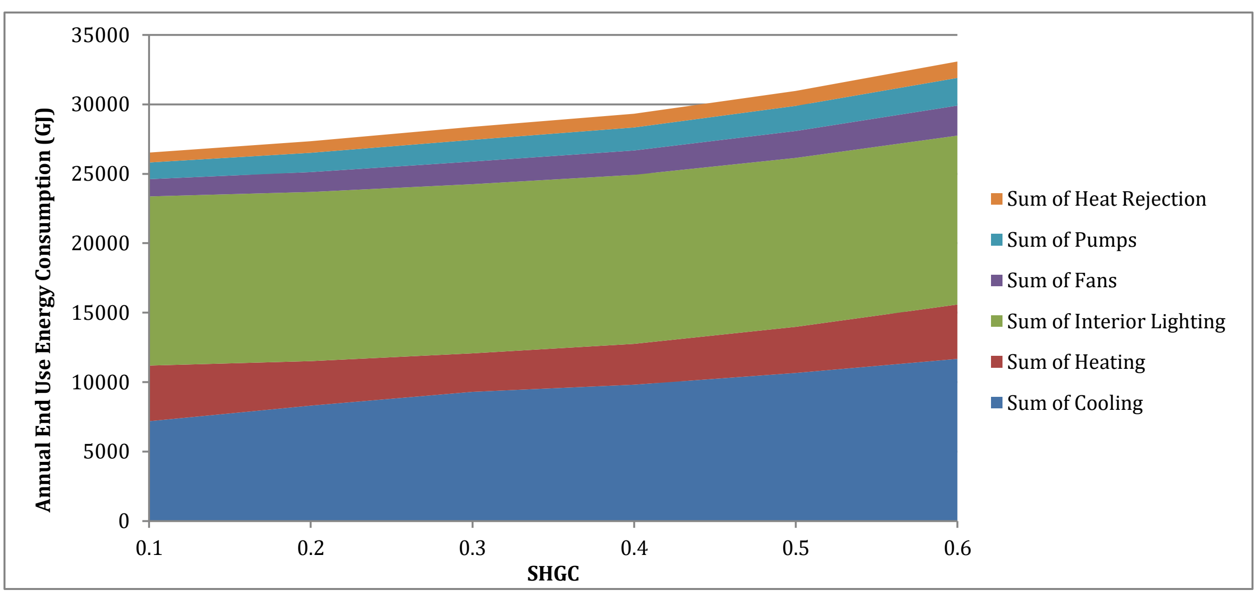

Figure 72: Annual End Use Energy Consumption vs. SHGC – Chicago, IL - U-0.2, VT 50%

minimum SHGC values. The reduction in heating energy from a SHGC of 0.1 to 0.3 is offset by the increase in cooling energy.

Figure 73 shows a similar graph, but versus U-value on the x-axis. The cooling energy is decreased slightly as the U-value increases. However, the driving factor for the reduced energy consumption at lower U-values is because of the decrease in heating energy required to overcome the conductance losses through the glazing.

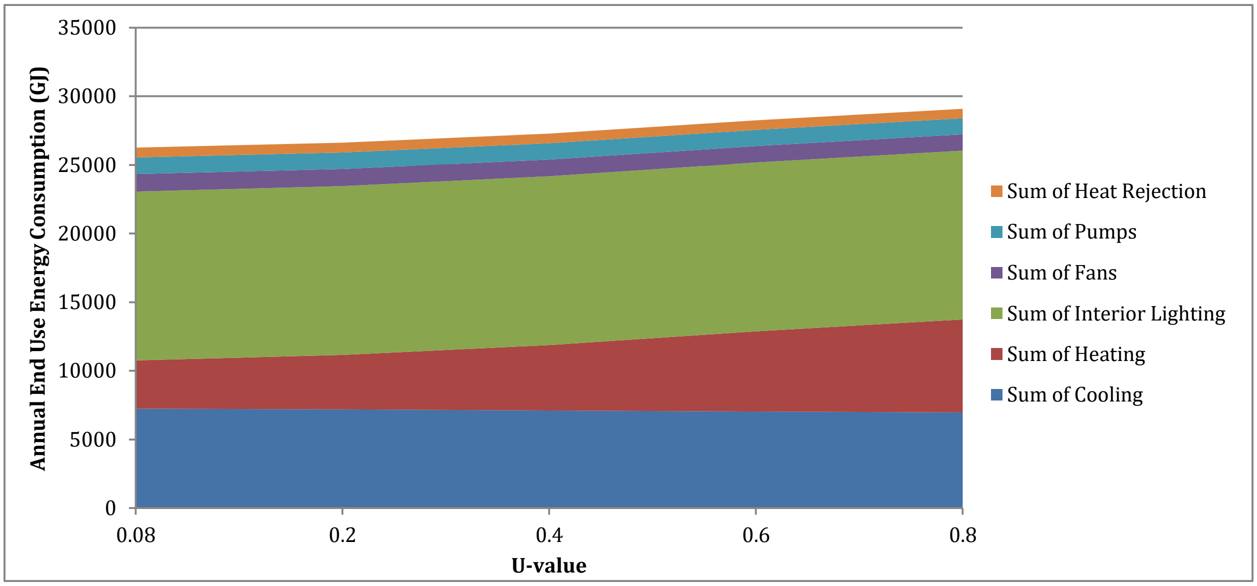

Figure 73: Annual End Use Energy Consumption vs. U-value - Chicago, IL - SHGC-0.2, VT 50%

6.1.2 Energy Consumption Optimization

The goal of the final analysis was to identify the optimal glazing selection for a curtainwall assembly in each climate zone. A total of 120 simulations were run for each climate zone, analyzing each possible combination of the glazing properties listed in Table 15. An important factor in the optimization of the glazing selection is the real-world limit on luminous efficacy. As discussed in Section 2.3.1 Tinted Glazing, the limits to luminous efficacy (ratio of visible transmittance to shading coefficient) determined by LBNL are 0.5

to 2.0. The final optimization study takes into account these limits when determining which glazing is the "optimum" glazing selection for each climate zone.

Figure 74 shows the optimum window property combination for each climate zone investigated, and corresponding annual energy consumption. As can be seen in the figure, for all climates (with the exception of Duluth, MN), the energy consumption is minimized when the SHGC is also minimized. Duluth, MN is a more heating-dominated climate, and it benefits more from the additional heat gains during the winter than it does from the reduction in solar gains during the summer months. The optimized glazing selections for Miami, Phoenix, Atlanta, and San Francisco have higher U-values, while all the other climates place priority on the lowest U-value glazing selection available.

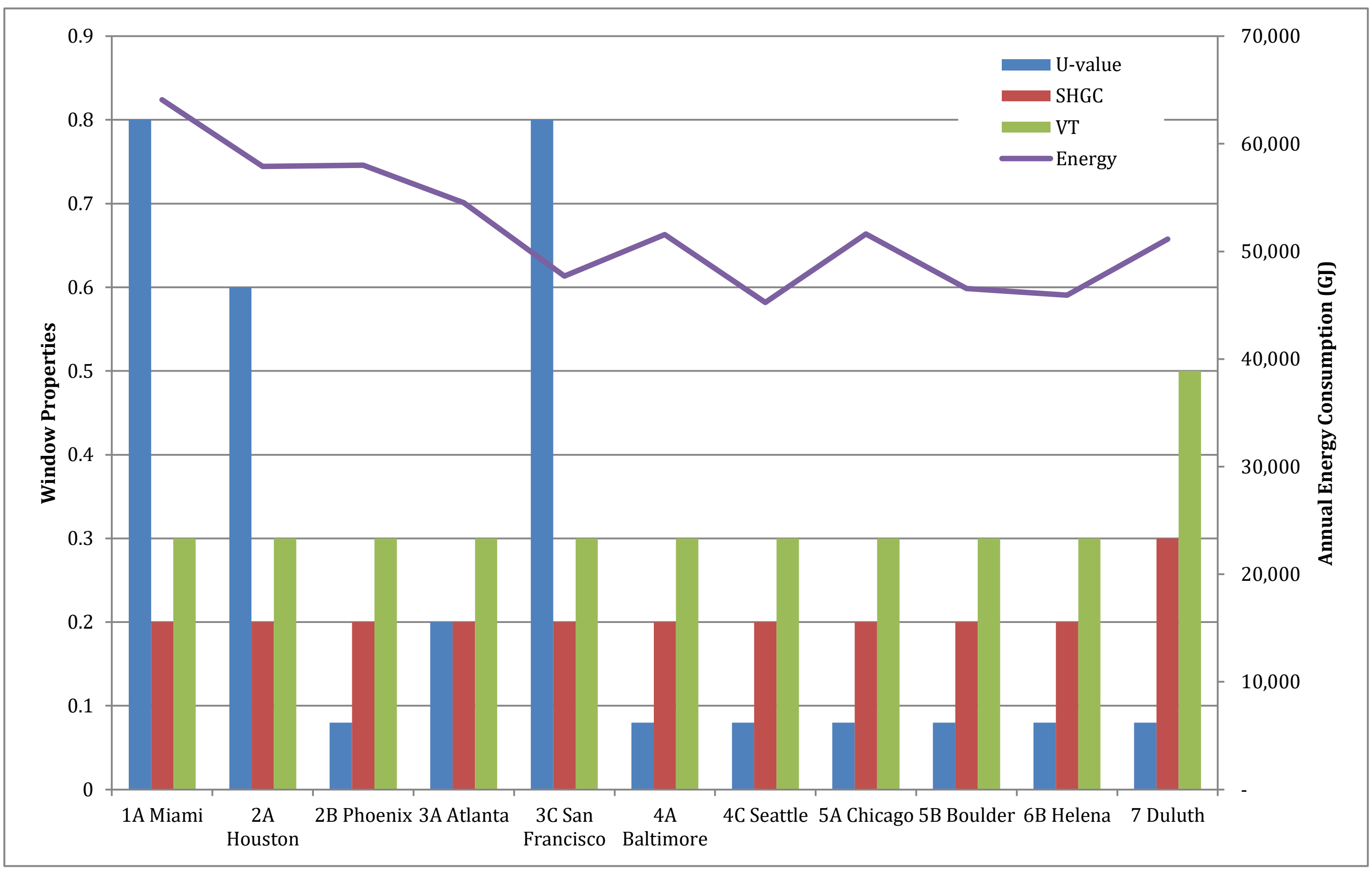

Figure 74: Window Properties Optimized for Energy Consumption per Climate Zone

Investigated more closely, it becomes clear that for the cooling-dominated climates, the SHGC is by far the most critical value in terms of energy efficiency. Figures 228-238 in Appendix F show the glazing properties of the ten lowest and the ten highest energy consumers for each climate zone. For climate zones 1A through 4C, the SHGC is the dominant window property, and there is very little increase in annual energy consumption (<1%) for any U-value when the SHGC and VT are minimized at 0.2 and 0.3, respectively. In climates 5A and above, the U-value begins to play a more critical role. However the lowest ten energy performers are all within 4% of the "optimum" glazing selection.

6.1.3 Energy Cost Optimization

In addition to weather differences across the climate zones, each climate zone has its own utility rate structure. Consumption charges vary between utility providers, as well as demand charges. The glazing selections not only affect annual energy consumption, but varying the glazing properties can also raise, lower, or shift the time and magnitude of the peak demand. For this reason, an "optimum selection" was investigated on a cost basis. Figure 75 below shows the window properties optimized on a cost basis for all climate zones investigated. The climate zones of Miami, San Francisco, Baltimore, Chicago, and Helena showed no change from the energy consumption optimization. The other climate zones (Houston, Phoenix, Atlanta, Seattle, Denver, and Duluth) had a different optimum selection when optimizing for cost.

While in most of these climate zones, optimizing for energy cost rather than energy consumption results in less than 1% difference in annual energy costs, the impacts for Duluth were more substantial. When seeking to minimize energy consumption, the optimum glazing selection is a glazing with U-0.08, SHGC-0.3, and VT-50%. By optimizing for cost rather than energy consumption, the optimum selection is a glazing with U-0.08, SHGC-0.2, and VT-30%. This change in window properties reduced the annual energy cost

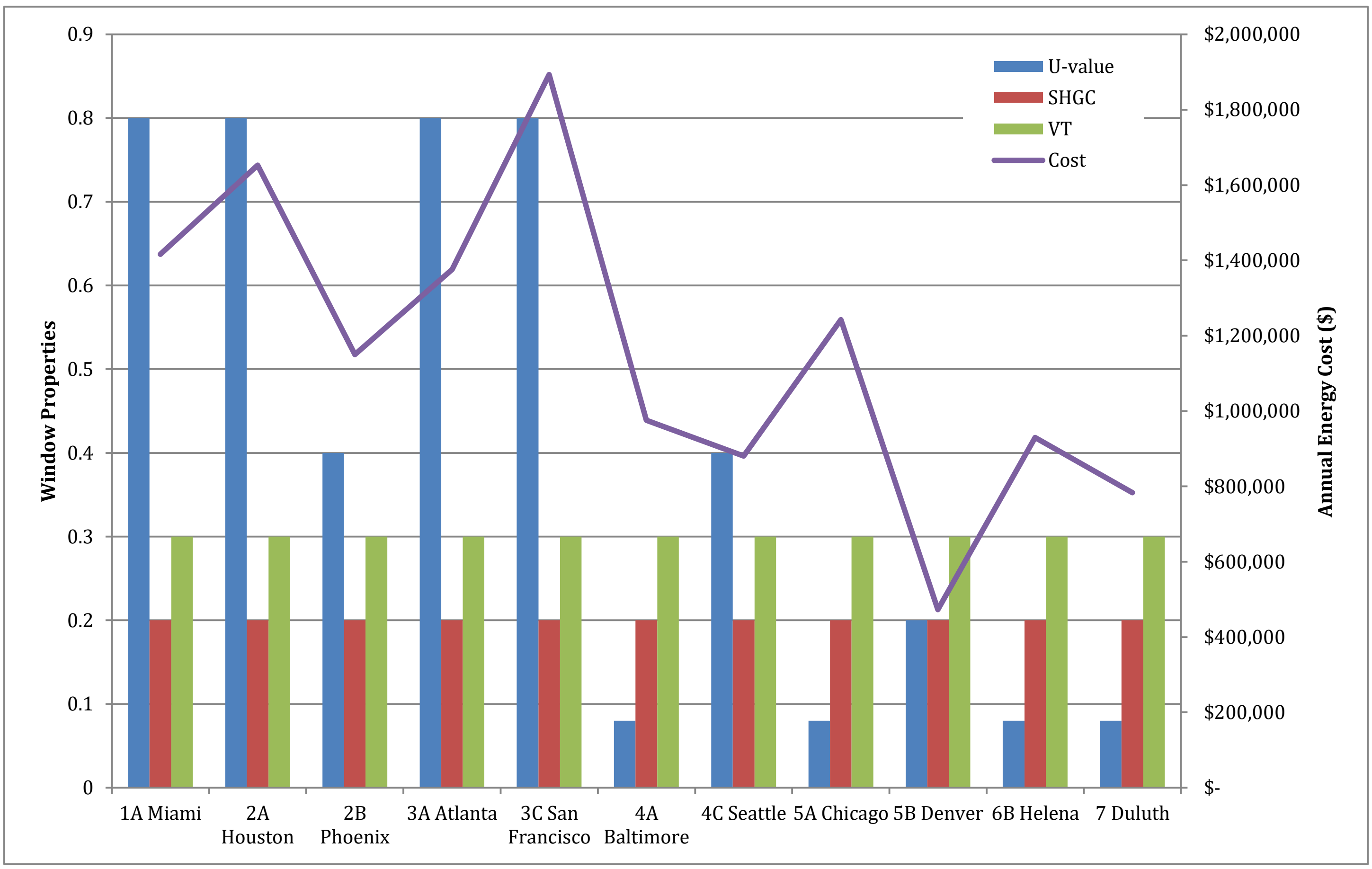

Figure 75: Window Properties Optimized for Energy Cost per Climate Zone

by $9,739 (1.2%). However, the most substantial potential cost savings for Duluth is tied to a potential reduction in required chiller capacity by 211 tons. This is due to the reduced

SHGC and VT, which reduces the incident solar radiation, thereby reducing the peak cooling loads in each of the exterior zones.

Each of the climate zones achieve the optimum energy cost point at minimum SHGC and VT levels. Because electricity is generally more expensive per unit of energy across all the climate zones, measures that reduce electricity consumption and demand have greater impacts on annual energy costs than those that reduce natural gas consumption. As discussed in the sensitivity analysis, the annual energy consumption of the facility is highly sensitive to SHGC selection. Because of the relatively higher cost of electricity, and the ability of the SHGC to minimize the peak cooling loads within the exterior zones, reducing the SHGC is essential to minimizing the annual energy costs of the facility.

6.2 Impacts of Optimization

6.2.1 Equipment Sizing

The cost optimization results are utilized for this portion of the discussion. There is relatively little difference in annual energy consumption between the optimum selection based on cost versus energy consumption. Figure 76 is a visual representation of the data in Table 16, which compares the highest and lowest annual utility cost cases for each

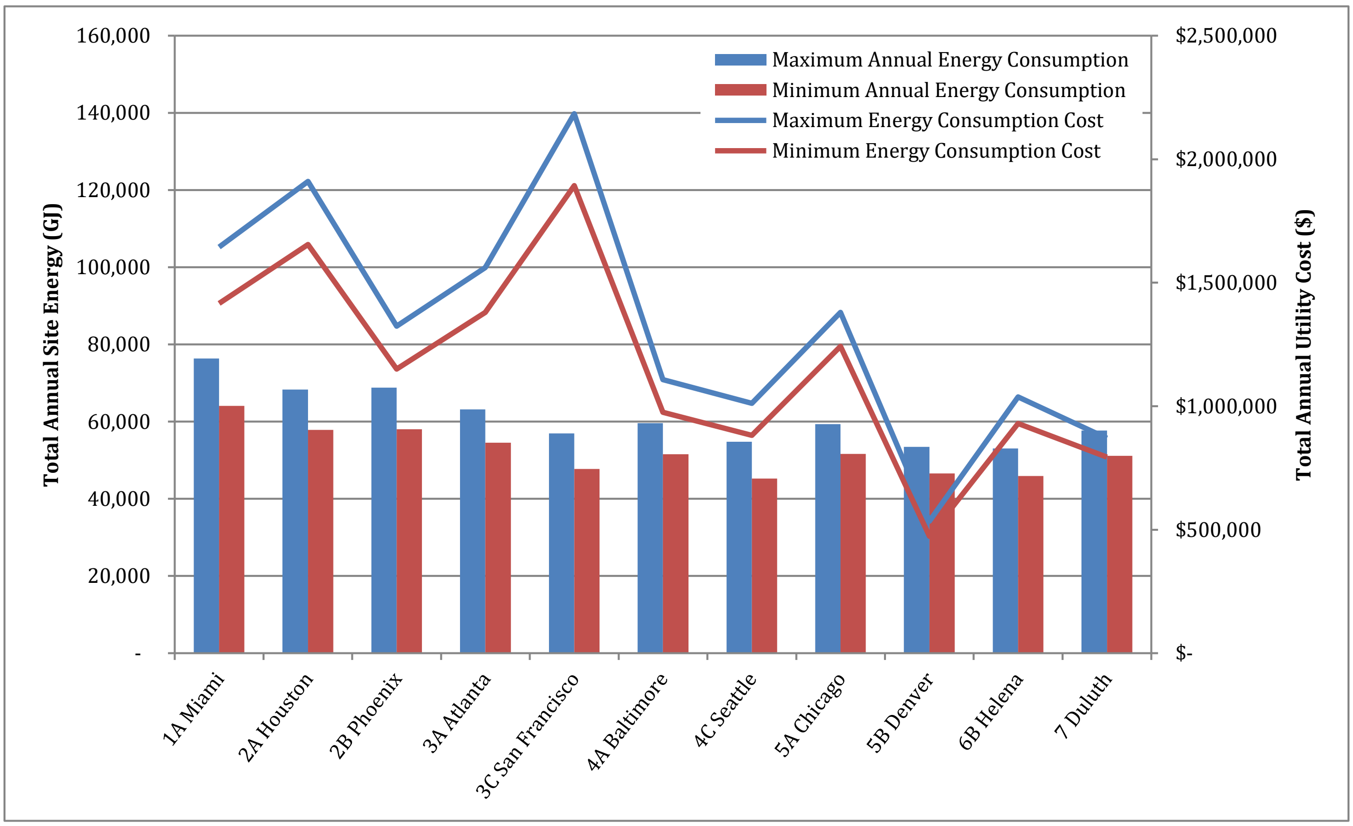

Figure 76: Maximum and Minimum Annual Energy Consumption in All Climate Zones and Associated Utility Costs

Climate Zone. As can be seen in Table 16, the optimization of the glazing properties results in 10-17% energy consumption and utility cost savings in each climate zone as compared to the worst-performing glazing selection. The utility cost savings range between $61,505 annual all the way up to $303,389. Each of the "maximum" glazing selections has glazing with SHGC-0.6 and VT-50%. Glazing with similar properties is available on today's market, so it is a realistic option for building owners and designers.

Table 16: Maximum and Minimum Annual Energy Consumption and Associated Utility Costs

	Annual Energy Consumption				Annual Utility Costs			
	Max (GJ)	Min (GJ)	Diff.	% Diff,	Max ($)	Min ($)	Diff.	% Diff,
1A Miami	76,399	64,094	12,305	16.1%	$1,644,600	$1,415,989	$228,612	13.9%
2A Houston	68,349	57,895	10,453	15.3%	$1,909,846	$1,653,099	$256,747	13.4%
2B Phoenix	68,780	58,033	10,747	15.6%	$1,324,483	$1,150,214	$174,268	13.2%
3A Atlanta	63,021	54,689	8,331	13.2%	$1,569,372	$1,375,972	$193,400	12.3%
3C San Fran	56,392	47,695	8,697	15.4%	$2,196,348	$1,892,959	$303,389	13.8%
4A Baltimore	59,591	51,554	8,037	13.5%	$1,107,754	$975,399	$132,355	11.9%
4C Seattle	54,808	45,406	9,402	17.2%	$1,011,470	$880,766	$130,704	12.9%
5A Chicago	59,387	51,614	7,773	13.1%	$1,379,393	$1,242,364	$137,029	9.9%
5B Denver	53,459	46,596	6,864	12.8%	$534,771	$473,265	$61,506	11.5%
6A Helena	53,048	45,947	7,101	13.4%	$1,037,959	$929,719	$108,240	10.4%
7 Duluth	57,713	51,159	6,554	11.4%	$870,502	$783,585	$86,916	10.0%

In addition to the annual energy consumption and utility cost implications associated with an optimized glazing selection, as previously discussed, the glazing properties are closely tied to the magnitude of the internal gains within the space and thereby the sizing of the HVAC equipment. Table 16: Maximum and Minimum Annual Energy Consumption and Associated Utility Costs shows the resulting differential in calculated chiller and boiler capacities for the worst-case versus optimum glazing selections analyzed.

The difference in chiller capacity from the worst-case glazing to the optimum glazing selection ranges between 550 tons in and 790 tons across the climate zones. Based on a typical cost per ton for a centrifugal chiller ($250/ton), the glazing optimization would result in initial chiller equipment cost savings between $137,500 and $197,500 [94]. This is a conservative estimate, as additional capital savings would be available by way of reduced pump and piping sizing, and smaller cooling tower capacity. If the improved glazing results in the ability to eliminate an entire chiller from the design, the mechanical room square footage could be reduced and labor and building automation controls installation costs would also be reduced. According to a white paper published by the International District Energy Association, the total installed cost of a chilled water system of this size is \$3,000/ton [95]. Given this figure, the initial cost savings could be in the realm of \$750,000 to \$2,270,000 for the chilled water system alone.

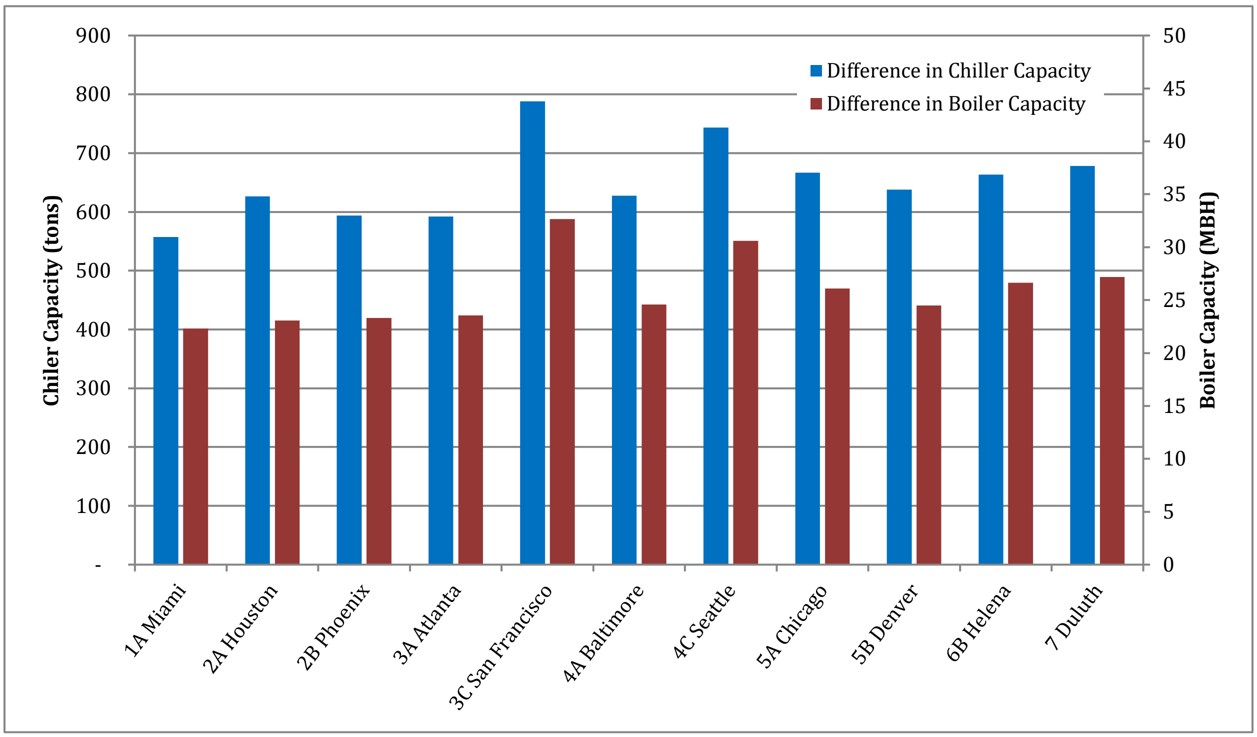

Figure 77: Reduction in Chiller and Boiler Capacity for Glazing Optimization

The difference in boiler capacity ranges between 22 MBH (million Btu/hr) in Miami and 33 MBH in San Francisco. According to a DOE study of installed cost for natural-gas-fired hot-water boilers, this translates to initial cost savings in the range of \$61,808 to \$91,376 [96]. The savings for the initial hot water system costs are similar in nature to those of the chilled water system: reduced boiler size, piping, pumps, mechanical room, and labor.

6.2.2 Occupant Comfort

Occupant comfort is a crucial function of the building's HVAC system. However the glazing properties play a crucial role in occupant comfort as well. EnergyPlus is able to calculate the total time throughout the occupied hours of the year in which the HVAC system fails to meet the operative temperature setpoint in each zone (Based on ASHRAE

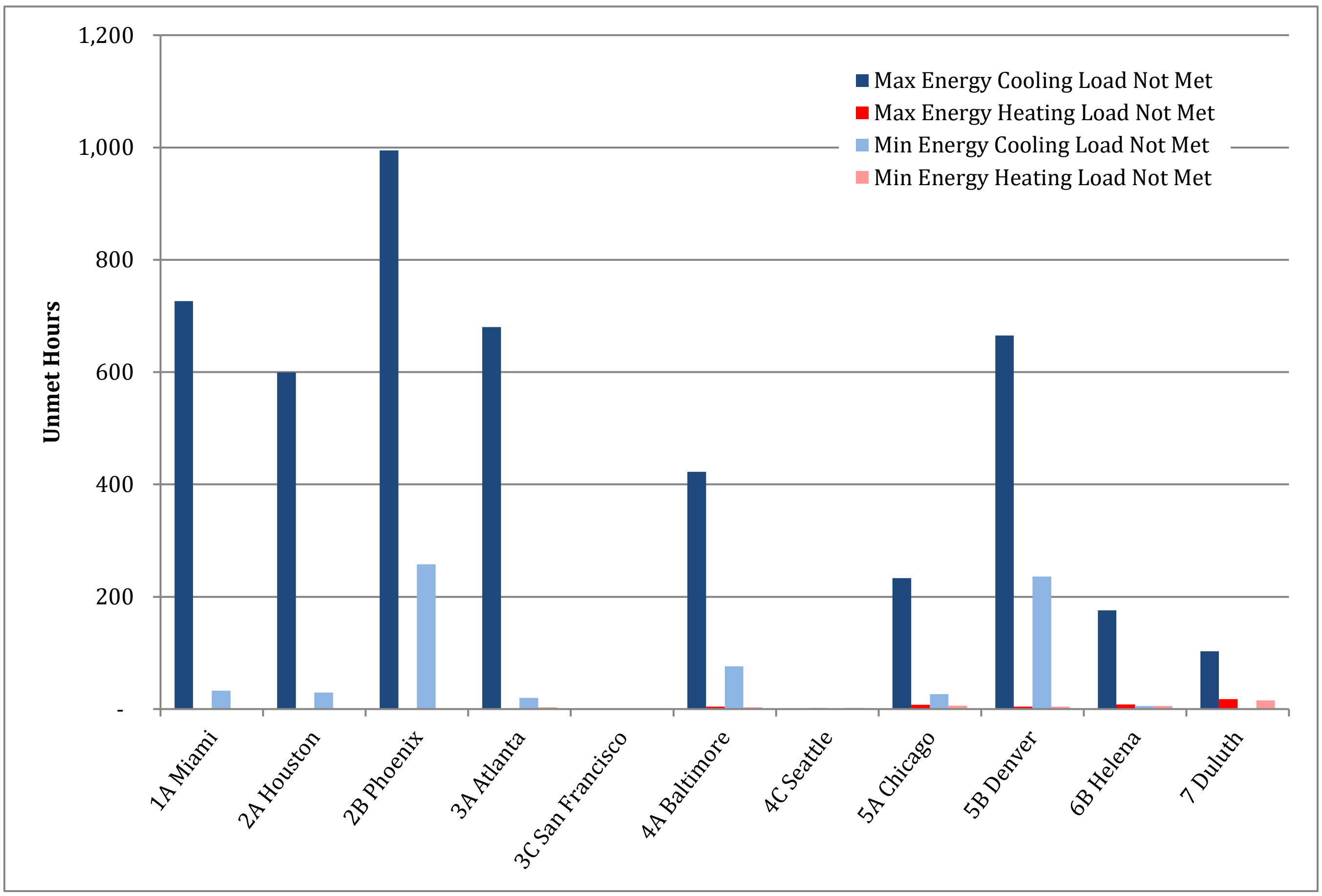

Figure 78: Unmet Cooling and Heating Hours for Maximum and Minimum Glazing Selections

55-2004). Figure 78 shows the total facility unmet cooling and heating hours (during occupied hours) for glazing selection with the highest and lowest energy consumption. This was investigated to verify that energy savings were not being achieved at the expense of occupant comfort. As shown in the graph, the glazing with the poorest energy performance actually has greater unmet hours than the optimum selection.

A detailed investigation of the source of the unmet cooling hours reveals that the vast majority of the unmet hours throughout the year occur in the south-facing zones throughout the building from 1:00pm to 5:00pm. The inability of the HVAC system to maintain the space temperature setpoint stems from the direct solar gains of the southern façade. The space temperature rises no more than 3degC above setpoint, but does result in unmet hours throughout the year. The simulations with lower SHGC and VT limit the direct solar gains within the south zones, thereby reducing hours throughout the year in which the temperature rises above setpoint.

The investigation of the unmet cooling and heating hours for the parametric analysis results reveal a side benefit of optimizing the glazing selection for energy performance. Glazing selections that minimize glare and reduce the peak heating and cooling loads also offer occupants a more consistent and comfortable operative temperature. In highrise buildings where floors are often leased to tenants, occupant comfort is critical, and should be factored into curtainwall glazing selections.

6.2.3 Aesthetic and View Quality

While reducing SHGC and VT is a cost-effective strategy across all climate zones, there are aesthetic and view-quality trade-offs that would need to be assessed by the building owner and design team. In order to achieve SHGC-0.2 and VT-30%, the glazing must be highly reflective and tinted. Below are images from the glazing manufacturer Viracon that show the aesthetic quality of glazing walls with SHGC-0.2 and VT-30% [93]. From the occupant's perspective, the daylight transmitted to the space will appear slightly dim. This may be advantageous to the use of the space and desirable to the owner. However, if natural light aesthetic and aggressive daylighting controls are high priorities for the owner and design team, this glazing selection methodology may not represent the "optimum" selection for the project. If a higher SHGC and VT are desired for aesthetic purposes, the design team must also be sure to understand the energy consumption, utility cost, and equipment sizing implications of moving away from selecting a less-than-optimum glazing selection.

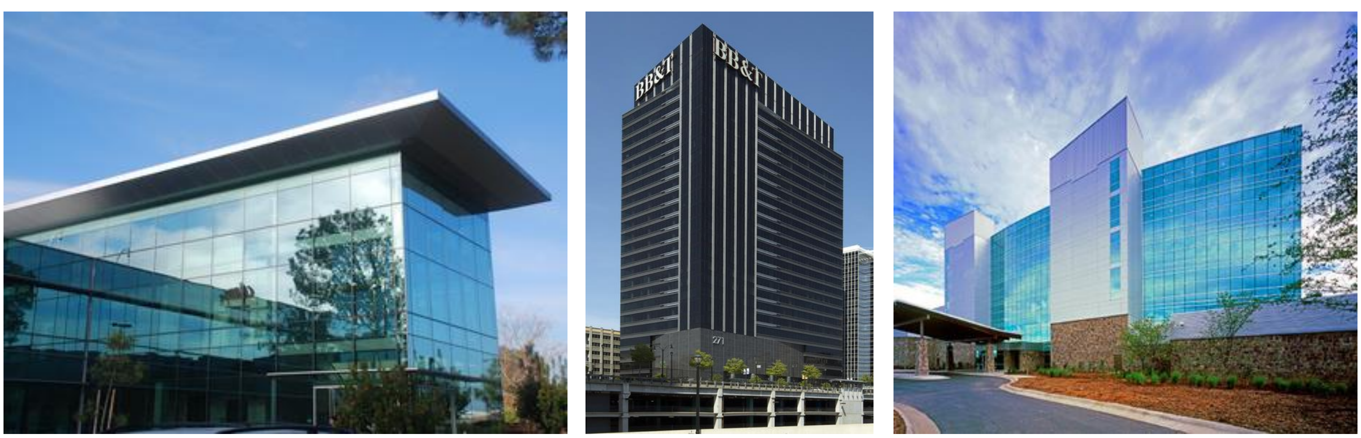

Figure 79: Viracon Glazing Examples: SHGC-0.2, VT-30% [93]

Chapter 7: Results

7.1 Design Recommendations

The analysis of the selected envelope parameters provides valuable insight into the nature of energy consumption within a highrise building, and what efforts should be made to improve the energy consumption of the building. For the curtainwall configuration analyzed for this study, with a window-to-wall ratio of 70%, the difference in energy consumption between the best- and worst-performing selections varies between 11.4% and 17.2% in all climate zones. Given the magnitude of potential impact to energy consumption, the optimization of curtainwall glazing properties should be a top priority for design teams in all climate zones.

The relative difference in annual utility cost between the best- and worst-performing selections varies between 9.9% and 13.9% in all climate zones. The annual utility cost difference ranges between $61,505 and $303,389. The true cost impact for an optimized glazing selection must also include the cost impacts of reduced equipment sizing. The parametric analysis revealed substantial differences in the building's peak heating and cooling loads over the range of glazing property combinations. Optimizing the glazing showed potential to impact the chilled and hot water system sizing by 20-33% across the climate zones. The savings available through reduced HVAC equipment sizing could contribute greatly to the potential added cost of improved glazing, and should be factored in the glazing selection cost analysis for any project.

The sensitivity and parametric analyses show that the most critical glazing property for curtainwall designs in highrise buildings is the SHGC of the glazing. Across all climate zones, the most efficient glazing selection minimizes SHGC, while maximizing the VT. While this glazing selection may not possess the design team's desired aesthetic or daylighting characteristics, it is the most efficient glazing selection.

One of the most compelling components of the results of this study is the degree to which the glazing selection has the ability to affect the annual energy consumption, annual utility cost, and initial HVAC equipment sizing across all climates. It is said that the most efficient building is one with no windows, no doors, no lights and no people. However, because the built environment is one in which people live, work, and play, there will always be tradeoffs between energy consumption, aesthetics, and occupant comfort. The results of this study show that careful consideration should be made when analyzing those tradeoffs and selecting a glazing for curtainwalls in highrise buildings. Whole building energy modeling can be extremely useful in helping building owners and architects to assess and understand the full impacts of the tradeoffs in glazing selection.

7.2 Summary and Future Work

Natural ventilation within a highrise building was identified as an energy efficiency measure in Chapter 2, but was not within the scope for this research. It would be meaningful to understand the effectiveness of natural ventilation within highrise buildings and determine the cost tradeoff between the energy saved and the additional cost for an operational envelope.

The daylighting controls assessed in this study represented a very basic daylighting strategy. Daylighting design is a complex process, and requires extensive modeling efforts to optimize the design characteristics of the space. A next step in assessing the optimization of curtainwall glazing properties in combination with daylighting would require a detailed daylighting study. For a particular project, the team may want to analyze specific glazing assemblies, complete with spectral properties and utilize the EnergyPlus complex glazing system calculations. With a relatively low surface area to volume ratio, the geometry of the DOE benchmark building does not maximize daylighting potential for a building of this size. There are a variety of variables that could be assessed such as internal surface reflectance, interior geometry (light shelves, open plenum design, and internal glazing), surface to volume ratio, and footprint geometry that could be analyzed to determine whether daylighting controls could be better utilized for a building of this size. In this study, the visible transmittance properties of the glazing may become more critical to the overall efficiency of the building.

Improved glazing and energy efficient curtain wall assemblies continue to be a large focus in research. Many of the glazing strategies identified in Chapter 2 were eliminated from this analysis because they were either too expensive to implement at current market price, or they were too complicated for the large façade sizes associated with highrise buildings. Continued research in both the glazing portion and the curtain wall assemblies could potentially open up opportunities for significant energy savings in the future.

7.3 Conclusion

The preceding study shows the importance of critically assessing glazing properties in curtainwall designs for highrise buildings. It also underscores the importance of understanding the total impacts of glazing selection including equipment sizing and thermal comfort. Architects are often driven by aesthetics at the expense of energy efficiency. However, the changing energy climate as well as the changing culture surrounding the design of the built environment is forcing these efficiency-related questions to the forefront. As shown above, whole-building energy modeling is a powerful tool that should be utilized in the design process for energy efficient curtain walls in highrise buildings. Careful glazing selection in a curtainwall design has the potential to dramatically minimize the contribution of the built environment to national energy consumption.

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Appendix A: Envelope Values

Roof U-values (Btu/h*ft^2*°F) for New Construction by Location		
Location	**DOE Benchmark (ASHRAE 90.1-1994)**	**Highrise Baseline (ASHRAE 90.1-2010)**
Miami, FL (1A)	0.063	0.063
Houston, TX (2A)	0.063	0.048
Phoenix, AZ (2B)	0.063	0.048
Atlanta, GA (3A)	0.063	0.048
San Francisco, CA (3C)	0.063	0.048
Baltimore, MD (4A)	0.063	0.048
Seattle, WA (4C)	0.063	0.048
Chicago, IL (5A)	0.063	0.048
Denver, CO (5B)	0.063	0.048
Helena, MT (6B)	0.063	0.048
Duluth, MN (7)	0.063	0.048

Wall U-values (Btu/h*ft^2*°F) for New Construction by Location				
Location	**DOE Benchmark (ASHRAE 90.1-1994)**		**Highrise Baseline (ASHRAE 90.1-2010)**	
	Steel Frame	**Mass**	**Steel Frame**	**Mass**
Miami, FL (1A)	0.124	0.580	0.124	0.580
Houston, TX (2A)	0.124	0.580	0.124	0.151
Phoenix, AZ (2B)	0.124	0.580	0.124	0.151
Atlanta, GA (3A)	0.124	0.151	0.084	0.123
San Francisco, CA (3C)	0.124	0.580	0.084	0.123
Baltimore, MD (4A)	0.124	0.580	0.064	0.104
Seattle, WA (4C)	0.124	0.151	0.064	0.104
Chicago, IL (5A)	0.084	0.151	0.064	0.090
Denver, CO (5B)	0.084	0.151	0.064	0.090
Helena, MT (6B)	0.084	0.123	0.064	0.080
Duluth, MN (7)	0.084	0.123	0.064	0.071

Wall Below-Grade C-factor (Btu/h*ft2*°F) for New Construction by Location				
Location	DOE Benchmark (ASHRAE 90.1-1994)		Highrise Baseline (ASHRAE 90.1-2010)	
	C-factor	Ins. Req'd	C-factor	Ins. Req'd
Miami, FL (1A)	1.140	NR	1.140	NR
Houston, TX (2A)	1.140	NR	1.140	NR
Phoenix, AZ (2B)	1.140	NR	1.140	NR
Atlanta, GA (3A)	1.140	NR	1.140	NR
San Francisco, CA (3C)	1.140	NR	1.140	NR
Baltimore, MD (4A)	1.140	NR	1.140	NR
Seattle, WA (4C)	1.140	NR	1.140	NR
Chicago, IL (5A)	1.140	NR	0.119	R-7.5 ci
Denver, CO (5B)	1.140	NR	0.119	R-7.5 ci
Helena, MT (6B)	1.140	NR	0.119	R-7.5 ci
Duluth, MN (7)	0.119	R-7.5 ci	0.119	R-7.5 ci

Slab-on-grade Floors F-factor (Btu/h*ft*°F) for New Construction by Location				
Location	DOE Benchmark (ASHRAE 90.1-1994)		Highrise Baseline (ASHRAE 90.1-2010)	
	F-factor	Ins. Req'd	F-factor	Ins. Req'd
Miami, FL (1A)	0.73	NR	0.73	NR
Houston, TX (2A)	0.73	NR	0.73	NR
Phoenix, AZ (2B)	0.73	NR	0.73	NR
Atlanta, GA (3A)	0.73	NR	0.73	NR
San Francisco, CA (3C)	0.73	NR	0.73	NR
Baltimore, MD (4A)	0.73	NR	0.73	NR
Seattle, WA (4C)	0.73	NR	0.73	NR
Chicago, IL (5A)	0.73	NR	0.73	NR
Denver, CO (5B)	0.73	NR	0.73	NR
Helena, MT (6B)	0.73	NR	0.54	R-10 for 24 in
Duluth, MN (7)	0.73	NR	0.52	R-15 for 24 in

Window Overall U-value (Btu/h*ft2*°F) and SHGC for New Construction by Location				
Location	DOE Benchmark (ASHRAE 90.1-1994)		Highrise Baseline (ASHRAE 90.1-2010)	
	U-value	SHGC	U-value	SHGC
Miami, FL (1A)	1.22	0.25	1.20	0.25
Houston, TX (2A)	1.22	0.25	0.70	0.25
Phoenix, AZ (2B)	1.22	0.25	0.70	0.25
Atlanta, GA (3A)	0.57	0.25	0.60	0.25
San Francisco, CA (3C)	1.22	0.34	0.60	0.25
Baltimore, MD (4A)	0.57	0.39	0.50	0.40
Seattle, WA (4C)	0.57	0.39	0.50	0.40
Chicago, IL (5A)	0.57	0.39	0.45	0.40
Denver, CO (5B)	0.57	0.39	0.45	0.40
Helena, MT (6B)	0.57	0.39	0.45	0.40
Duluth, MN (7)	0.57	0.49	0.40	0.45

Appendix B: Window-to-Wall Ratio Results

Miami, FL WTW Ratio Results

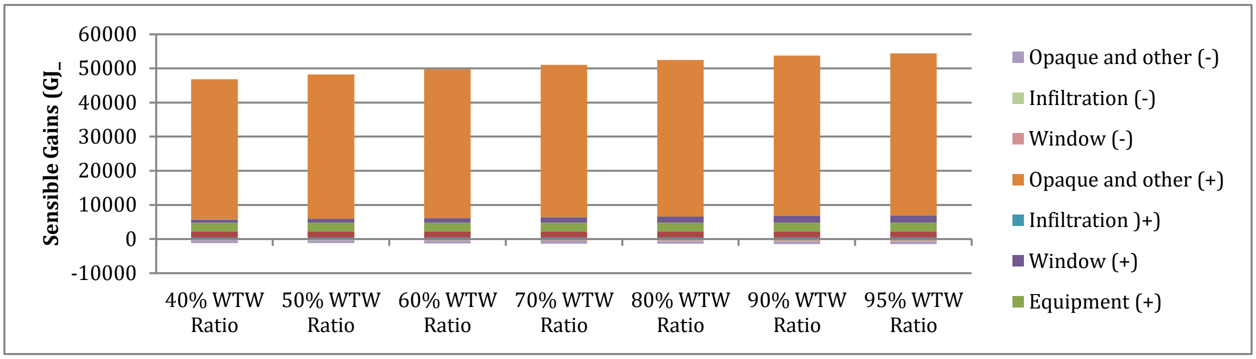


Figure 80: WTW Ratio - Sensible Gains - Miami, FL

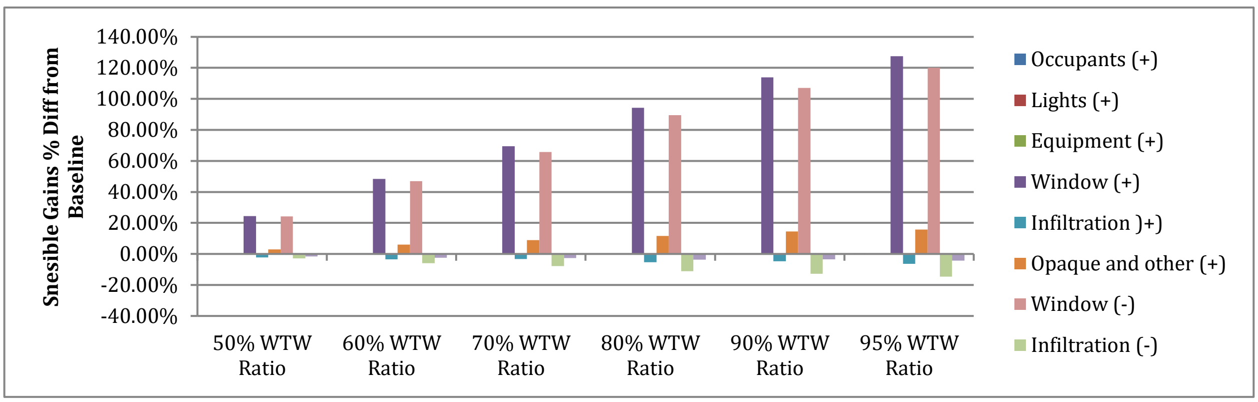


Figure 81: WTW Ratio - Sensible Gains Change from Baseline - Miami, FL

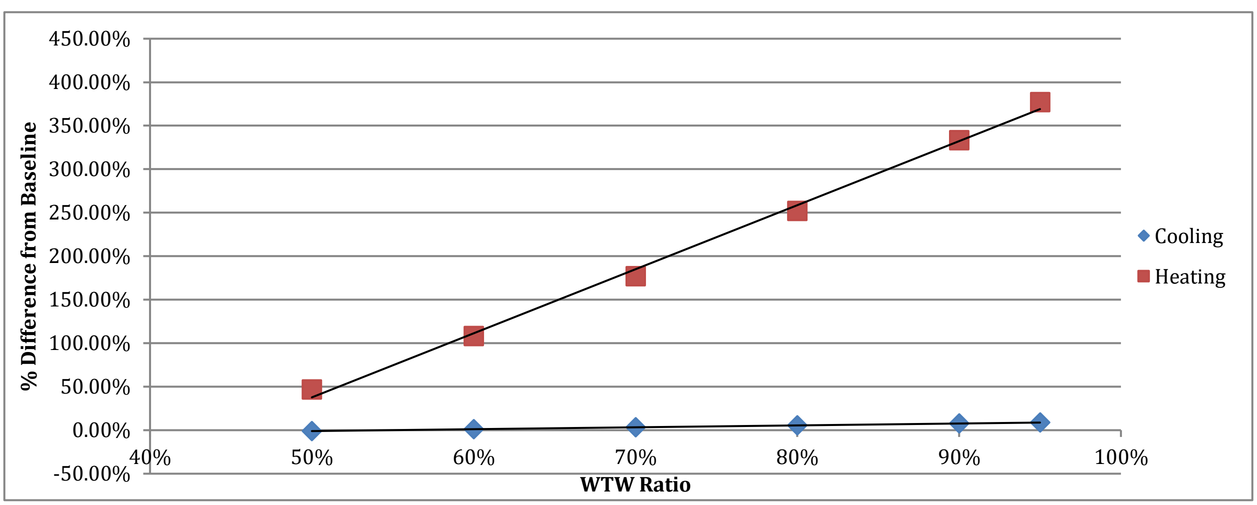


Figure 82: WTW Ratio - Heating and Cooling Energy % Difference from Baseline - Miami, FL

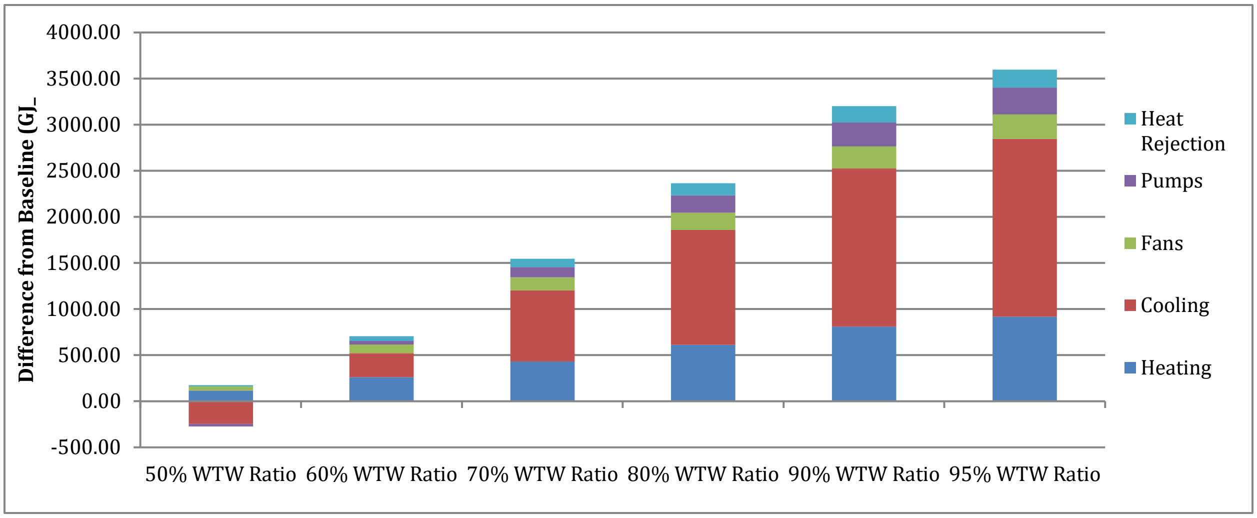


Figure 83: WTW Ratio - Energy Consumption Difference from Baseline - Miami, FL

Houston, TX Results

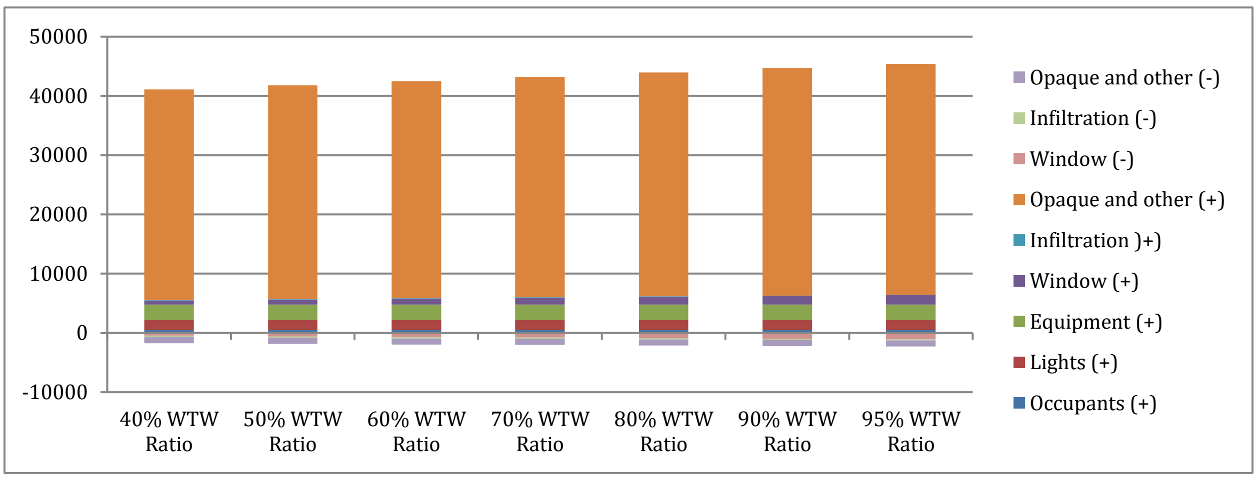


Figure 84: WTW Ratio - Sensible Gains - Houston, TX

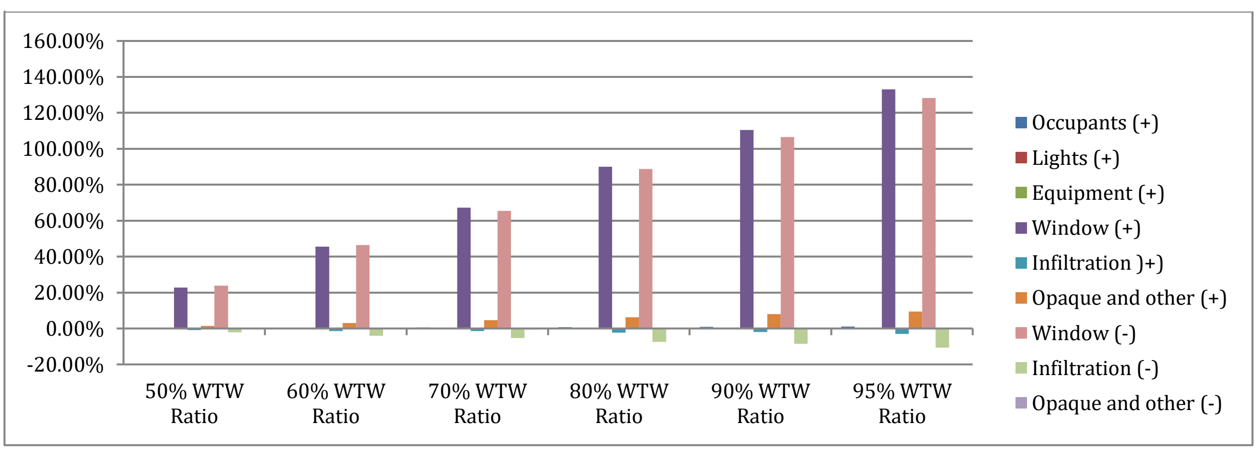


Figure 85: WTW Ratio - Sensible Gains Change from Baseline - Houston, TX

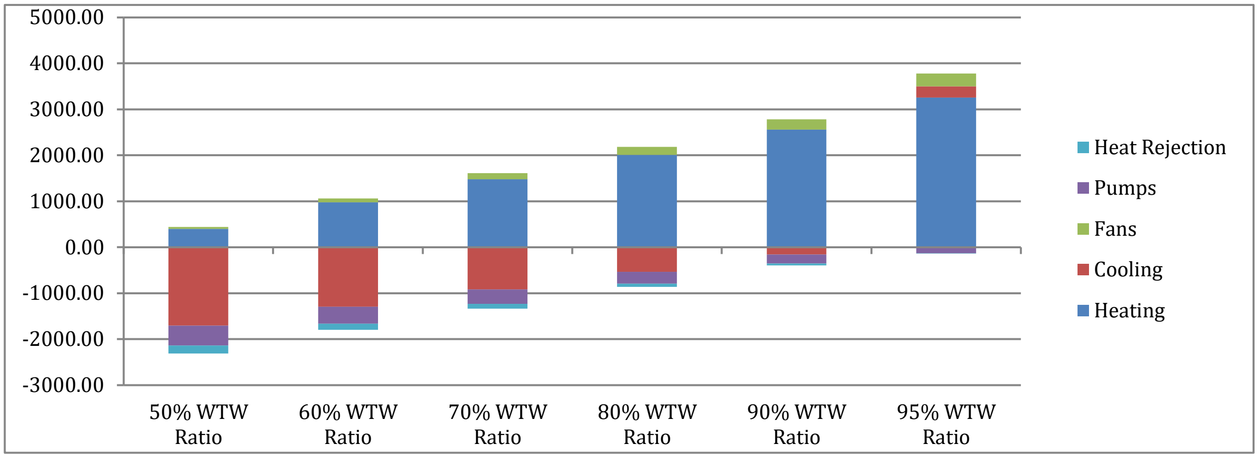


Figure 86: WTW Ratio - Energy Consumption Difference from Baseline - Houston, TX

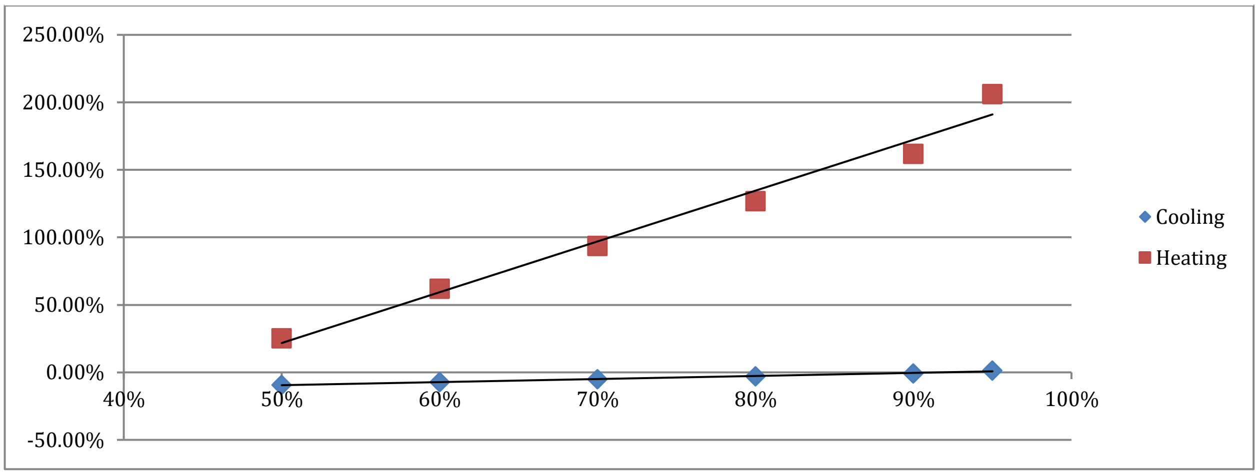


Figure 87: WTW Ratio - Heating and Cooling Energy % Difference from Baseline -

Phoenix, AZ WTW Ratio Results

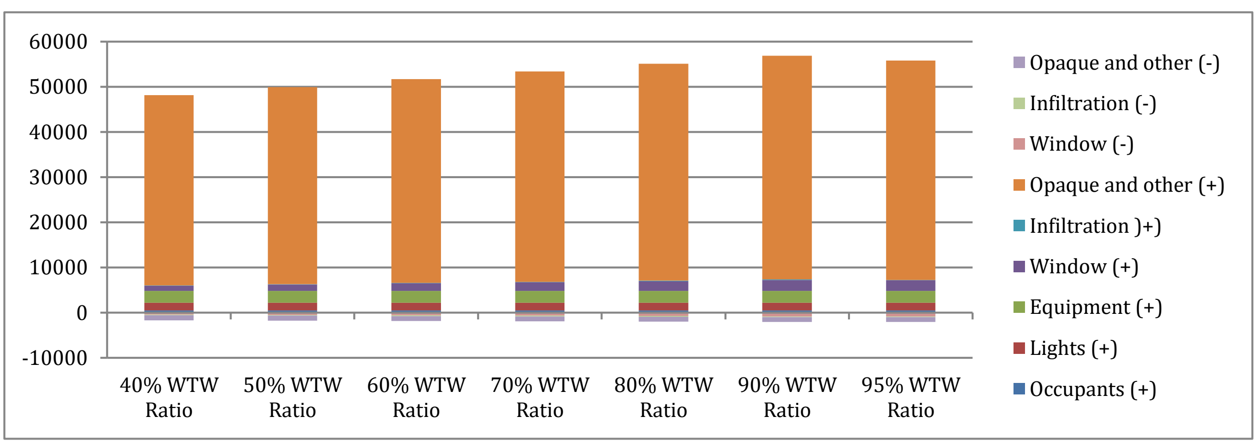


Figure 88: WTW Ratio - Sensible Gains - Phoenix, AZ

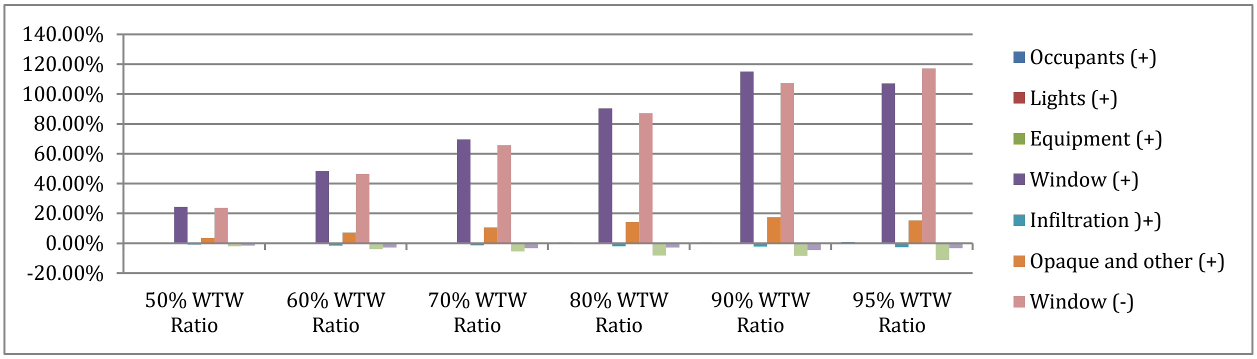


Figure 89: WTW Ratio - Sensible Gains Change from Baseline - Phoenix, AZ

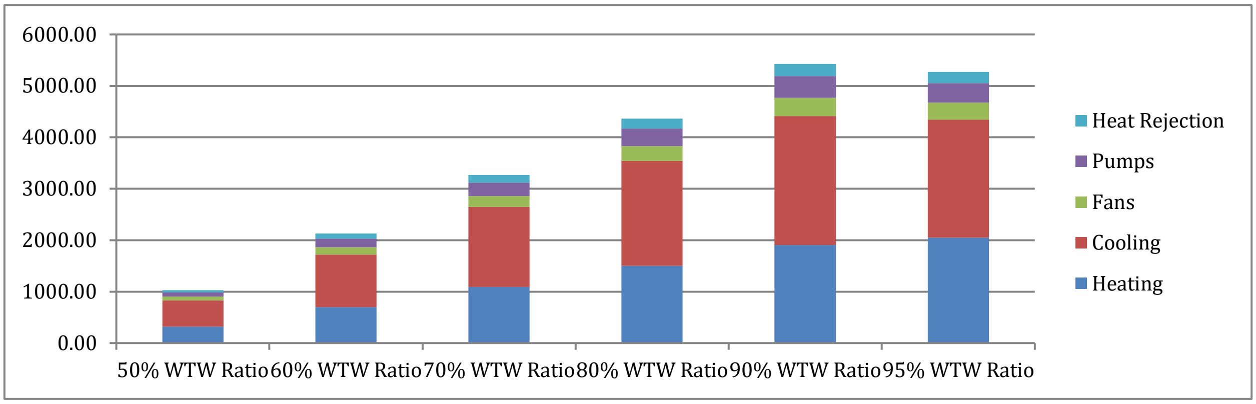


Figure 90: WTW Ratio - Energy Consumption Difference from Baseline - Phoenix, AZ

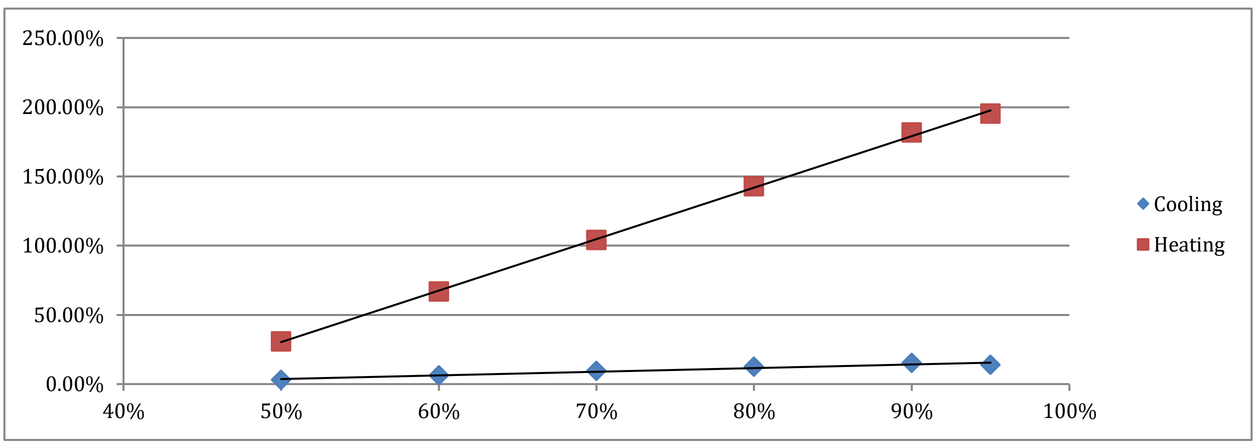


Figure 91: WTW Ratio - Heating and Cooling Energy % Difference from Baseline - Phoenix, AZ

Atlanta, GA WTW Ratio Results

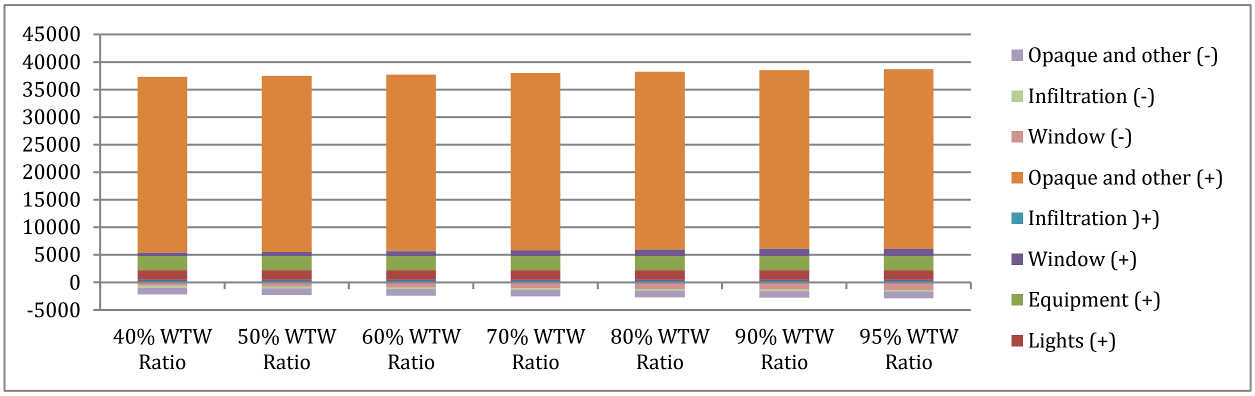


Figure 92: WTW Ratio - Sensible Gains - Atlanta, GA

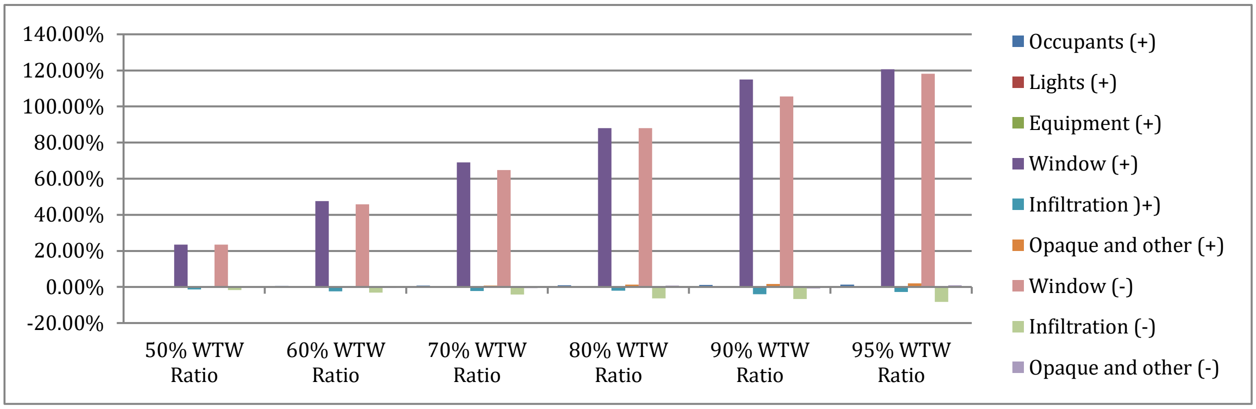


Figure 93: WTW Ratio - Sensible Gains Change from Baseline - Atlanta, GA

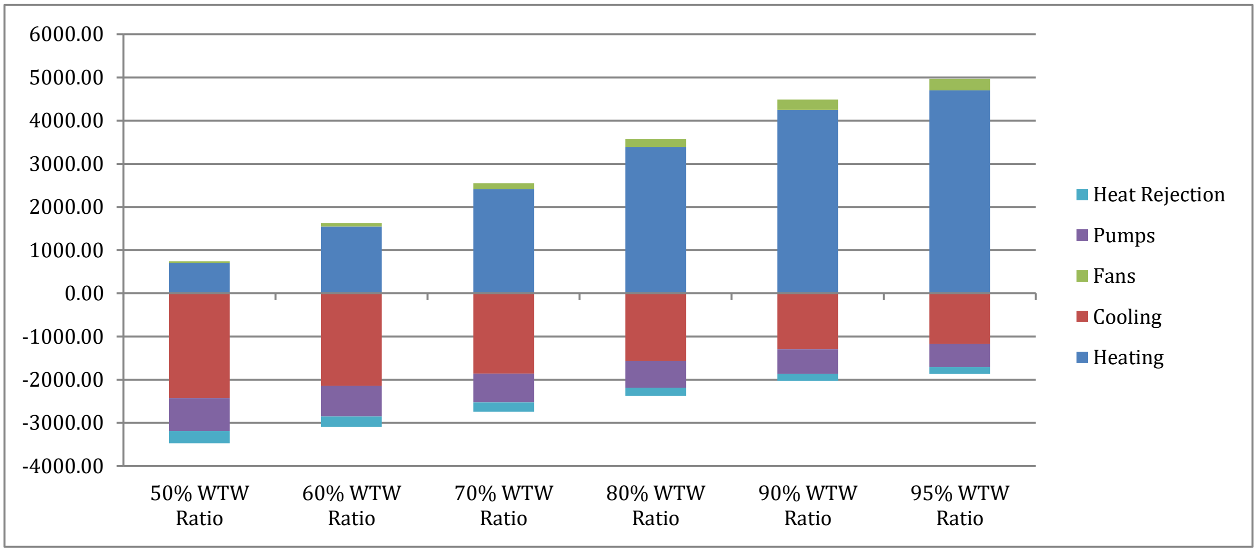


Figure 94: WTW Ratio - Energy Consumption Difference from Baseline - Atlanta, GA

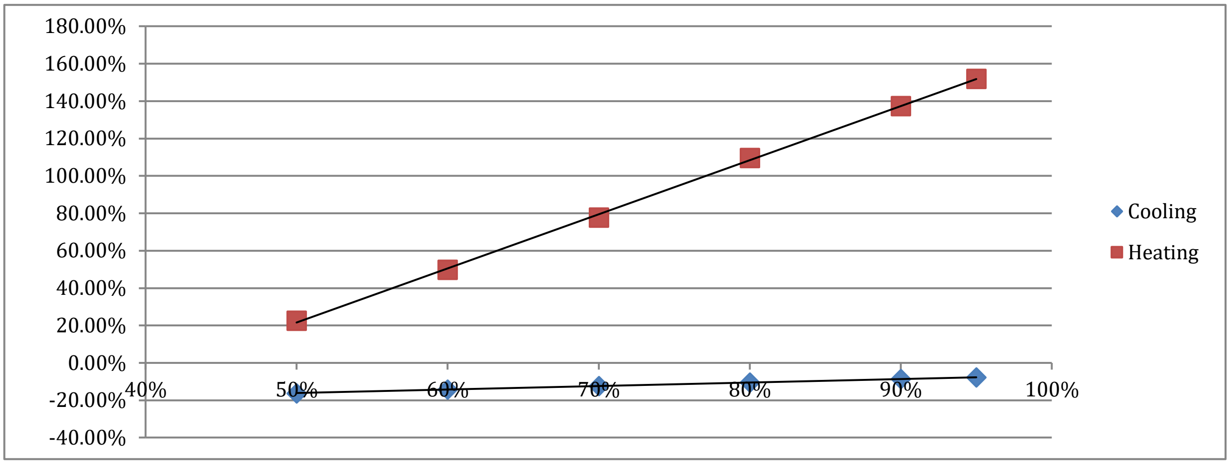


Figure 95: WTW Ratio - Heating and Cooling Energy % Difference from Baseline - Atlanta, GA

San Francisco, CA WTW Ratio Results

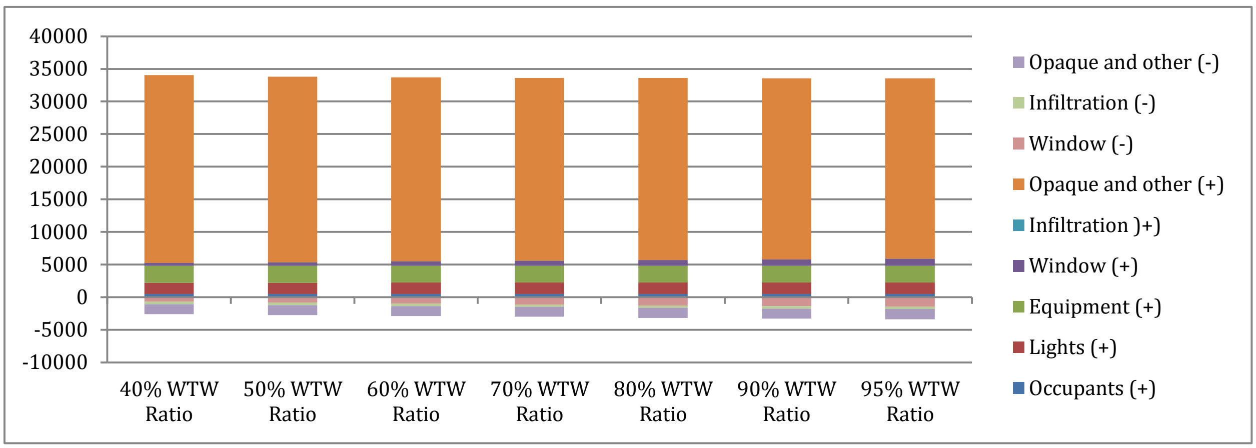


Figure 96: WTW Ratio - Sensible Gains - San Francisco, CA

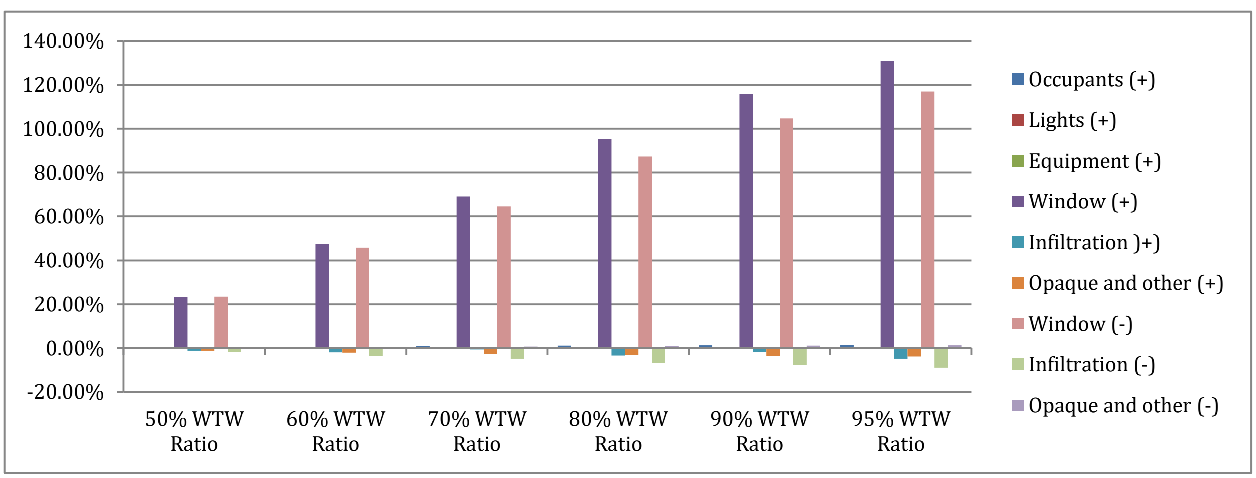


Figure 97: WTW Ratio - Sensible Gains Change from Baseline - San Francisco, CA

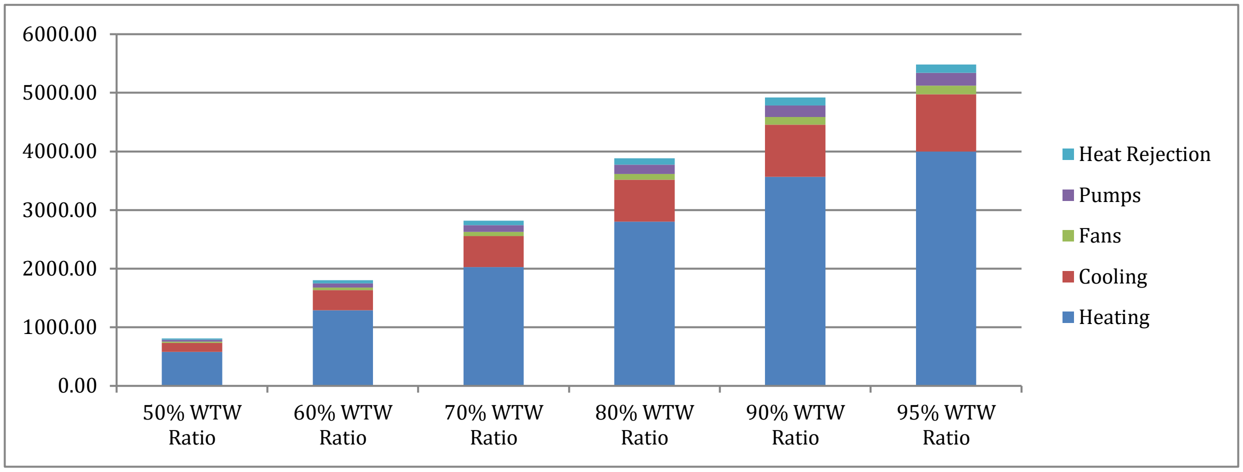


Figure 98: WTW Ratio - Energy Consumption Difference from Baseline - San Francisco, CA

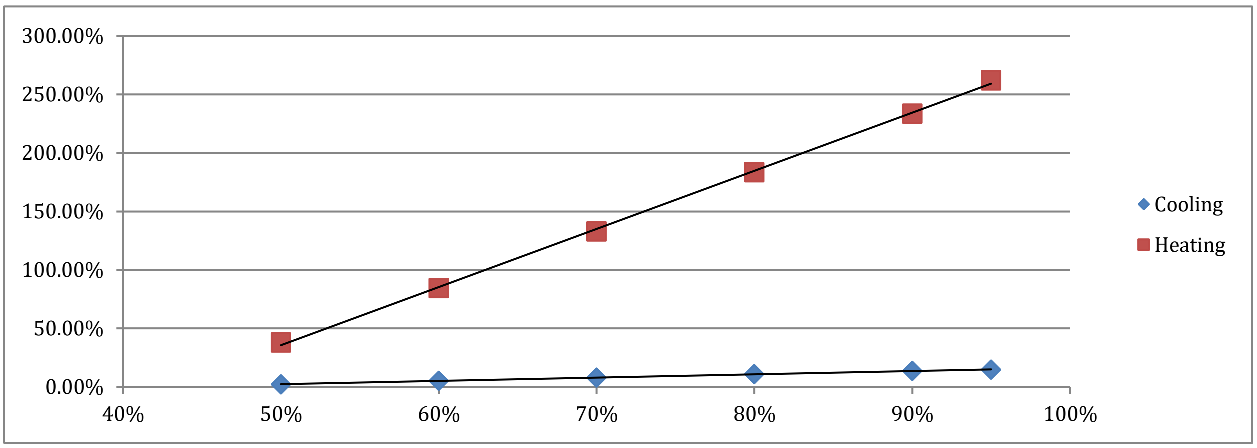


Figure 99: WTW Ratio - Heating and Cooling Energy % Difference from Baseline - San Francisco, CA

Baltimore, MD WTW Ratio Results

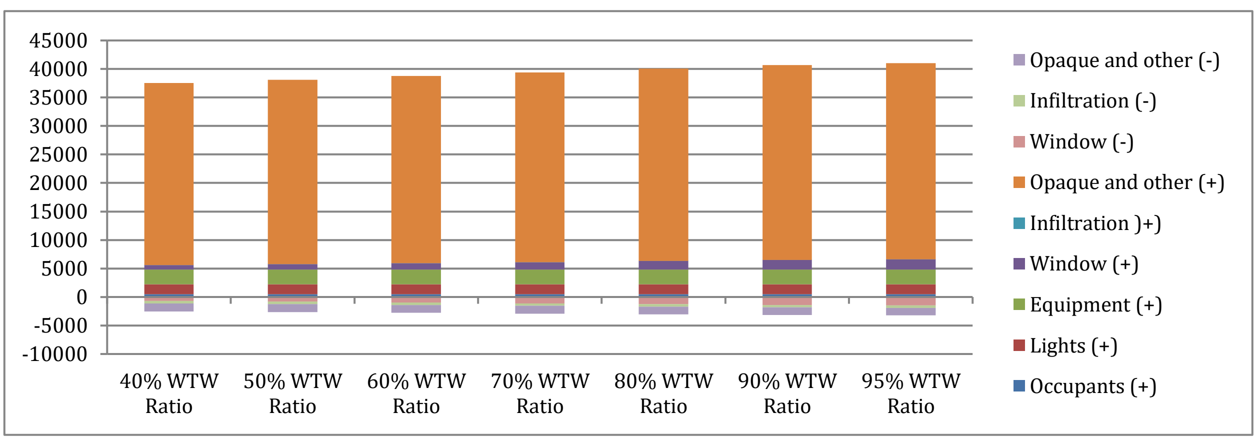


Figure 100: WTW Ratio - Sensible Gains - Baltimore, MD

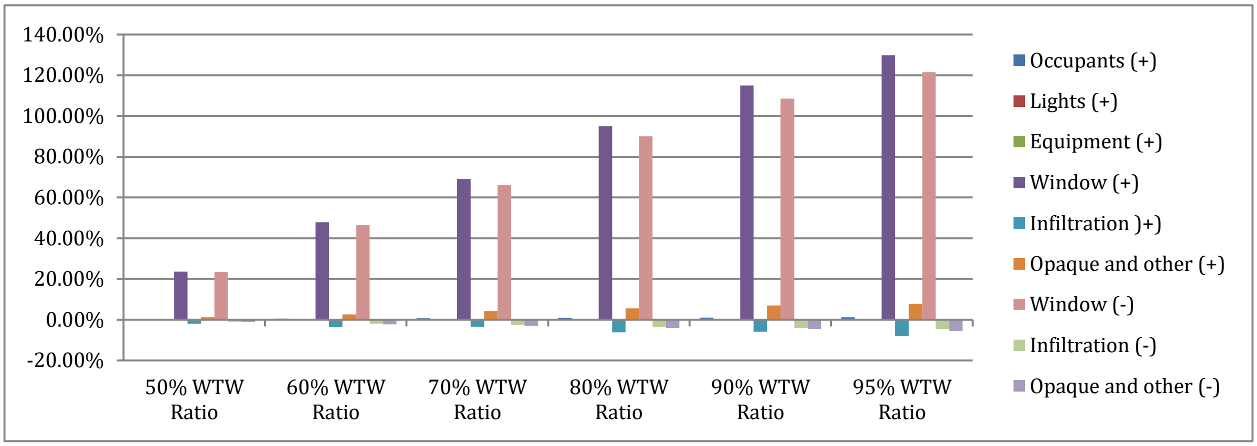


Figure 101: WTW Ratio - Sensible Gains Change from Baseline - Baltimore, MD

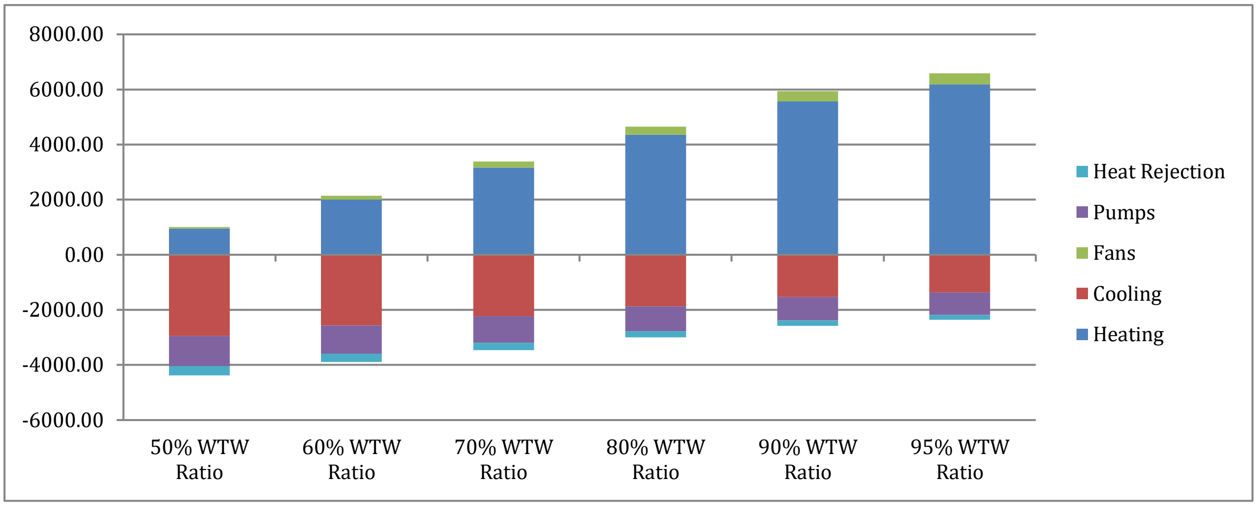


Figure 102: WTW Ratio - Energy Consumption Difference from Baseline - Baltimore, MD

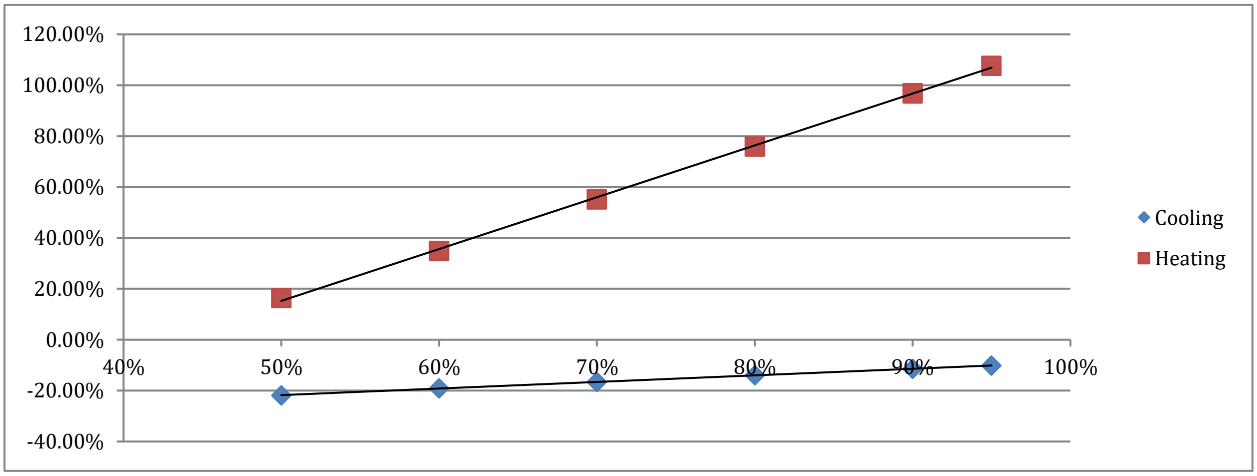


Figure 103: WTW Ratio - Heating and Cooling Energy % Difference from Baseline - Baltimore, MD

Seattle, WA WTW Ratio Results

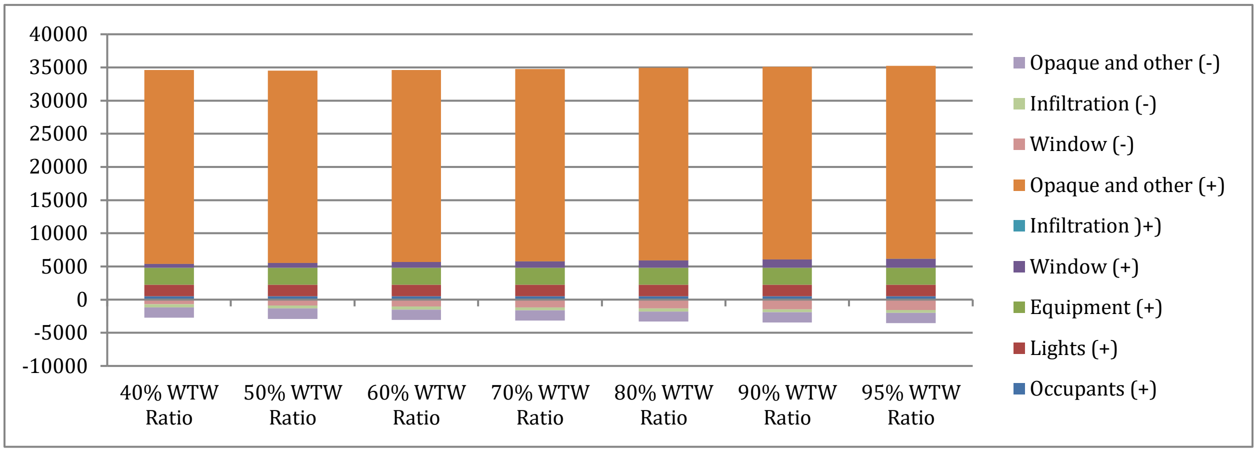


Figure 104: WTW Ratio - Sensible Gains - Seattle, WA

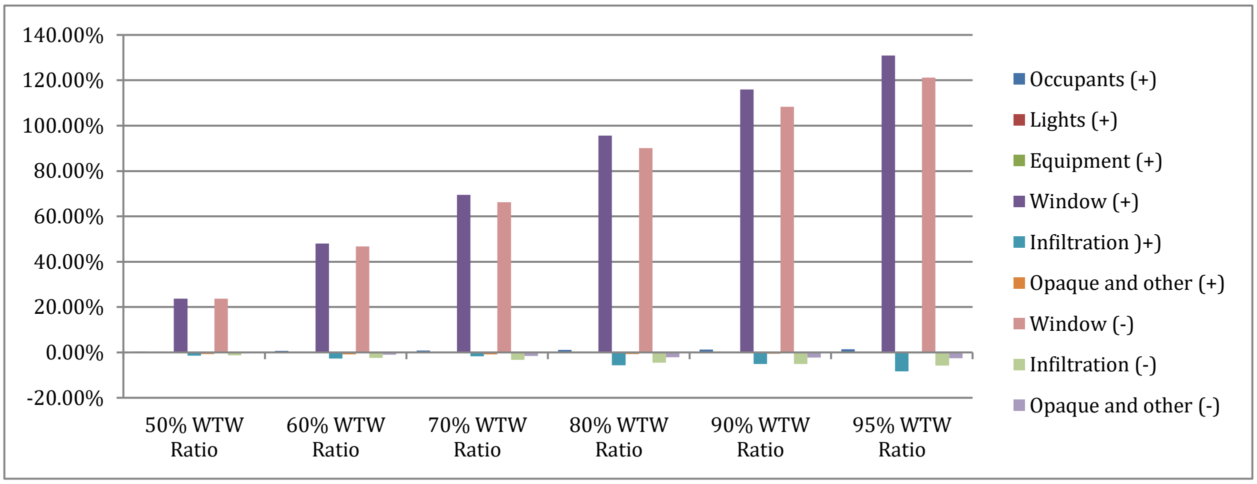


Figure 105: WTW Ratio - Sensible Gains Change from Baseline - Seattle, WA

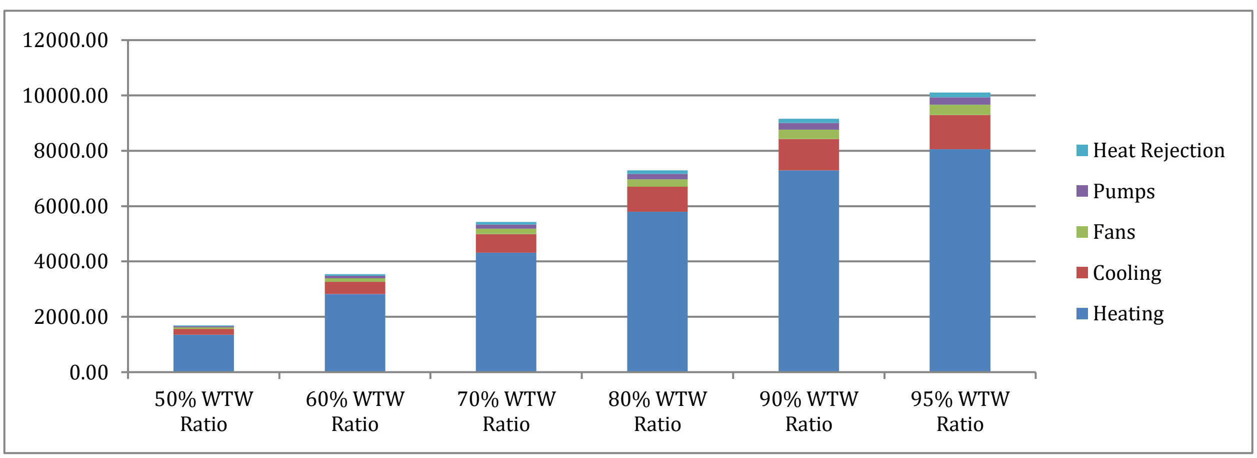


Figure 106: WTW Ratio - Energy Consumption Difference from Baseline - Seattle, WA

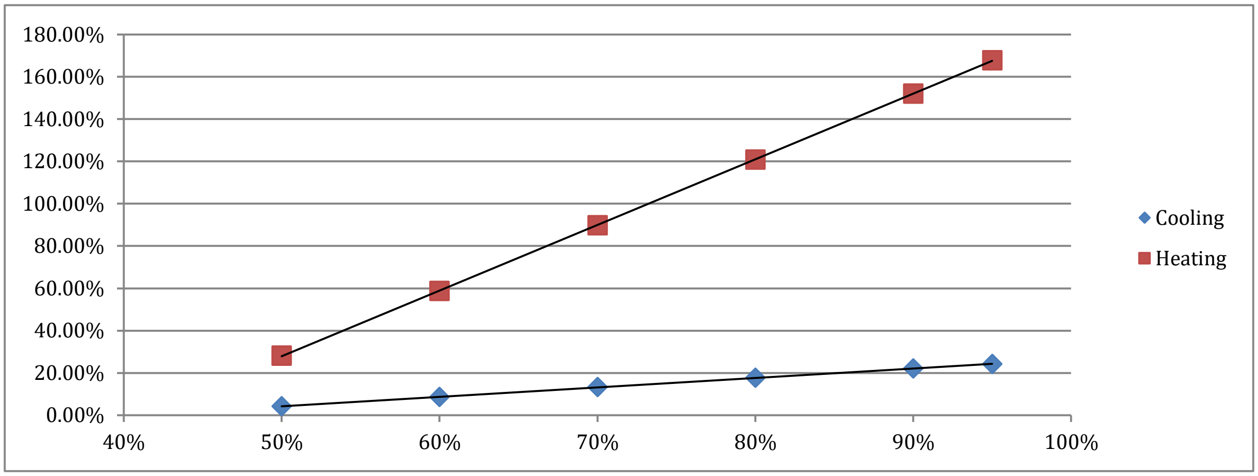


Figure 107: WTW Ratio - Heating and Cooling Energy % Difference from Baseline - Seattle, WA

Chicago, IL WTW Ratio Results

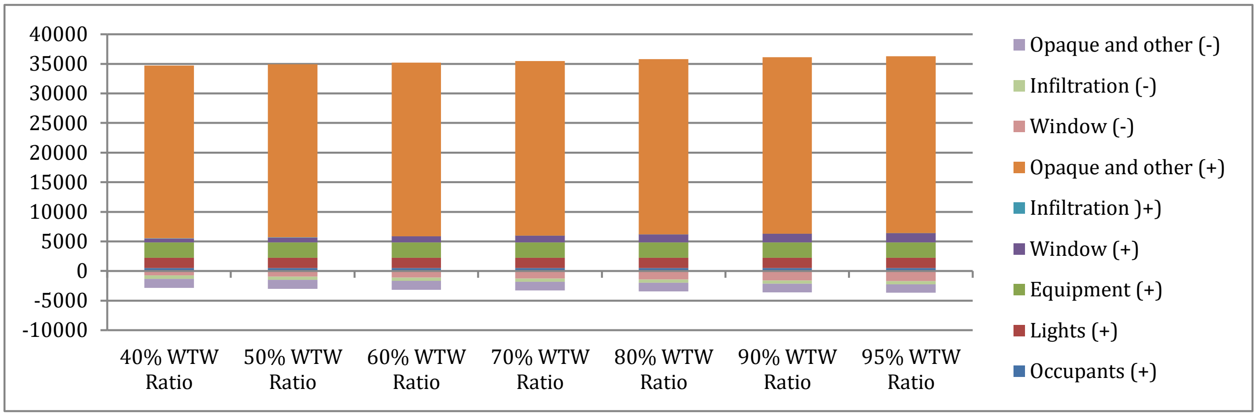


Figure 108: WTW Ratio - Sensible Gains - Chicago, IL

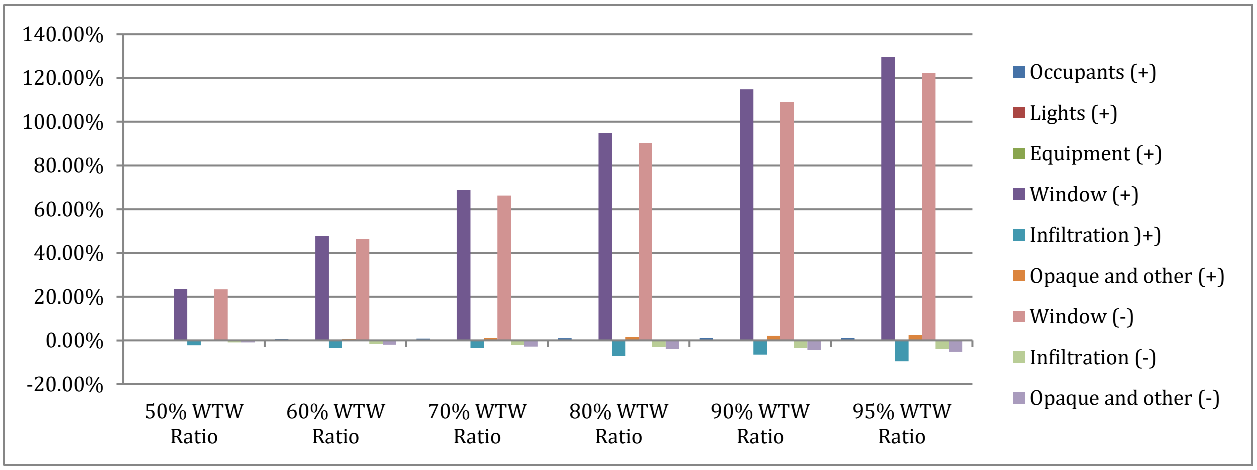


Figure 109: WTW Ratio - Sensible Gains Change from Baseline - Chicago, IL

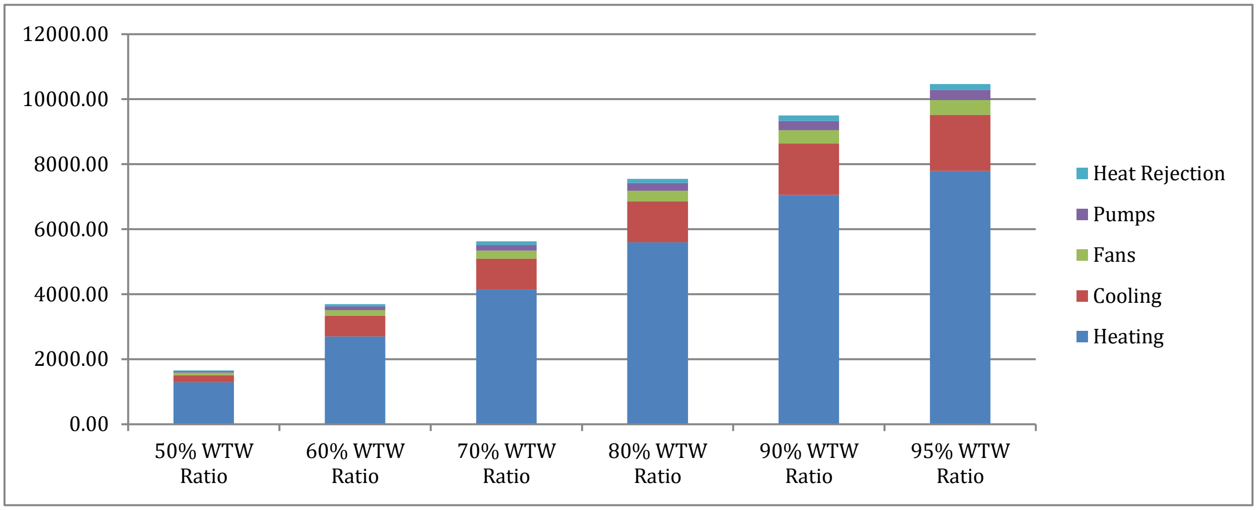


Figure 110: WTW Ratio - Energy Consumption Difference from Baseline - Chicago, IL

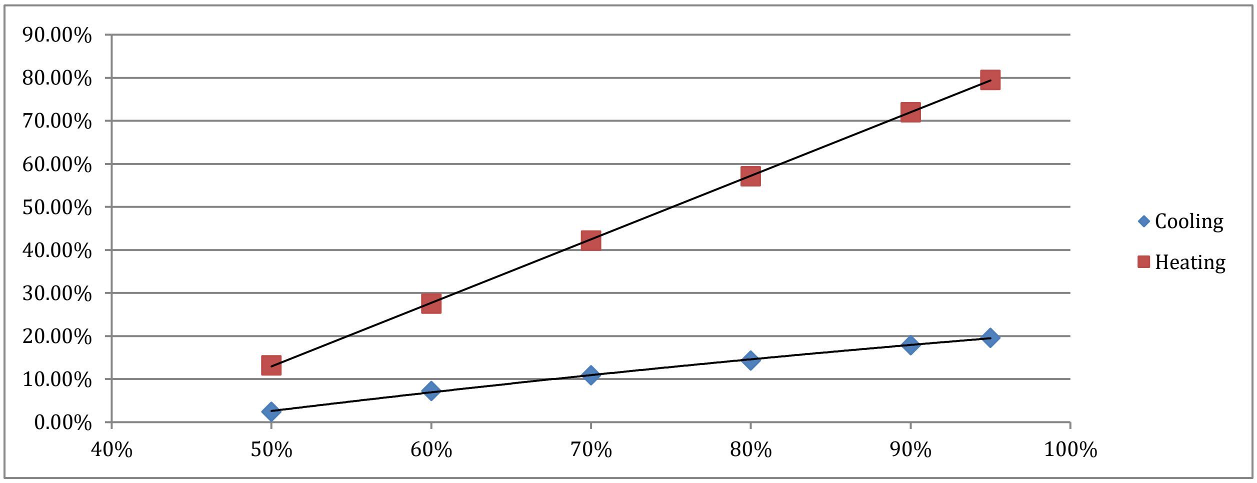


Figure 111: WTW Ratio - Heating and Cooling Energy % Difference from Baseline - Chicago, IL

Denver, CO WTW Ratio Results

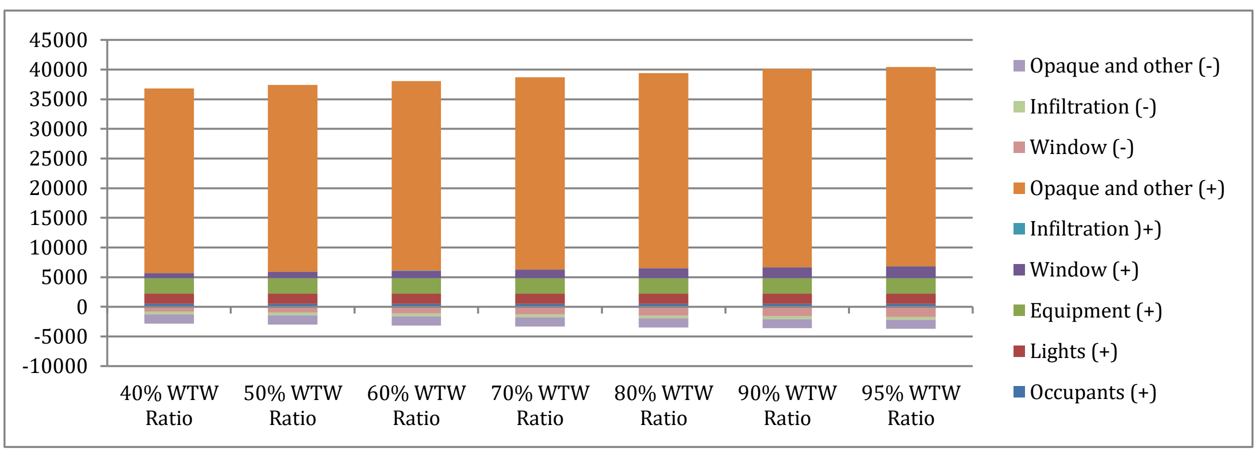


Figure 112: WTW Ratio - Sensible Gains - Denver, CO

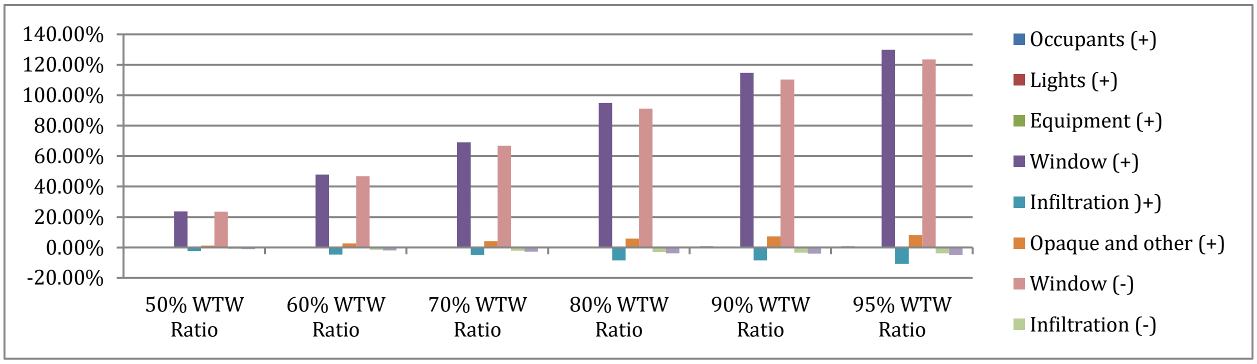


Figure 113: WTW Ratio - Sensible Gains Change from Baseline - Denver, CO

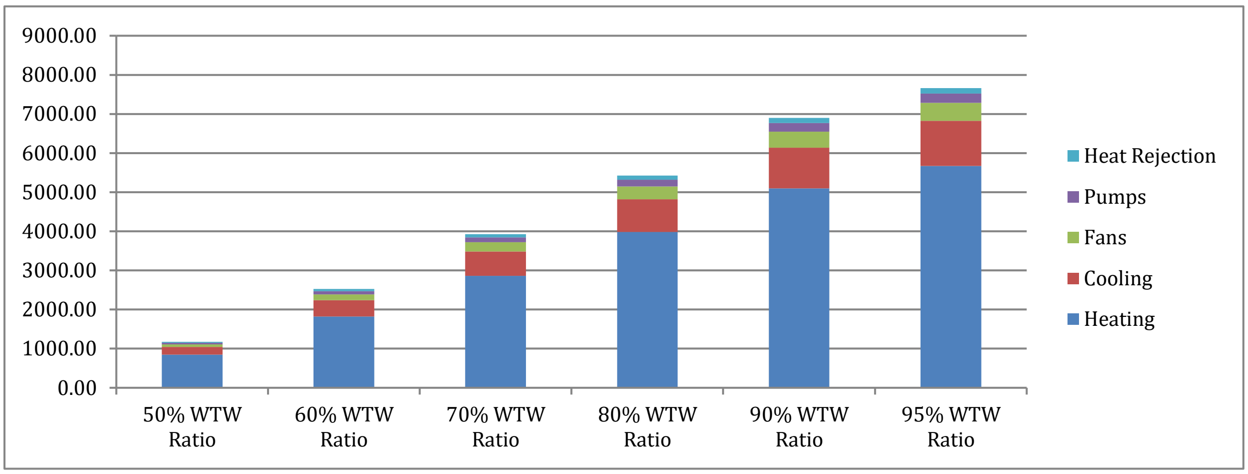


Figure 114: WTW Ratio - Energy Consumption Difference from Baseline - Denver, CO

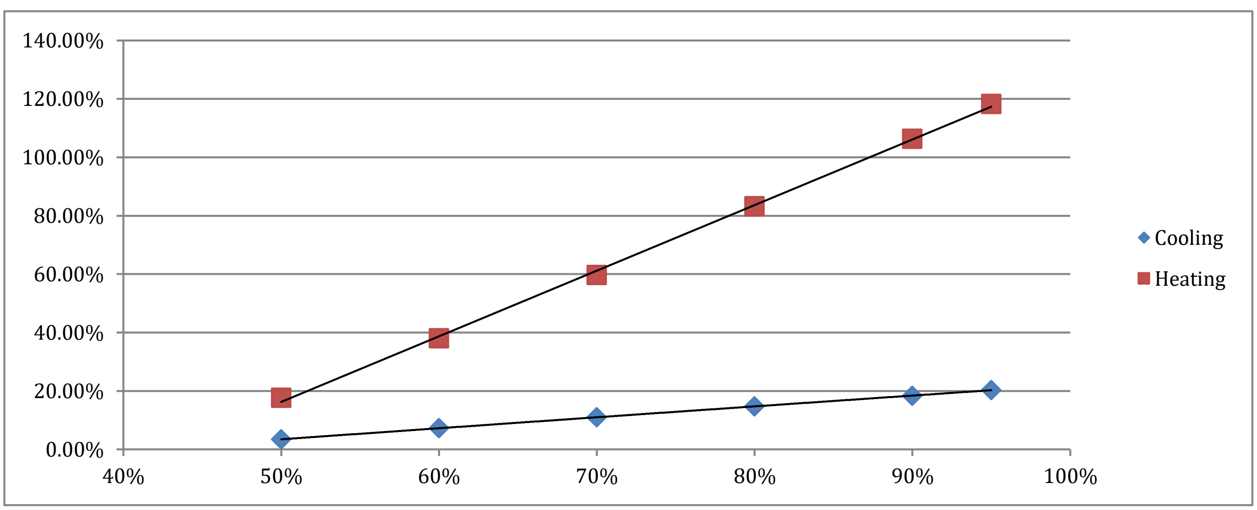


Figure 115: WTW Ratio - Heating and Cooling Energy % Difference from Baseline - Denver, CO

Helena, MT WTW Ratio Results

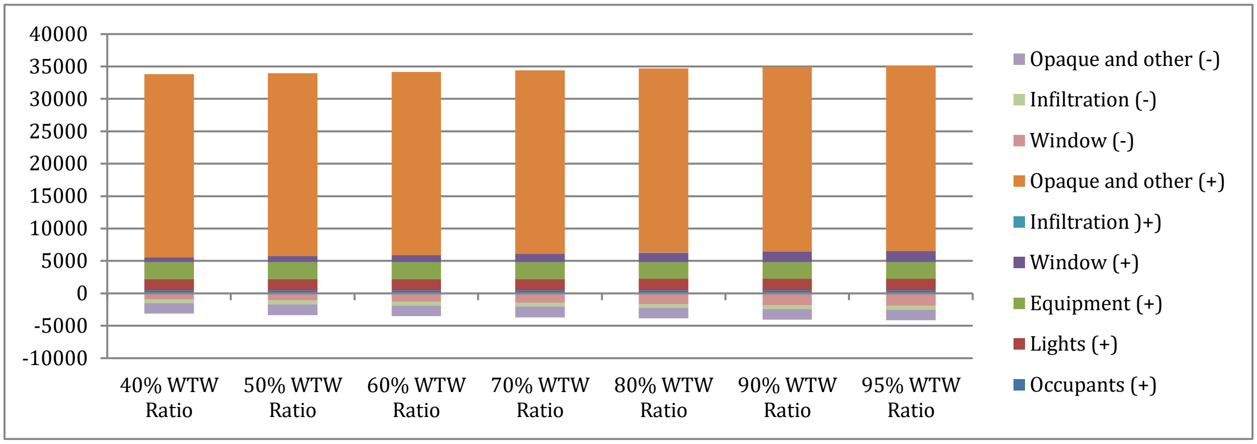


Figure 116: WTW Ratio - Sensible Gains - Helena, MT

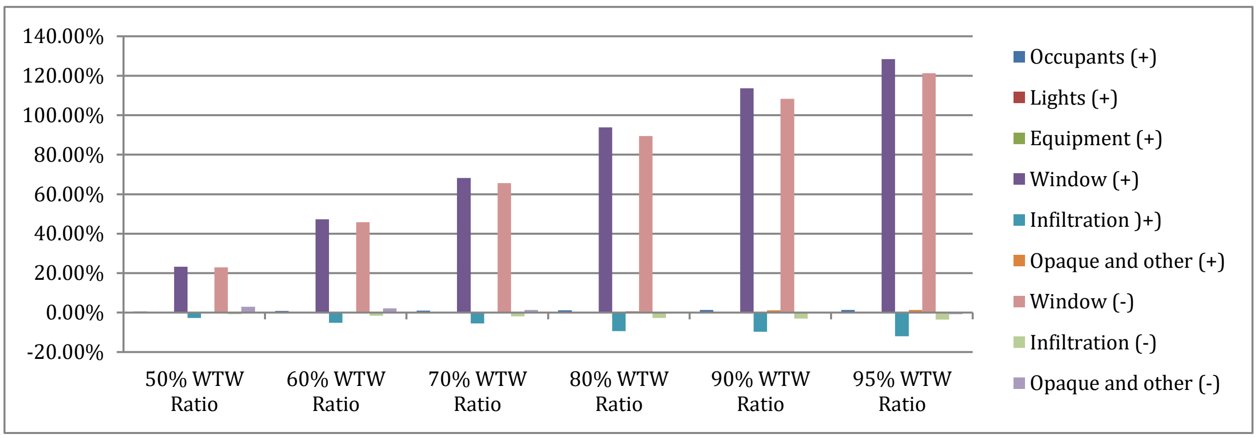


Figure 117: WTW Ratio - Sensible Gains Change from Baseline - Helena, MT

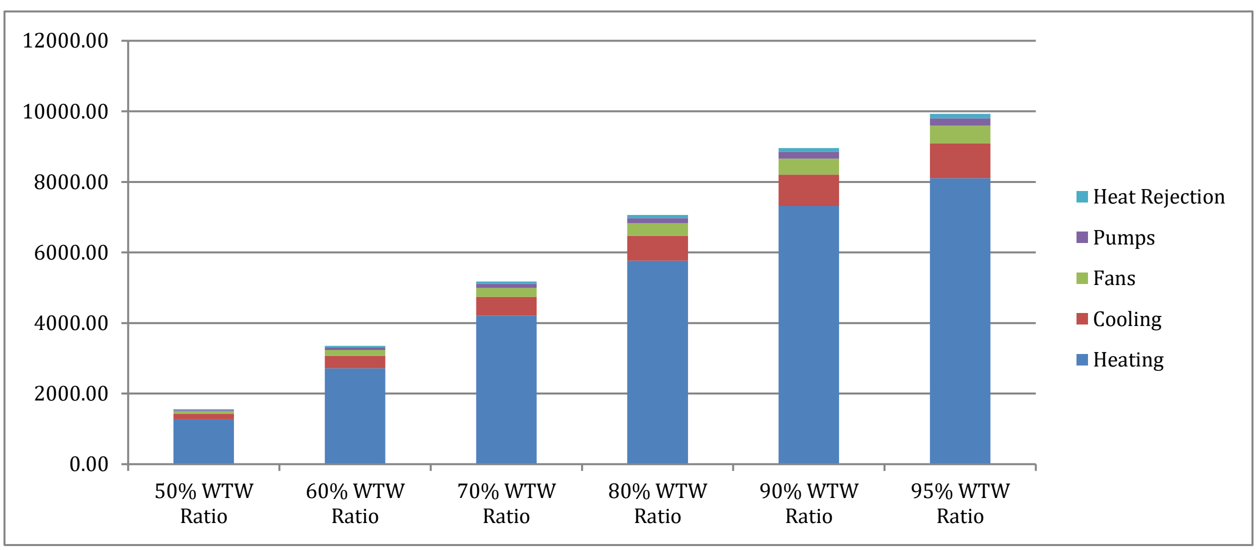


Figure 118: WTW Ratio - Energy Consumption Difference from Baseline - Helena, MT

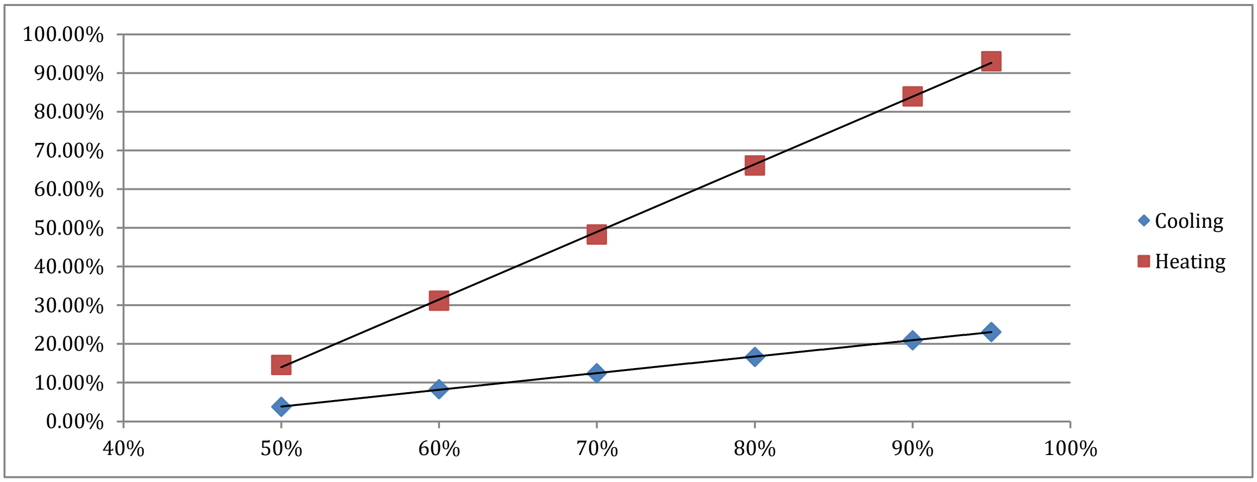


Figure 119: WTW Ratio - Heating and Cooling Energy % Difference from Baseline - Helena, MT

Duluth, MN WTW Ratio Results

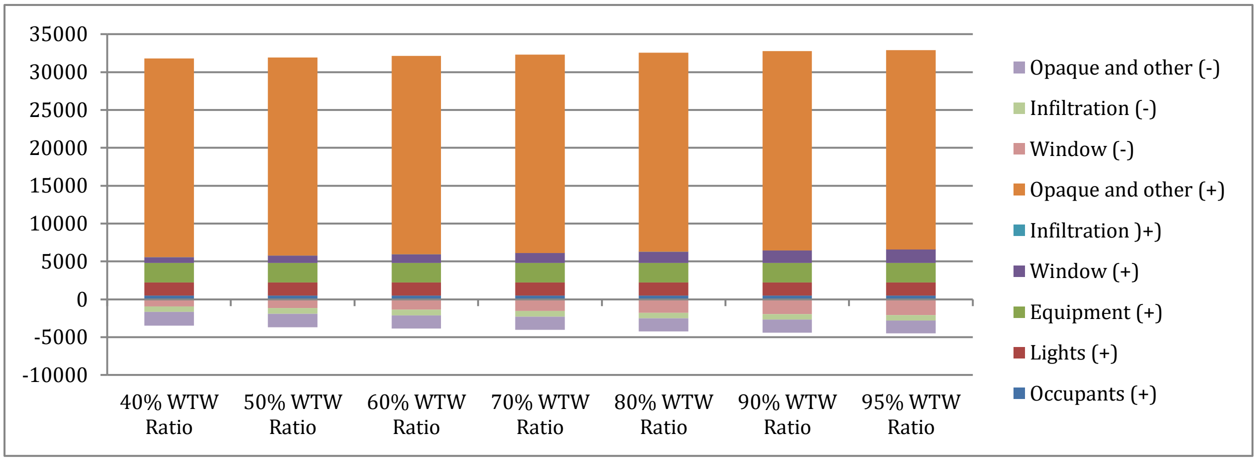


Figure 120: WTW Ratio - Sensible Gains - Duluth, MN

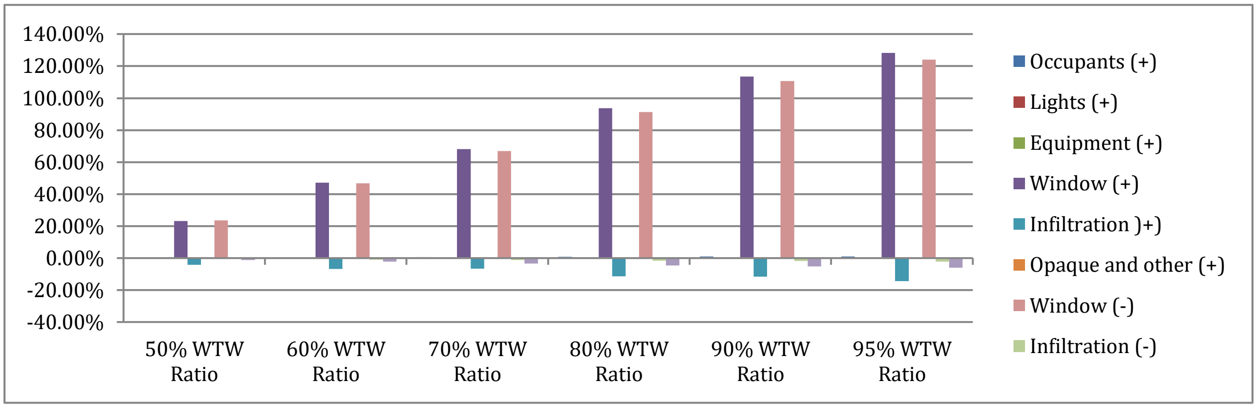


Figure 121: WTW Ratio - Sensible Gains Change from Baseline - Duluth, MN

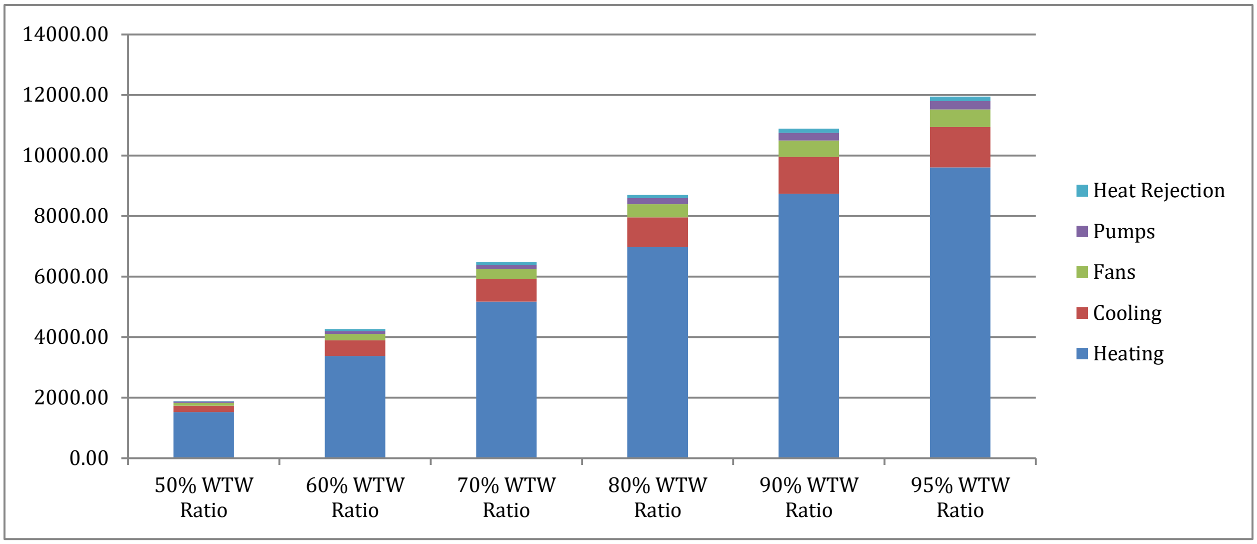


Figure 122: WTW Ratio - Energy Consumption Difference from Baseline - Duluth, MN

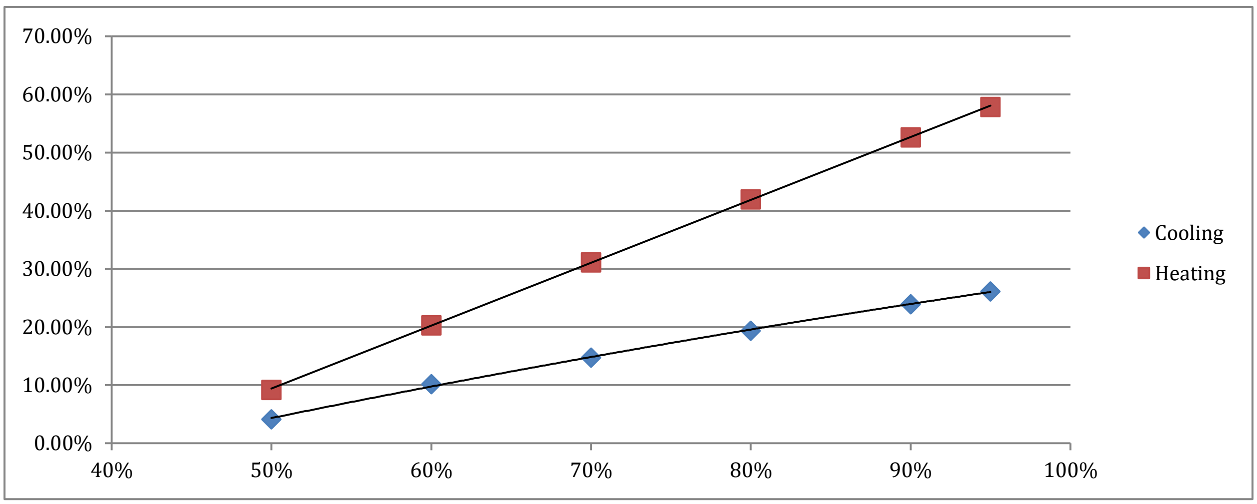


Figure 123: WTW Ratio - Heating and Cooling Energy % Difference from Baseline - Duluth, MN

Appendix C: Window U-values Results

Miami, FL Window U-value Results

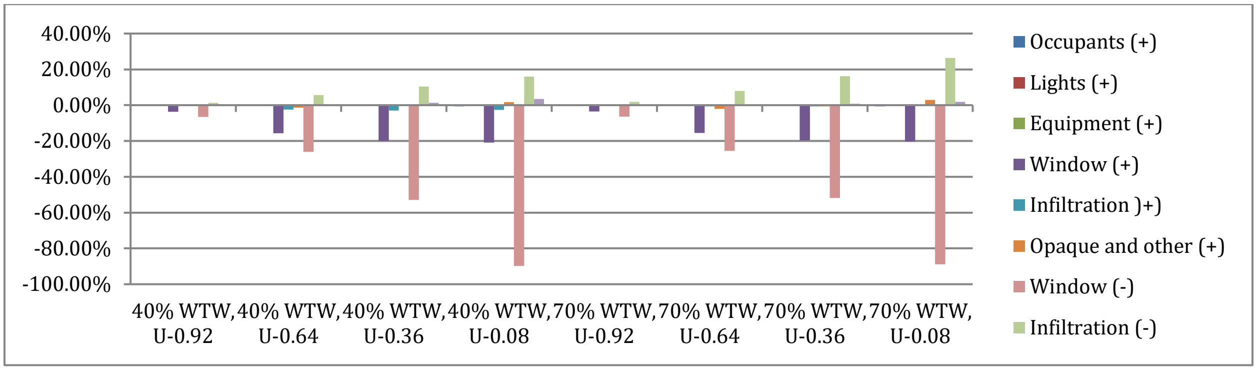


Figure 124: Window U-value - Sensible Gains % Difference from Baseline - Miami, FL

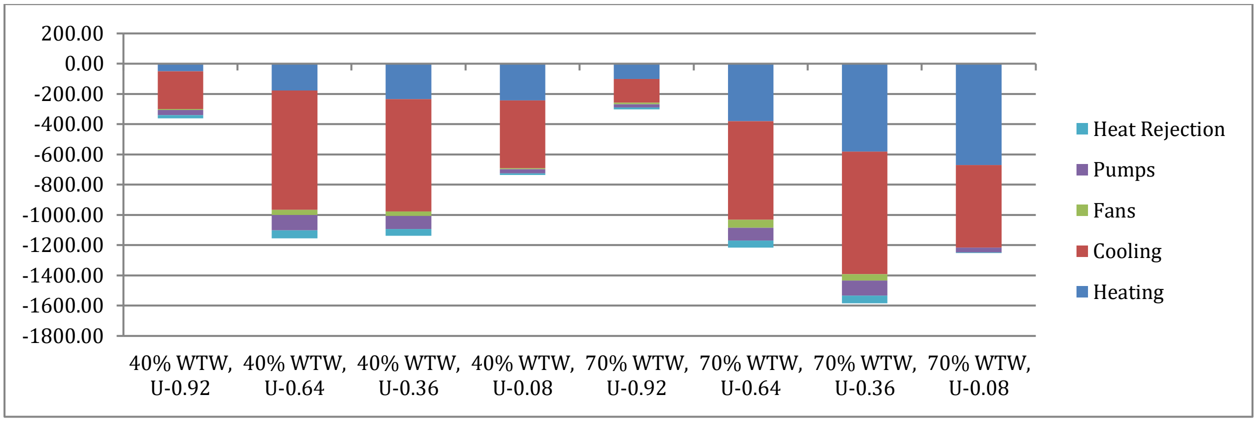


Figure 125: Window U-value - Energy Consumption Difference from Baseline - Miami, FL

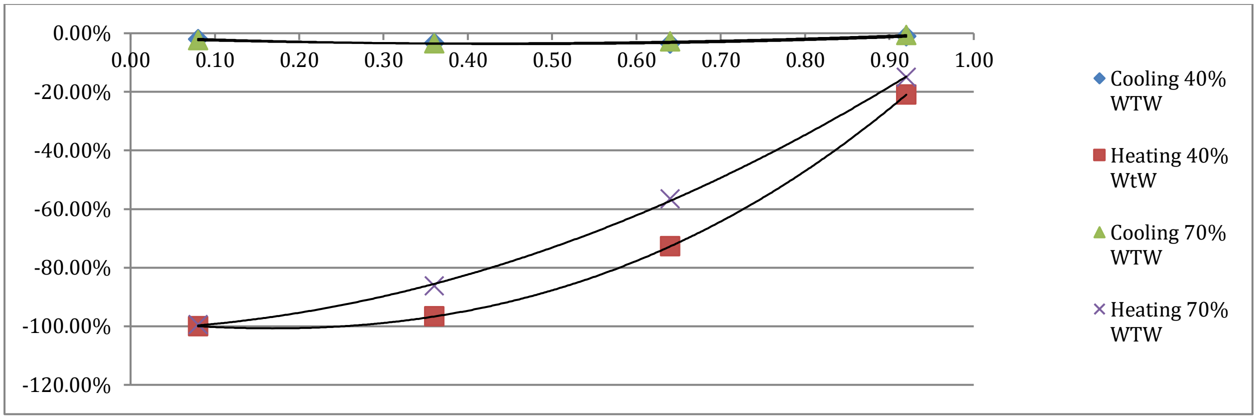


Figure 126: Window U-value - Heating and Cooling Energy % Difference from Baseline - Miami, FL

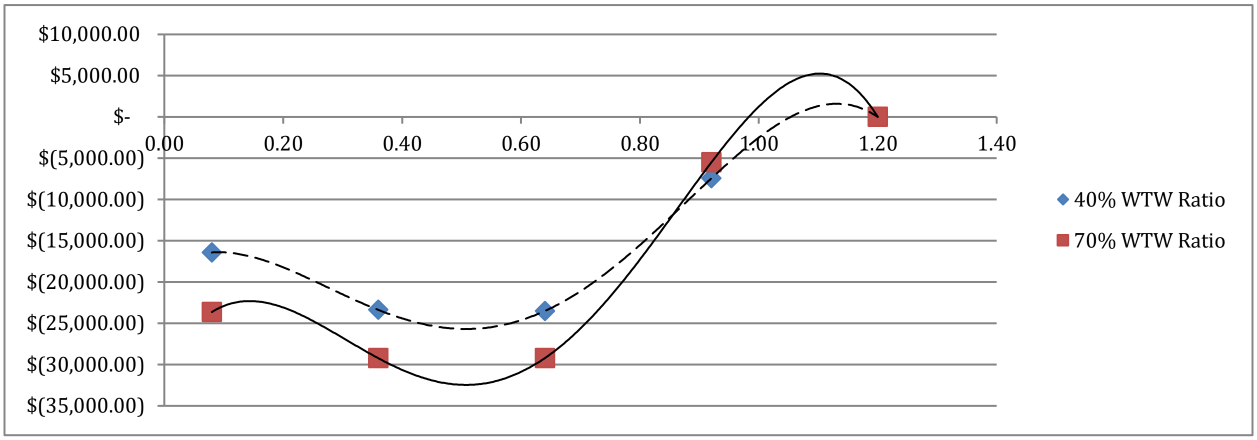


Figure 127: Window U-value Energy Cost Difference from Baseline - Miami, FL

Houston, TX Window U-value Results

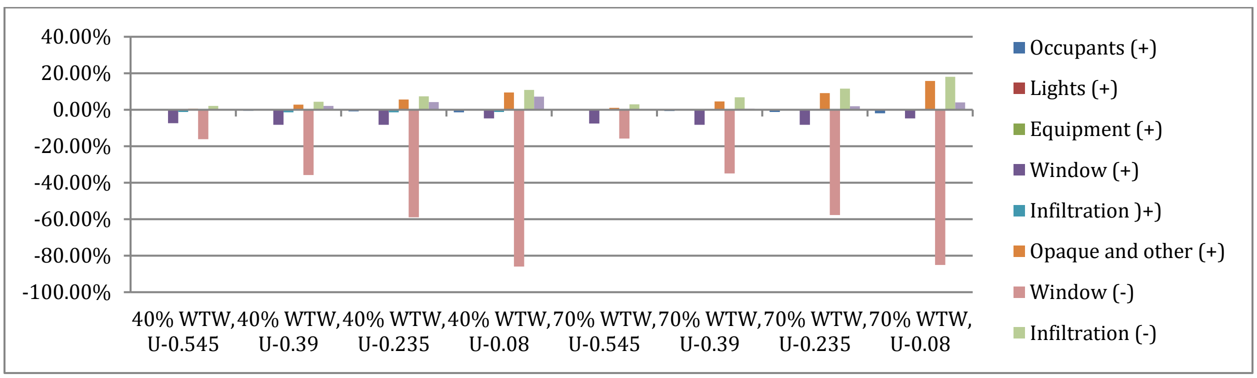


Figure 128: Window U-value - Sensible Gains % Difference from Baseline - Houston, TX

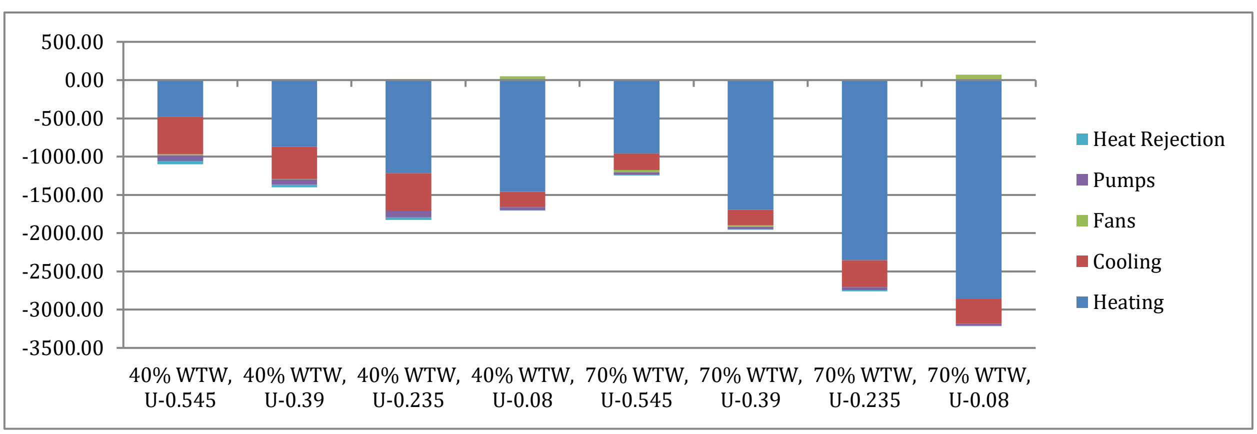


Figure 129: Window U-value Energy Consumption Difference from Baseline - Houston, TX

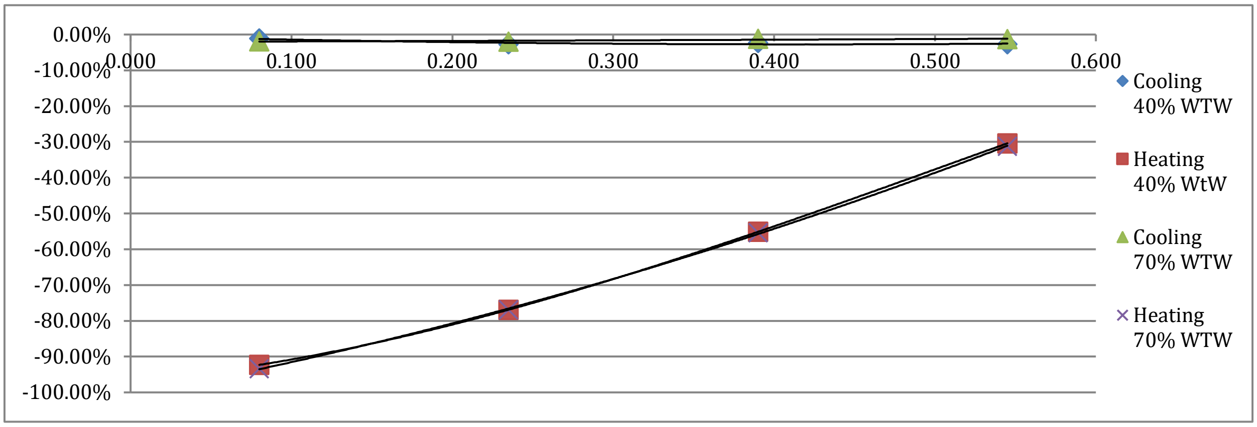


Figure 130: Window U-value - Heating and Cooling Energy % Difference from Baseline – Houston, TX

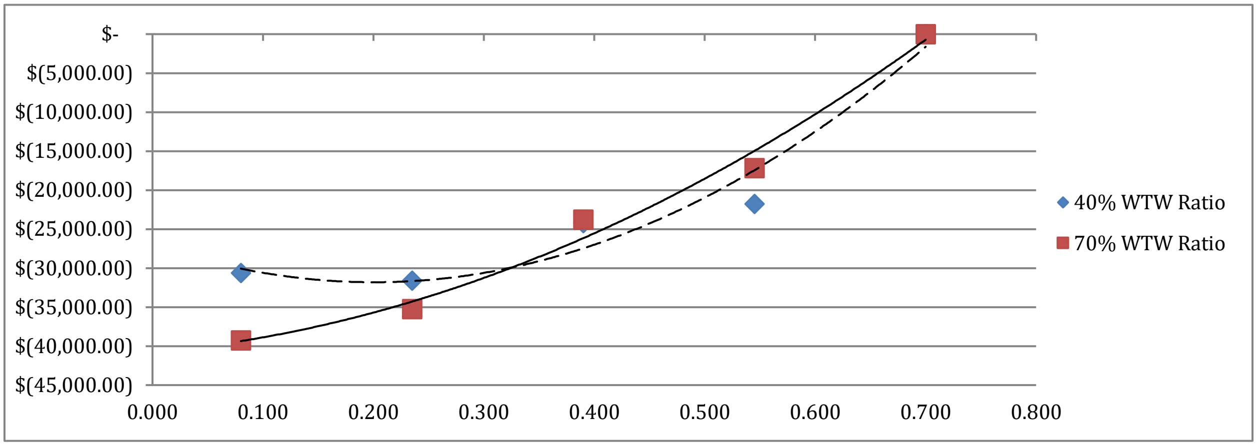


Figure 131: Window U-value - Energy Cost Difference from Baseline- Houston, TX

Phoenix, AZ Window U-value Results

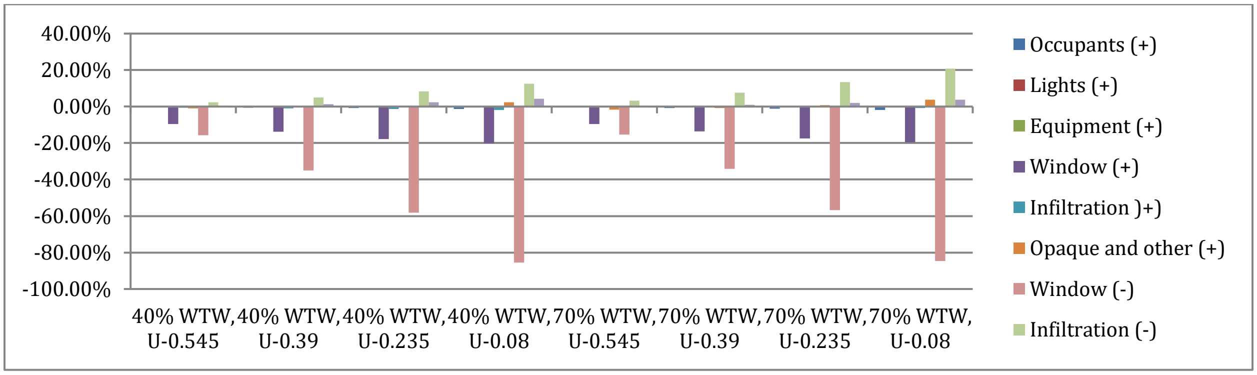


Figure 132: Window U-value - Sensible Gains % Difference from Baseline - Phoenix, AZ

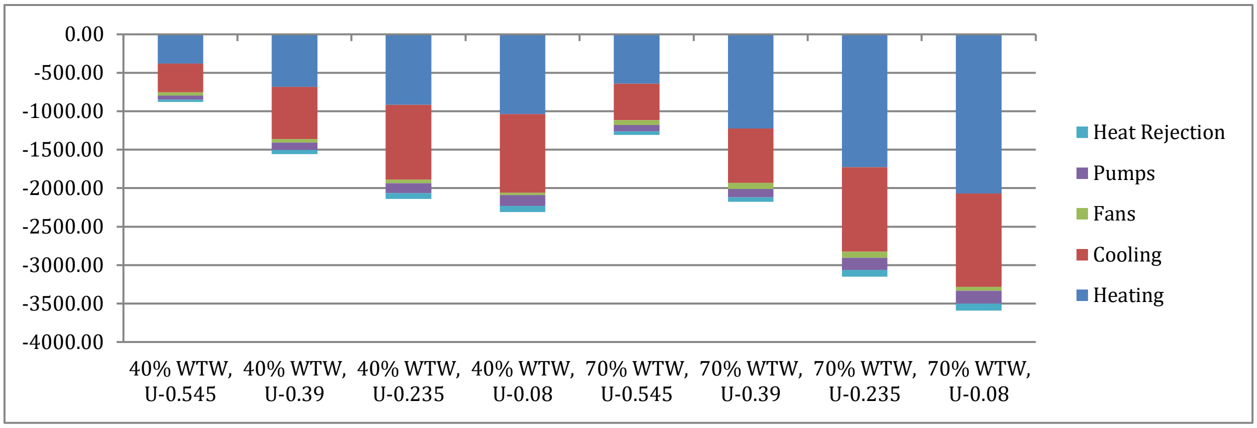


Figure 134: Window U-value Energy Consumption Difference from Baseline –Phoenix, AZ

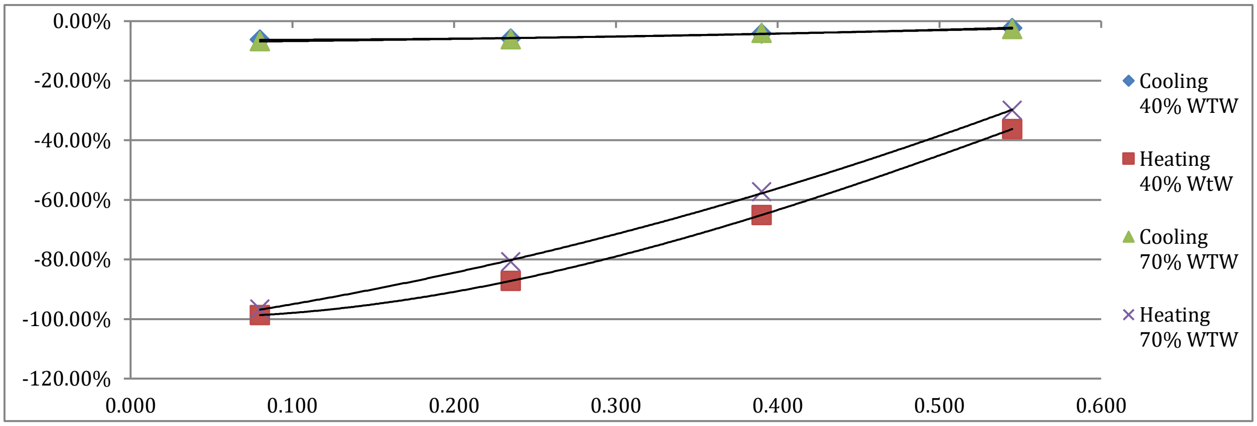


Figure 135: Window U-value - Heating and Cooling Energy % Difference from Baseline – Phoenix, AZ

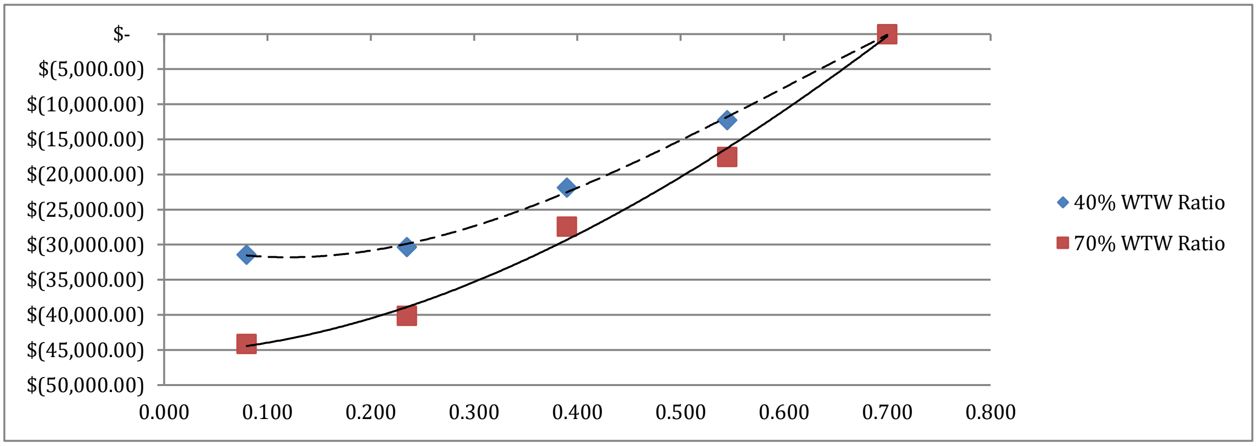


Figure 133: Window U-value - Energy Cost Difference from Baseline- Phoenix, AZ

Atlanta, GA Window U-value Results

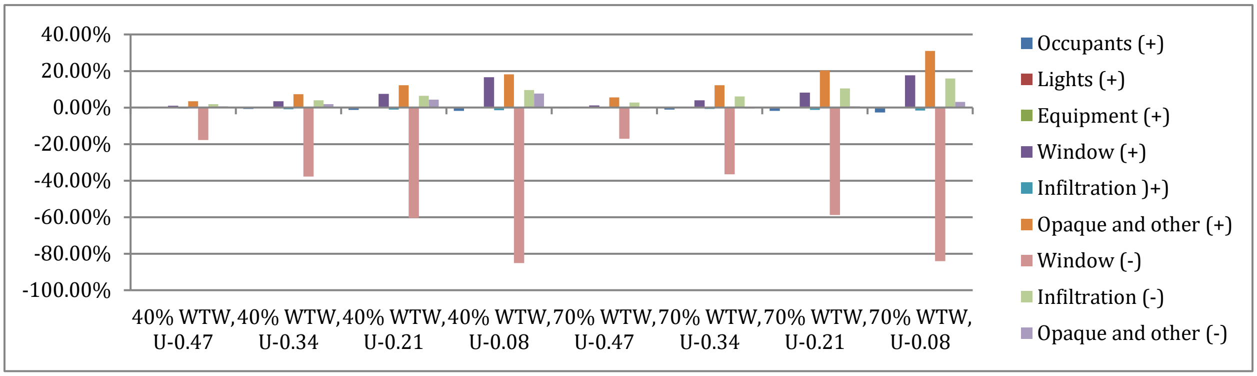


Figure 136: Window U-value - Sensible Gains % Difference from Baseline –Atlanta, GA

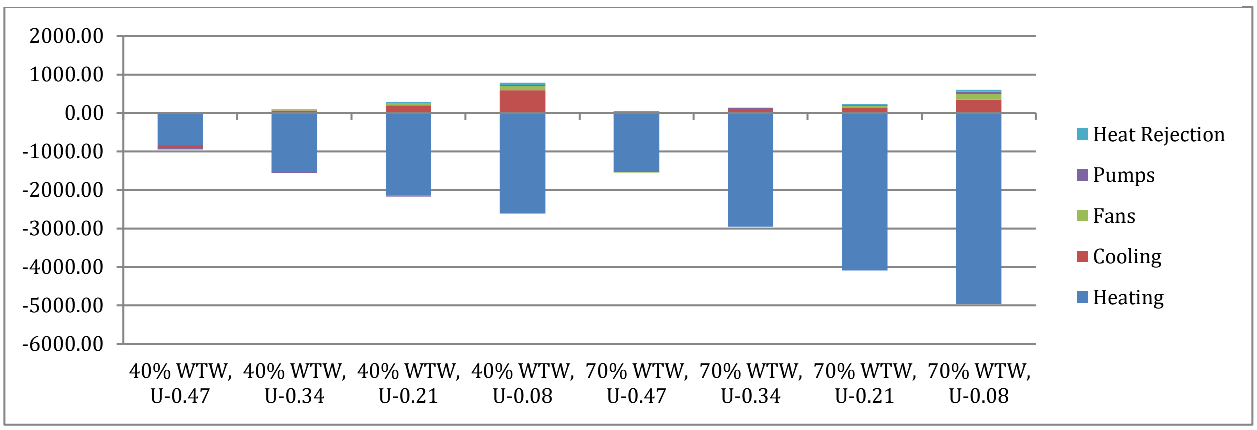


Figure 138: Window U-value Energy Consumption Difference from Baseline -Atlanta, GA

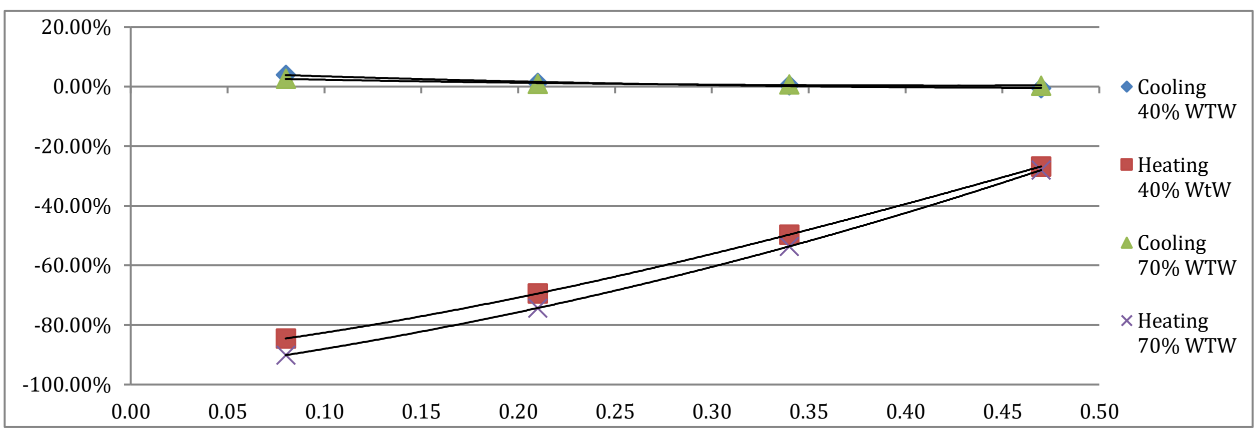


Figure 137: Window U-value - Heating and Cooling Energy % Difference from Baseline – Atlanta, GA

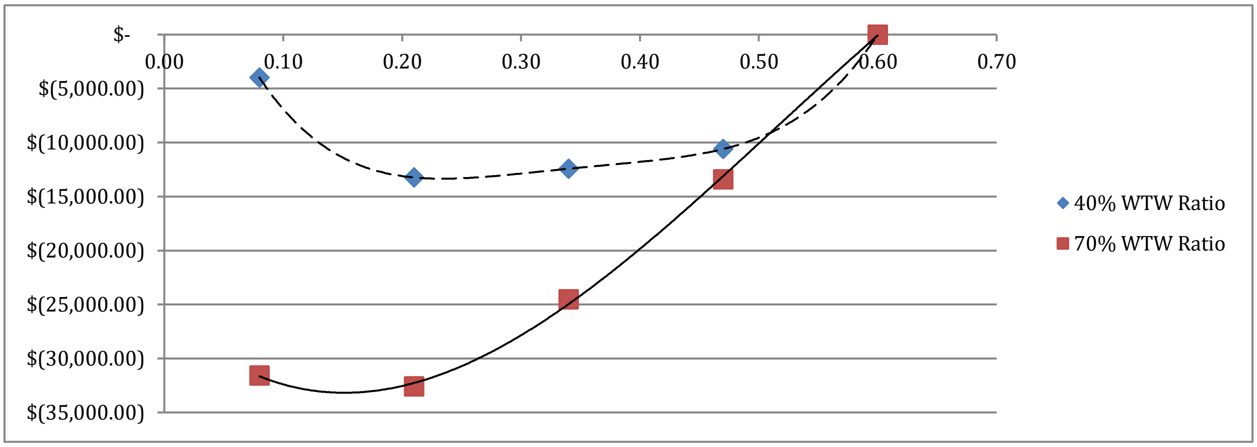


Figure 139: Window U-value - Energy Cost Difference from Baseline – Atlanta, GA

San Francisco, CA Window U-value Results

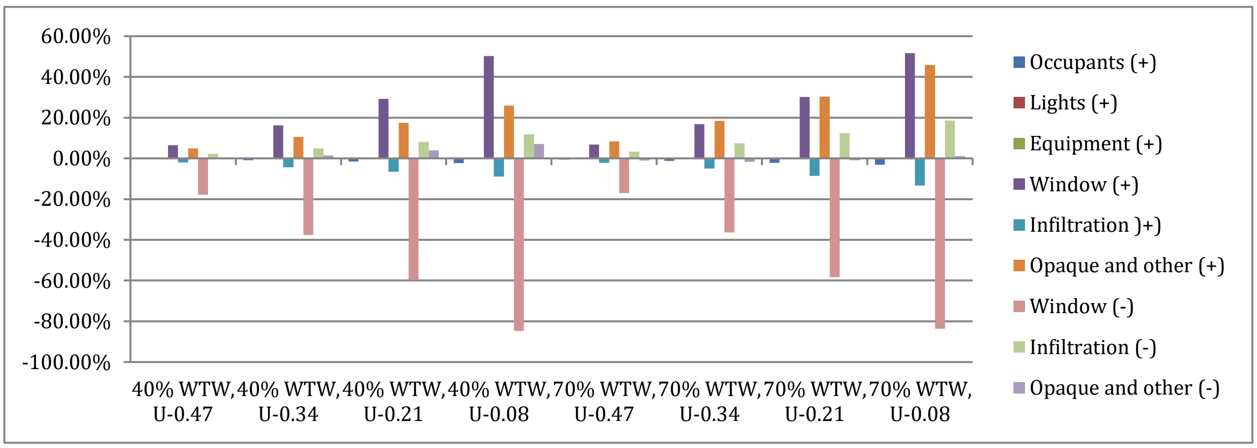


Figure 141: Window U-value - Sensible Gains % Difference from Baseline - San Francisco, CA

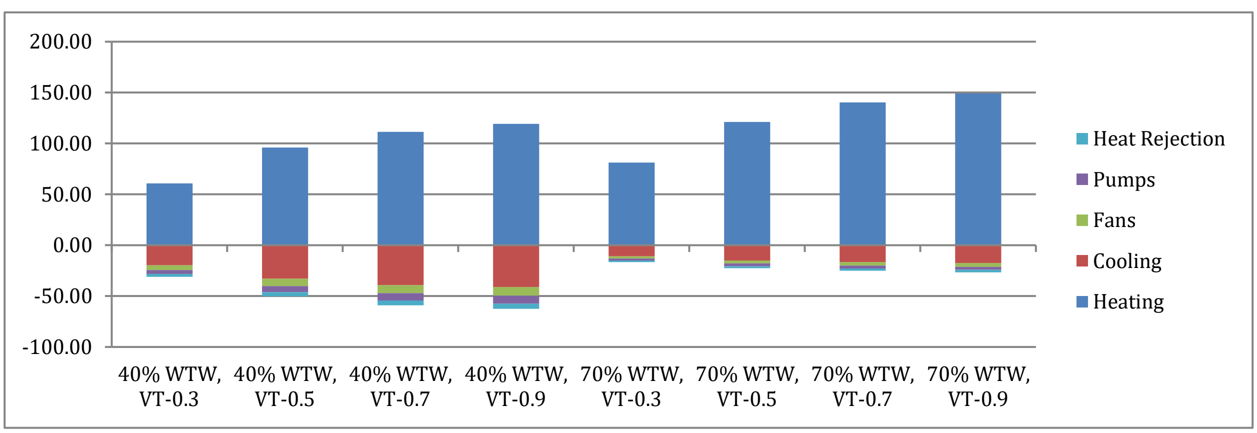


Figure 140: Window U-value Energy Consumption Difference from Baseline - San Francisco, CA

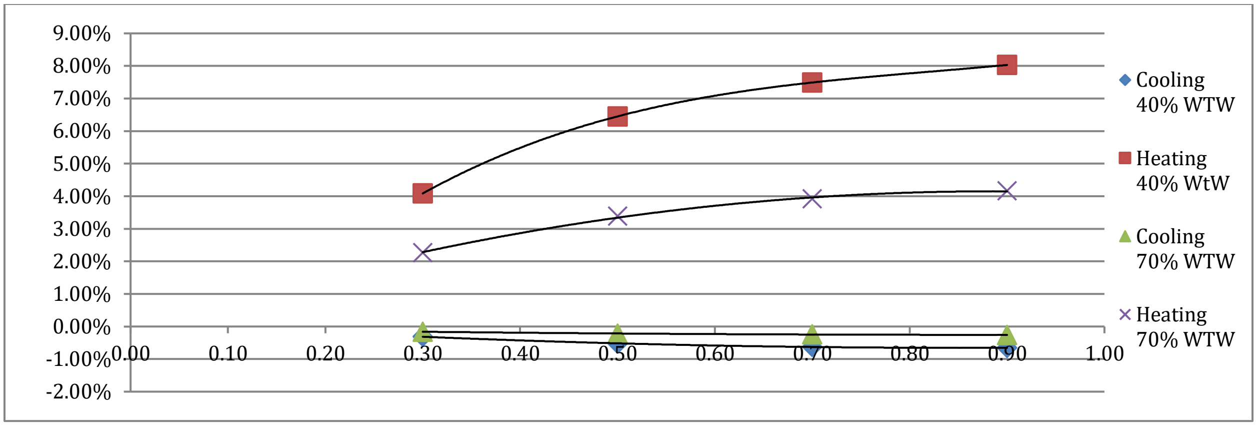


Figure 142: Window U-value - Heating and Cooling Energy % Difference from Baseline – San Francisco, CA

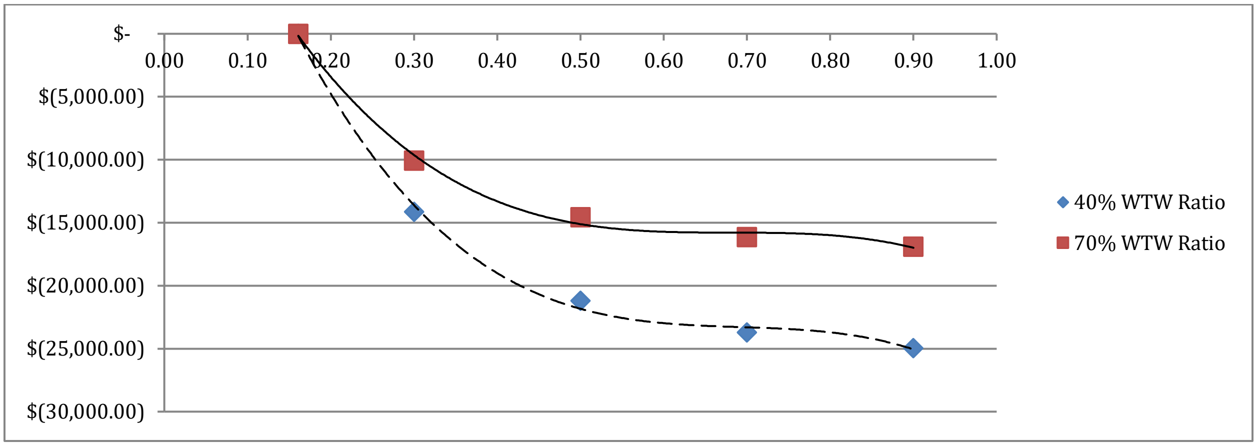


Figure 143: Window U-value - Energy Cost Difference from Baseline- San Francisco, CA

Baltimore, MD Window U-value Results

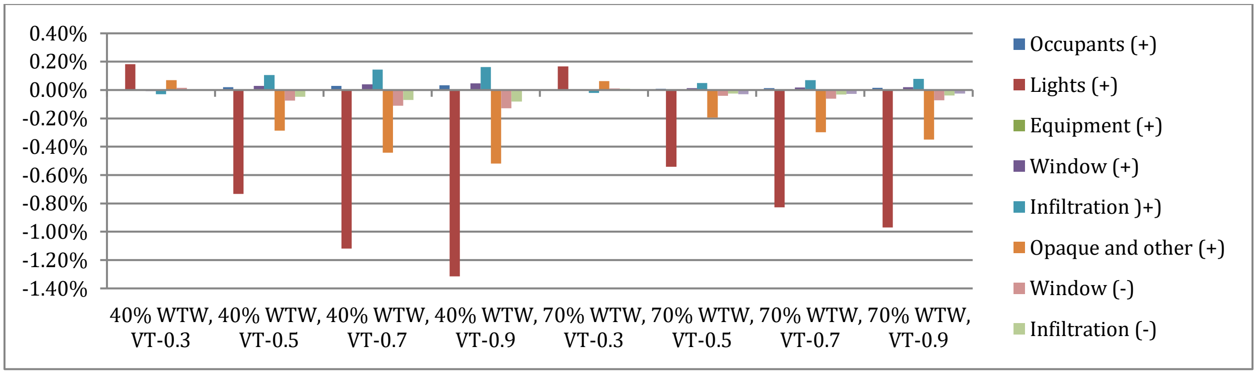


Figure 144: Window U-value - Sensible Gains % Difference from Baseline - Baltimore, MD

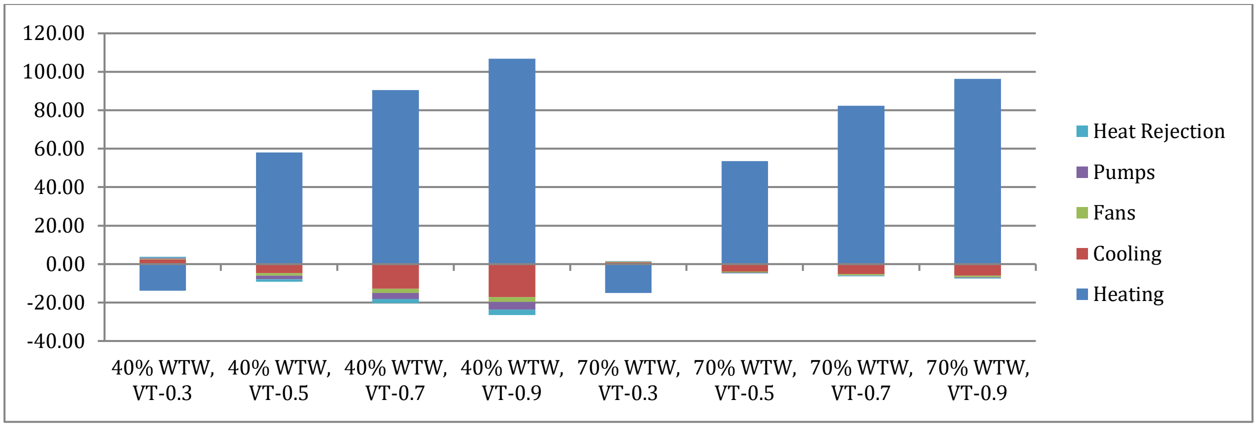


Figure 145: Window U-value Energy Consumption Difference from Baseline - Baltimore, MD

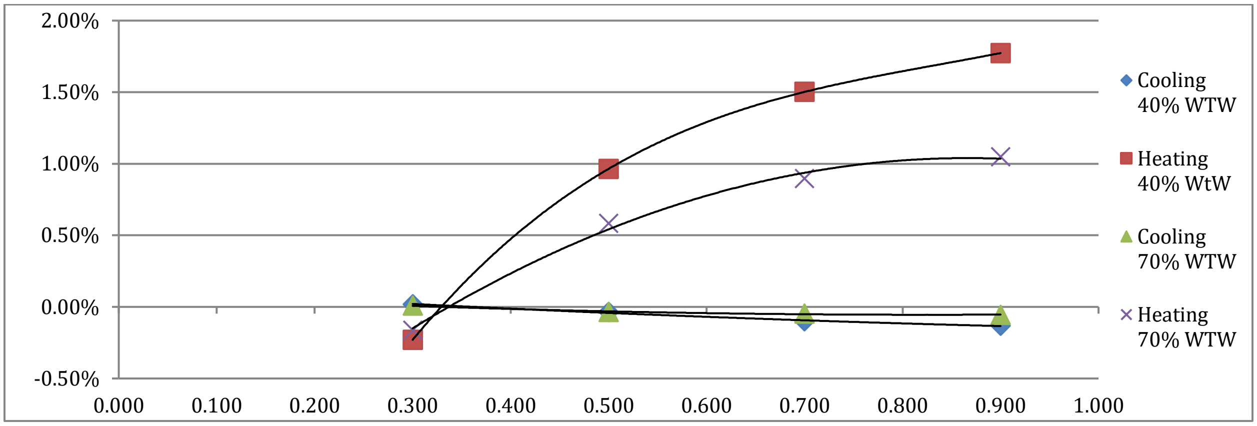


Figure 147: Window U-value - Heating and Cooling Energy % Difference from Baseline – Baltimore, MD

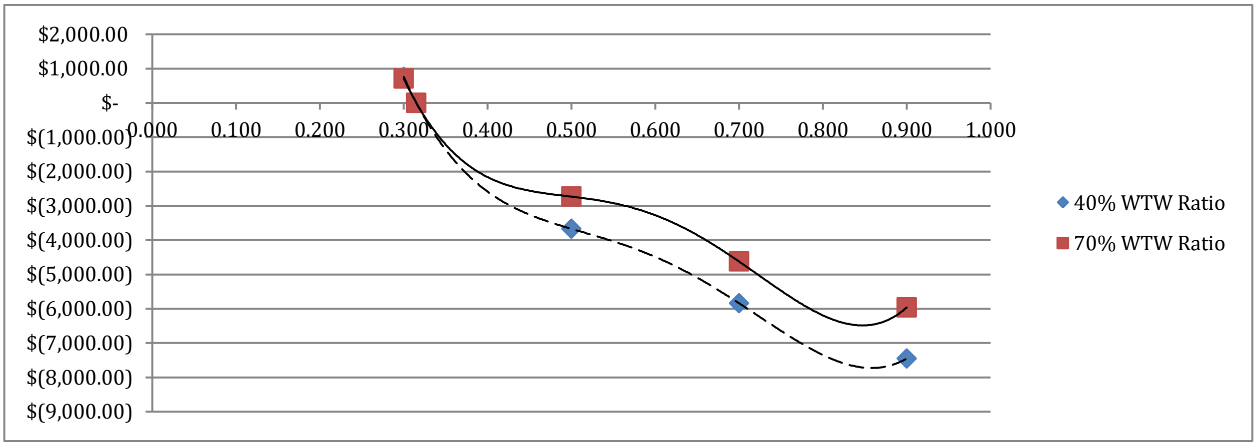


Figure 146: Window U-value - Energy Cost Difference from Baseline- Baltimore, MD

Seattle, WA Window U-value Results

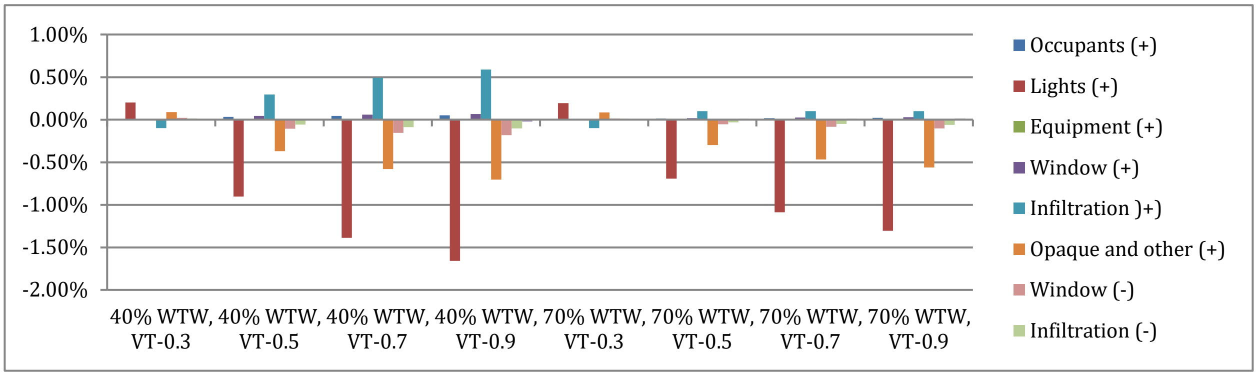


Figure 148: Window U-value - Sensible Gains % Difference from Baseline - Seattle, WA

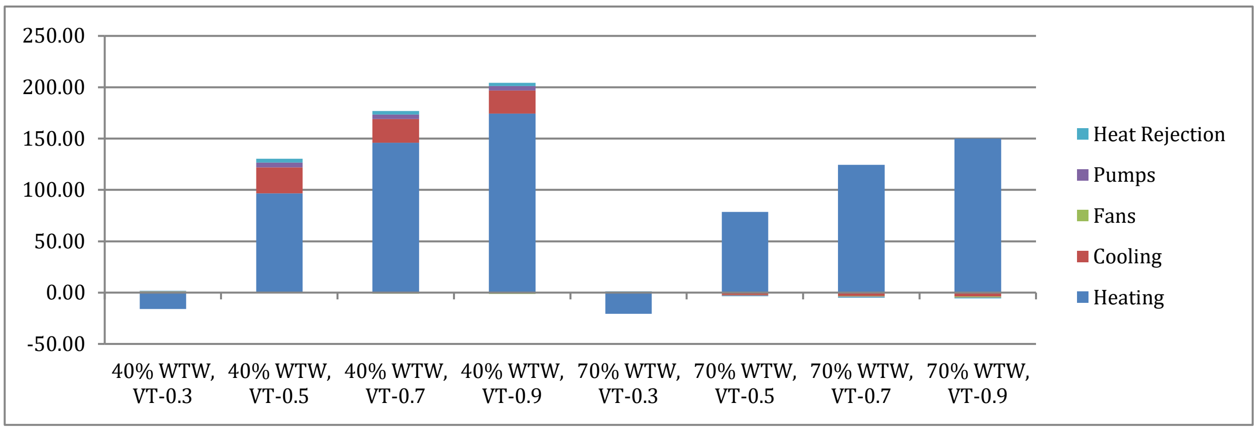


Figure 149: Window U-value Energy Consumption Difference from Baseline - Seattle, WA

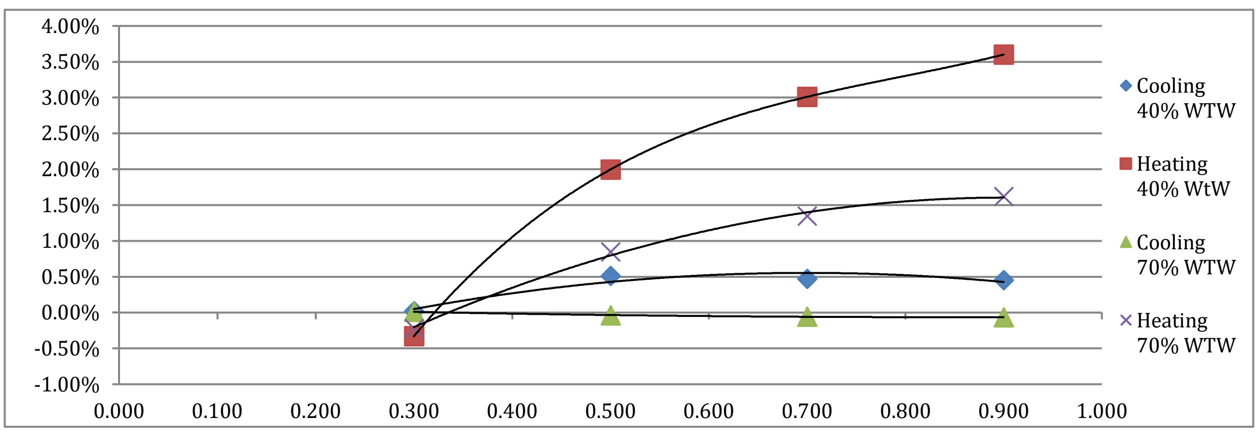


Figure 150: Window U-value - Heating and Cooling Energy % Difference from Baseline – Seattle, WA

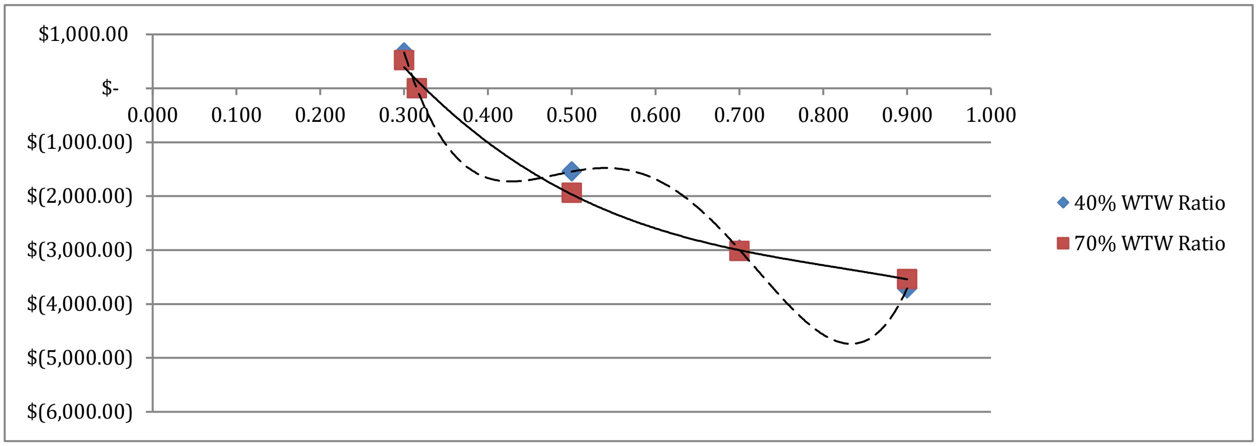


Figure 151: Window U-value - Energy Cost Difference from Baseline- Seattle, WA

Chicago, IL Window U-value Results

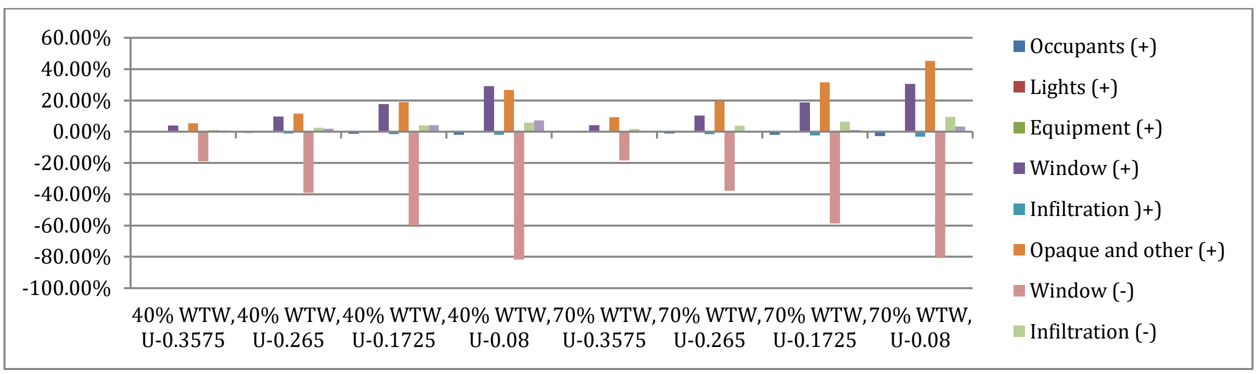


Figure 152: Window U-value - Sensible Gains % Difference from Baseline - Chicago, IL

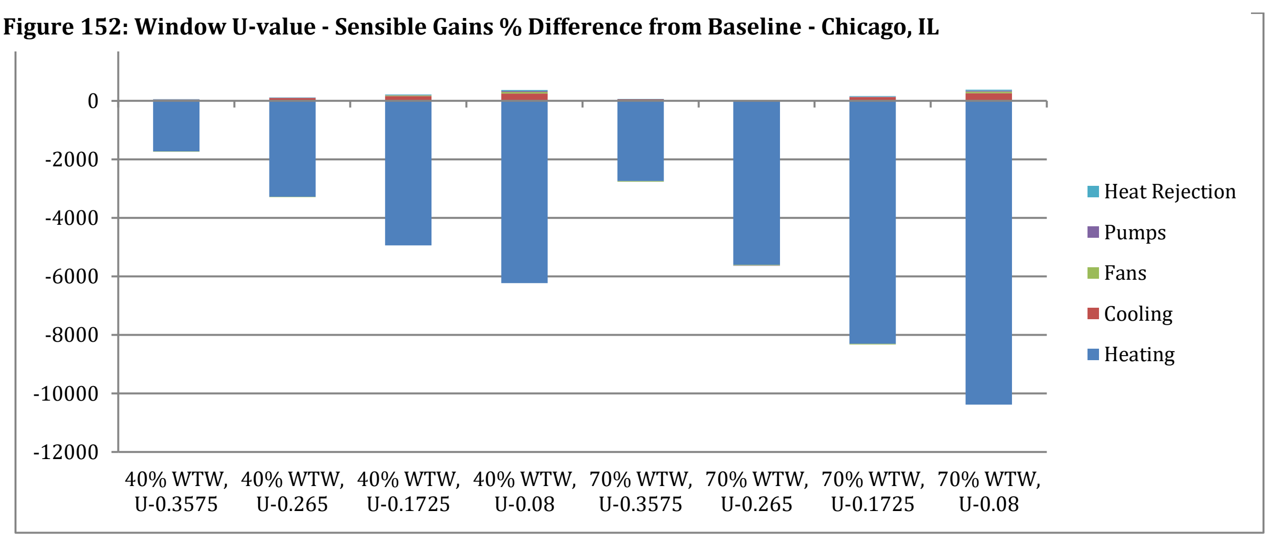


Figure 153: Window U-value Energy Consumption Difference from Baseline - Chicago, IL

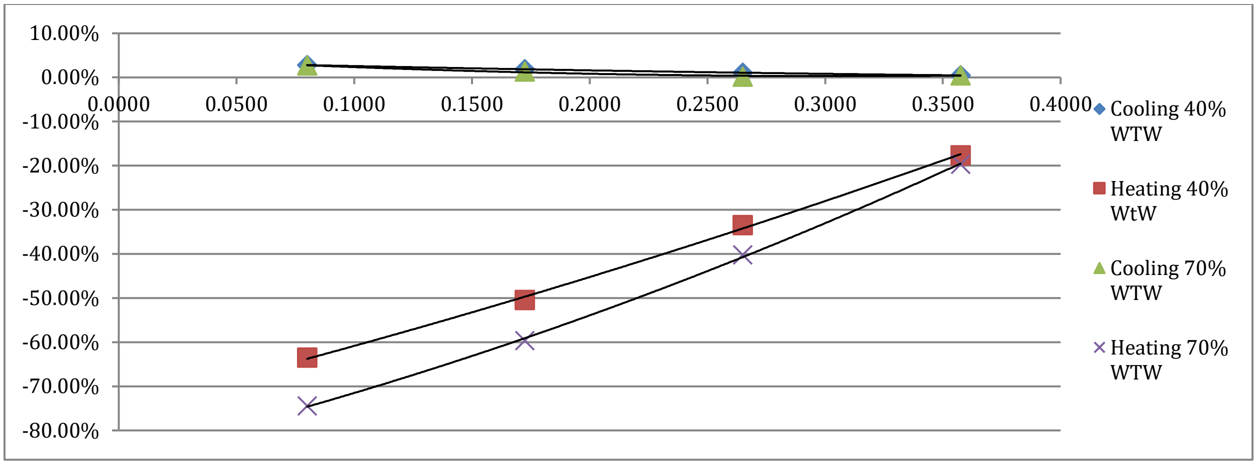


Figure 154: Window U-value - Heating and Cooling Energy % Difference from Baseline – Chicago, IL

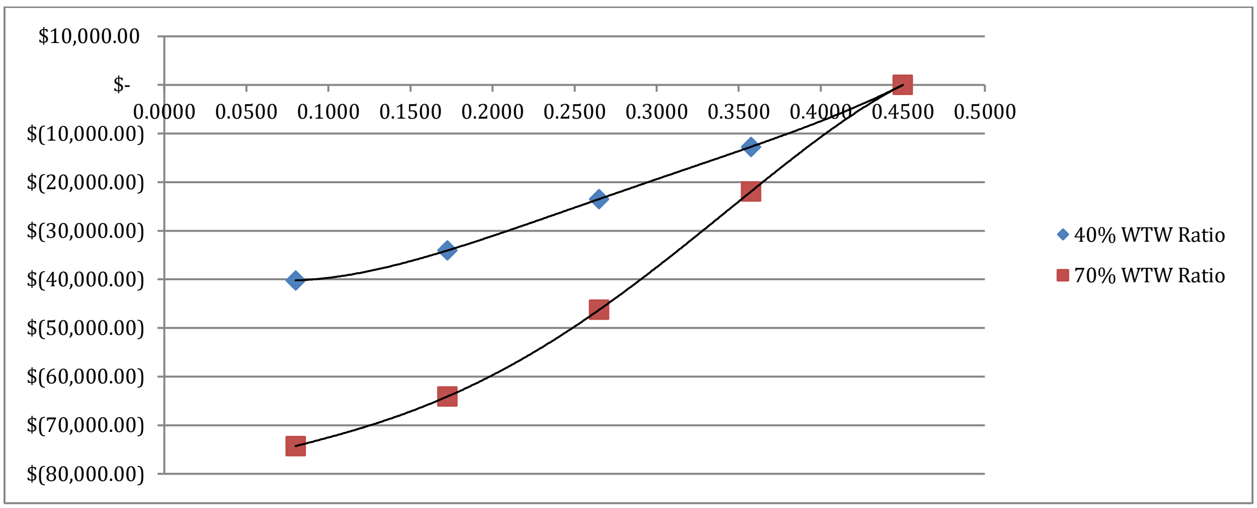


Figure 155: Window U-value - Energy Cost Difference from Baseline- Chicago, IL

Denver, CO Window U-value Results

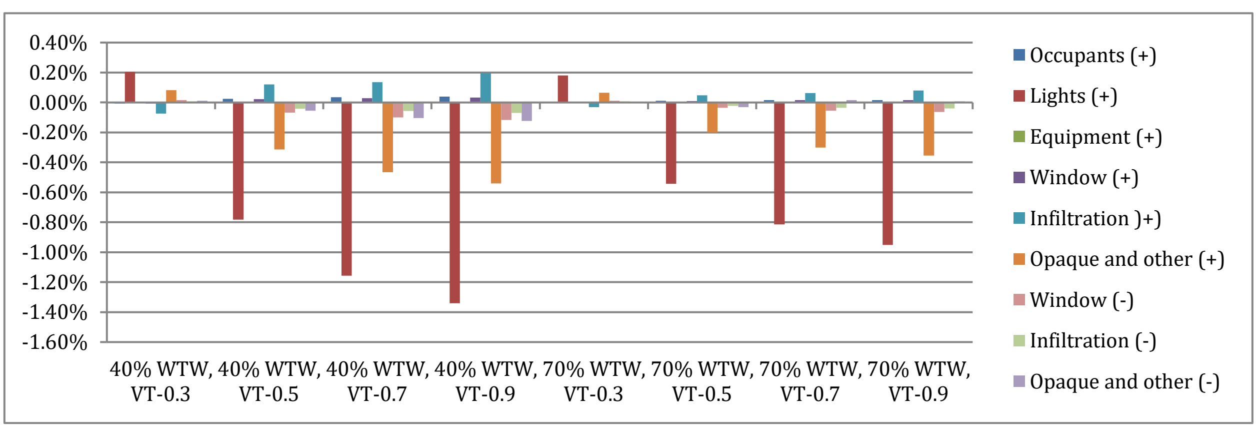


Figure 156: Window U-value - Sensible Gains % Difference from Baseline - Denver, CO

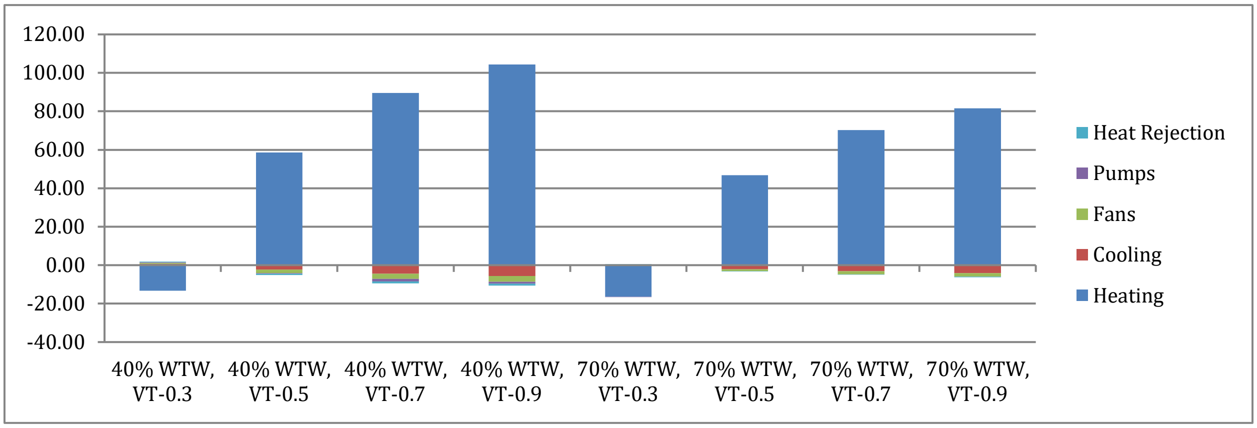


Figure 158: Window U-value Energy Consumption Difference from Baseline - Denver, CO

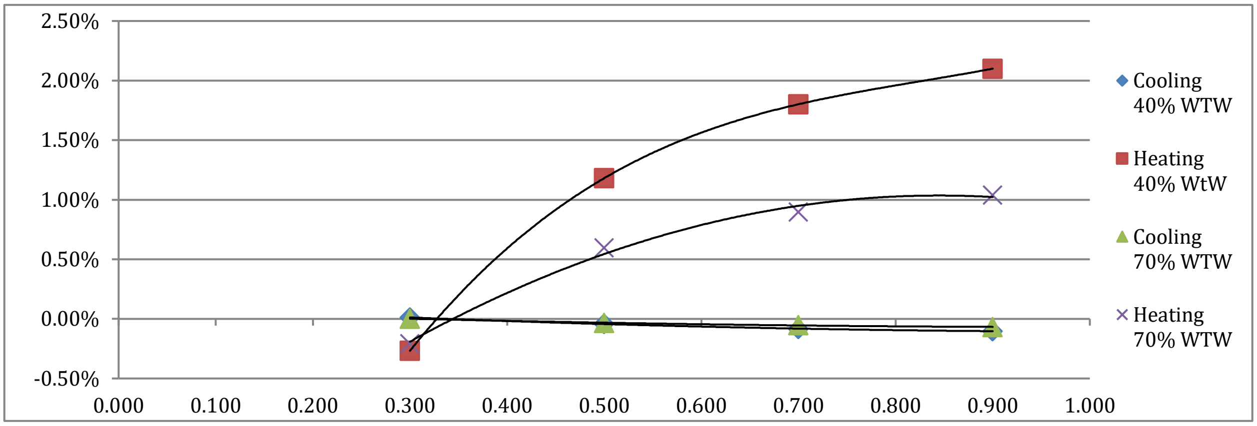


Figure 157: Window U-value - Heating and Cooling Energy % Difference from Baseline – Denver, CO

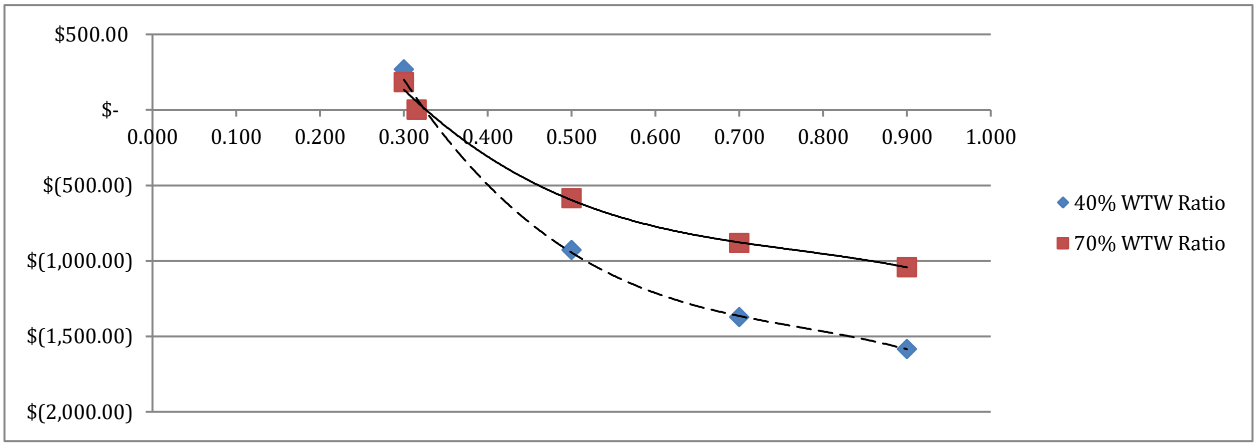


Figure 159: Window U-value - Energy Cost Difference from Baseline- Denver, CO

Helena, MT Window U-value Results

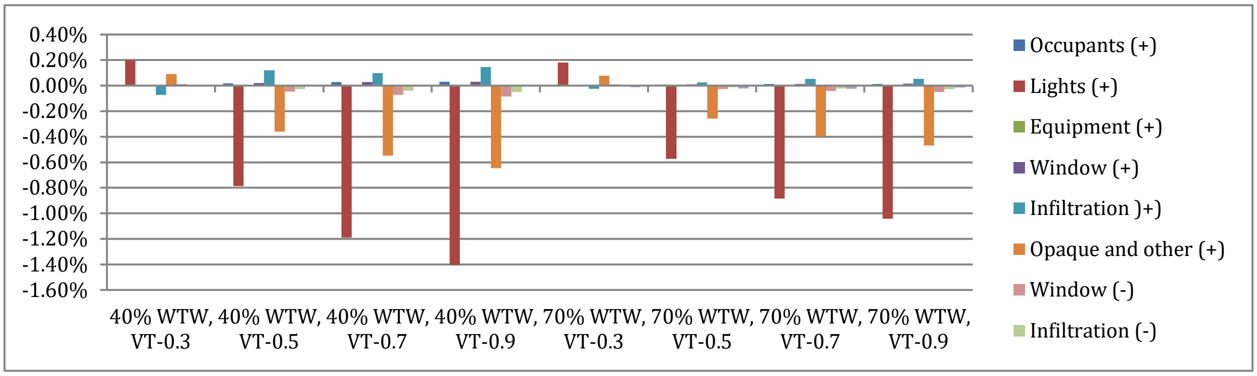


Figure 160: Window U-value - Sensible Gains % Difference from Baseline - Helena, MT

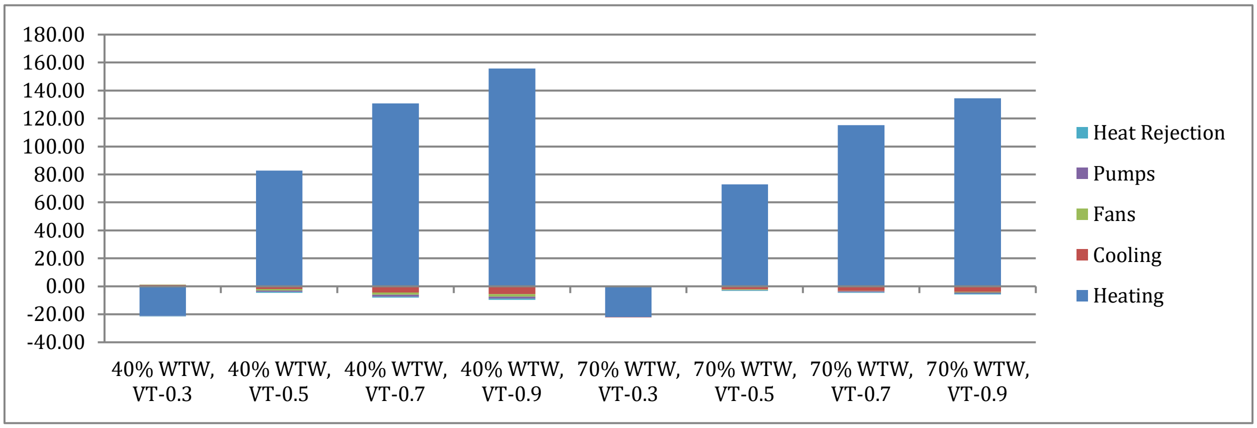


Figure 161: Window U-value Energy Consumption Difference from Baseline - Helena, MT

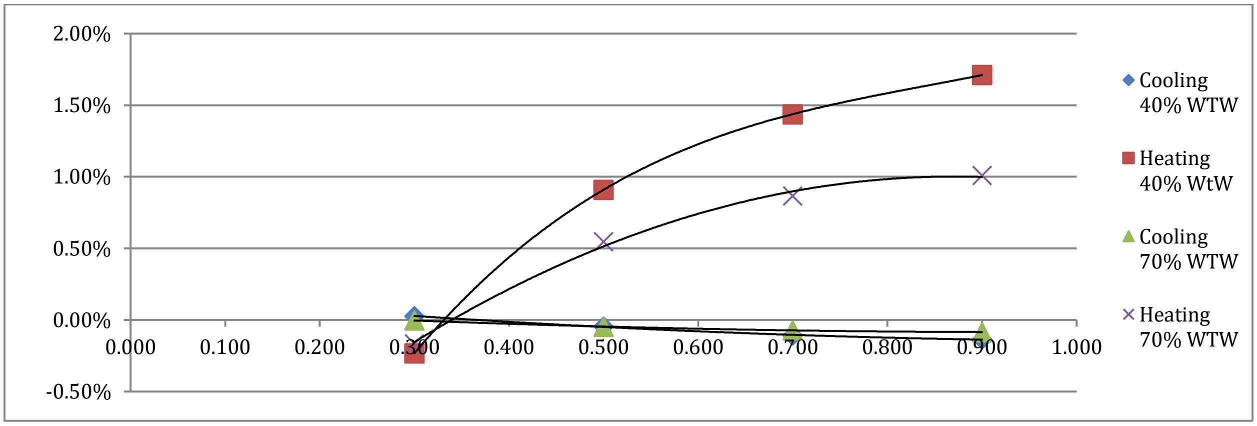


Figure 162: Window U-value - Heating and Cooling Energy % Difference from Baseline – Helena, MT

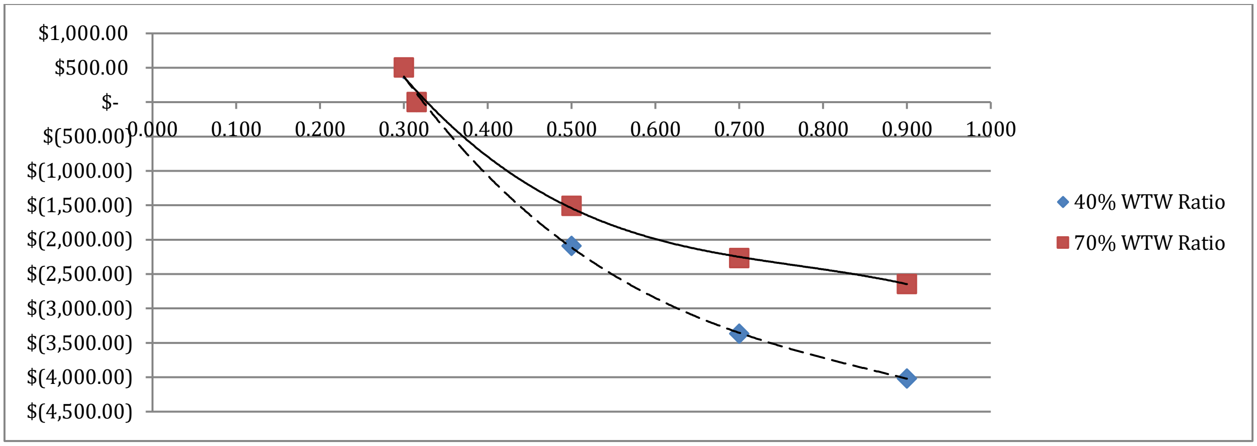


Figure 163: Window U-value - Energy Cost Difference from Baseline- Helena, MT

Duluth, MN Window U-value Results

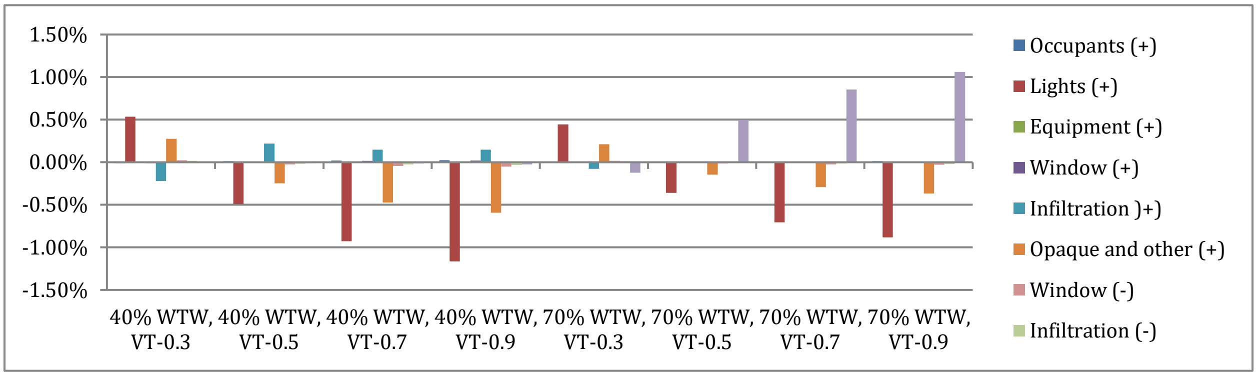


Figure 164: Window U-value - Sensible Gains % Difference from Baseline - Duluth, MN

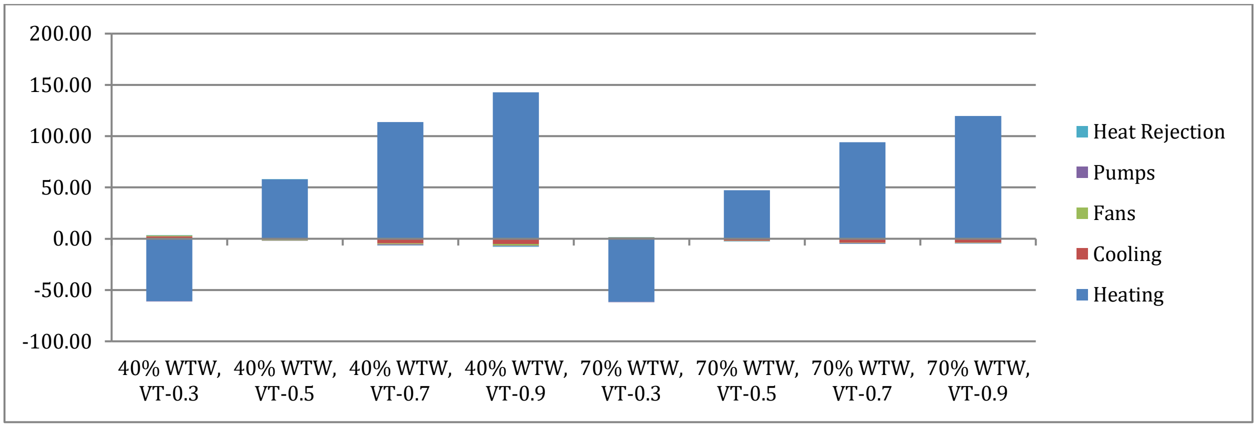


Figure 165: Window U-value Energy Consumption Difference from Baseline - Duluth, MN

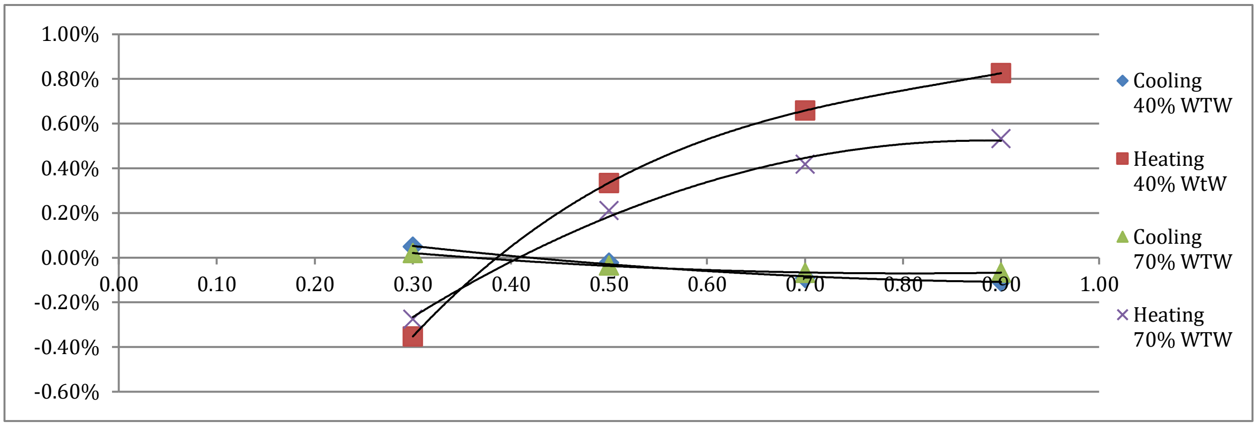


Figure 167: Window U-value - Heating and Cooling Energy % Difference from Baseline – Duluth, MN

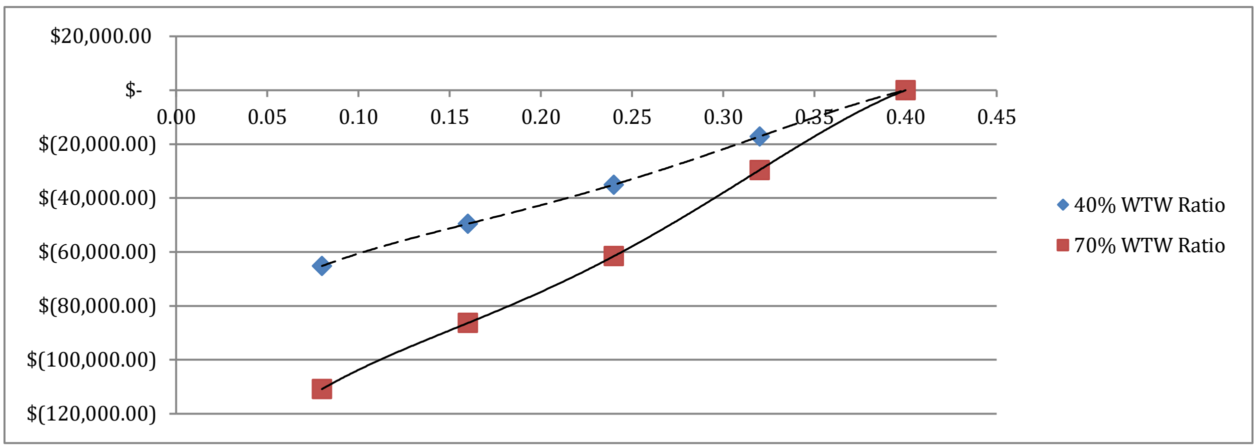


Figure 166: Window U-value - Energy Cost Difference from Baseline- Duluth, MN

Appendix D: Solar Heat Gain Coefficient Analysis Results

Miami, FL SHGC Results

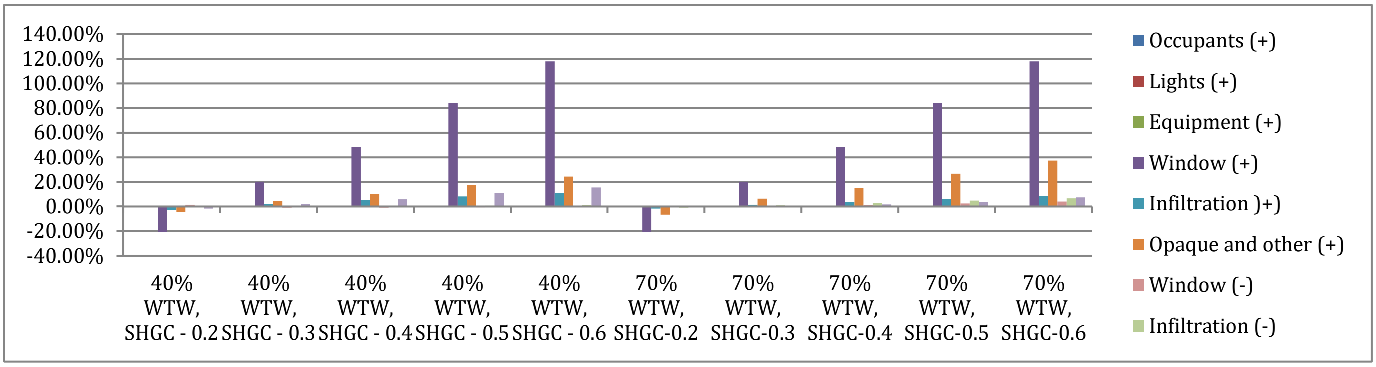


Figure 169: SHGC - Sensible Heat Gains % Difference from Baseline - Miami, FL

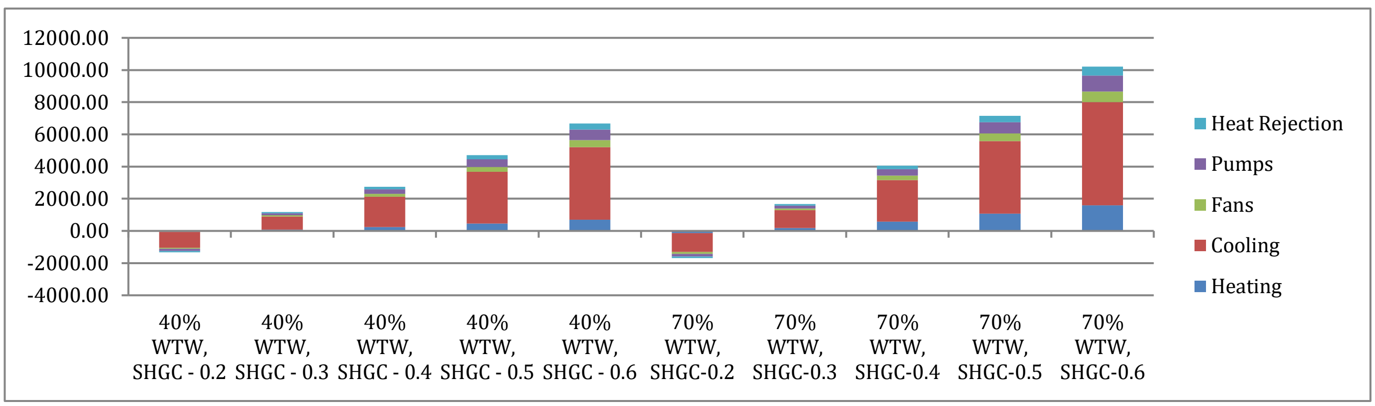


Figure 168: SHGC - Energy Consumption Difference from Baseline - MIami, FL

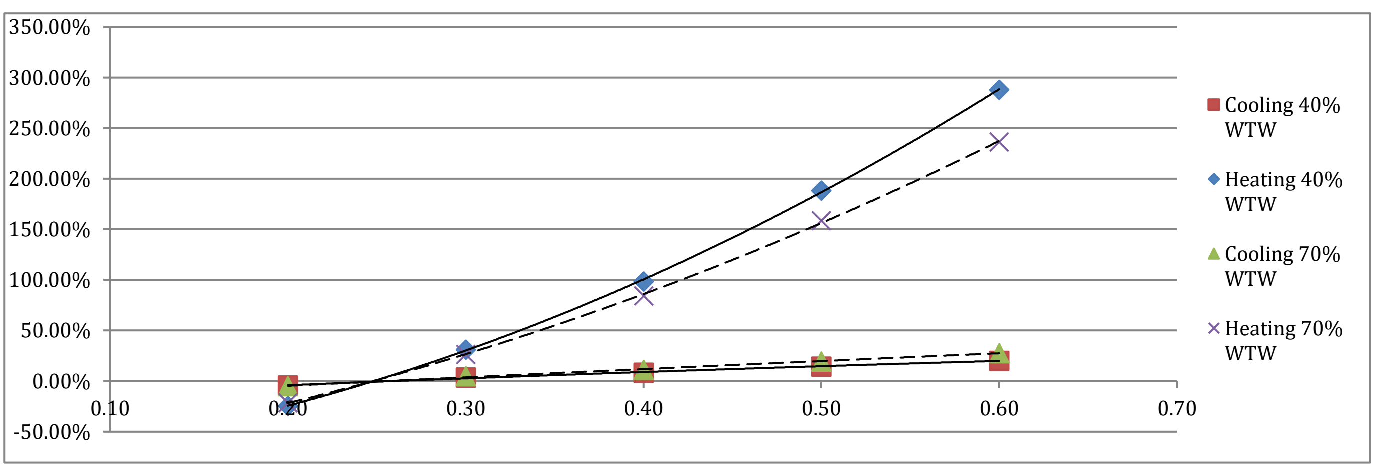


Figure 170: SHGC - Heating and Cooling Energy % Difference from Baseline - Miami, FL

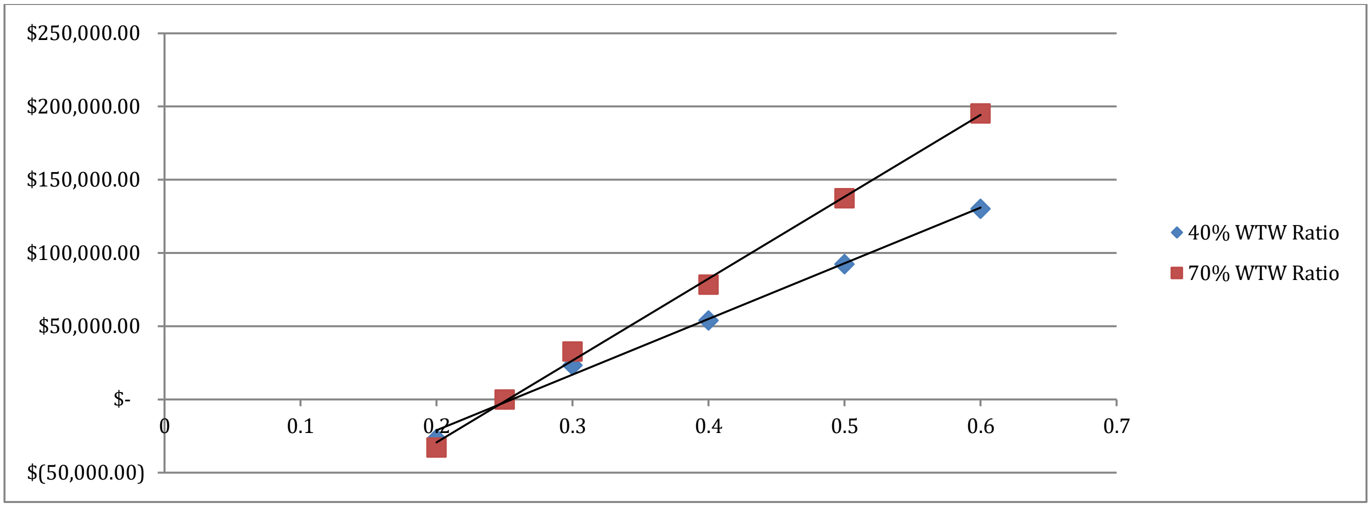


Figure 171: SHGC - Energy Cost Savings from Baseline - Miami, FL

Houston, TX SHGC Results

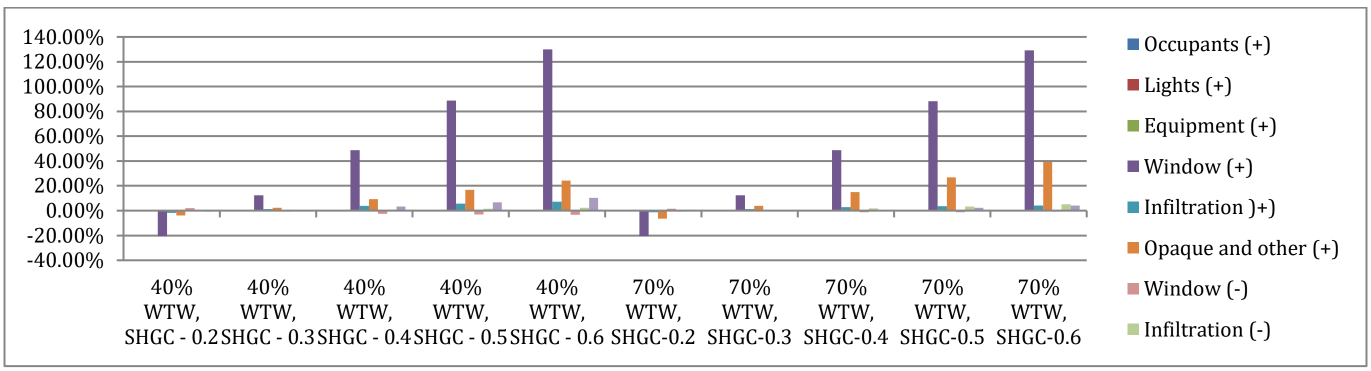


Figure 172: SHGC - Sensible Heat Gains % Difference from Baseline - Houston, TX

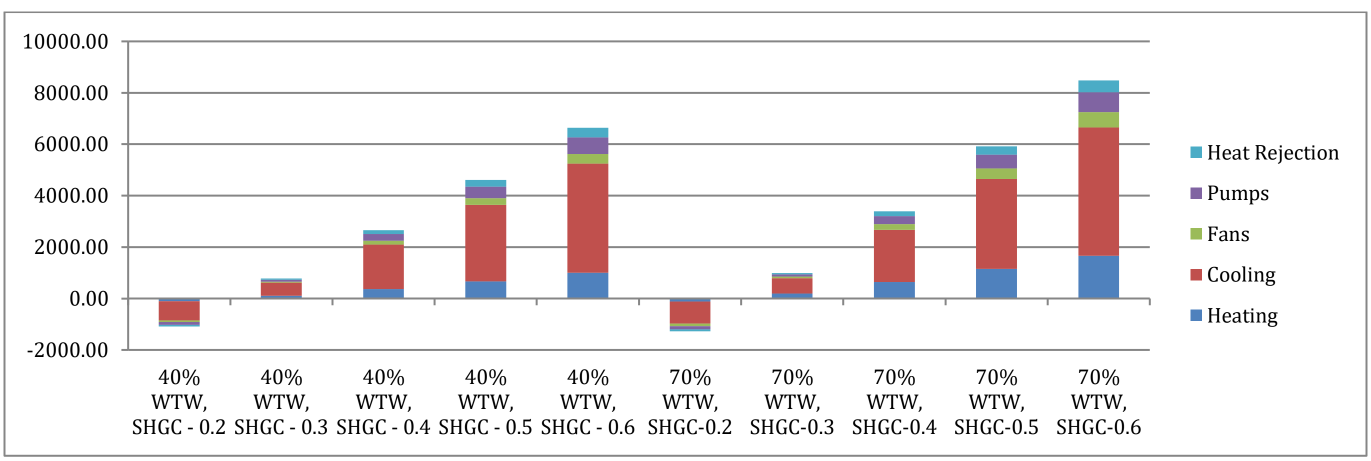


Figure 173: SHGC - Energy Consumption Difference from Baseline - Houston, TX

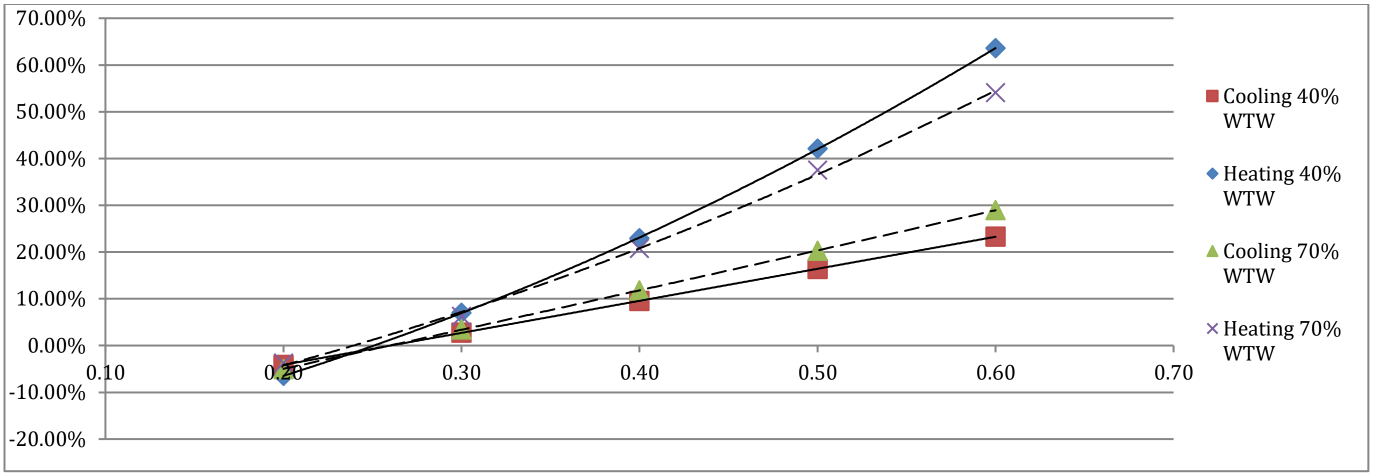


Figure 174: SHGC - Heating and Cooling Energy % Difference from Baseline - Houston, TX

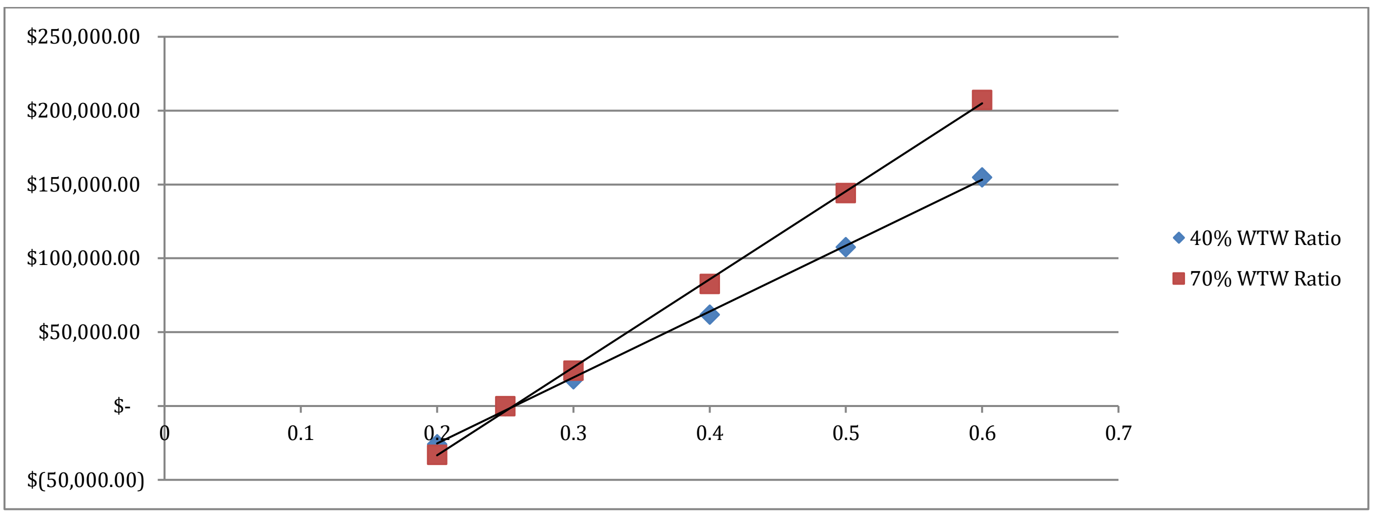


Figure 175: SHGC - Energy Cost Savings from Baseline - Houston, TX

Phoenix, AZ SHGC Results

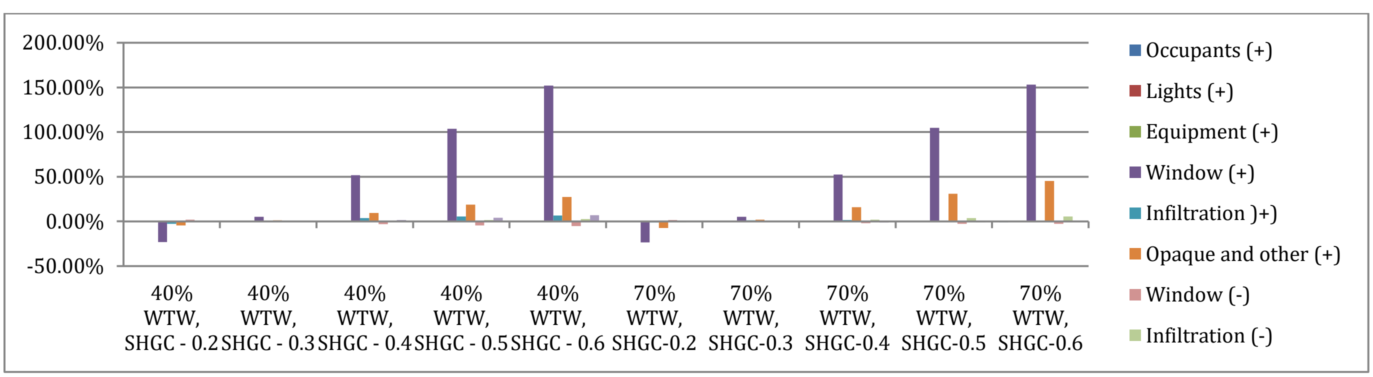


Figure 176: SHGC - Sensible Heat Gains % Difference from Baseline - Phoenix, AZ

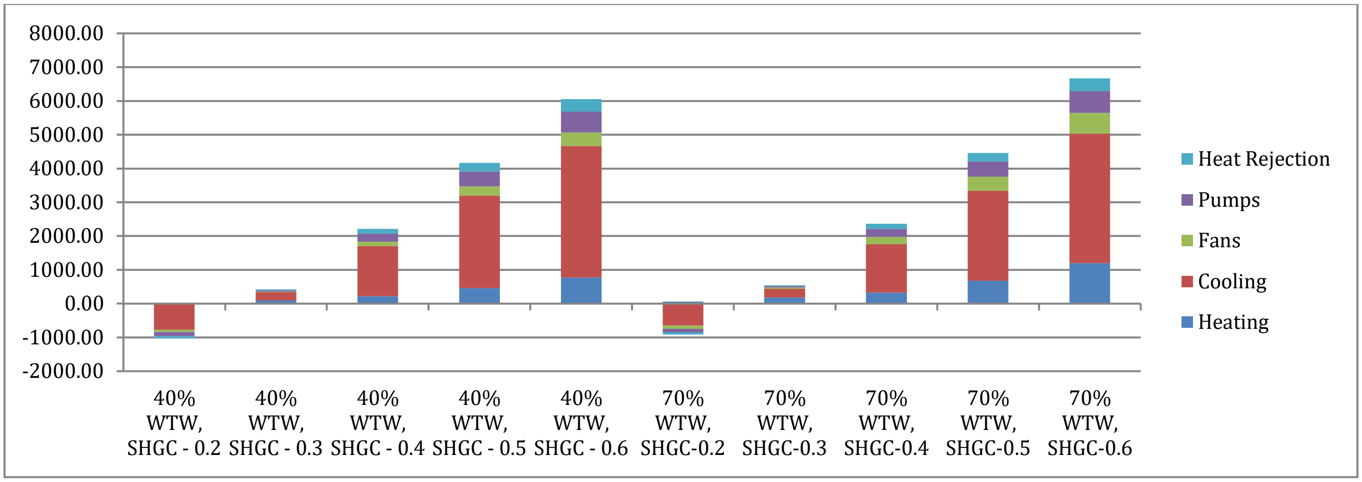


Figure 177: SHGC - Energy Consumption Difference from Baseline - Phoenix, AZ

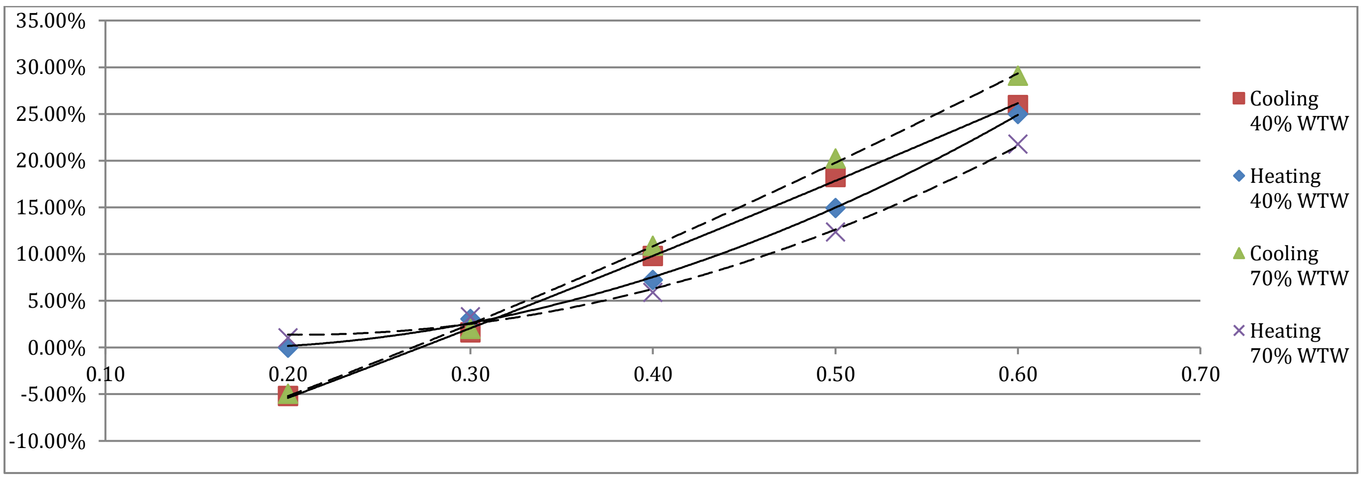


Figure 178: SHGC - Heating and Cooling Energy % Difference from Baseline - Phoenix, AZ

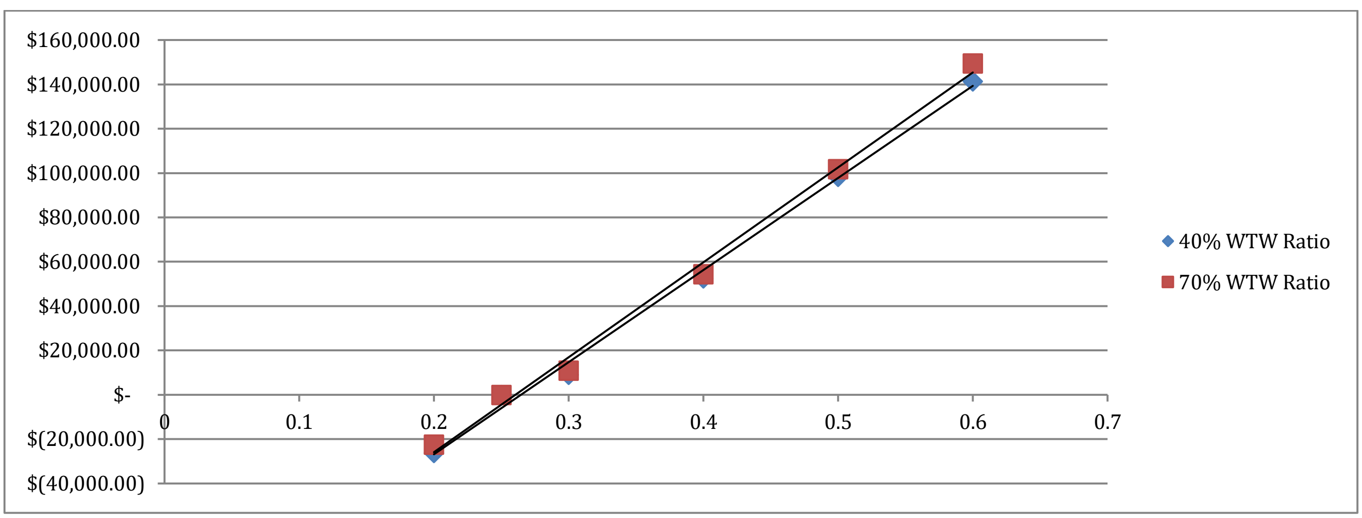


Figure 179: SHGC - Energy Cost Savings from Baseline - Phoenix, AZ

San Francisco, CA SHGC Results

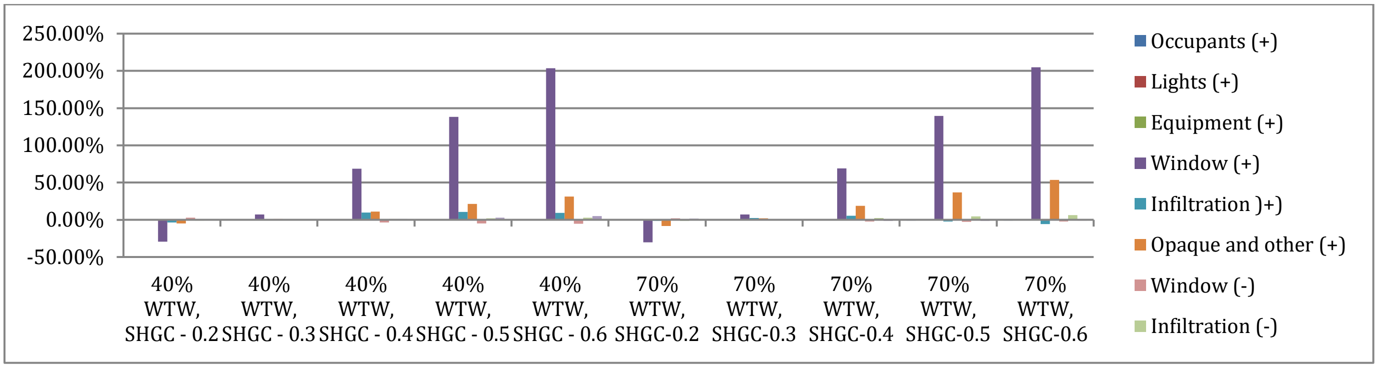


Figure 180: SHGC - Sensible Heat Gains % Difference from Baseline - San Francisco, CA

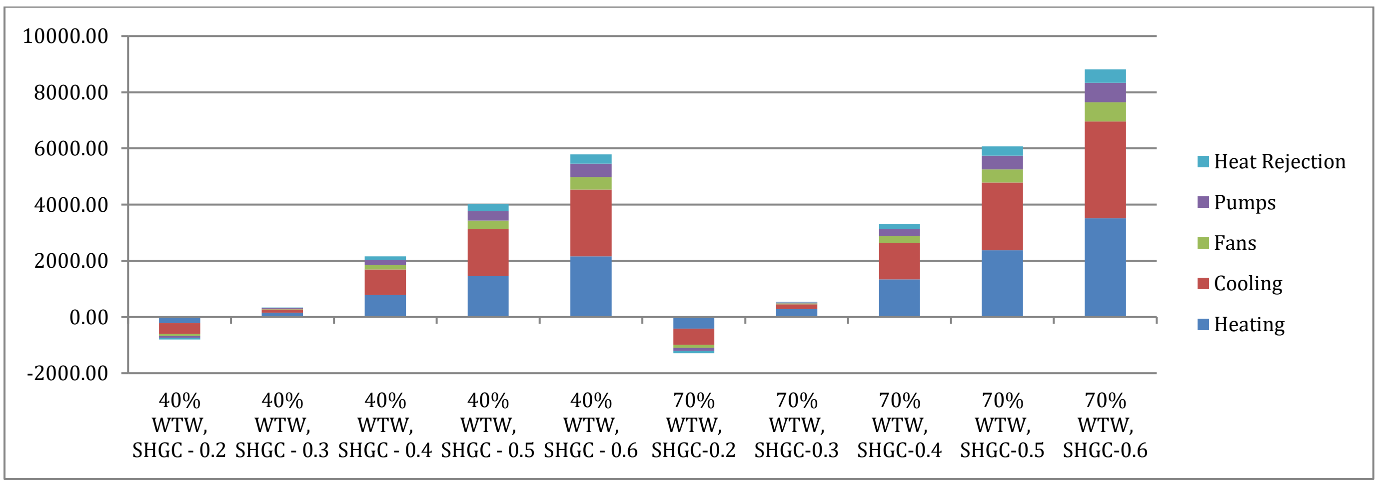


Figure 181: SHGC - Energy Consumption Difference from Baseline - San Francisco, CA

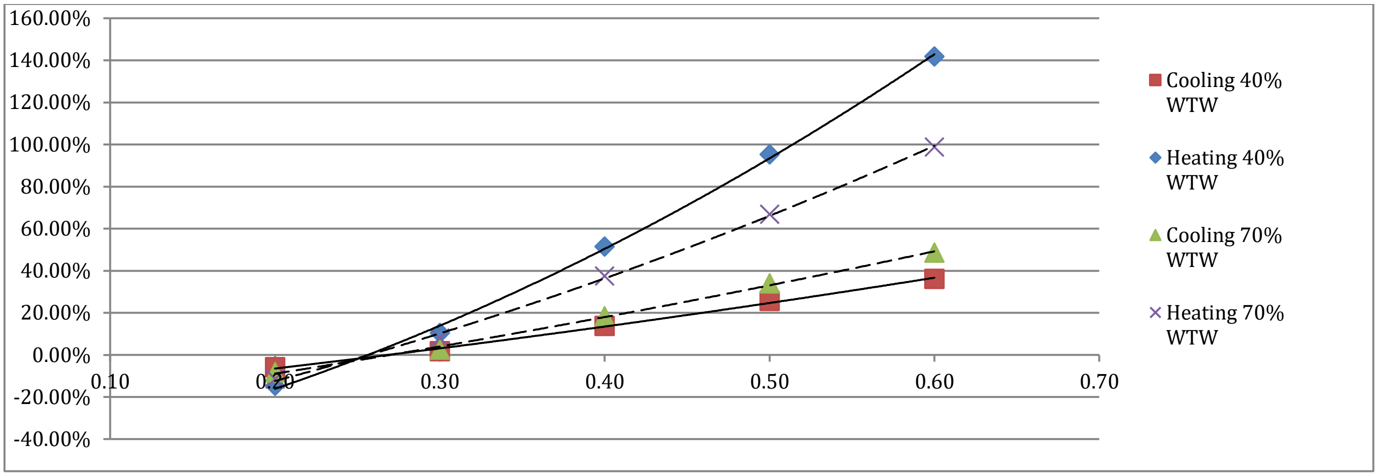


Figure 182: SHGC - Heating and Cooling Energy % Difference from Baseline - San Francisco, CA

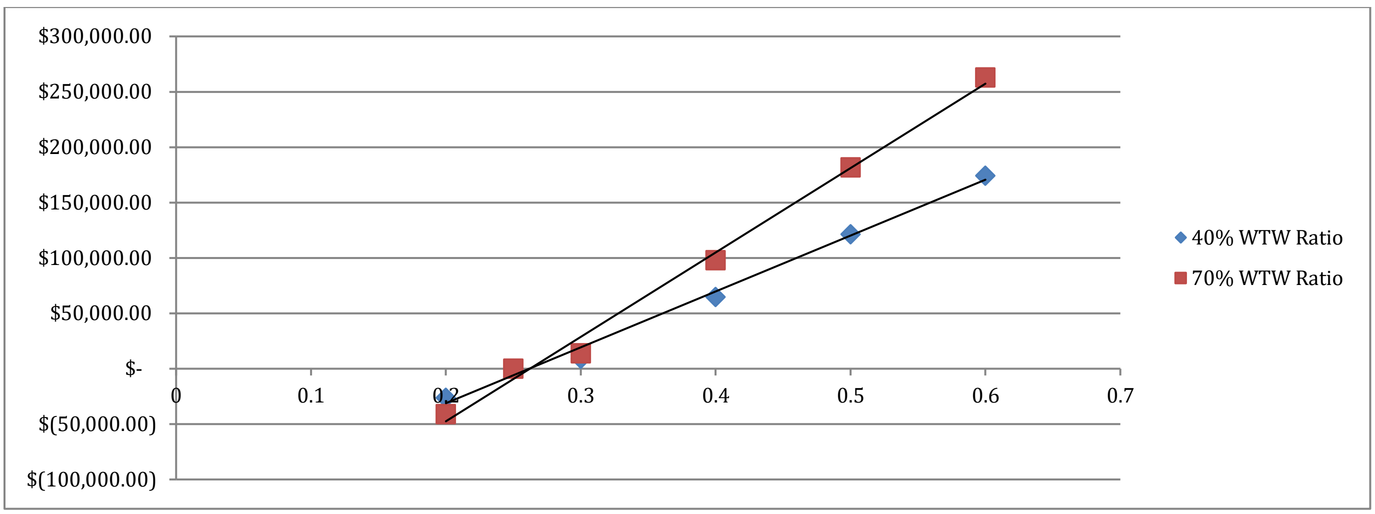


Figure 183: SHGC - Energy Cost Savings from Baseline - San Francisco, CA

Baltimore, MD SGHC Results

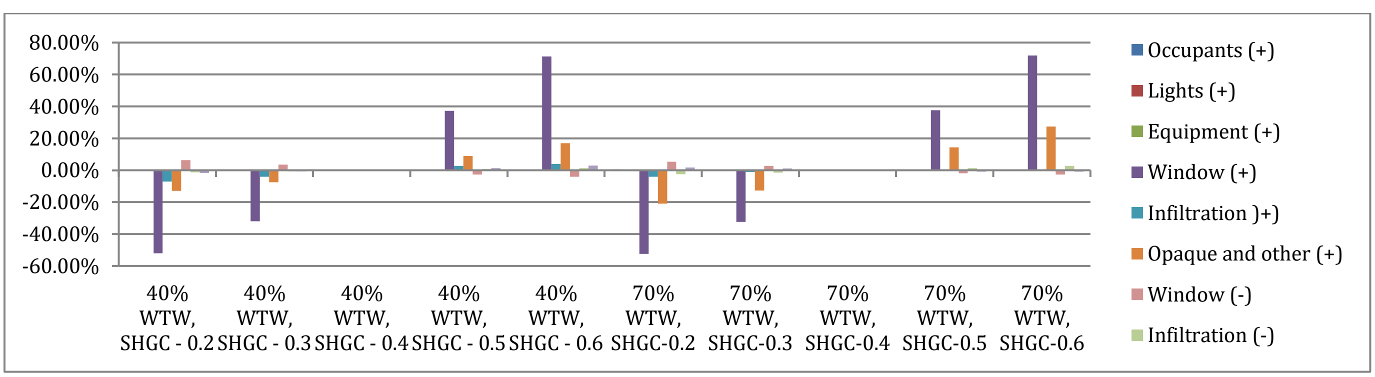


Figure 184: SHGC - Sensible Heat Gains % Difference from Baseline - Baltimore, MD

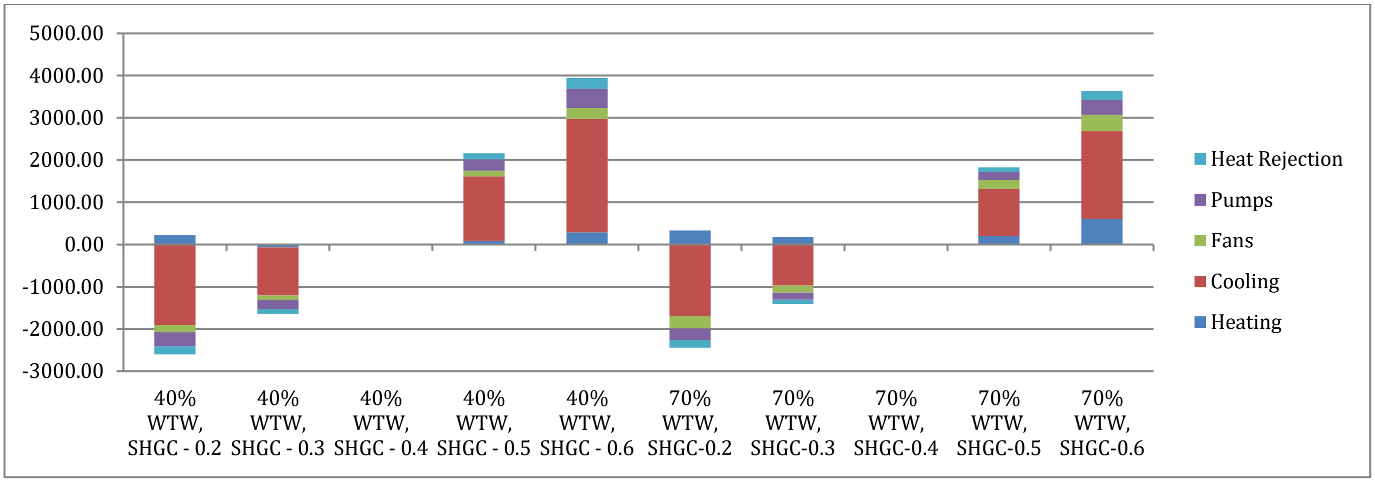


Figure 185: SHGC - Energy Consumption Difference from Baseline - Baltimore, MD

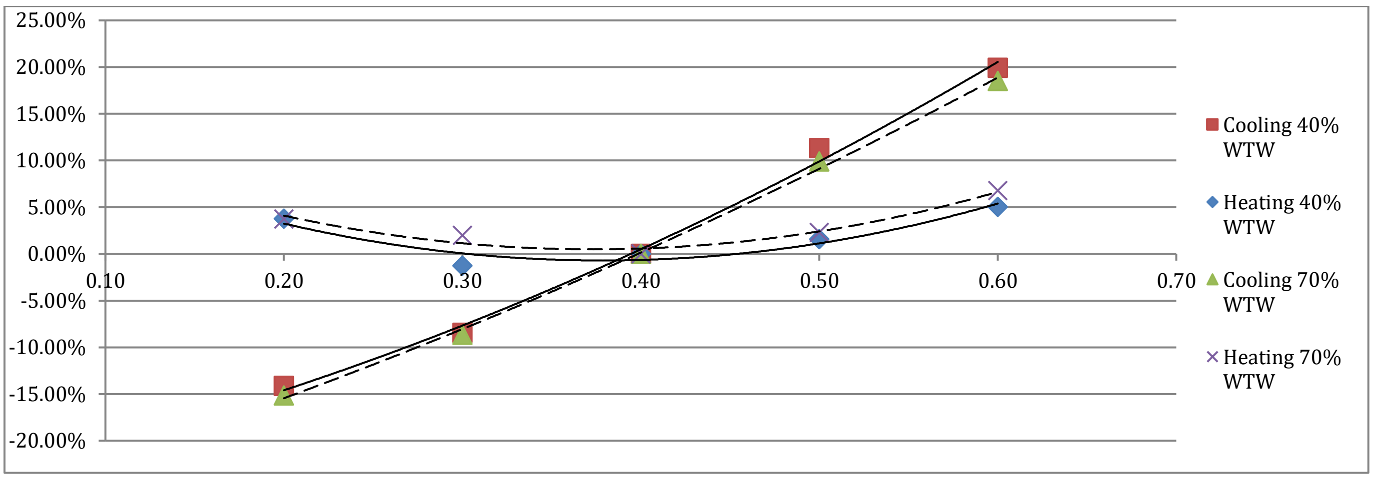


Figure 186: SHGC - Heating and Cooling Energy % Difference from Baseline - Baltimore, MD

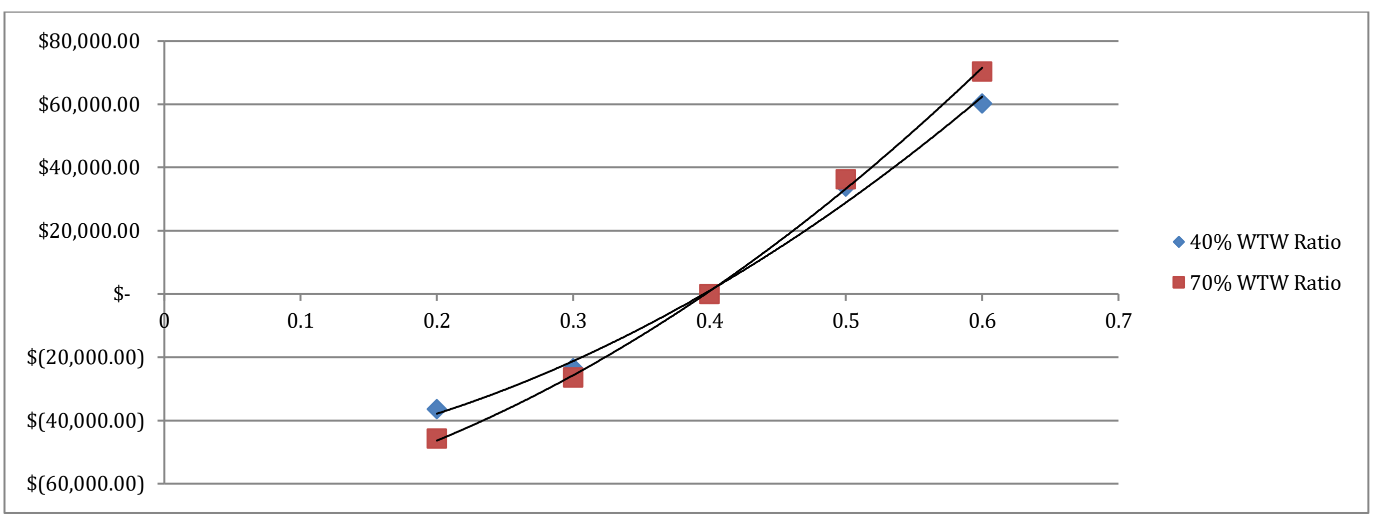


Figure 187: SHGC - Energy Cost Savings from Baseline - Baltimore, MD

Seattle, WA SHGC Results

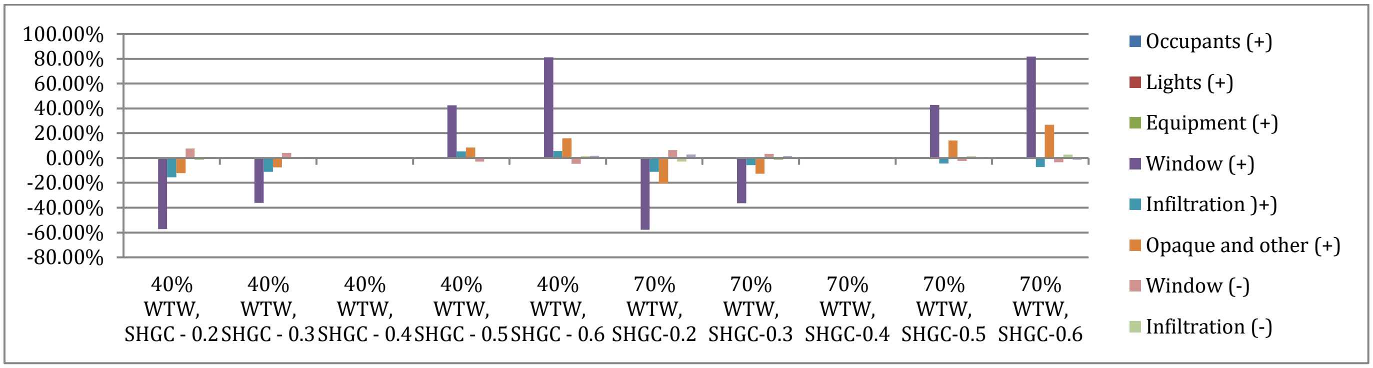


Figure 188: SHGC - Sensible Heat Gains % Difference from Baseline - Seattle, WA

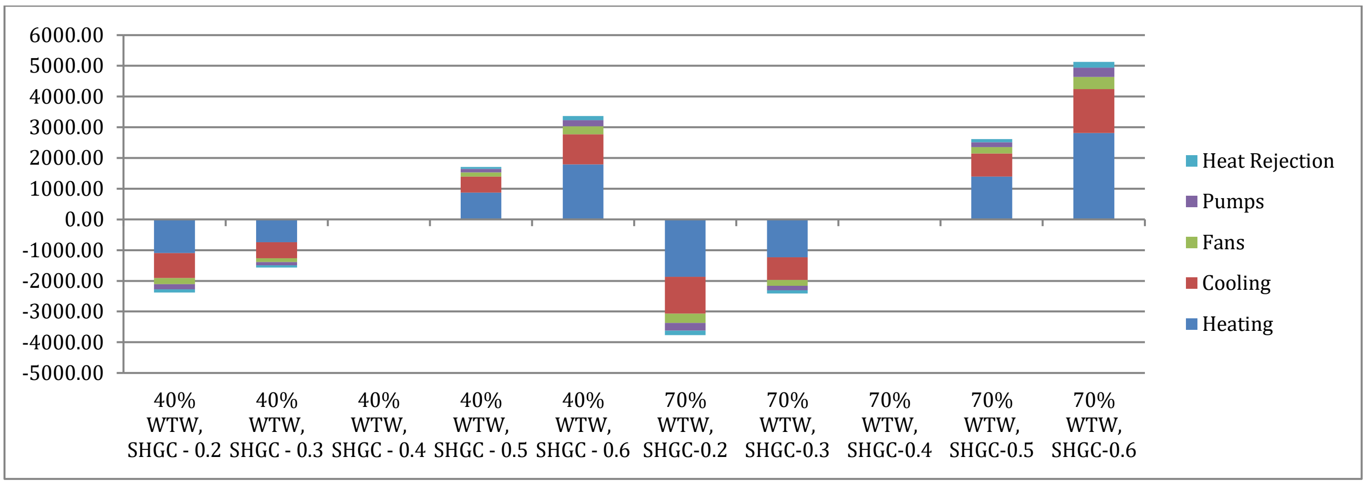


Figure 189: SHGC - Energy Consumption Difference from Baseline - Seattle, WA

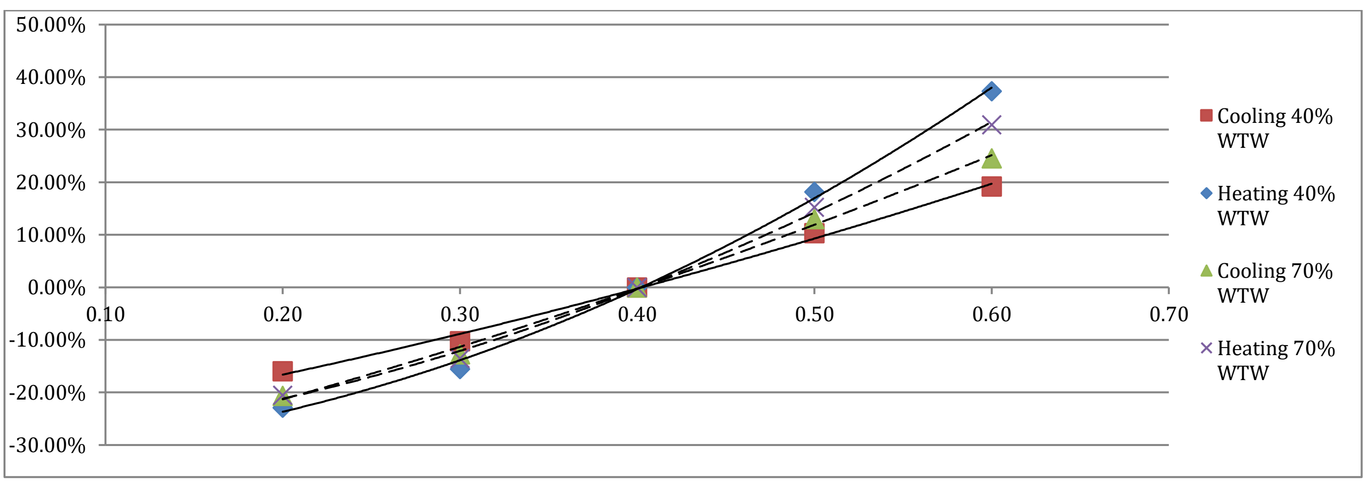


Figure 190: SHGC - Heating and Cooling Energy % Difference from Baseline – Seattle, WA

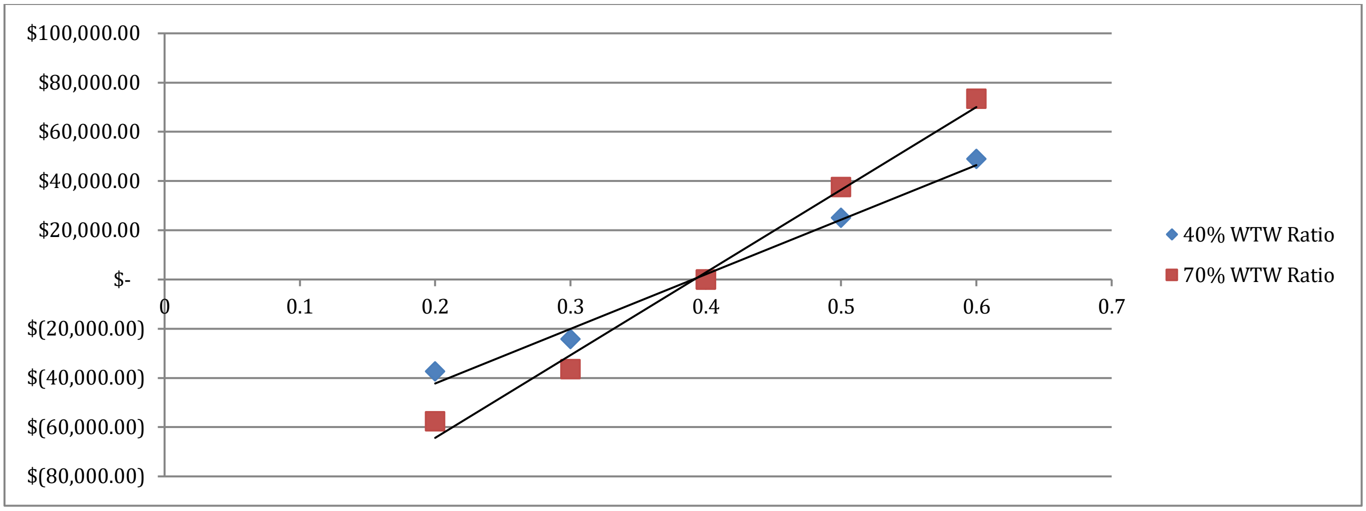


Figure 191: SHGC - Energy Cost Savings from Baseline – Seattle, WA

Chicago, IL SHGC Results

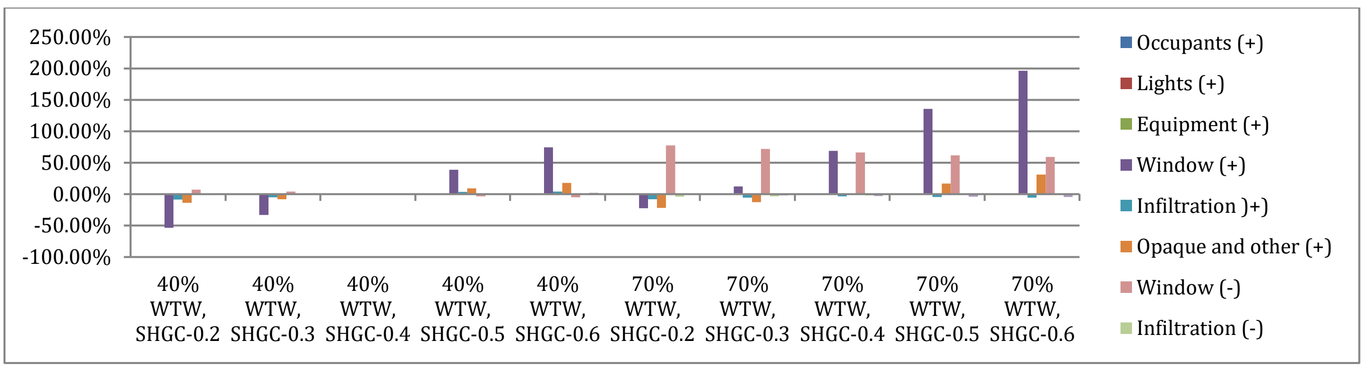


Figure 192: SHGC - Sensible Heat Gains % Difference from Baseline - Chicago, IL

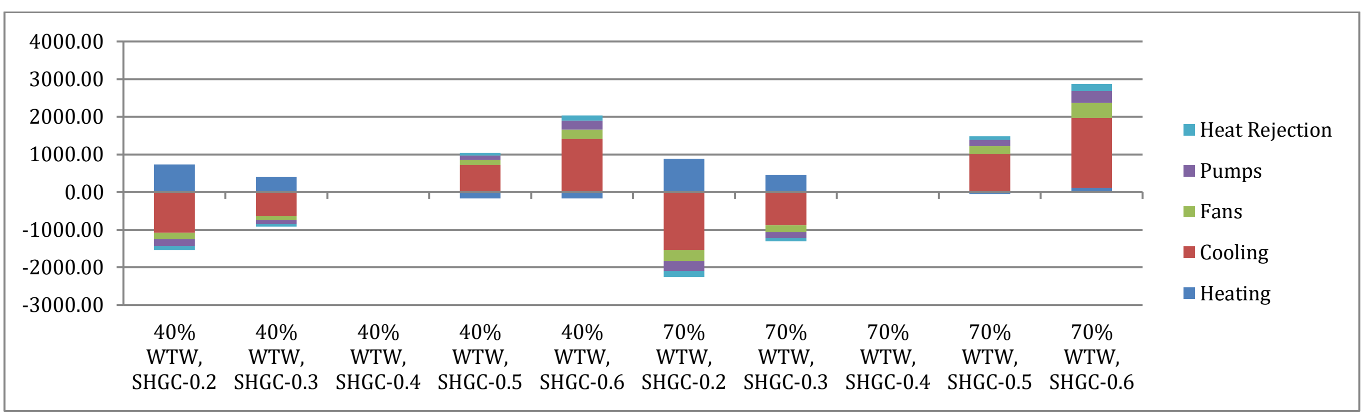


Figure 193: SHGC - Energy Consumption Difference from Baseline - Chicago, IL

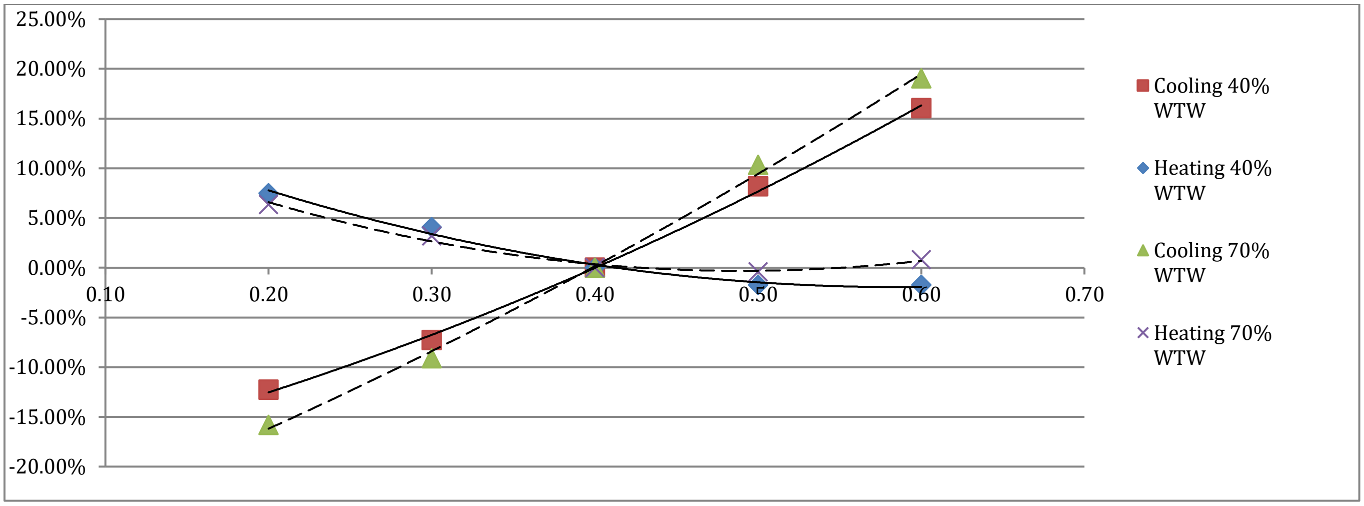


Figure 194: SHGC - Heating and Cooling Energy % Difference from Baseline - Chicago, IL

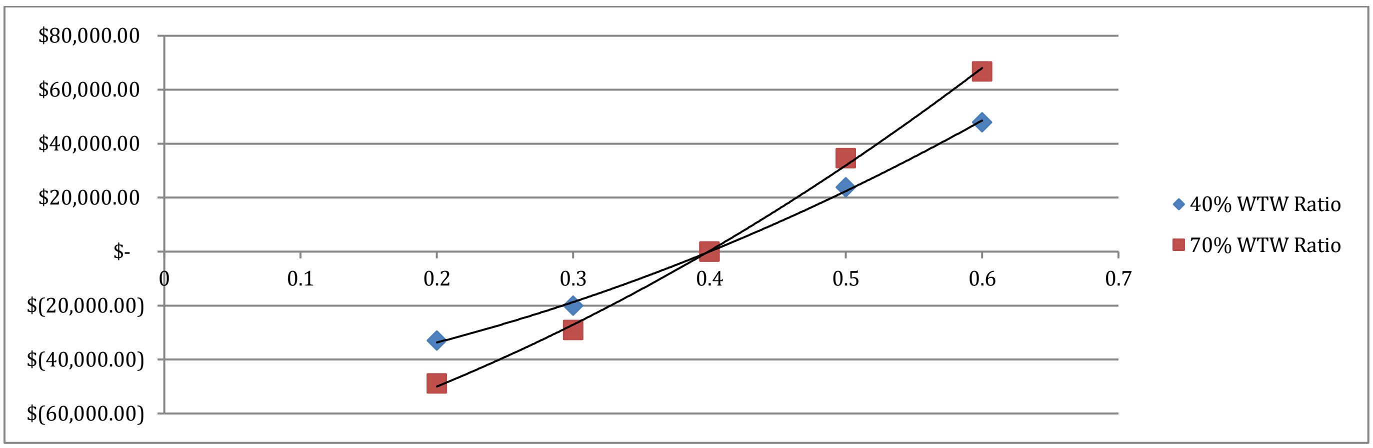


Figure 195: SHGC - Energy Cost Savings from Baseline - Chicago, IL

Denver, CO SHGC Results

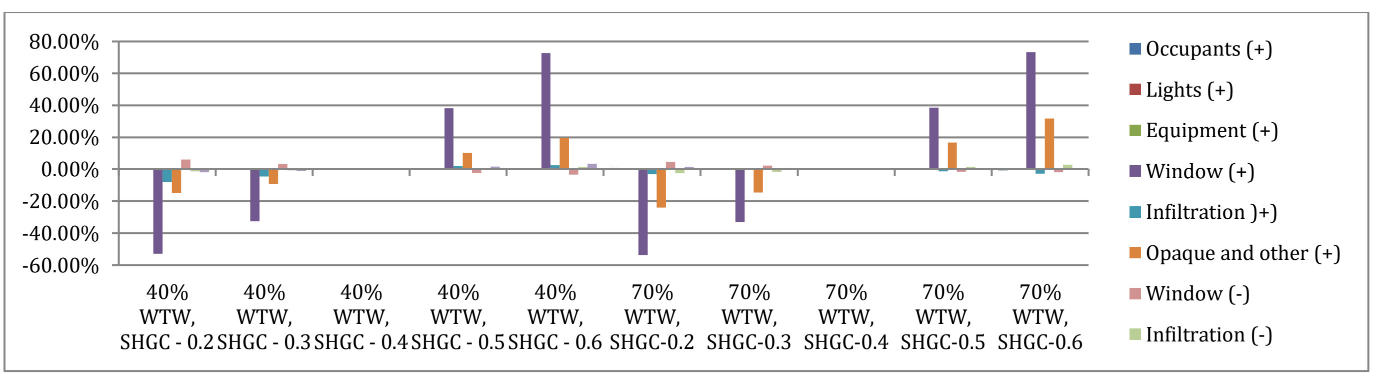


Figure 196: SHGC - Sensible Heat Gains % Difference from Baseline - Denver, CO

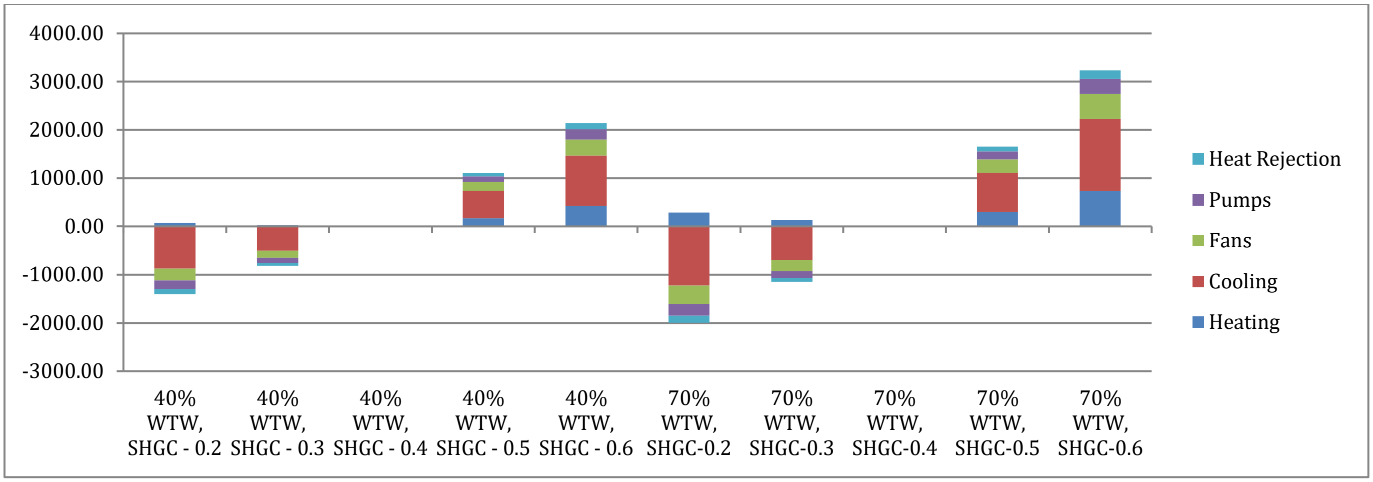


Figure 197: SHGC - Energy Consumption Difference from Baseline - Denver, CO

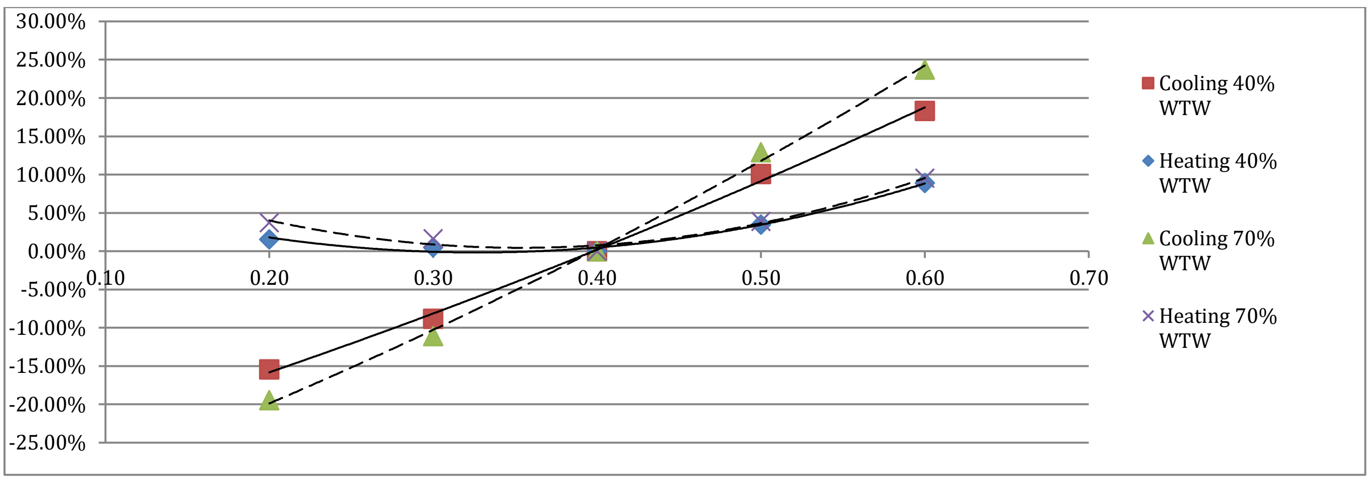


Figure 198: SHGC - Heating and Cooling Energy % Difference from Baseline - Denver, CO

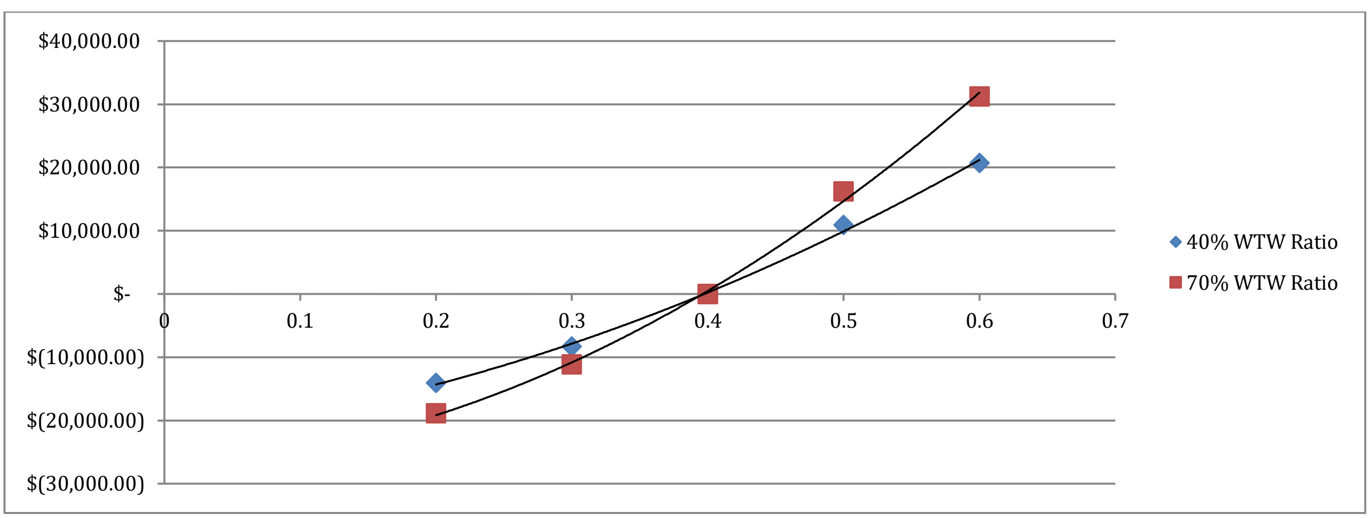


Figure 199: SHGC - Energy Cost Savings from Baseline - Denver, CO

Helena, MT SHGC Results

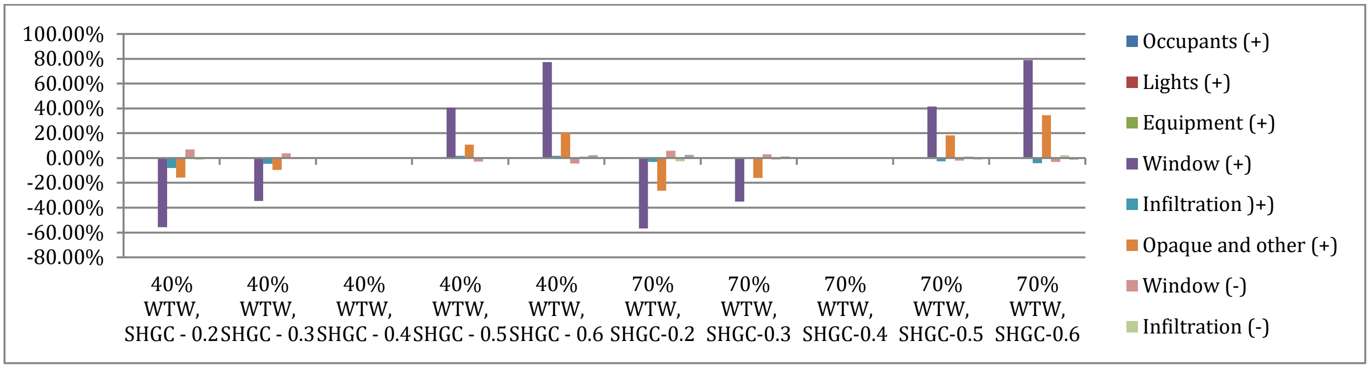


Figure 200: SHGC - Sensible Heat Gains % Difference from Baseline - Helena, MT

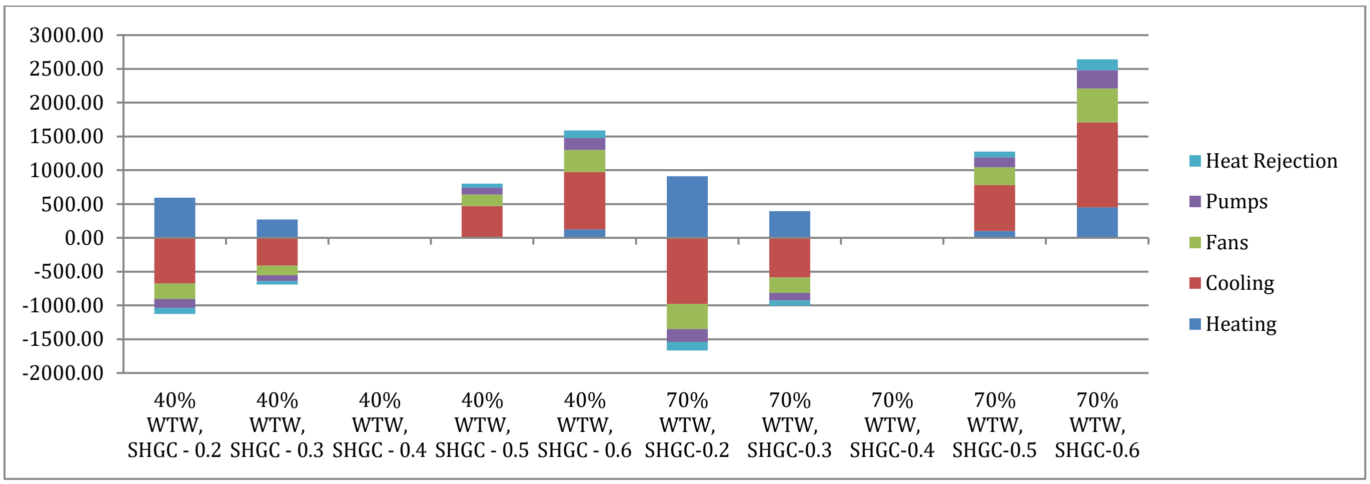


Figure 201: SHGC - Energy Consumption Difference from Baseline - Helena, MT

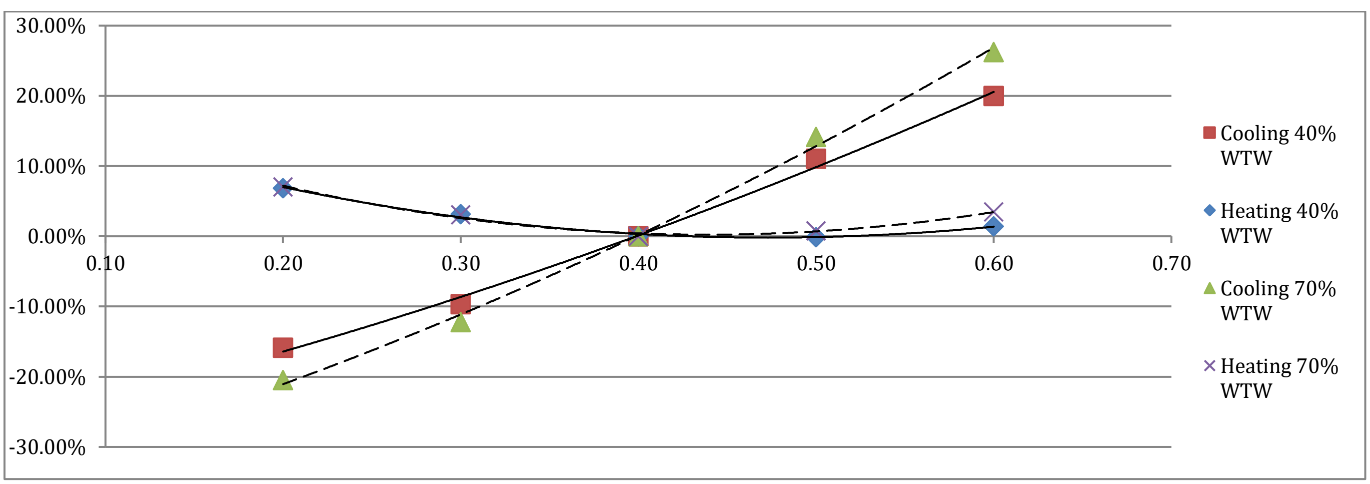


Figure 202: SHGC - Heating and Cooling Energy % Difference from Baseline - Helena, MT

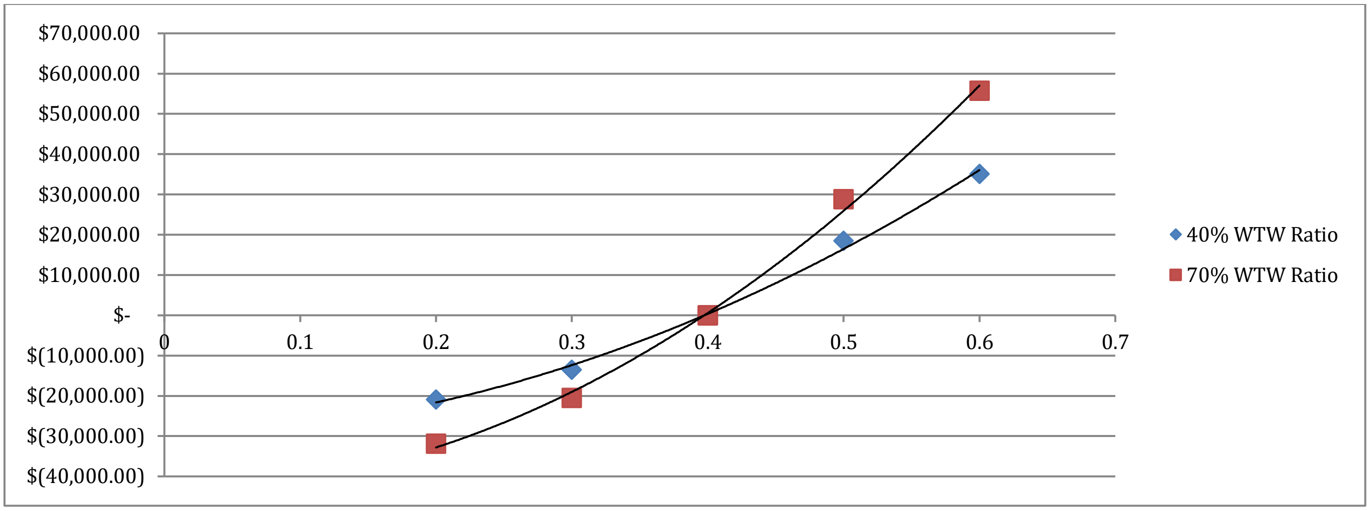


Figure 203: SHGC - Energy Cost Savings from Baseline - Helena, MT

Duluth, MN SHGC Results

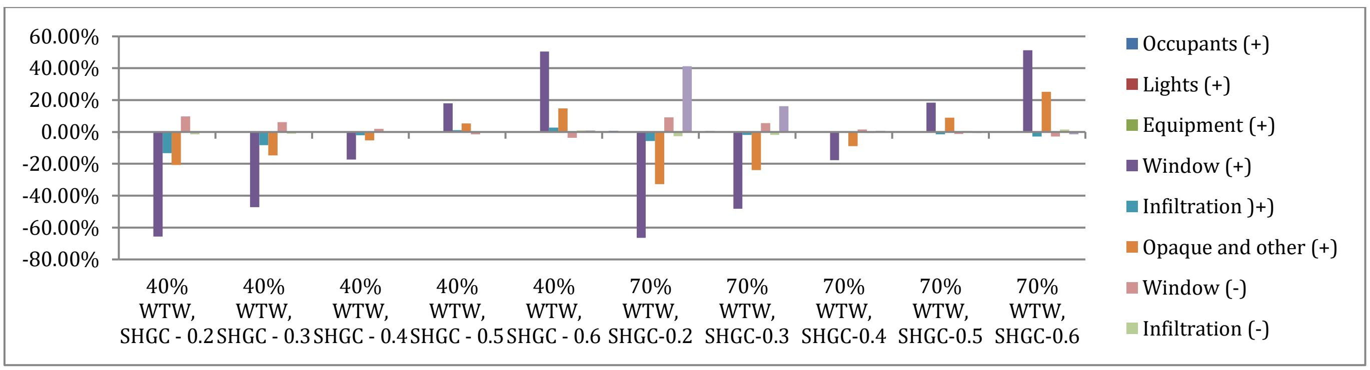


Figure 204: SHGC - Sensible Heat Gains % Difference from Baseline - Duluth, MN

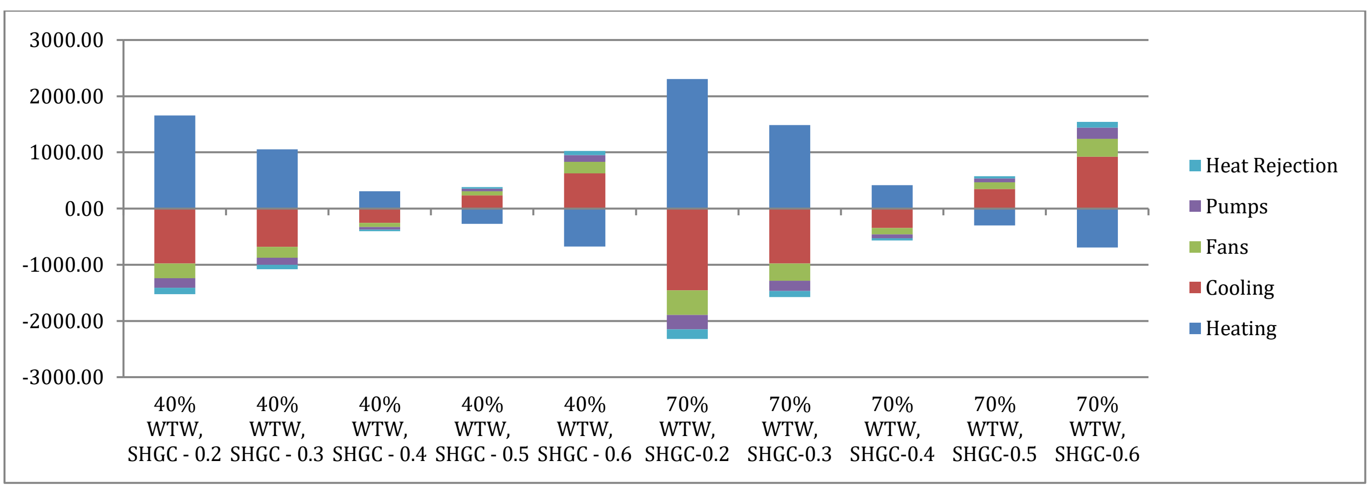


Figure 205: SHGC - Energy Consumption Difference from Baseline - Duluth, MN

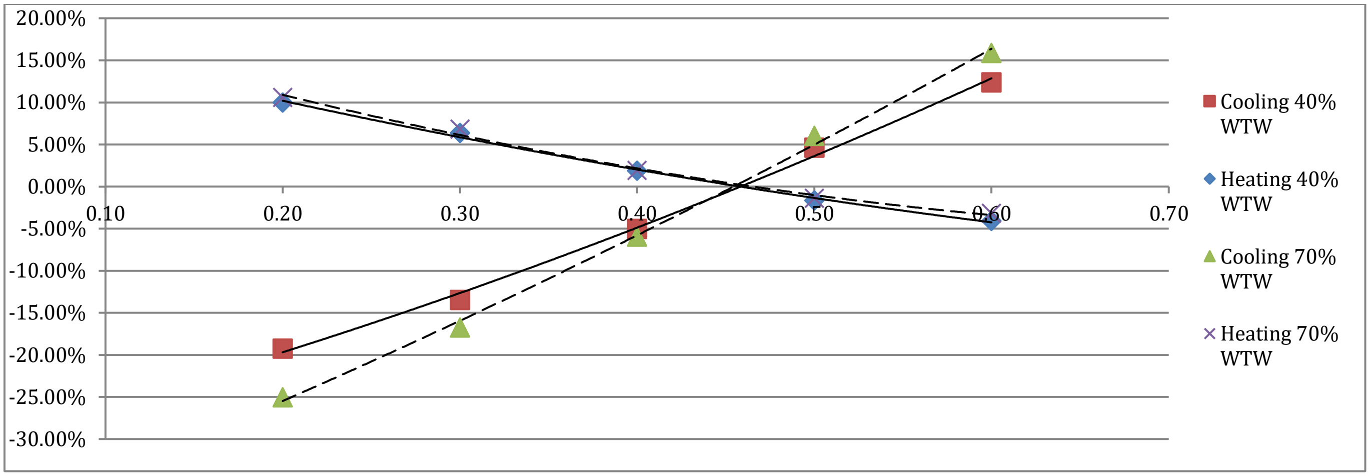


Figure 206: SHGC - Heating and Cooling Energy % Difference from Baseline - Duluth, MN

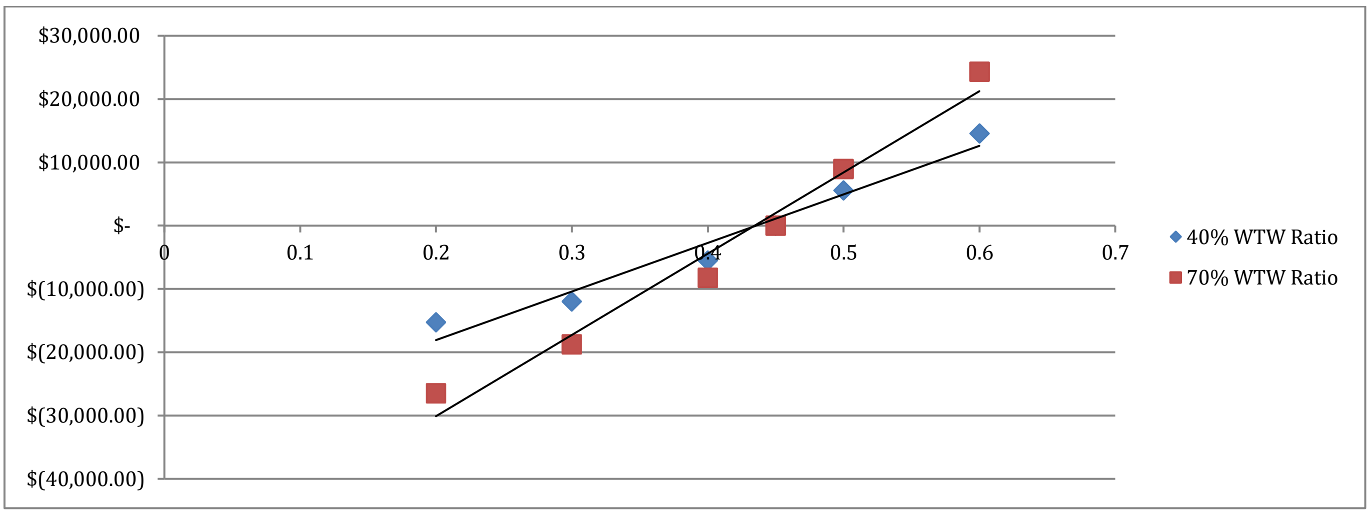


Figure 207: SHGC - Energy Cost Savings from Baseline - Duluth, MN

Appendix E: Visible Transmittance Analysis Results

Miami, FL Visible Transmittance Results

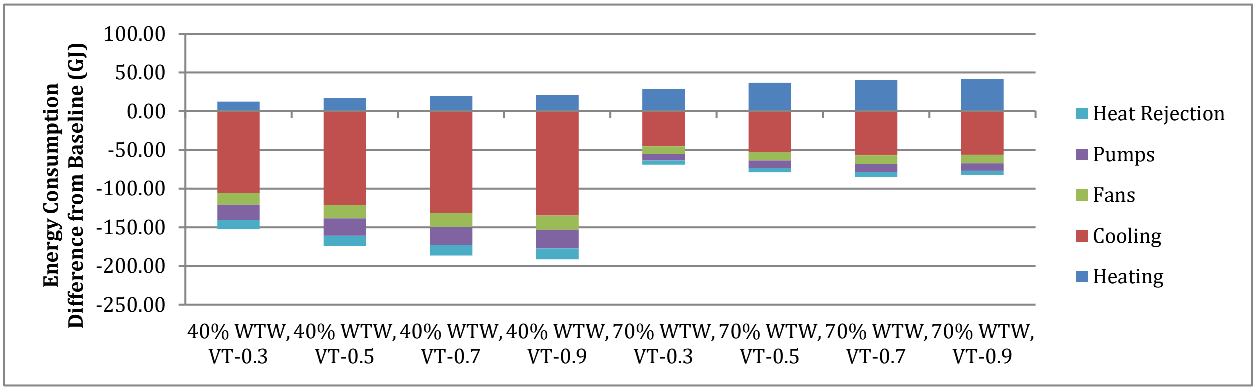


Figure 208: Visible Transmittance - Annual Energy Consumption Difference from Daylight Baseline - Miami, FL

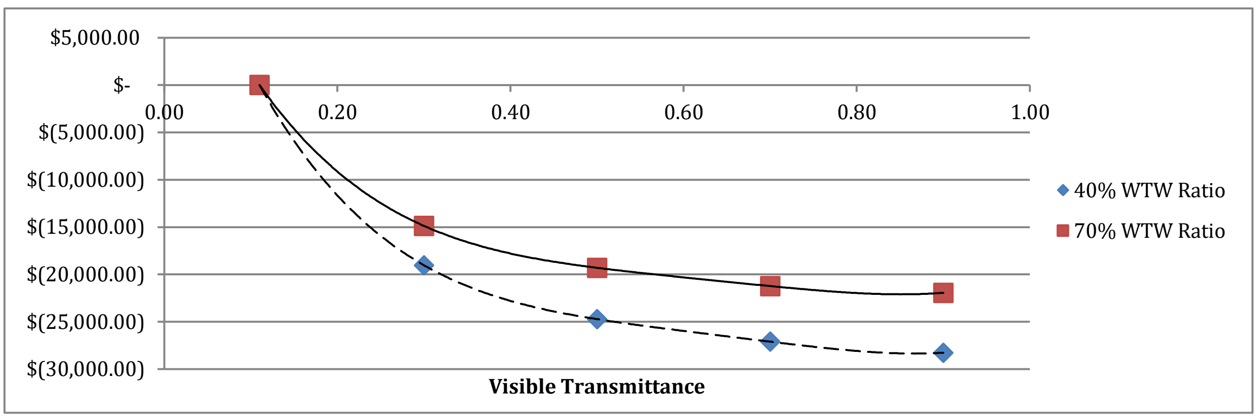


Figure 209: Visible Transmittance - Annual Energy Cost Difference from Daylight Baseline - Miami, FL

Houston, TX Visible Transmittance Results

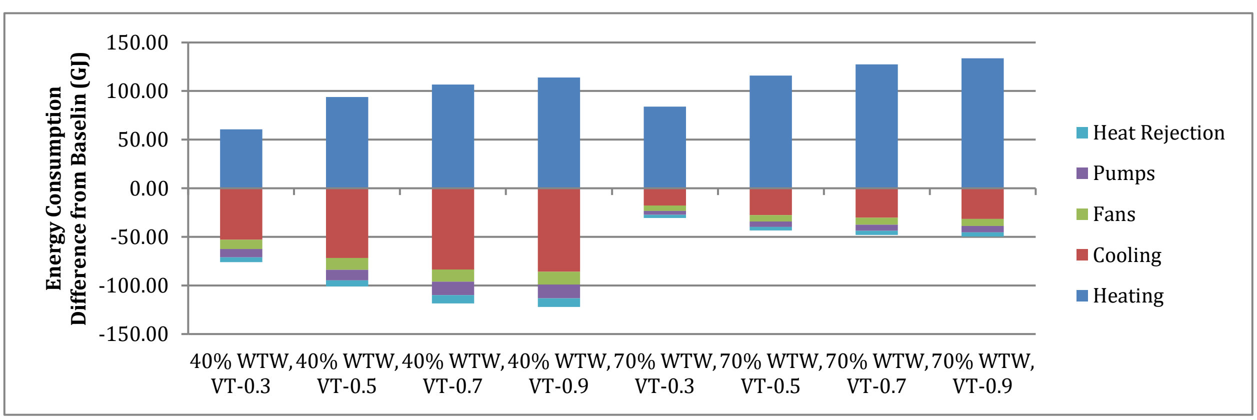


Figure 210: Visible Transmittance - Annual Energy Consumption Difference from Daylight Baseline - Houston, TX

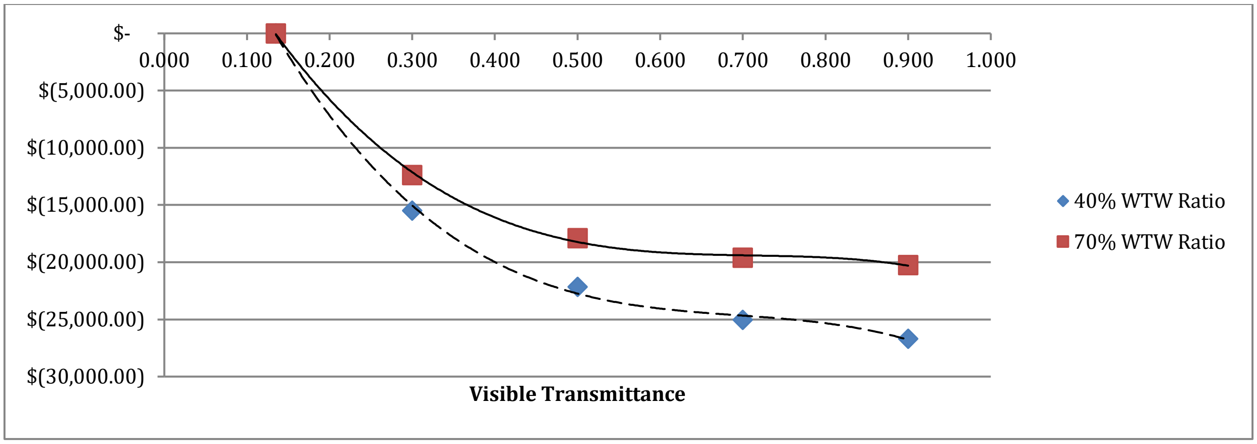


Figure 211: Visible Transmittance - Annual Energy Cost Difference from Daylight Baseline - Houston, TX

Phoenix, AZ Visible Transmittance Results

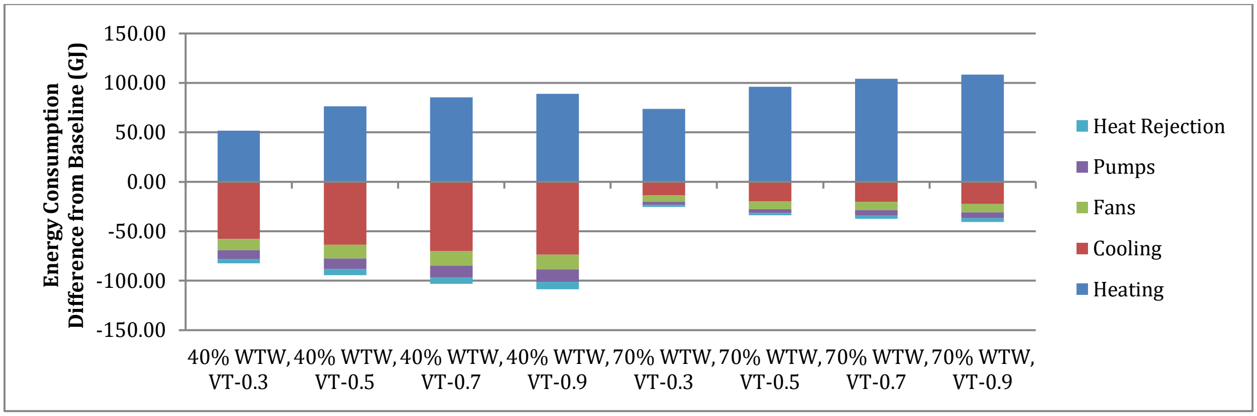
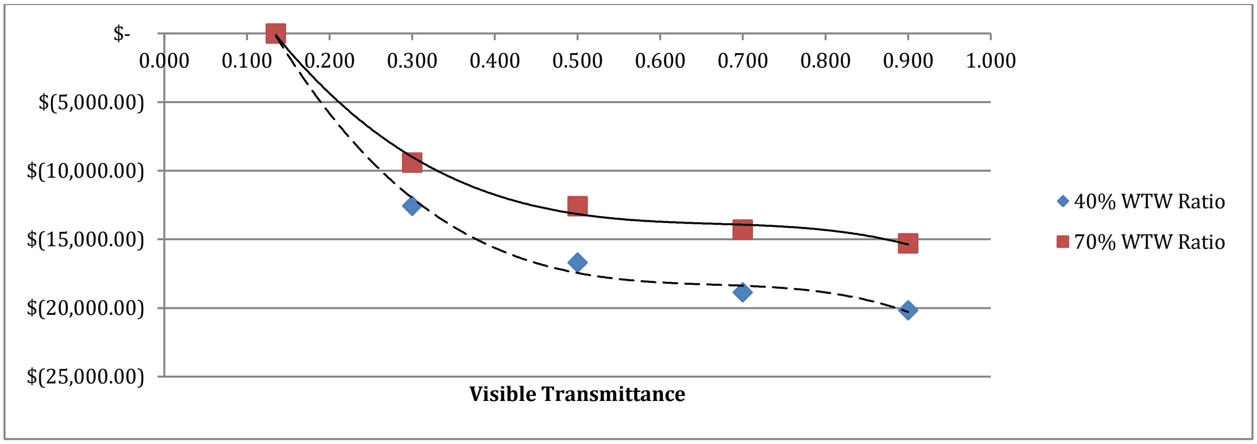


Figure 212: Visible Transmittance - Annual Energy Consumption Difference from Daylight Baseline - Phoenix, AZ



Atlanta, GA Visible Transmittance Results

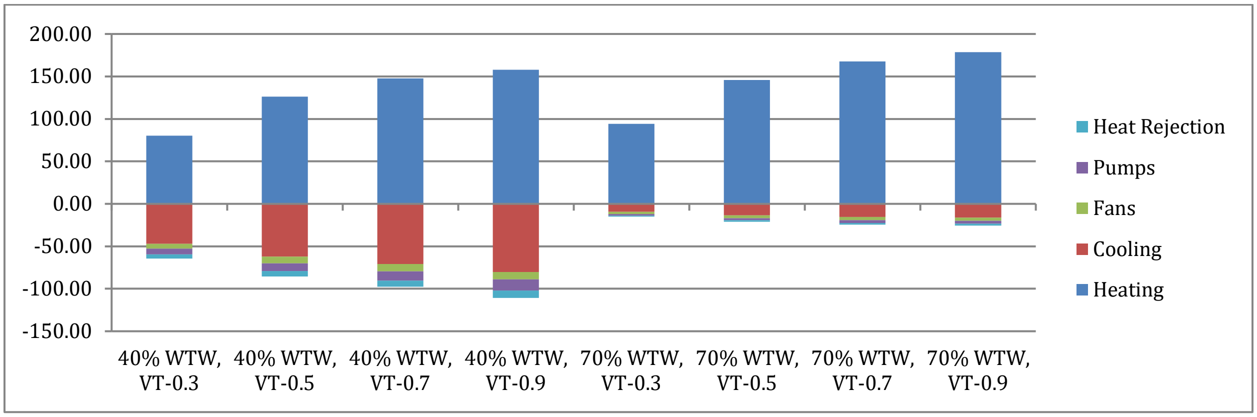


Figure 213: Visible Transmittance - Annual Energy Consumption Difference from Daylight Baseline - Atlanta, GA

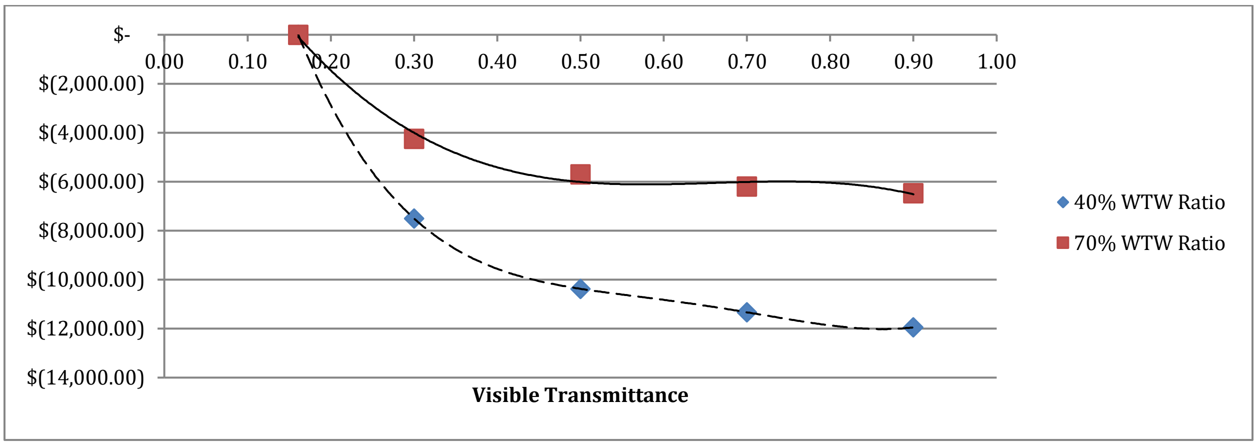


Figure 214: Visible Transmittance - Annual Energy Cost Difference from Daylight Baseline - Atlanta, GA

San Francisco, CA Visible Transmittance Results

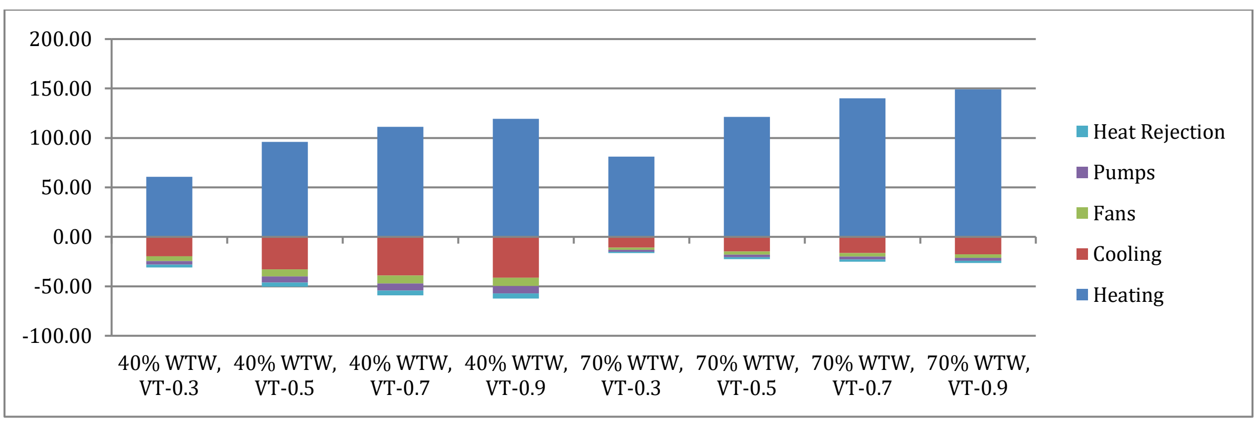
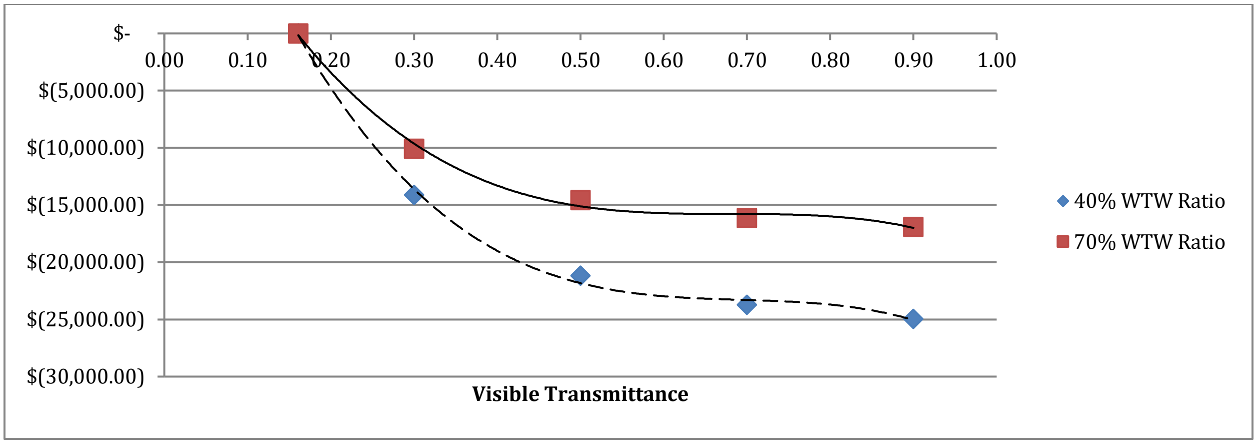


Figure 215: Visible Transmittance - Annual Energy Consumption Difference from Daylight Baseline - San Francisco, CA



Baltimore, MD Visible Transmittance Results

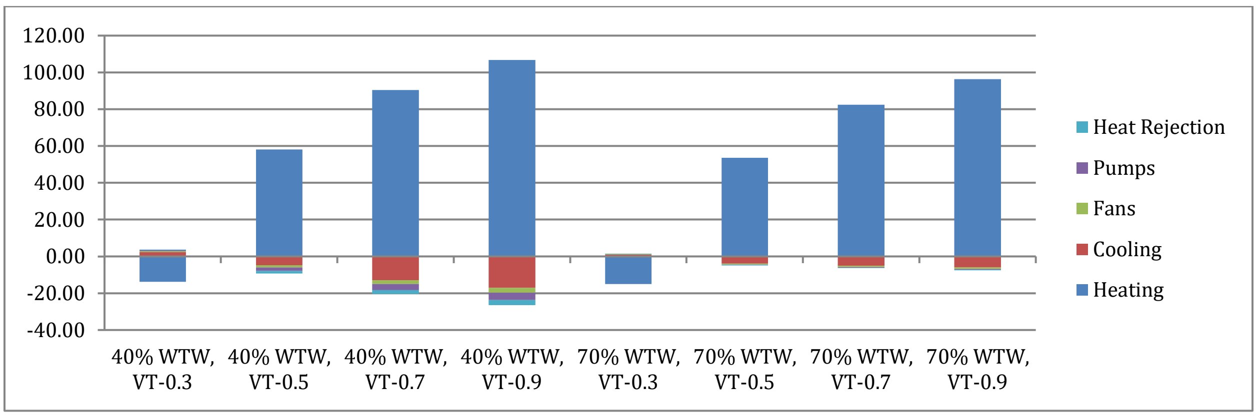


Figure 216: Visible Transmittance - Annual Energy Consumption Difference from Daylight Baseline - Baltimore, MD

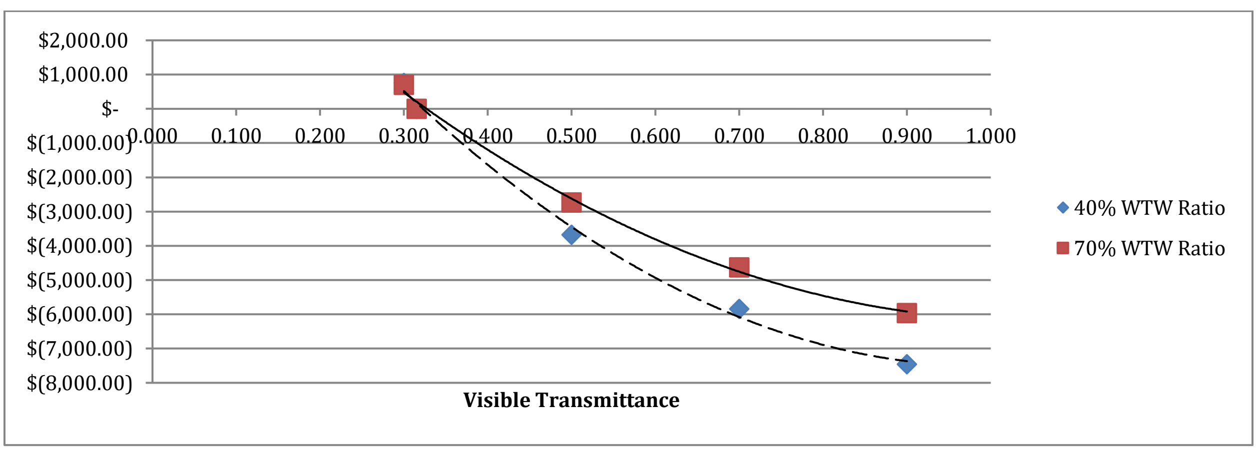


Figure 217: Visible Transmittance - Annual Energy Cost Difference from Daylight Baseline - Baltimore, MD

Seattle, WA Visible Transmittance Results

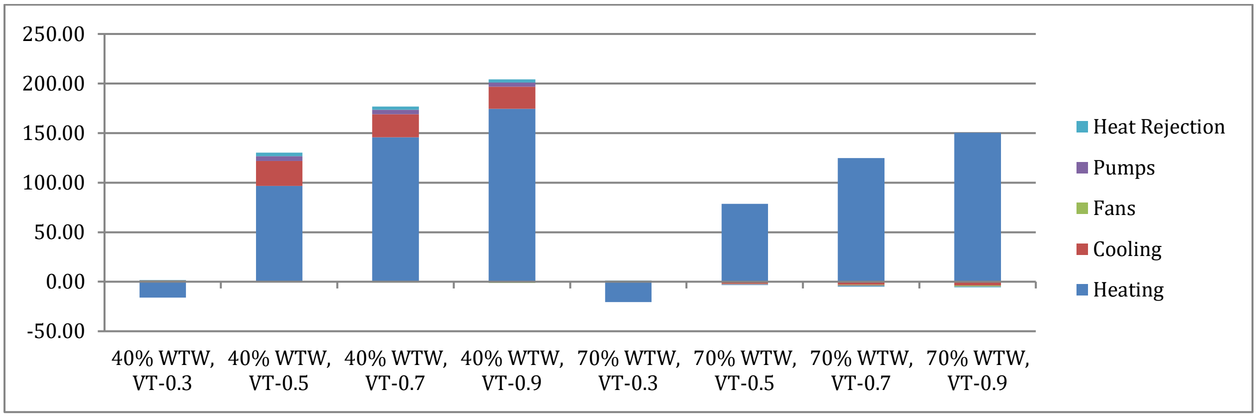


Figure 218: Visible Transmittance - Annual Energy Consumption Difference from Daylight Baseline - Seattle, WA

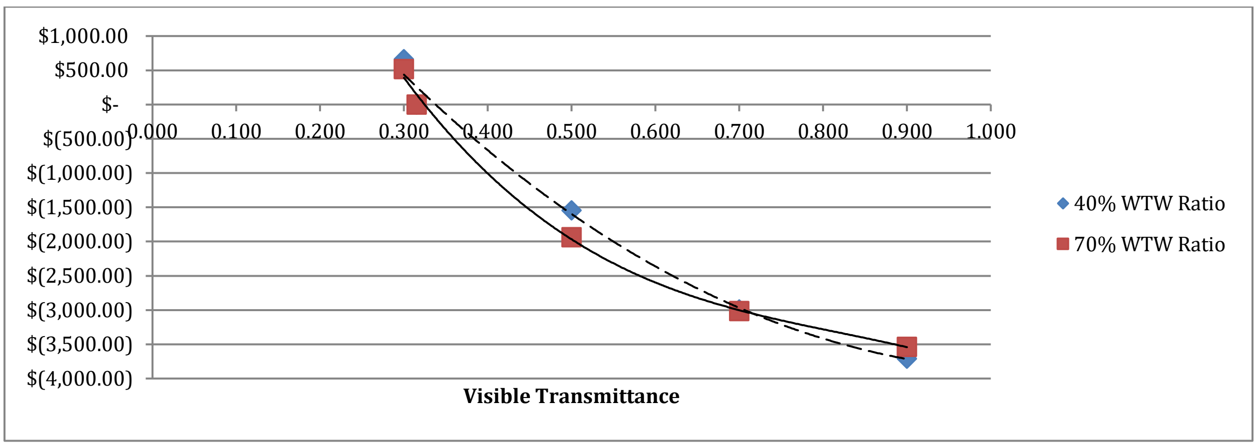


Figure 219: Visible Transmittance - Annual Energy Cost Difference from Daylight Baseline - Seattle, WA

Chicago, IL Visible Transmittance Results

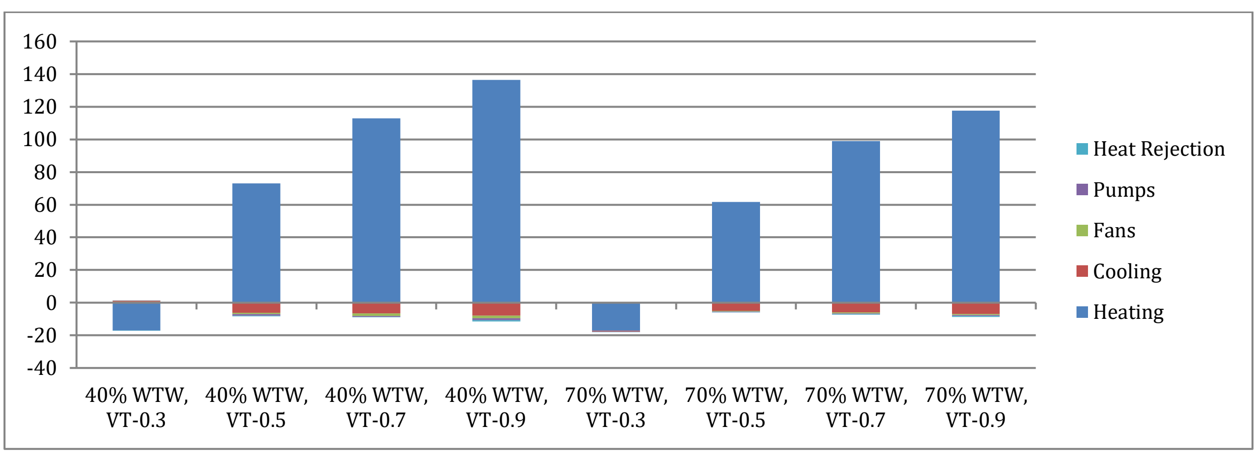


Figure 220: Visible Transmittance - Annual Energy Consumption Difference from Daylight Baseline - Chicago, IL

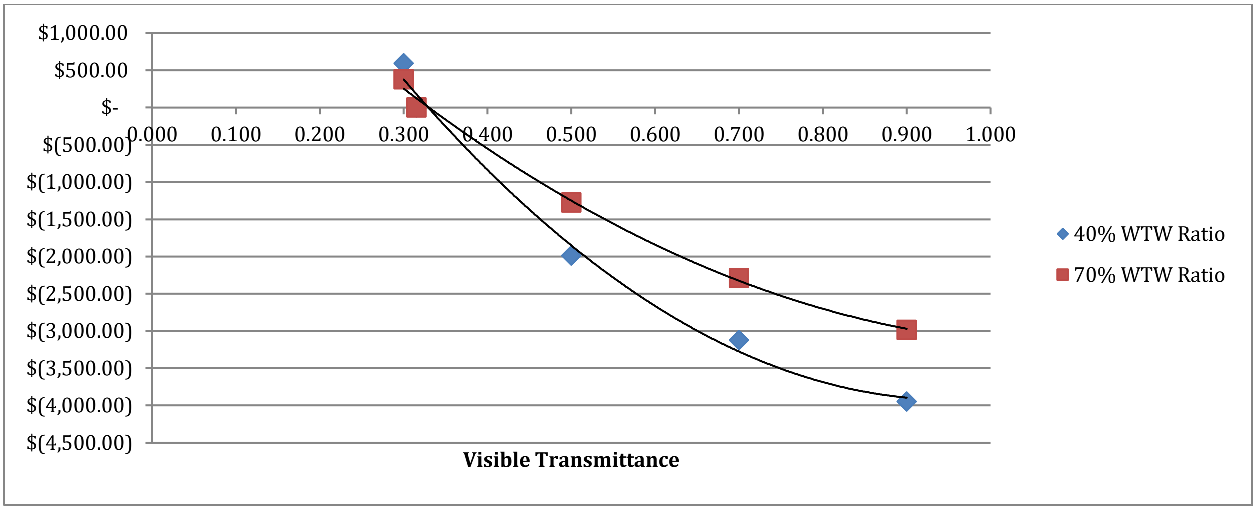


Figure 221: Visible Transmittance - Annual Energy Cost Difference from Daylight Baseline - Chicago, IL

Denver, CO Visible Transmittance Results

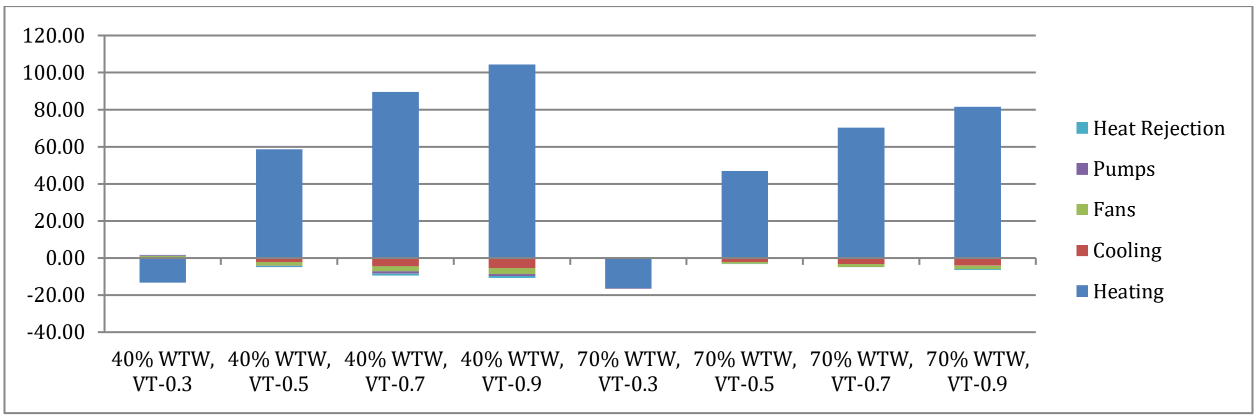


Figure 222: Visible Transmittance - Annual Energy Consumption Difference from Daylight Baseline - Denver, CO

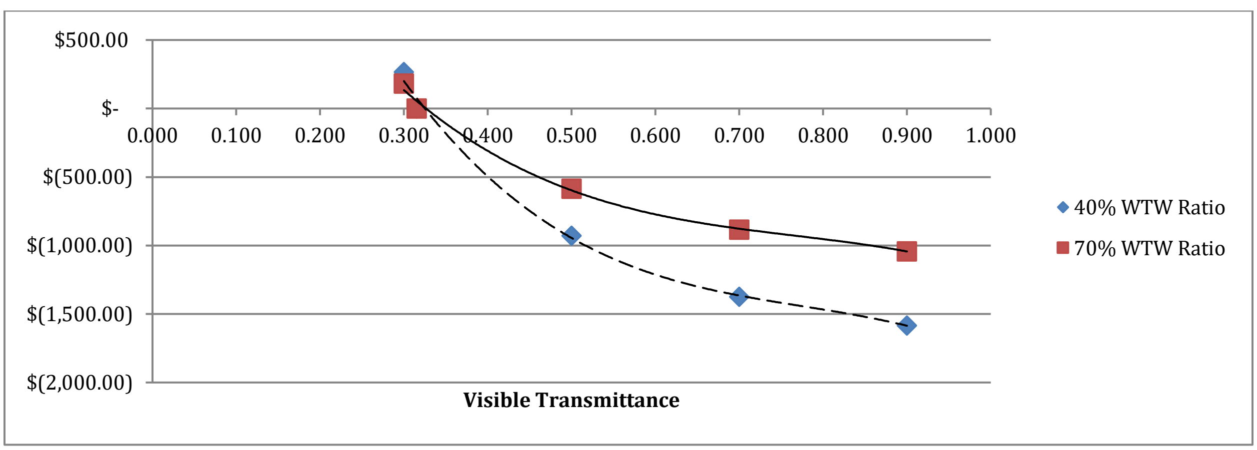


Figure 223: Visible Transmittance - Annual Energy Cost Difference from Daylight Baseline - Denver, CO

Helena, MT Visible Transmittance Results

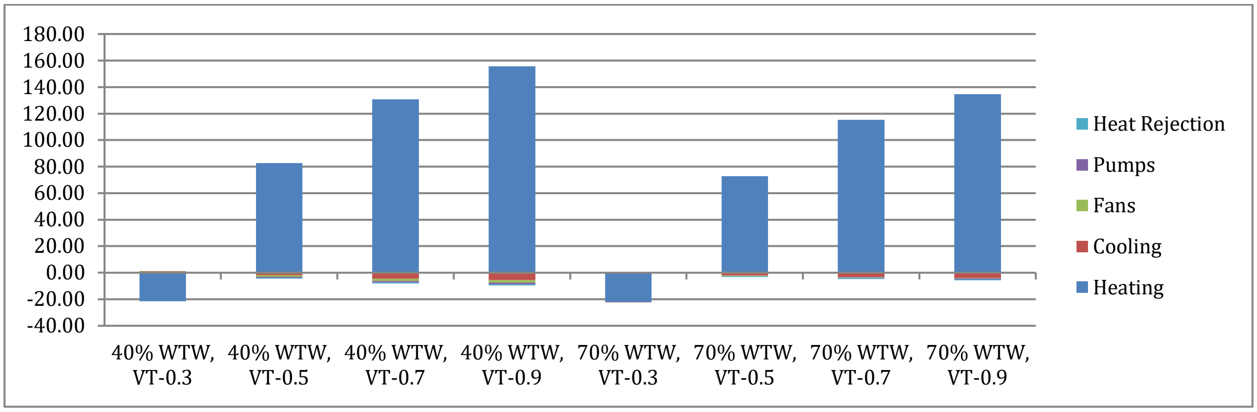


Figure 224: Visible Transmittance - Annual Energy Consumption Difference from Daylight Baseline - Helena, MT

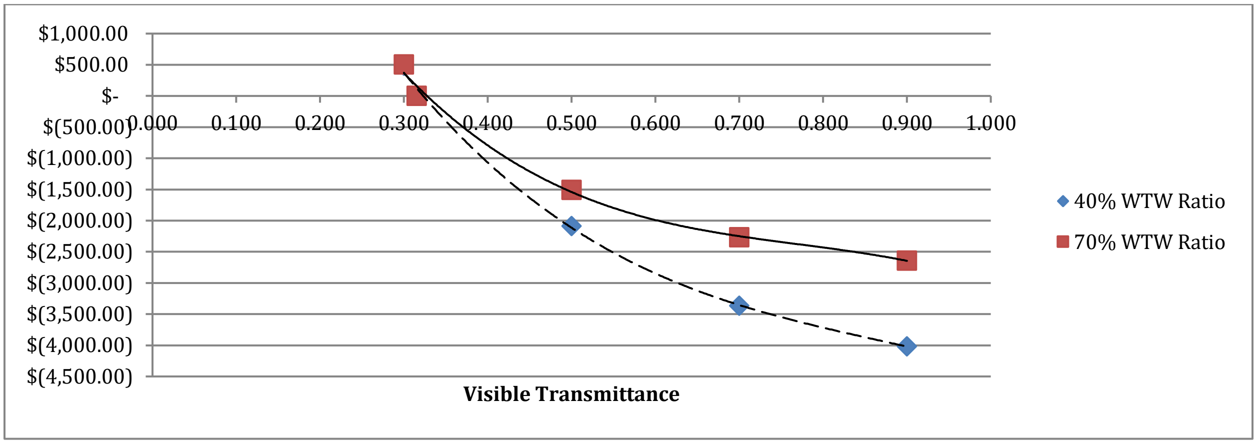


Figure 225: Visible Transmittance - Annual Energy Cost Difference from Daylight Baseline - Helena, MT

Duluth, MN Visible Transmittance Results

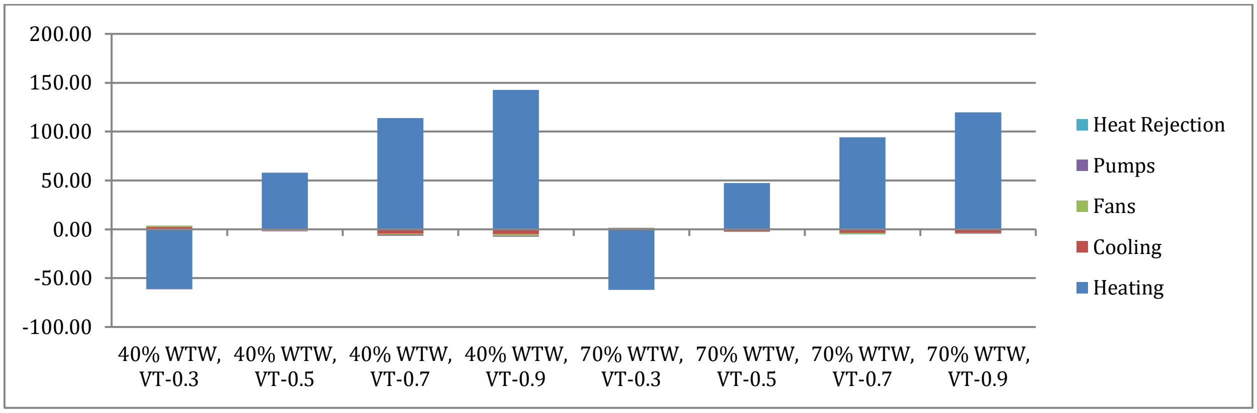


Figure 226: Visible Transmittance - Annual Energy Consumption Difference from Daylight Baseline - Duluth, MN

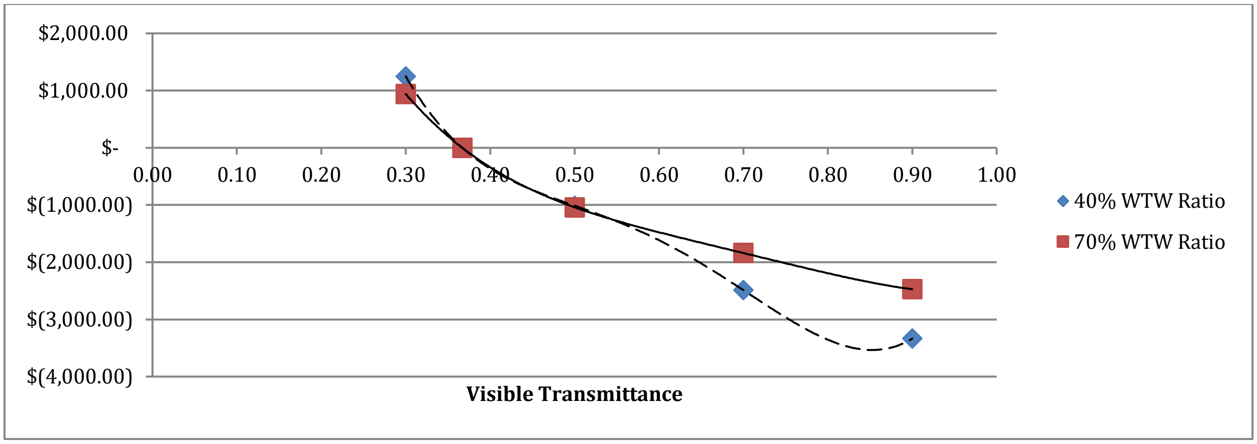


Figure 227: Visible Transmittance - Annual Energy Cost Difference from Daylight Baseline - Duluth, MN

Appendix F: Window Properties for Highest and Lowest Ten Energy Consumers

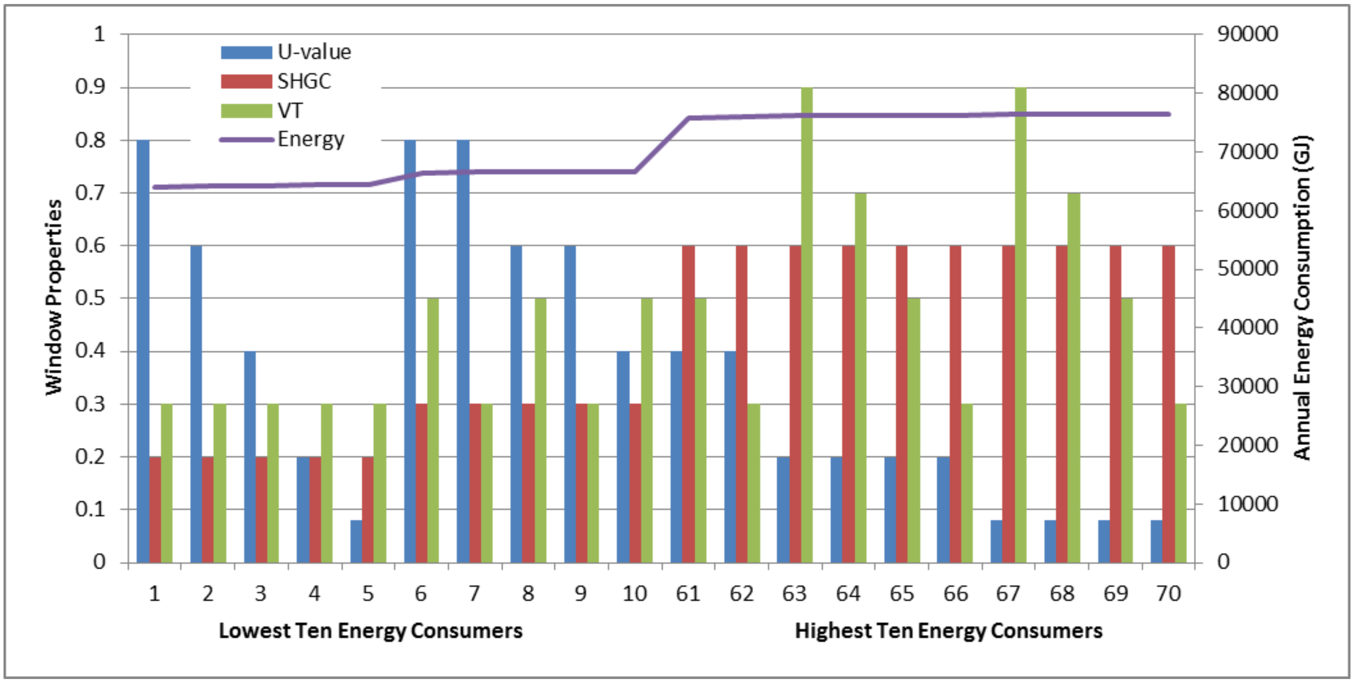


Figure 228: Window Properties for Highest and Lowest Ten Energy Consumers - Miami, FL

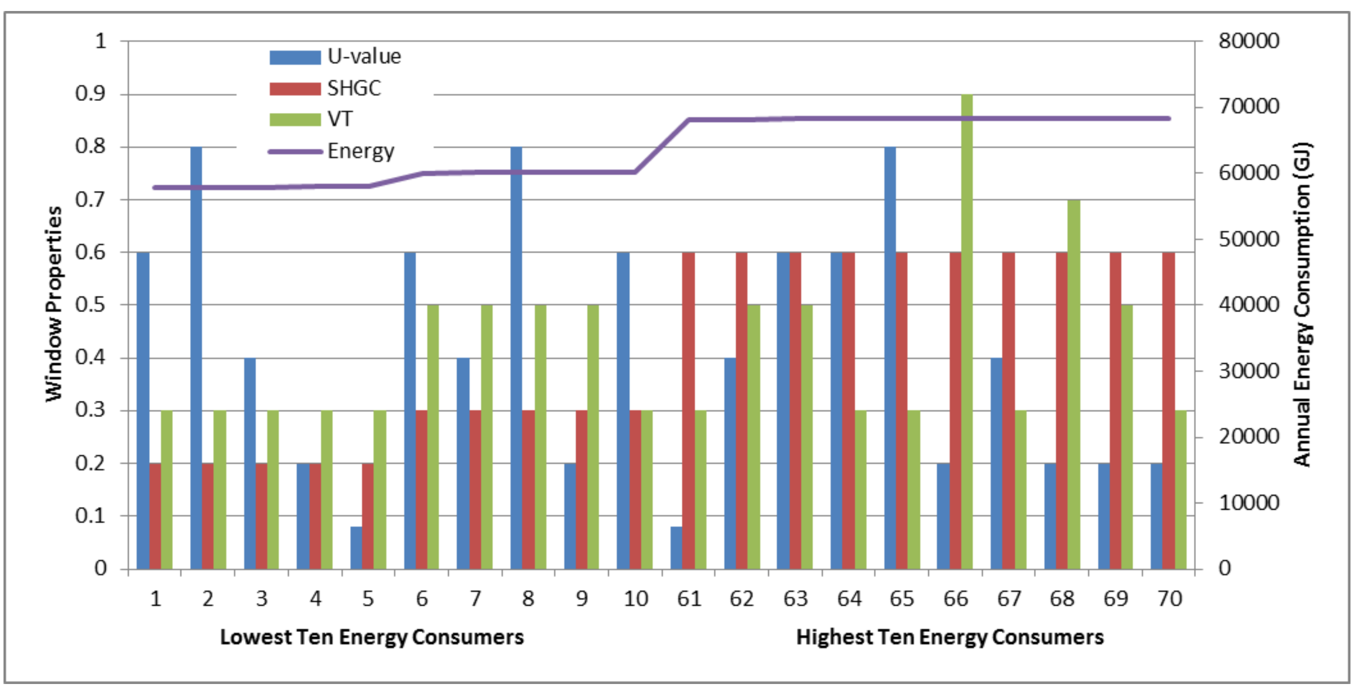


Figure 229: Window Properties for Highest and Lowest Ten Energy Consumers - Houston, TX

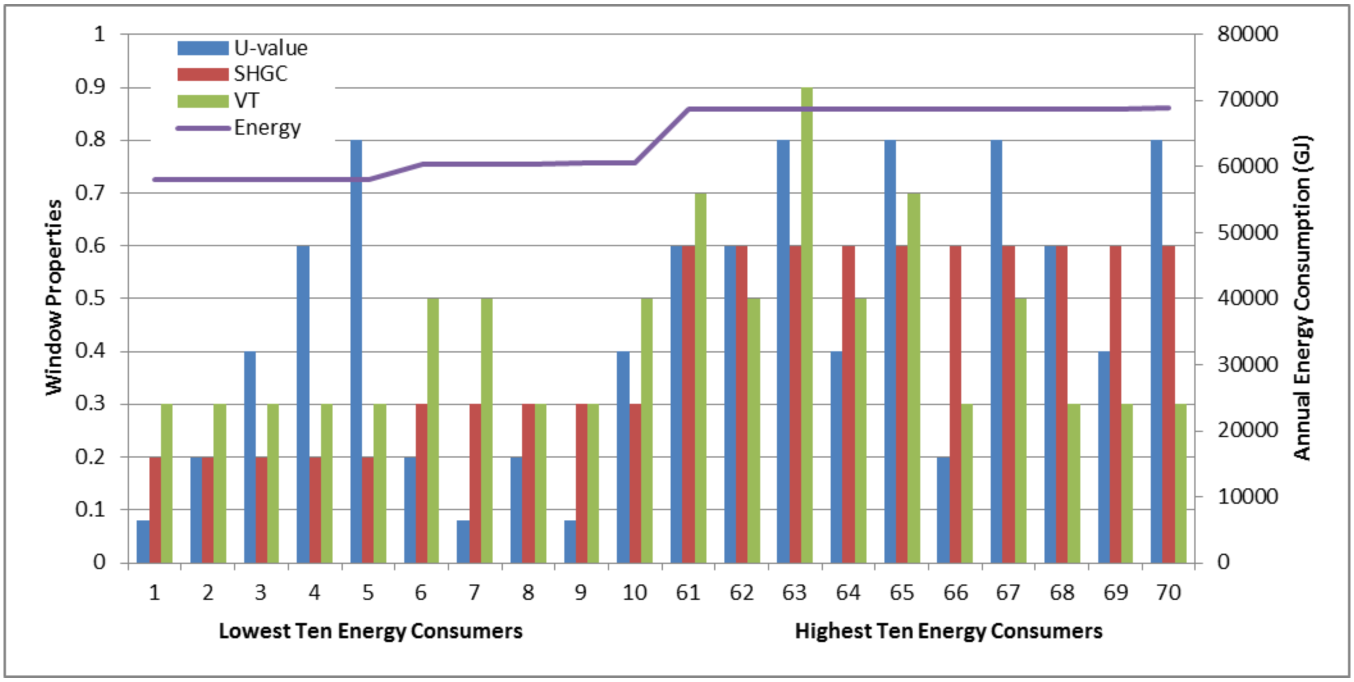


Figure 230: Window Properties for Highest and Lowest Ten Energy Consumers - Phoenix, AZ

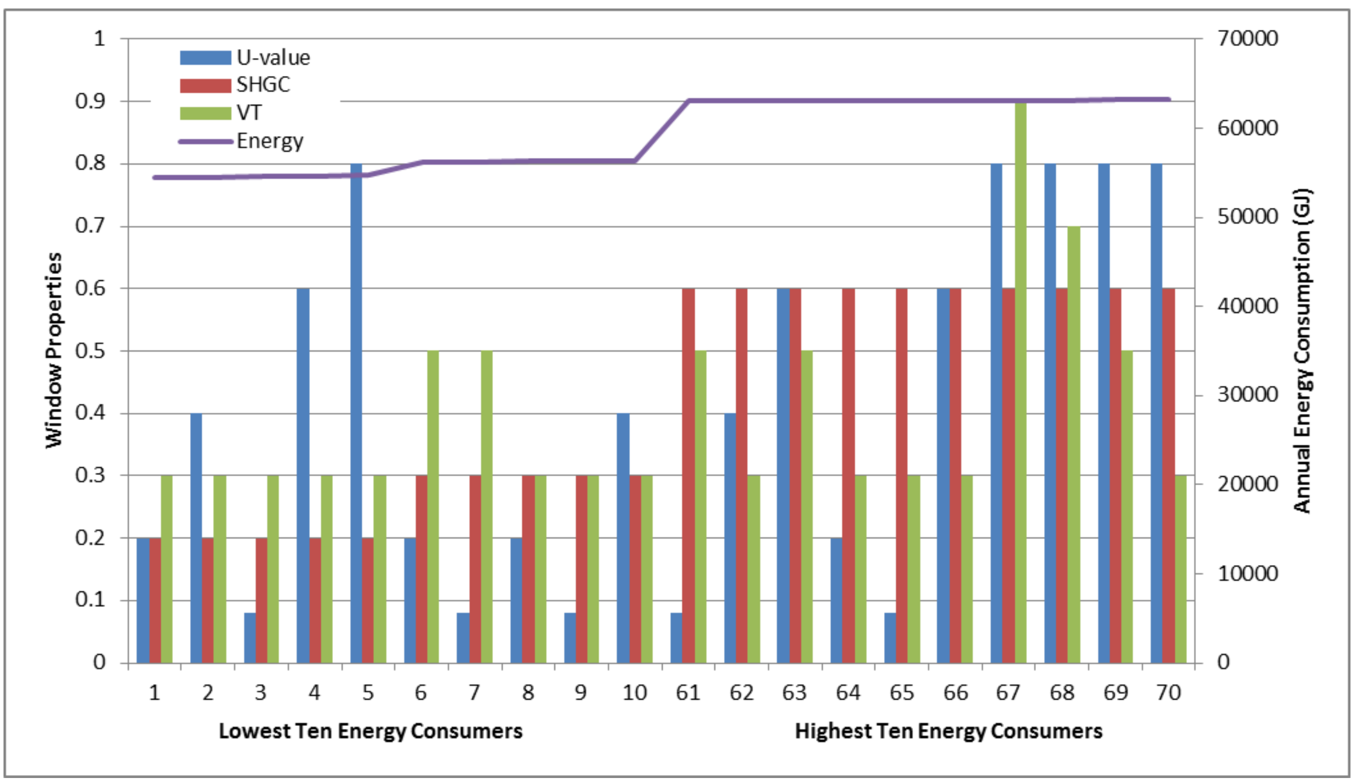


Figure 231: Window Properties for Highest and Lowest Ten Energy Consumers - Atlanta, GA

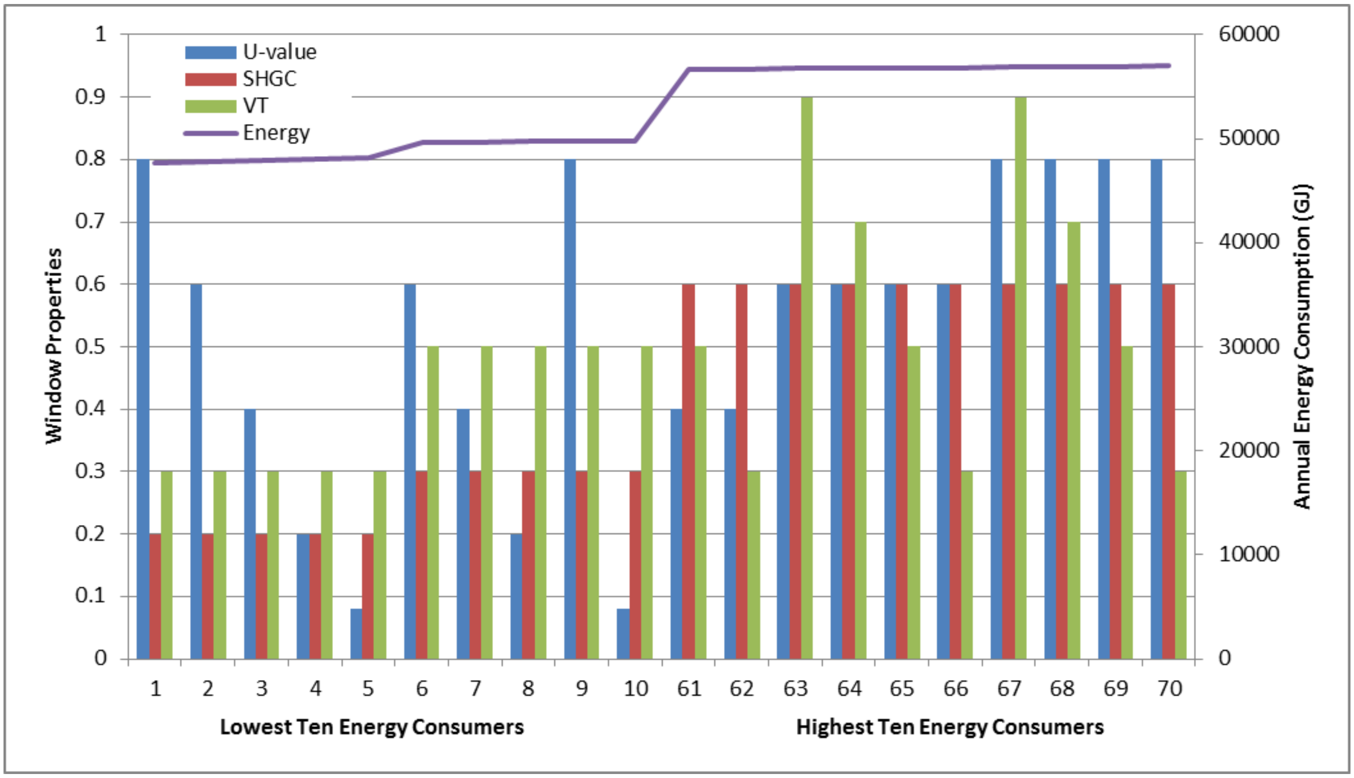


Figure 232: Window Properties for Highest and Lowest Ten Energy Consumers - San Francisco, CA

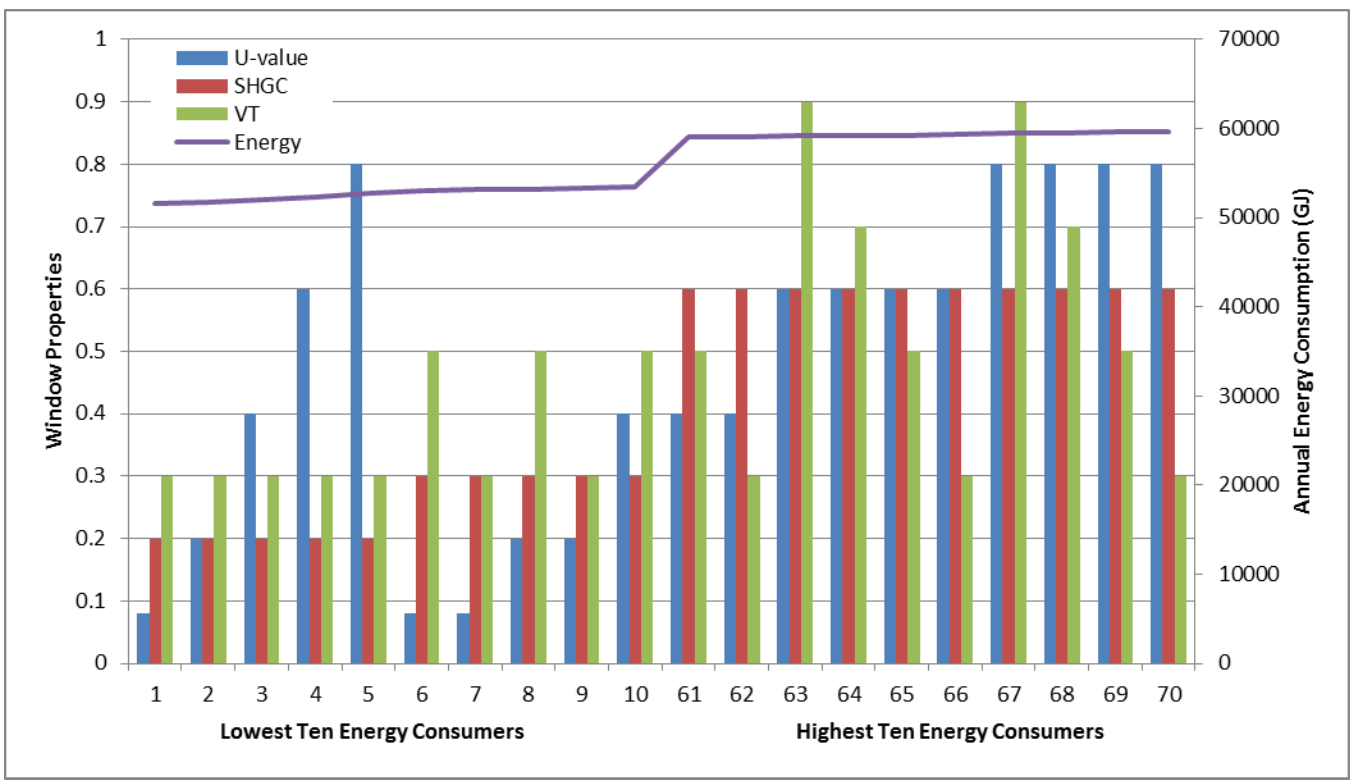


Figure 233: Window Properties for Highest and Lowest Ten Energy Consumers - Baltimore, MD

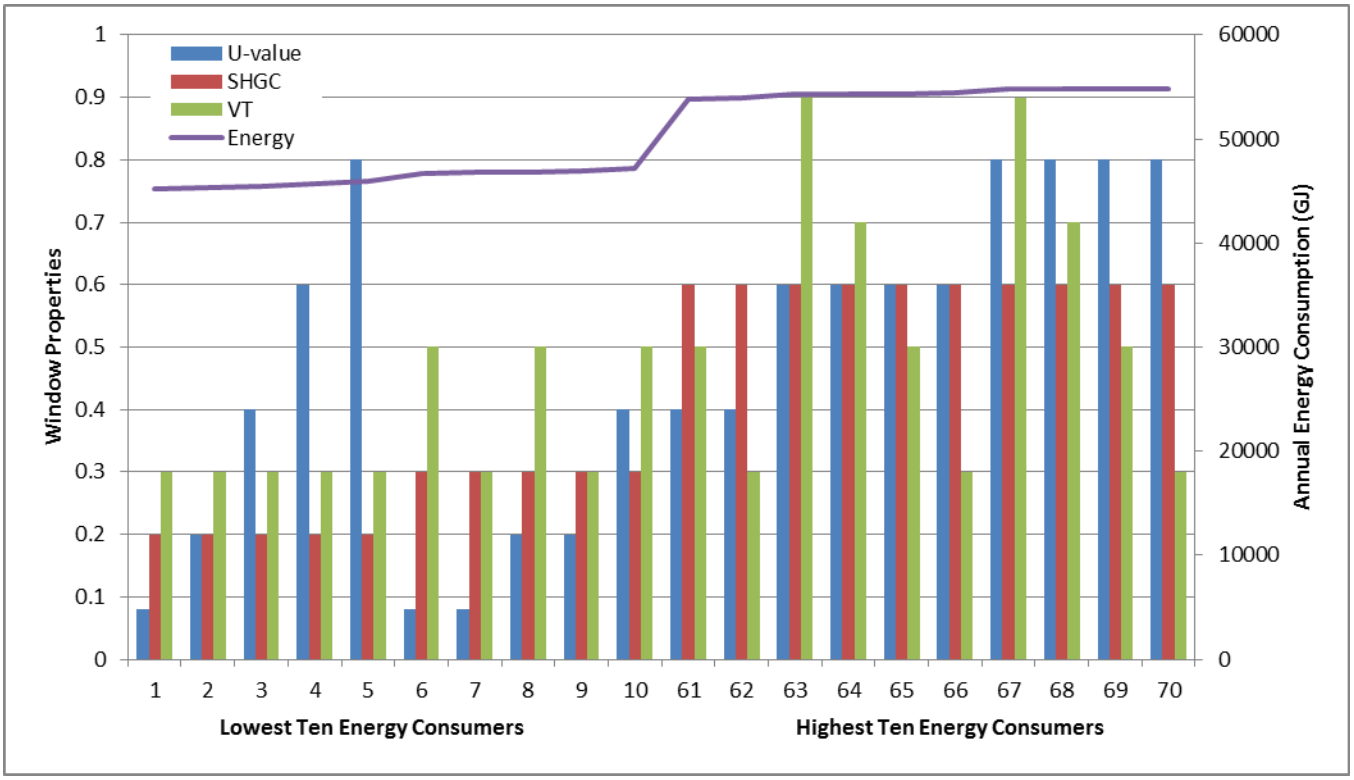


Figure 234: Window Properties for Highest and Lowest Ten Energy Consumers - Seattle, WA

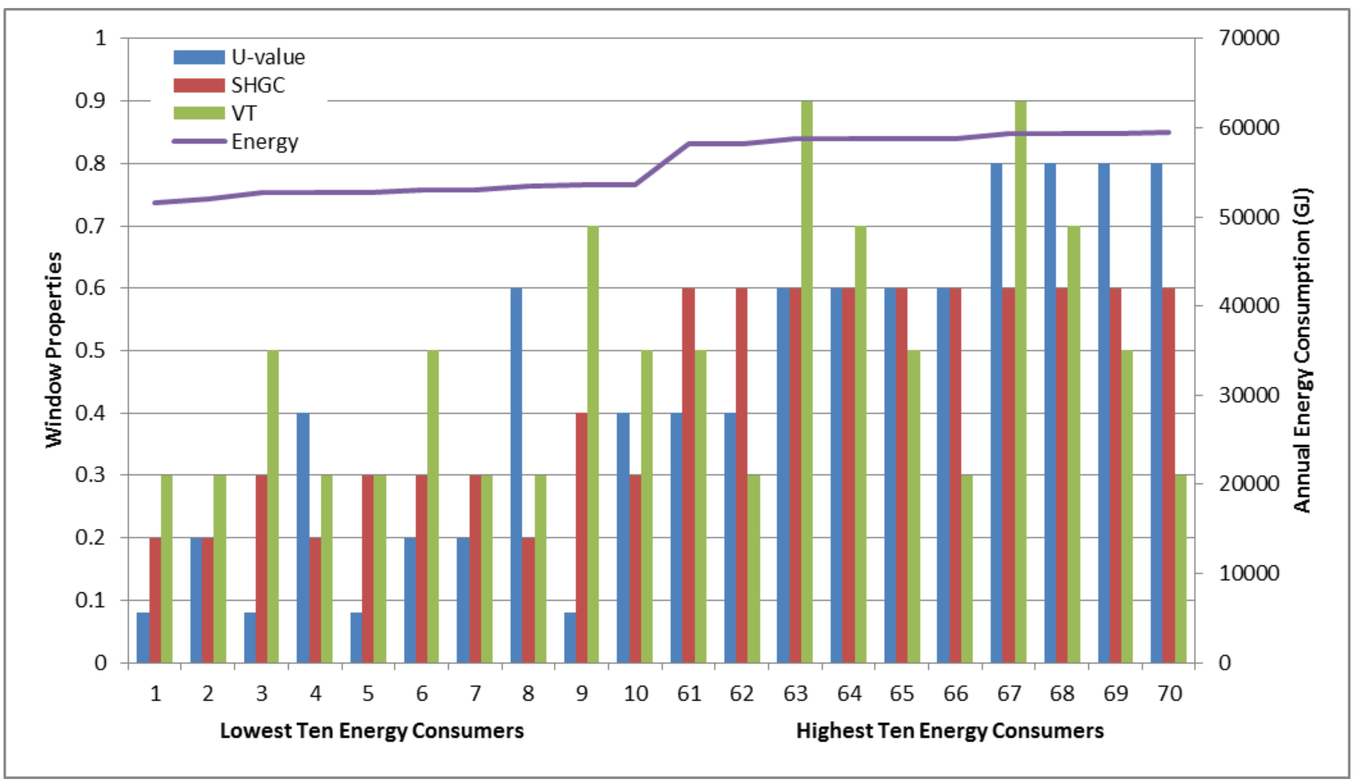


Figure 235: Window Properties for Highest and Lowest Ten Energy Consumers - Chicago, IL

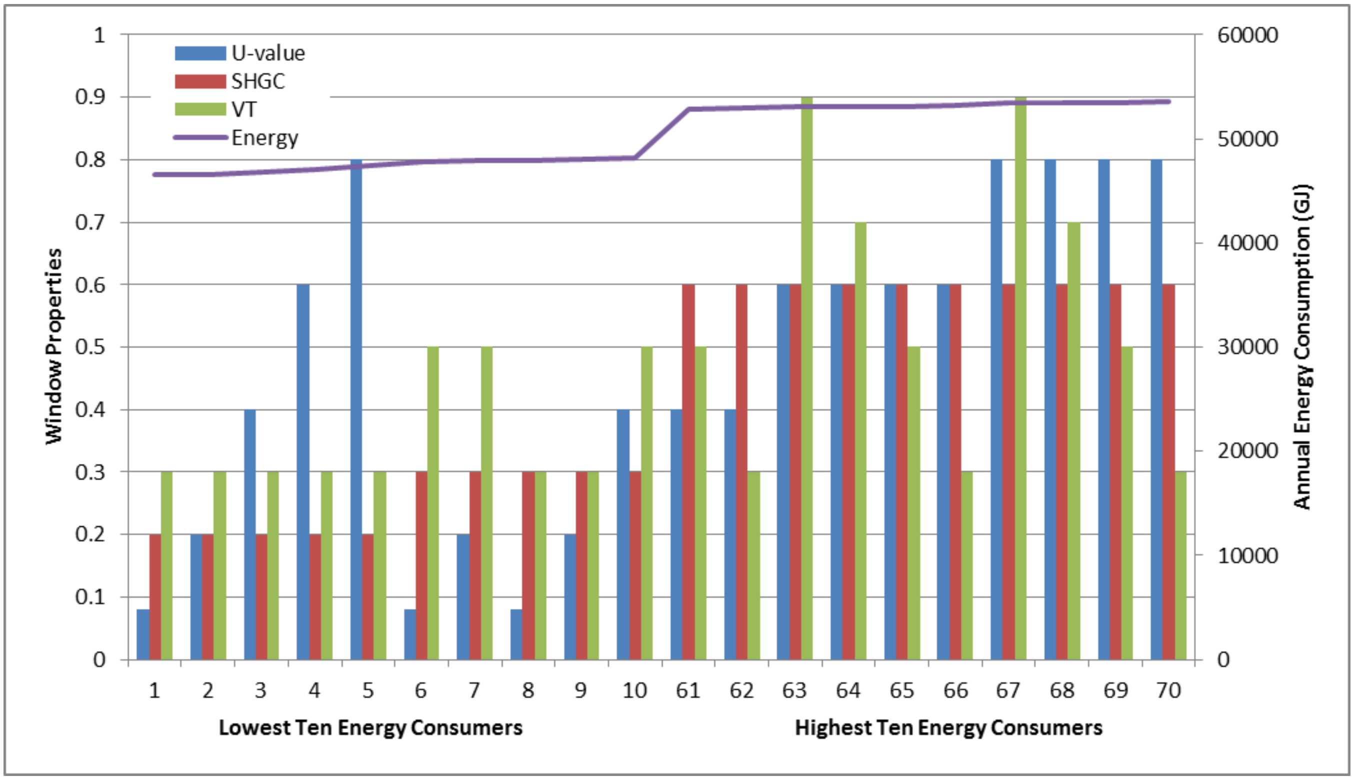


Figure 236: Window Properties for Highest and Lowest Ten Energy Consumers - Denver, CO

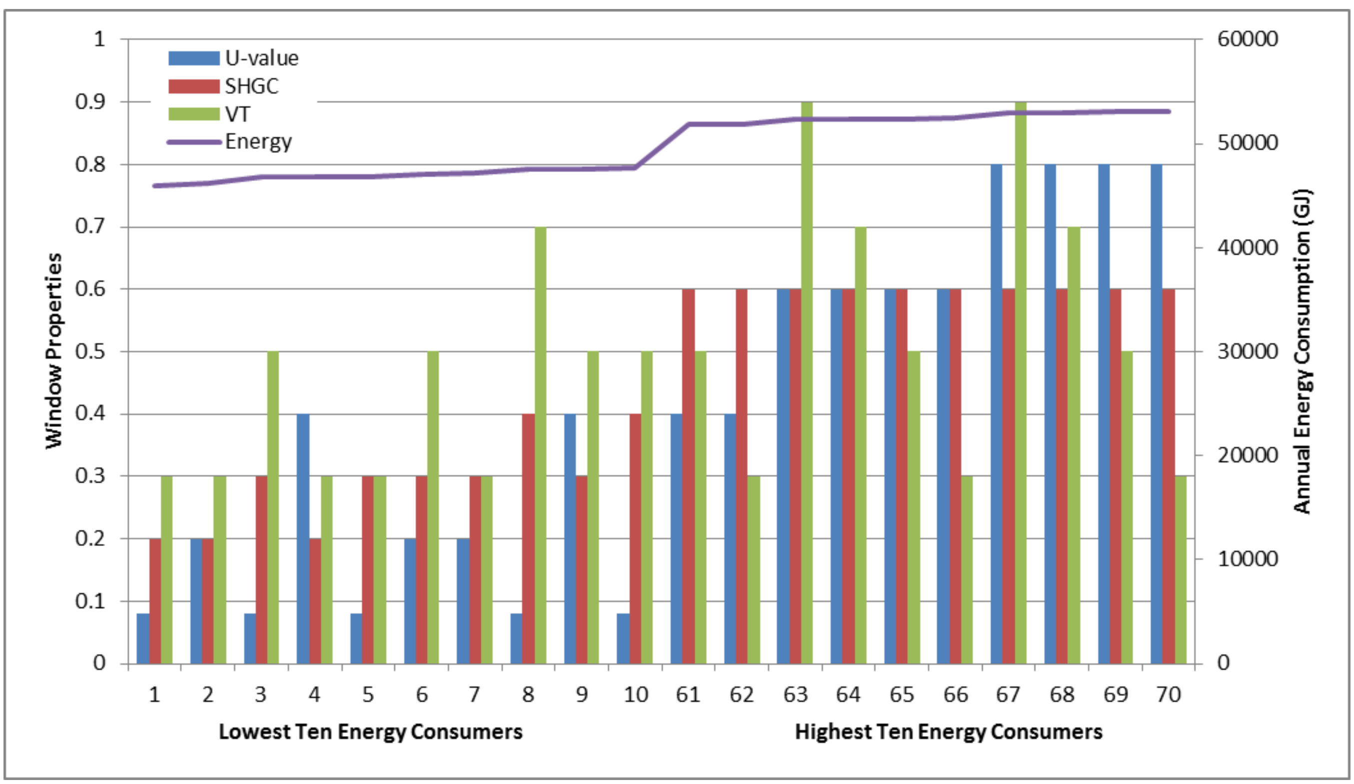


Figure 237: Window Properties for Highest and Lowest Ten Energy Consumers - Helena, MT

Figure 238: Window Properties for Highest and Lowest Ten Energy Consumers - Duluth, MN