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Modeling of Buildings with Electrochromic Windows and Thermochromic Roofs

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by

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ABSTRACT

Air conditioning and heating have increased substantially during the past two decades. According to a survey, buildings consume about 73% of the total electricity in the United States, accounting for 41% of all other energy in the world. At the same time, building skin technologies are constantly improving. Electrochromic and thermochromic are two exciting new technologies that can help reduce the energy consumption of a building. The purpose of this work is to increase our understanding of how much the use of electrochromic (EC) and thermochromic (TC) technologies can reduce the energy consumption of residential and commercial buildings in two different climate zones. With the use of the software eQUEST and specific parameters for EC and TC materials and devices, the energy performance of these buildings is simulated. Furthermore, simulations are used to compare the difference in energy consumption between a building that uses low-E double pane windows and a cool roof and a building that uses EC windows and a TC roof. The results for two cities, Tampa and Chicago, are obtained to determine the performance of EC windows and TC roofs in two different climates. These results suggest that the utilization of both EC windows and TC roofs can save 27.8% - 35% and 6.2% - 23.8% of the energy consumed by commercial and residential buildings, respectively. Although these results are only an estimate, they do demonstrate the potential of EC and the TC technologies to reduce the energy consumption of buildings.

1. INTRODUCTION

Florida temperature data show that the annual high temperature is about 81.7 °F. In the warmest month, August, the average daytime temperature rises to 90°F [1]. According to the Energy Information Administration (EIA), the average monthly electricity bill in the United States (U.S.) was $118 in 2018. However, in Florida the average electricity bill was $128, which is 9% higher than the average U.S. total electricity bill [2]. In addition, energy consumption has become an important issue because higher energy use leads to higher environmental pollution. A recent survey by the U.S. Green Building Council (USGBC) shows that buildings consume about 73% of the total electricity in the United States, accounting for 41% of all other energy in the world, while emitting 38% of the total carbon dioxide into the atmosphere each year [3]. Modern buildings usually have large facades of windows, known as glazings. Glazings provide good daytime illumination but reduce the energy efficiency of buildings [4]. In particular, cooling has increased significantly in recent years. According to the EIA, energy lost through conventional windows accounts for about 30% of the heating and cooling energy costs [5]. Shadows, blinds, shutters, fins or other mechanized solar control devices are used, but they can cut off connection to the outdoors.

Fortunately, new technologies are developed that can be used to provide comfort and reduced energy consumption. New emerging technologies that utilize "electrochromism" and "thermochromism" can control the inflow of solar energy and produce higher energy efficiency than traditional glass windows that use static solutions or conventional roofs [6].

All abbreviations listed and explained in Table 1. The purpose of this research is to understand the impact electrochromic windows and thermochromic roofs can have on the energy consumption of buildings. At this time, there is no research paper published that addresses the use of both electrochromic windows and thermochromic roof coatings to simulate the energy consumption of a building [7-13].

Table 1. Table of nomenclature

TC	Thermochromic	EC	Electrochromic
NFRC	National Fenestration Rating Council	NRCA	National Roofing Contractors Association
FL	Florida	IL	Illinois
EIA	Energy Information Administration	ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
DOE	Department of Energy	SHGC	Solar Heat Gain Coefficient
VT	Visible Transmittance	CR	Condensation Resistance
AL	Air Leakage	USGBC	U.S. Green Building Council
SPF	Spray Polyurethane Foam	Low-E	Low Emissivity
SC	Shading Coefficient	BUR	Built-Up Roofing
UV	Ultraviolet	U.S.	United States

2. BACKGROUND - ELECTROCHROMISM AND THERMOCHROMISM

In recent years, these two new technologies are receiving more and more attention. More detailed information about electrochromic and thermochromic technologies is presented in the following section.

2.1. Electrochromic Devices and Technologies

Electrochromism is a property of some materials that reversibly change color under an applied electric potential. Electrochromic (EC) glass or "Smart Glass" is a common name for EC windows. The EC window allows the user to control the light and heat passing through the window. In addition, the EC window can be completely transparent or tinted to reduce light and heat without the need for louvers or curtains. Some can also be set to block light while maintaining a view.

On the other hand, even though EC glass was proposed in 1984, it was introduced to the market during 2010s [7]. The EC technology is presently being used in windows for commercial buildings, to combine energy efficiency with good indoor comfort.

2.2. Thermochromic Materials and Technologies

Thermochromism is a property of some materials that change color due to a change in temperature. According to Warwick (2016), an idealized spectrum can be used to understand the TC properties of materials and determine the materials that are most important for energy saving applications. The results indicate that the optimum TC material can lead to energy savings up to 30% to 45% in different environments, while maximizing efficiency in hot environments [8].

The two main types of TC are “liquid crystals” and “leuco dyes.” By far the most frequent TC applications use liquid crystals [14]. Today, liquid crystals are used in many products, including forehead thermometers, indoor and refrigerated thermometers, and other applications including food quality indicators. Liquid crystals TCs are very good materials, but are difficult to use and require highly specialized manufacturing techniques. Another type of TC material, leuco dyes, are commonly used in manufacturing and control processes, advertising, consumer packaging, product labeling, security printing, novel applications, promotional items, toys and textiles. In this thesis, leuco dyes are used because they are more common and easier to work with.

3. METHODOLOGY

The eQUEST software is currently the most popular energy modeling program and is used by energy modelers and engineers around the world. Important factors for its popularity are its low cost (free) and that it is based on the department of energy 2 (DOE-2) simulation engine [15].

The eQUEST building creation wizard guides the user through the process of creating a building model. The eQUEST, DOE-2.2, provides hourly data for a building taking into consideration windows, walls, people, glass, plug loads, and ventilation. DOE-2.2 also simulates the performance of pumps, fans, chillers, boilers, and other energy consuming devices. eQUEST allows users to create multiple simulations and view alternate results in parallel graphics. It provides energy cost estimates, daylighting and lighting system control, and automatic implementation of energy efficiency measures [16]. An additional benefit of eQUEST is that it can be used at every stage of a building's development, from an early design to the final product. Therefore, in this research, the eQUEST software is used to simulate the energy consumption of buildings that incorporate EC windows and TC roofs.

3.1. Analyzed Structures (Buildings)

In this study, eQUEST has been used to create two prototype models of an office building and a residential house. These building models are shown in Figures 1 and 2. The commercial office building is eight stories, has a flat brown roof and concrete walls (See Figure A4, Appendix B). Some basic information for this building is shown in Table 2, with additional information given in Appendix B.

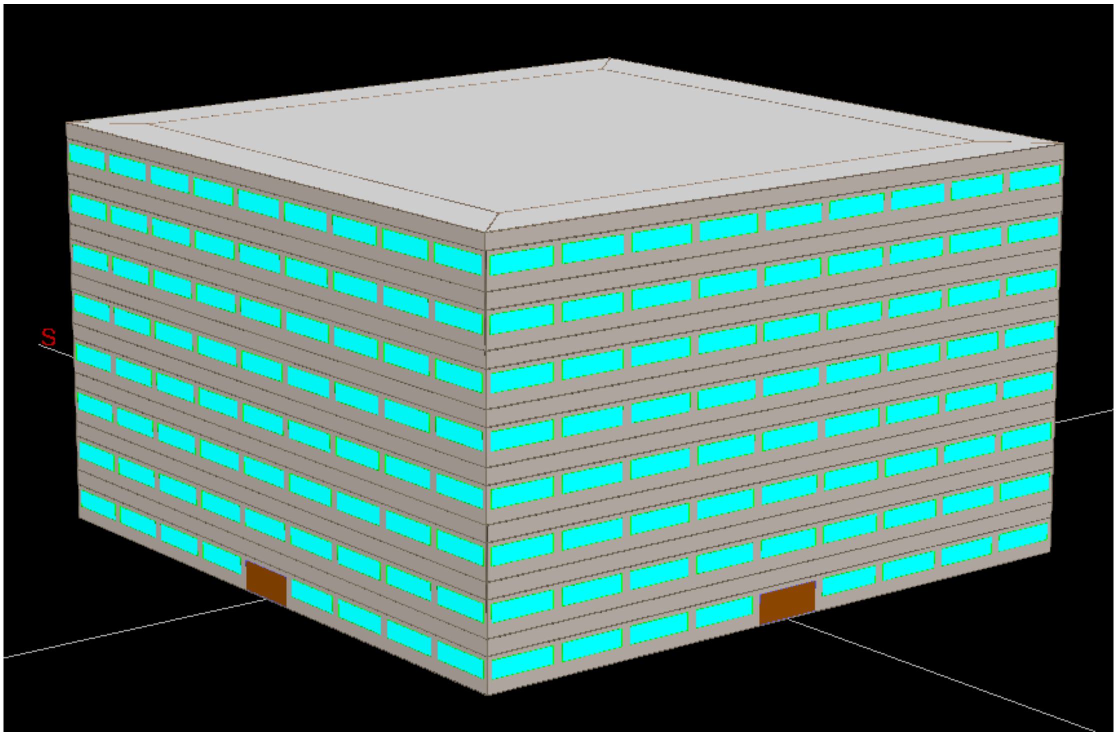


Figure 1. 3D illustration of a commercial office building

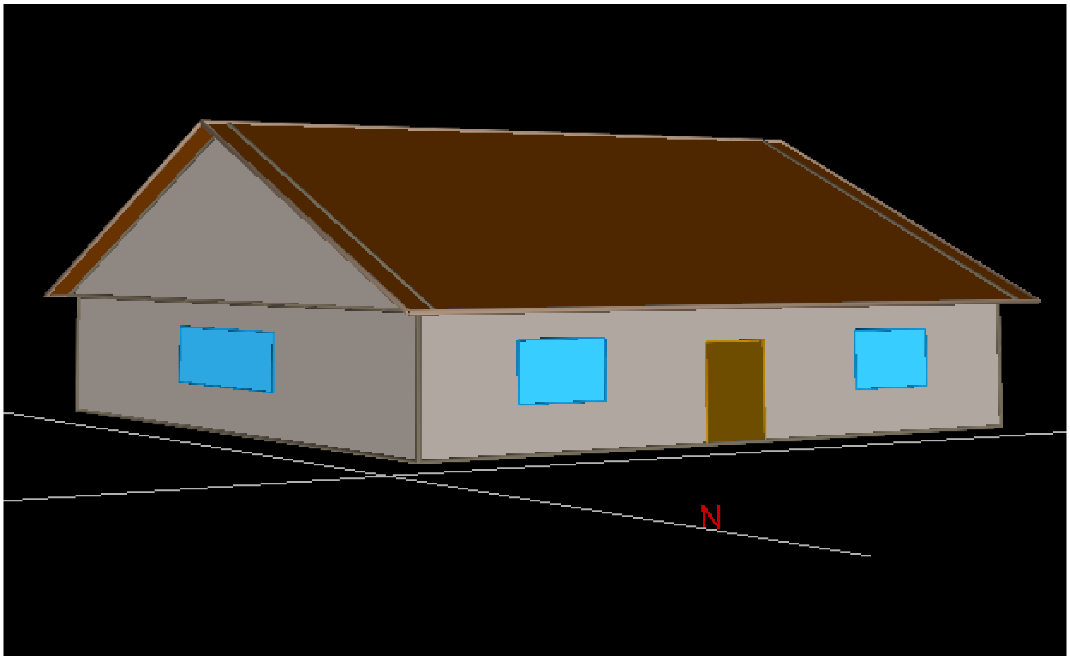


Figure 2. 3D illustration of a residential house

Table 2. Basic information for the office building

Building orientation	North
Building area (per floor)	31,250 (ft^2)
Number of floors	8
Number of windows	285
Number of doors	3
Material of roof	Built-up roofing
Material of window	Double clear glass
Type of door	Revolving door

The residential house has a pitched roof and one floor. The roof color is dark brown and the walls are wood. Some of the essential information is presented in Table 3. Moreover, there are no louvers or curtains to block the sun light. In fact, with a few exceptions, all the default settings in eQUEST were used in the design of this model. The software default data is presented in Appendix B. In this paper, we focus on the window and roof. Hence, the next two sections will introduce the details of windows and roofs.

Table 3. Basic information for the residential house

Building orientation	North
Building area (per floor)	2,500 (ft^2)
Number of floors	1
Number of windows	6
Number of doors	2
Material of roof	Shingle
Material of window	Double clear glass
Type of door	Opaque (wood)

3.2. Introduction of Windows

In this research, three types of glass were used: “clear glass”, “low emissivity (low-E) glass”, and “electrochromic glass.” This section will introduce the information of these glass windows and how to evaluate the advantages and disadvantages.

3.2.1. Clear Glass

Clear glass is the most commonly used basic glass in doors and windows [17]. It is almost colorless and the edges are green or blue. Typically, the thickness is between 3/32 inches and 3/4 inches. A clear 1/4 inch thick glass will allow approximately 90% of the visible light to pass through and will reflect about 8% of visible light [18]. When viewed through the glass, as the glass becomes thicker, the light green color becomes more pronounced and the light transmittance decreases.

3.2.2. Low-E Glass

Low-E glass is a type of reflective glass that looks transparent when it reflects heat back to its source. The "E" in low-E glass refers to emissivity. Emissivity is the ability of a material or surface to radiate energy. Thus, low-E glass refers to the surface of the glass, which minimizes the increase in solar heat. This is achieved by coating the surface of the glass with a special coating made of microscopic, transparent metal or metal oxide. Low-E glass provides maximum light transmission while reducing heat loss and helps protect against ultraviolet (UV) rays. A slight tint can be seen depending on the angle of view and the sun. Glass from different batches or with different metal oxide coatings will show excellent phase or color differences, making it difficult to match multiple low-E glasses. However, low-E glass improves insulation and therefore helps reduce heating and energy costs. It also can be used for annealing, toughening and lamination.

3.2.3. Electrochromic (EC) Glass

EC glass (a.k.a. smart glass or dynamic glass) is an electronically tinted glass for windows, skylights, exterior walls and curtain walls. EC glass, which can be directly controlled by building dwellers, is popular for its ability to improve occupant comfort, maximize daylight and outdoor visibility, reduce energy costs, and provide architects with more design freedom.

EC glass is an intelligent building solution for buildings facing the challenges of solar control, including classroom environments, medical facilities, commercial offices, retail spaces, museums and cultural institutions. Interior spaces with atrium or skylights can also benefit from the use of smart glass.

For example, SageGlass, a well-known EC glass product, has been installed on many buildings that provide solar control to protect people from high temperatures and glare. It maximizes indoor daylight, maintains visibility, and keeps people connected to the outdoors. EC glass also saves energy by using the warm rays of the sun during the winter and deflecting the light during the hot summer months. In addition, it offers a variety of control options. With advanced algorithms, users can automate control settings to manage light, glare, energy usage and color rendering. Controls can also be integrated into existing building automation systems [5].

3.2.4. Glass Assessment

The National Fenestration Rating Council (NFRC) is a non-profit public/private organization created for doors and windows, the skylight industry. It consists of manufacturers, suppliers, regulatory officials, researchers and government agencies. All major standards and programs for window energy efficiency, including building energy regulations, tax credits and utility incentives, ENERGY STAR, etc. Their standards are based on NFRC certification levels. To ensure that their products are recognized, manufacturers must participate in the NFRC certification and labeling program.

The NFRC label is the only reliable way to determine window energy characteristics and compare products. It is attached to all NFRC certified products and all ENERGY STAR designed windows and skylights. The energy performance ratings include U-factor, Solar Heat Gain Coefficient (SHGC), Visible Transmittance (VT) and, optionally, Air Leakage (AL) and Condensation Resistance (CR) ratings [19].

Typically, U-factor, SHGC, and VT are sufficient to evaluate windows. Hence, this section only describes these three energy performance levels.

3.2.4.1. U-factor (U-value)

A method of measuring the amount of heat or loss obtained by glass due to the difference between indoor and outdoor air temperatures. The U-factor or U-value is also referred to as the total heat transfer coefficient. A lower U-value indicates better insulation performance (0-1) [20], and its unit is Btu/(hr)(ft^2)(°F).

3.2.4.2. SHGC (Solar Heat Gain Coefficient)

The percent of solar energy incident on the glass that is transferred indoors both directly and indirectly through the glass. The direct gain portion is equal to the transmittance of the solar energy, and the indirect gain portion is the ratio of incident sunlight that is incident on the glass and is absorbed and re-radiated or convected indoors. For reference, the SHGC of 1/8 inch uncoated clear glass is about 0.86, with 0.84 being the direct gain (sun transmittance) and 0.02

being the indirect gain (convection/ re-radiation).

The Shading Coefficient (SC) is a measure of the amount of heat that the glass receives from solar radiation. In particular, SC is the ratio of the solar heat gain of a particular type of glass to a dual strength transparent glass. A lower SC indicates lower solar heat gain. For example, the value of 1/8 inch clear glass is 1.00 (SC is the old term replaced by SHGC) [21].

3.2.4.3. VT (Visible transmittance)

The VT is an optical property that indicates the proportion of visible light passing through the window. This is separate from SHGC because many modern windows contain spectrally selective coatings that allow transmittance of different amounts of visible light, infrared and UV light.

The NFRC's VT is an overall window specification level that includes the impact of the frame area. Since the frame does not transmit any light, VT may be lower than expected. However, this is done to match the overall window level of the U-factor and SHGC. Although VT theoretically varies from 0 and 1, most of the values in the dual and three pane windows are between 0.3 and 0.7 [22]. The higher the VT, the more light is transmitted. Thus, a high VT is required to maximize daylight.

3.3. Introduction of Roofs

3.3.1. Commercial Roofs

In general, there are currently five basic commercial roof types with flat or low slope configurations, which are "Built-up roofing", "Metal roofing", "Modified bitumen roofing", "Single-ply roofing", and "Spray polyurethane foam (SPF roofing)." In this paper, built-up roofing has been chosen for use in the simulation program because this is a very old low-slope roof system and is one of the most cost-effective and sturdy roof types in the market today [23]. Thus, information about built-up roofing is described below.

3.3.1.1. Built-up Roofing (BUR)

Built-up roofing has been popular in North America for more than a hundred years and is often referred to as "BUR" and "tar and gravel" roofs [24]. This is a flexible roof type because the number of layers can be changed to help control costs or meet some of the durability requirements. Typically, it consist of alternating layers of bitumen and layers of reinforcing fabric that together form the final roofing membranes. These membranes are arranged on a cross section of the top surface of the building. In most cases, built-up roofing is fixed to the roof deck and insulation to maintain adhesion. The membranes are generally known as plies, but the reinforcement layers are also known as “roof felts” or “ply sheets.” The number of plies on the roof indicates the number of layers. For instance, three-plies means a three-layer flat roof membrane system.

The bitumen found in BUR is typically composed of asphalt, coal tar, or cold compress adhesive. For surface layers, this roof type may include a layer of hot asphalt applied on the entire surface of the top of the building, an aluminum coating, an elastomeric coating, an aggregate “mixture” (such as gravel or slag), or a fiber glass surface or mineral surface cap sheets [25].

3.3.2. Residential Roofs

For residential roofs, there are six common roof types: “Asphalt shingle roof”, “Clay tile roof", "Metal roof", "Slate roof tiles", "Wood roof shingles", and "Rubber roof tiles." In this study, asphalt tile roofs were chosen in the simulation program because asphalt is available in a variety of colors and is widely used and is one of the cheapest materials, therefore, relevant information is provided below.

3.3.2.1. Asphalt Shingles

The most common residential roofing materials used in the United States are asphalt shingles because they are economical and easy to install. These shingles can be reinforced with fiberglass or organic materials without altering the appearance of the shingle. However, asphalt has a shorter life than other roofing materials, does not provide insulation from other materials and varies in quality. Asphalt shingles have a variety of architectural styles, the most popular of which is the traditional suburban style. For cost and life span, the price range is $0.7 to $1.2 per square foot, and if properly maintained, shingles will last for 20 to 25 years [26].

3.3.3. Roof Assessment

The National Roofing Contractors Association (NRCA) is one of the most respected industry associations in the construction industry and is the voice and leading authority in the field of information, education, technology and communications in the roof industry [27]. It has a powerful website and resources to provide contractors with all relevant information about the roof. Their easy to navigate website provides a comprehensive overview of materials, applications, courses and other resources for contractors and building professionals. In general, any issues related to the roof can be addressed by NRCA.

On the other hand, insulation is critical to a comfortable and energy efficient home. The commonality between insulation varieties is the R-value. R-value is a measure of thermal resistance that measures the ability of heat to pass from one side of the object to the other. In addition, R-value is generally not used as a measure in glazing products. Along with knowing the R-value of a particular insulation, it is also important to calculate the R-value of the entire system.

For example, a wall with 3-1/2 inch fiberglass batt (R-value 10.8-11.9) may have a total R-value of approximately 14 due to the siding, sheath and drywall [28]. Several factors determine the insulation required when selecting a roofing material. These factors include geographic location and type of heating system used.

3.4. Variable Parameters

In this study we use different parameters to compare the energy consumption of a building. These are generally divided into three parts:

3.4.1. Different types of Windows

The baseline window design is the double pane clear glass. Its performance will be compared to the double pane low-E glass and double pane low-E EC glass. Information for these windows is shown in Figure 3, 4, and 5.

3.4.2. TC coating on the Roofs

Next a TC roof coating will be introduce and the results will be compared with previous results obtained for the low-E EC glass.

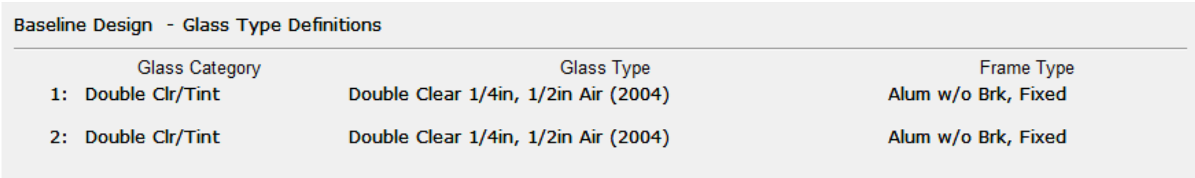


Figure 3. Double pane clear glass window data

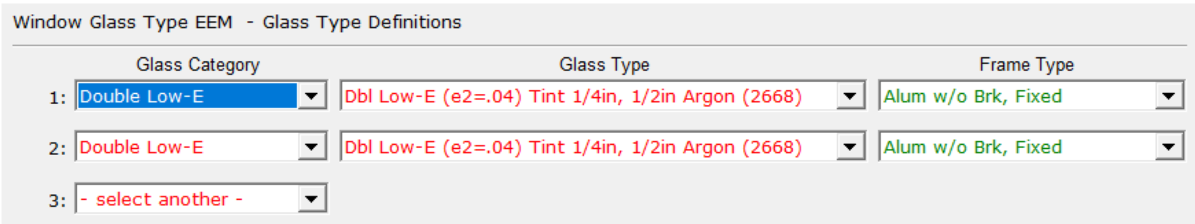


Figure 4. Double pane low-E glass window data

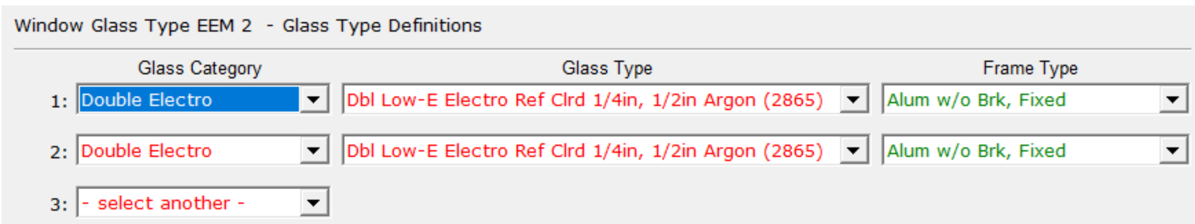


Figure 5. Double pane low-E EC glass window data

3.4.3. Different Locations

In this research, two different locations were chosen that represent warm and cold climates: the first location Tampa, a city located in the climatic zone 2 (2A), and the second location Chicago, a city located in the climatic zone 5 (5A), as shown in Figure 6. Comparison of the two different climates will give us a better idea of the impact of EC windows and TC roofs on buildings.

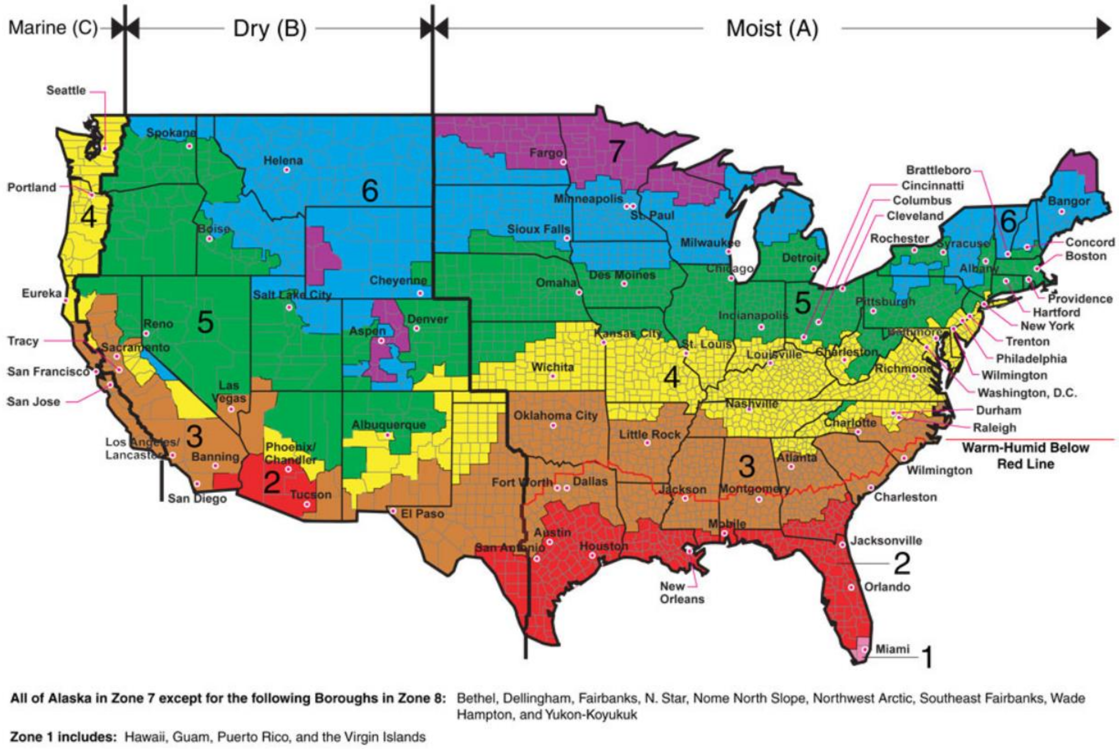


Figure 6. ASHRAE climate zones [29]

3.5. Electricity Consumption Calculations

3.5.1. Commercial Building

The data for electricity cost calculations for Tampa and Chicago are very different. Based on the "Electricity Local", the average commercial electricity rate in Tampa is 10.21¢/kWh and in Chicago is 4.05 ¢/kWh [30]. The average (commercial) electricity rate in Tampa is 5.69% greater than the Florida average rate of 9.66¢/kWh. For the power calculation method used in the software (See Figures 7 and 8), the type is selected as "Block Charges" and the block type is selected as "Incremental Block." For example, for an office building in Tampa in the summer, the electricity rate is 0.102 $/kWh for the first 1,000 kWh, and the remainder is 0.065 $/kWh.

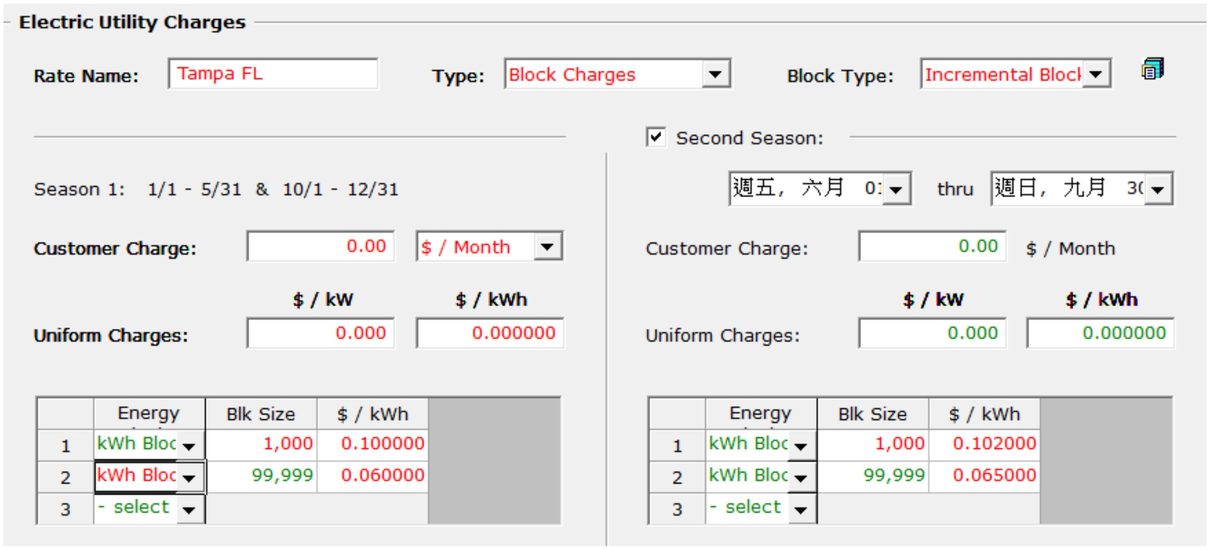


Figure 7. Electricity bill calculation method for an office building in Tampa

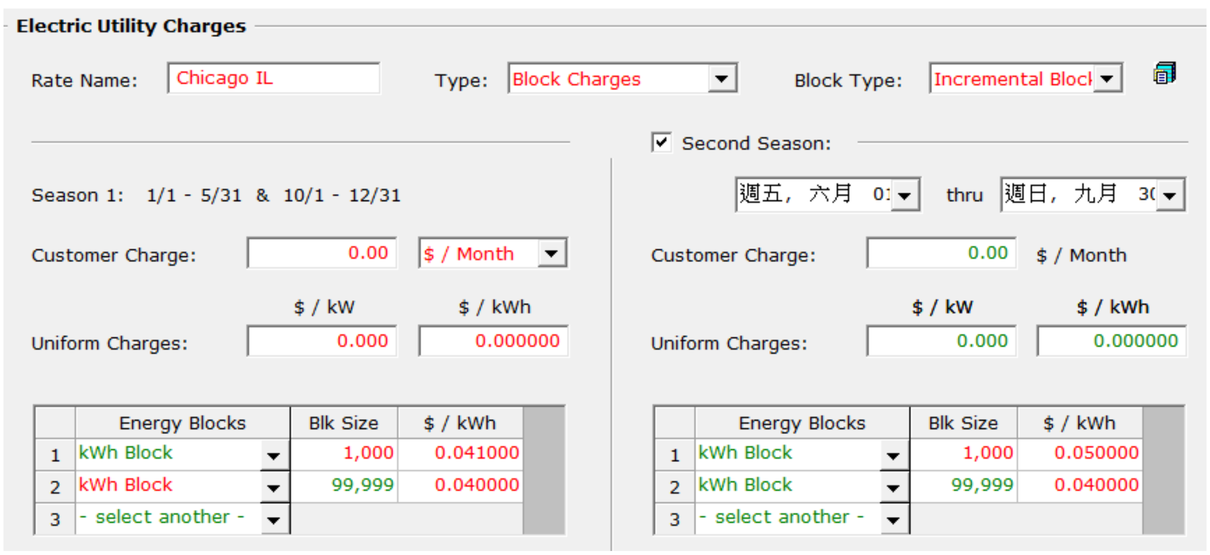


Figure 8. Electricity bill calculation method for an office building in Chicago

3.5.2. Residential Building

As mentioned before, the data for these two locations are very different. According to the "Electricity Local", the average residential electricity rate in Tampa is 11.42¢/kWh and in Chicago is 10.44¢/kWh [30]. This average (residential) electricity rate in Tampa is equal to the Florida average rate of 11.42¢/kWh.

However, the average (residential) electricity price in Chicago is 8.26% lower than the average electricity price in Illinois at 11.38¢/kWh. The power calculation method used in the software (See Figures 9 and10) is the same as that for the office building. For instance, for a residential building in Chicago in the winter, the electricity rate is 0.1 $/kWh for the first 1,000 kWh, and above that it is 0.06 $/kWh.

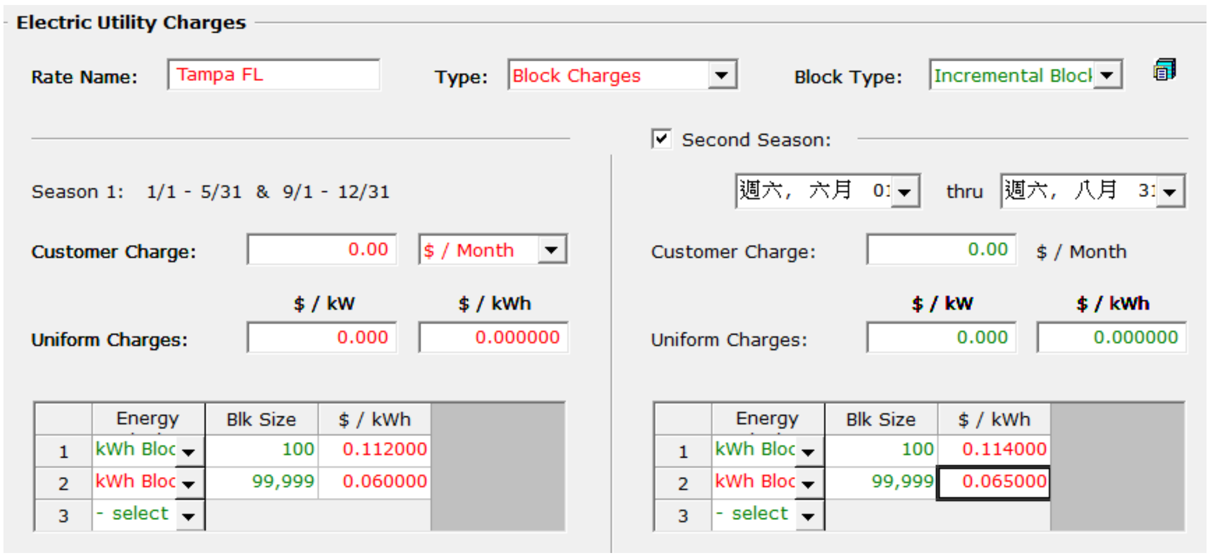


Figure 9. Electricity bill calculation method for a residential house in Tampa

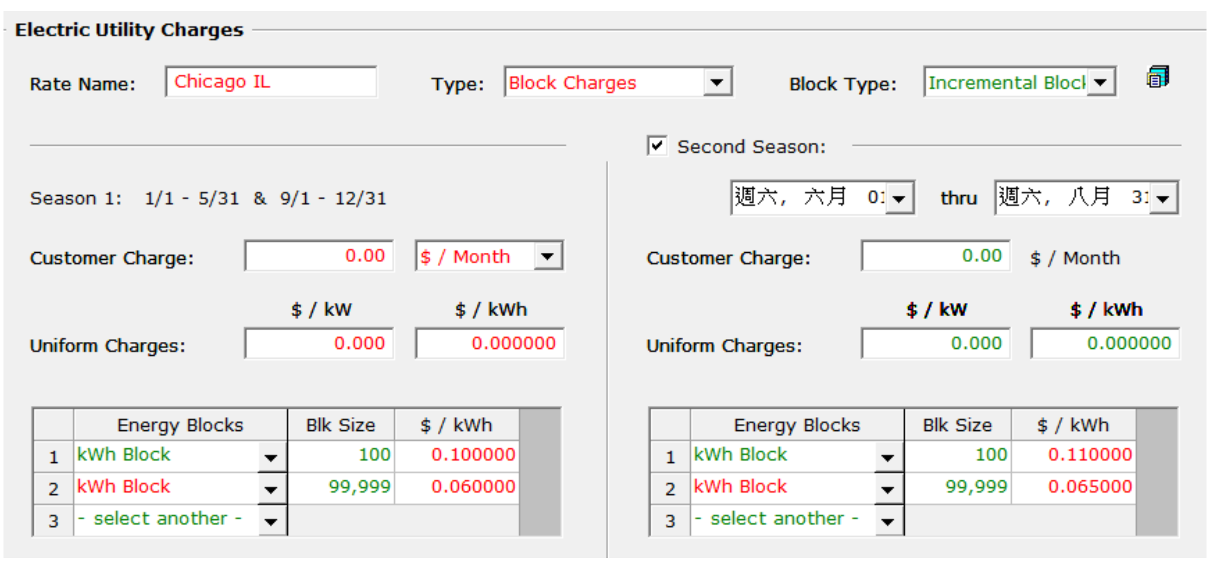
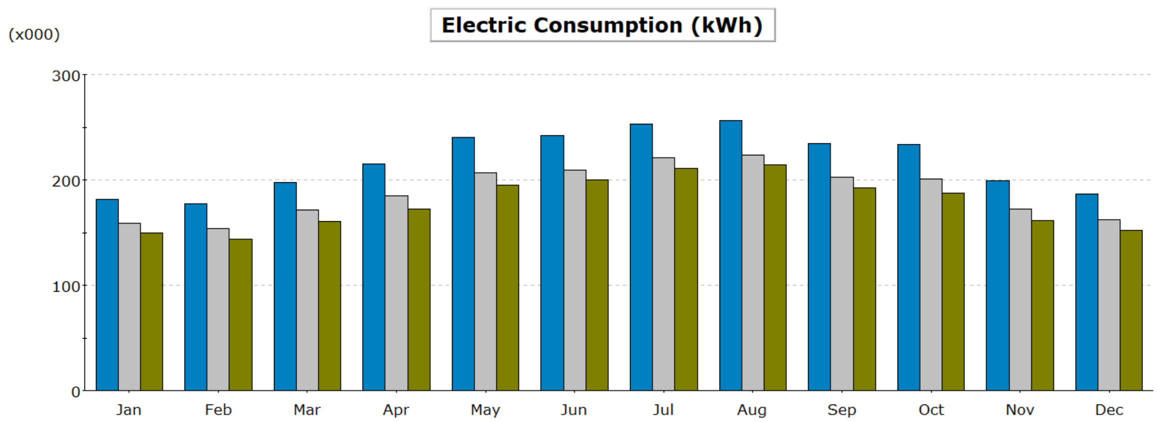


Figure 10. Electricity bill calculation method for a residential house in Chicago

3.6. Simulation Results and Discussion

Using the eQUEST software, energy savings were obtained from the simulation model when using low-E glass and low-E EC glass. The base design uses clear glass in Tampa and there is no TC coating on the roof. The simulation results for an office building indicate that the low-E glass saves 13% of energy or $29,179 per year, while the Low-E EC glass saves 18% of energy or $41,016 each year (See Figure 11 and Table 4).



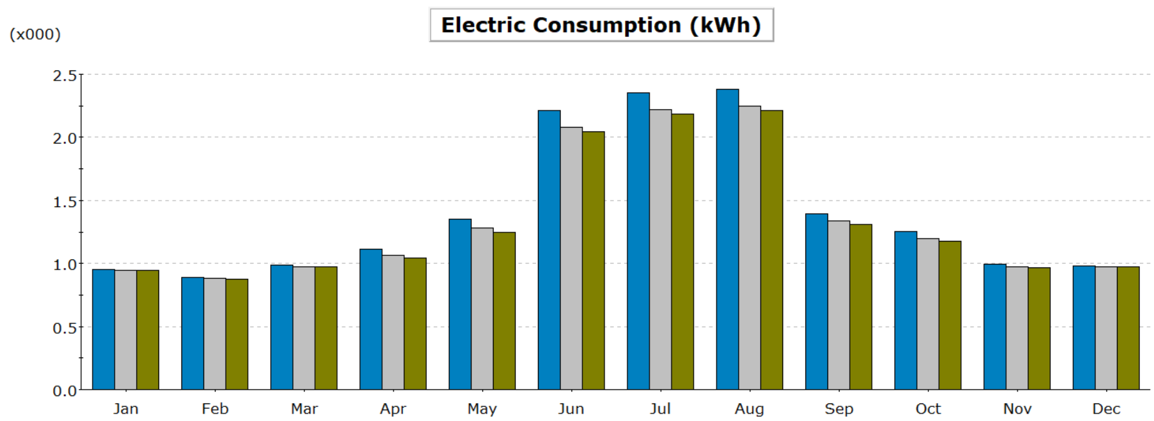
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Run 1.	181.4	177.2	197.4	214.9	240.1	241.7	253.1	256.3	234.3	233.2	199.3	186.4	2,615.4
Run 2.	159.1	153.7	171.7	185.0	206.9	209.2	220.9	223.7	202.9	200.5	172.3	162.3	2,268.2
Run 3.	149.4	143.4	160.5	172.3	194.7	199.6	211.3	214.0	192.9	187.7	161.0	152.1	2,138.9

Figure 11. Electricity consumption for an office building in Tampa (Windows). Run 1 is the base design with clear glass (blue line). Run 2 with low-E glass (gray line). Run 3 with low-E EC glass (green line).

Table 4. Annual bill for an office building in Tampa (Windows)

Windows	Dollars ($)
Clear glass (Base design)	224,719
Low-E glass	195,540
Low-E EC glass	183,703

For the residential house (See Figure 12 and Table 5), the use of low-E glass saves 4% of the energy or $110 per year, while the Low-E EC glass saves 5.3% of the energy or $146 each year. As can be seen from these results, office buildings can save more energy than residential buildings because of the large difference in the overall window area. The larger the area of the glass, the more energy the EC glass can save.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Run 1.	0.95	0.89	0.99	1.11	1.35	2.21	2.35	2.38	1.40	1.25	0.99	0.98	16.86
Run 2.	0.95	0.88	0.97	1.07	1.28	2.08	2.22	2.25	1.34	1.20	0.98	0.97	16.17
Run 3.	0.94	0.88	0.97	1.04	1.25	2.05	2.18	2.22	1.31	1.17	0.97	0.97	15.95

Figure 12. Electricity consumption for a residential house in Tampa (Windows). Run 1 is the base design with clear glass (blue line). Run 2 with low-E glass (gray line). Run 3 with low-E EC glass (green line).

Table 5. Annual bill for a residential house in Tampa (Windows)

Windows	Dollars ($)
Clear glass (Base design)	1,776
Low-E glass	1,666
Low-E EC glass	1,630

In the second phase a TC roof is added to the simulation. As the temperature changes, the TC roof color reversibly changes from white to black. 30 years of Tampa average weather data (1985-2015) were used in the simulations [31].

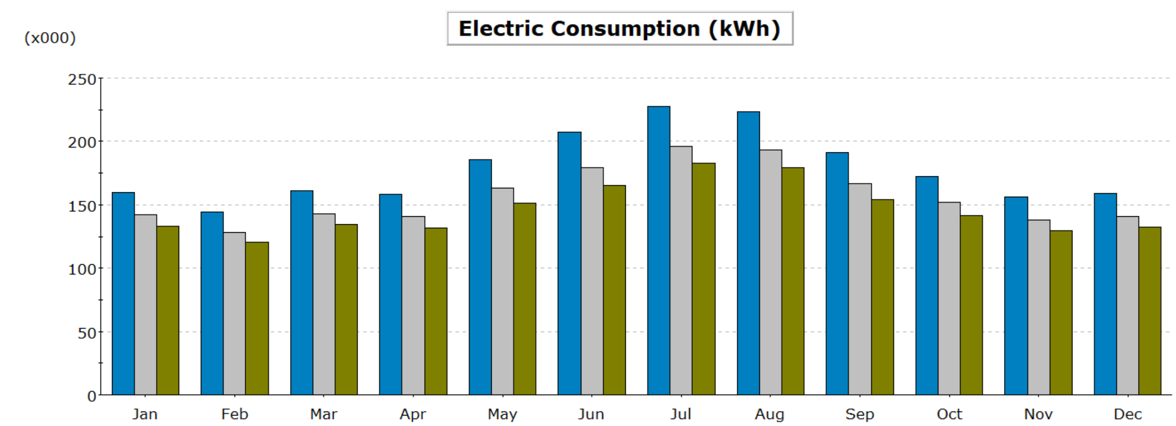
In the simulations it was assumed at temperatures above 77°F (25°C), the roof will turn white and turn black below 77°F (25°C). Based on the weather data (See Table 6), we can estimate the time when the roof is white or black. In addition, we have assumed that the roof temperature follows the average weather temperatures, and that solar reflectance and infrared emittance do not affect the roof temperature. From calculations, the roof is white for an average 41.67% of the time each year. In contrast, the roof is black for 58.33% of the time.

Table 6. Average weather temperatures over the past 30 years in Tampa (1985-2015)

Month	**Average temperature (°F)**	**Temperature range (°F)**
January	61.5	52-71
February	63.5	54-73
March	67.5	58-77
April	72.5	63-82
May	78.5	69-88
June	82	74-90
July	83	75-91
August	83	75-91
September	82	74-90
October	76	67-85
November	69.5	60-79
December	64	54-74

Next, when the roof is white the "cool roof calculator" is used. The results show that saves 0.095 $\$/ft^2$ per year for the office building. The cool roof calculator uses certain values, such as the R-value, solar reflectance, and infrared emittance [32]. For our model, the R-value is 18, the solar reflectance is 70, and the infrared emittance is 90. The rest of the data relates to electricity calculation, climate, and location. Subsequently, the data is combined with the weather data to obtain results for the TC roof. The results show that for the office building the TC roof saves 0.1504 $\$/ft^2$ per year, this corresponds to $37,600 per year. Similarly, the "cool roof calculator" for the residential building gives savings of 0.07 $\$/ft^2$ per year. Data integration shows that the TC roof can save 0.1108 $\$/ft^2$ per year or \$277 per year. Finally, the simultaneous use of low-E EC glass and TC roof provides energy savings of 35% for the office building and 23.8% for the residential building in Tampa.

The final stage is to identify a location in Chicago to run the simulations. For this case, only the low-E glass and low-E EC glass were used and the results are shown in Figure 13 and Table 7. For the office building, the low-E glass saves 12% of the energy or \$16,800 per year, while the Low-E EC glass saves 18% of energy or \$26,055 each year. Comparing the two locations, Tampa and Chicago, the effects of EC windows are roughly the same and even though Tampa consumes more electricity than Chicago, the energy savings are almost the same.



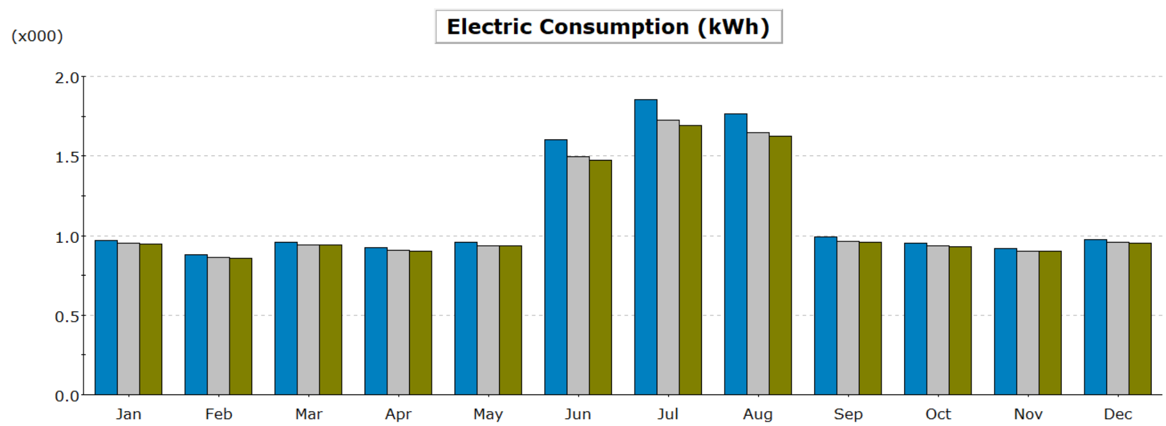
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Run 1.	159.8	144.3	161.3	158.5	185.7	207.0	227.6	223.1	191.0	172.6	155.9	158.7	2,145.4
Run 2.	141.9	128.1	143.0	140.7	162.9	179.1	196.3	193.4	166.5	151.8	138.2	141.0	1,882.8
Run 3.	133.4	120.3	134.1	131.5	151.0	165.4	182.6	179.1	154.1	141.7	129.7	132.5	1,755.4

Figure 13. Electricity consumption for an office building in Chicago (Windows). Run 1 is the base design with clear glass (blue line). Run 2 with low-E glass (gray line). Run 3 with low-E EC glass (green line).

Table 7. Annual electricity bill - office building in Chicago (Windows)

Windows	Dollars (\$)
Clear glass (Base design)	138,245
Low-E glass	121,445
Low-E EC glass	112,190

The results for the residential house are shown in Figure 14 and Table 8. Low-E glass saves 3.8% of the energy or $59 per year, while Low-E EC glass saves 4.6% of energy or $73 each year. From the chart (See Figure 14), we found that most savings are obtained in the summer. Regardless of the location, Tampa or Chicago, EC glass can actually save energy.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Run 1.	0.97	0.88	0.96	0.92	0.96	1.60	1.85	1.76	0.99	0.96	0.92	0.98	13.75
Run 2.	0.95	0.86	0.94	0.91	0.94	1.50	1.72	1.65	0.96	0.93	0.90	0.96	13.23
Run 3.	0.95	0.86	0.94	0.90	0.93	1.47	1.69	1.62	0.96	0.93	0.90	0.95	13.12

Figure 14. Electricity consumption for a residential house in Chicago (Windows).Run 1 is the base design with clear glass (blue line). Run 2 with low-E glass (gray line). Run 3 with low-E EC glass (green line).

Table 8. Annual electricity bill - residential house in Chicago (Windows)

Windows	Dollars ($)
Clear glass (Base design)	1,369
Low-E glass	1,310
Low-E EC glass	1,296

In the last part, low-E EC glass and TC roof in Chicago were used to run the simulation. From the calculations through weather data (See Table 9), the average white roof usage per year is 8.33% and the roof is black for 91.67% of the time. For the office building, when the roof is white the "cool roof calculator" gives savings of 0.032 $/ft^2 per year, and when the roof is black the simulations indicate savings of 0.05 \$/ft^2 or \$12,500 per year.

For the residential building, with a cool roof the energy savings correspond to 0.0048 \$/ft^2 or \$12 per year. When both low-E EC glass and TC roof are used, the energy savings are 27.8% for a commercial building and 6.2% for the residential building.

Table 9. Average weather temperatures over the past 30 years in Chicago (1985-2015)

Month	Average temperature (°F)	Temperature range (°F)
January	26.5	20-33
February	29	22-36
March	39	31-47
April	50.5	41-60
May	61.5	52-71
June	71.5	62-81
July	76.5	68-85
August	74	66-82
September	67	58-76
October	54.5	46-63
November	42	35-49
December	31	25-37

4. CONCLUSIONS

This study aims to assess the impact EC and TC technologies can have on buildings. eQUEST software is used to simulate and evaluate the energy performance of a commercial office building and a residential house. The simulations include modeling of low-E glass, low-E EC glass and TC roof for two climatic zones in the US, zones 2 and 5. The simulation results show the use of EC glass in an office building can produce 12% to 18% energy savings, while in residential buildings 3.8% to 5.3%. The influence of EC glass on a commercial office building is much greater than that in a residential unit because of the number of glass windows used in a commercial building. A cool roof calculator was used to estimate the energy savings resulting from the use of a white reflecting roof. When both a TC roof and EC glass windows are used, the results show that the energy savings for an office building are 27.8% to 35%, while for residential buildings about 6.2% to 23.8%, depending on the climatic zones. These are important results and suggest the significance. This is an important energy saving measure for buildings, depending on location, which may have a greater impact.

In summary, all the results show that using EC glass and TC roofs significant impact on a building's energy use. Although this results are approximate and only just one piece of data, because we ignored some factors that may affect them, it is significant enough to encourage additional, more detailed, studies. In addition, cost, a very significant part of this analysis, was not considered in this study. In the future, these technologies may turn into mainstream products.

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APPENDIX A. DOE GLASS LIBRARY

DOE-2 Glass Library, Sorted by Glass Type Code	Glass Type Code	# Panes	Gap Thickness (in)	Gap Gas Fill	Center Glass U-Value	Glass+Frame (NFRC) U-Value			Solar Heat Gain Coeff. SHGC	Shading Coeff. SC	Visible Trans. Tvis	Solar Trans. Tsol	Visible Reflect. Rfvis	Solar Reflect. Rfsol
Doe-2 Glass Library Entry Name						Alum No Break	Alum w Break	Alum Clad Wood						
Double Clear	2000	2	0.25	Air	0.57	0.76	0.62	0.57	0.76	0.88	0.81	0.7	0.15	0.13
Double Clear	2001	2	0.50	Air	0.49	0.65	0.53	0.49	0.76	0.89	0.81	0.7	0.15	0.13
Double Clear	2002	2	0.50	Argon	0.46	0.61	0.50	0.46	0.76	0.89	0.81	0.7	0.15	0.13
Double Clear	2003	2	0.25	Air	0.56	0.75	0.61	0.56	0.69	0.81	0.78	0.6	0.14	0.11
Double Clear	2004	2	0.50	Air	0.48	0.64	0.52	0.48	0.70	0.81	0.78	0.6	0.14	0.11
Double Clear	2005	2	0.50	Argon	0.45	0.60	0.49	0.45	0.70	0.81	0.78	0.6	0.14	0.11

DOE-2 Glass Library, Sorted by Glass Type Code	Glass Type Code	# Panes	Gap Thickness (in)	Gap Gas Fill	Center Glass U-Value	Glass+Frame (NFRC) U-Value			Solar Heat Gain Coeff. SHGC	Shading Coeff. SC	Visible Trans. Tvis	Solar Trans. Tsol	Visible Reflect. Rfvis	Solar Reflect. Rfsol
Doe-2 Glass Library Entry Name						Alum No Break	Alum w Break	Alum Clad Wood						
Double Low-E (e3=.4) Clear	2600	2	0.25	Air	0.5	0.71	0.57	0.53	0.72	0.84	0.77	0.63	0.18	0.15
Double Low-E (e3=.4) Clear	2601	2	0.50	Air	0.41	0.59	0.47	0.43	0.73	0.85	0.77	0.63	0.18	0.15
Double Low-E (e3=.4) Clear	2602	2	0.50	Argon	0.36	0.51	0.41	0.38	0.73	0.85	0.77	0.63	0.18	0.15
Double Low-E (e3=.2) Clear	2610	2	0.25	Air	0.46	0.66	0.53	0.49	0.72	0.84	0.74	0.62	0.18	0.15
Double Low-E (e3=.2) Clear	2611	2	0.50	Air	0.35	0.50	0.40	0.37	0.73	0.85	0.74	0.62	0.18	0.15
Double Low-E (e3=.2) Clear	2612	2	0.50	Argon	0.3	0.43	0.34	0.32	0.74	0.86	0.74	0.62	0.18	0.15
Double Low-E (e3=.2) Clear	2613	2	0.25	Air	0.45	0.64	0.51	0.48	0.66	0.77	0.72	0.53	0.17	0.13
Double Low-E (e3=.2) Clear	2614	2	0.50	Air	0.35	0.50	0.40	0.37	0.67	0.78	0.72	0.53	0.17	0.13
Double Low-E (e3=.2) Clear	2615	2	0.50	Argon	0.29	0.41	0.33	0.31	0.68	0.79	0.72	0.53	0.17	0.13
Double Low-E (e2=.1) Clear	2630	2	0.25	Air	0.44	0.63	0.50	0.47	0.60	0.69	0.77	0.54	0.14	0.22
Double Low-E (e2=.1) Clear	2631	2	0.50	Air	0.32	0.46	0.37	0.34	0.60	0.69	0.77	0.54	0.14	0.22
Double Low-E (e2=.1) Clear	2632	2	0.50	Argon	0.26	0.37	0.30	0.27	0.59	0.69	0.77	0.54	0.14	0.22
Double Low-E (e2=.1) Clear	2633	2	0.25	Air	0.43	0.61	0.49	0.45	0.56	0.65	0.75	0.47	0.11	0.2
Double Low-E (e2=.1) Clear	2634	2	0.50	Air	0.31	0.44	0.35	0.33	0.56	0.65	0.75	0.47	0.11	0.2
Double Low-E (e2=.1) Clear	2635	2	0.50	Argon	0.26	0.37	0.30	0.27	0.56	0.66	0.75	0.47	0.11	0.2
Double Low-E (e2=.1) Tint	2636	2	0.25	Air	0.43	0.61	0.49	0.45	0.39	0.45	0.44	0.28	0.05	0.1
Double Low-E (e2=.1) Tint	2637	2	0.50	Air	0.31	0.44	0.35	0.33	0.37	0.43	0.44	0.28	0.05	0.1
Double Low-E (e2=.1) Tint	2638	2	0.50	Argon	0.26	0.37	0.30	0.27	0.37	0.43	0.44	0.28	0.05	0.1
Double Low-E (e3=.1) Clear	2640	2	0.25	Air	0.44	0.63	0.50	0.47	0.63	0.74	0.77	0.54	0.13	0.23
Double Low-E (e3=.1) Clear	2641	2	0.50	Air	0.32	0.46	0.37	0.34	0.64	0.75	0.77	0.54	0.13	0.23
Double Low-E (e3=.1) Clear	2642	2	0.50	Argon	0.26	0.37	0.30	0.27	0.65	0.75	0.77	0.54	0.13	0.23
Double Low-E (e2=.04) Clear	2660	2	0.25	Air	0.42	0.60	0.48	0.44	0.44	0.51	0.7	0.39	0.12	0.36
Double Low-E (e2=.04) Clear	2661	2	0.50	Air	0.3	0.43	0.34	0.32	0.44	0.51	0.7	0.39	0.12	0.36
Double Low-E (e2=.04) Clear	2662	2	0.50	Argon	0.24	0.34	0.27	0.25	0.43	0.5	0.7	0.39	0.12	0.36
Double Low-E (e3=.04) Clear	2663	2	0.25	Air	0.42	0.60	0.48	0.44	0.42	0.49	0.68	0.34	0.12	0.31
Double Low-E (e3=.04) Clear	2664	2	0.50	Air	0.29	0.41	0.33	0.31	0.42	0.48	0.68	0.34	0.12	0.31
Double Low-E (e3=.04) Clear	2665	2	0.50	Argon	0.23	0.33	0.26	0.24	0.42	0.48	0.68	0.34	0.12	0.31
Double Low-E (e2=.04) Tint	2666	2	0.25	Air	0.42	0.60	0.48	0.44	0.31	0.35	0.41	0.21	0.08	0.14
Double Low-E (e2=.04) Tint	2667	2	0.50	Air	0.29	0.41	0.33	0.31	0.29	0.33	0.41	0.21	0.08	0.14
Double Low-E (e2=.04) Tint	2668	2	0.50	Argon	0.23	0.33	0.26	0.24	0.28	0.32	0.41	0.21	0.08	0.14

DOE-2 Glass Library, Sorted by Glass Type Code	Glass Type Code	# Panes	Gap Thickness (in)	Gap Gas Fill	Center Glass U-Value	Glass+Frame (NFRC) U-Value			Solar Heat Gain Coeff. SHGC	Shading Coeff. SC	Visible Trans. Tvis	Solar Trans. Tsol	Visible Reflect. Rfvis	Solar Reflect. Rfsol
Doe-2 Glass Library Entry Name						Alum No Break	Alum w Break	Alum Clad Wood						
Double Low-E (e2=.029) Electrochromic Absorbing Bleached/Colored, 6.3-mm	2840	2	0.25	Air	0.41	0.59	0.47	0.43	0.44	0.51	0.66	0.34	0.14	0.33
Double Low-E (e2=.029) Electrochromic Absorbing Bleached/Colored, 6.3-mm	2841	2	0.25	Air	0.41	0.59	0.47	0.43	0.16	0.18	0.1	0.06	0.08	0.19
Double Low-E (e2=.029) Electrochromic Absorbing Bleached/Colored, 12.7-mm	2842	2	0.50	Air	0.29	0.41	0.33	0.31	0.51	0.59	0.66	0.34	0.14	0.33
Double Low-E (e2=.029) Electrochromic Absorbing Bleached/Colored, 12.7-mm	2843	2	0.50	Air	0.29	0.41	0.33	0.31	0.13	0.15	0.1	0.06	0.08	0.19
Double Low-E (e2=.029) Electrochromic Absorbing Bleached/Colored, 12.7-mm	2844	2	0.50	Argon	0.23	0.33	0.26	0.24	0.52	0.6	0.66	0.34	0.14	0.33
Double Low-E (e2=.029) Electrochromic Absorbing Bleached/Colored, 12.7-mm	2845	2	0.50	Argon	0.23	0.33	0.26	0.24	0.12	0.14	0.1	0.06	0.08	0.19
Double Low-E (e2=.029) Electrochromic Reflecting Bleached/Colored, 6.3-mm	2860	2	0.25	Air	0.41	0.59	0.47	0.43	0.46	0.54	0.64	0.32	0.14	0.32
Double Low-E (e2=.029) Electrochromic Reflecting Bleached/Colored, 6.3-mm	2861	2	0.25	Air	0.41	0.59	0.47	0.43	0.16	0.18	0.12	0.07	0.08	0.22
Double Low-E (e2=.029) Electrochromic Reflecting Bleached/Colored, 12.7-mm	2862	2	0.50	Air	0.29	0.41	0.33	0.31	0.47	0.55	0.64	0.32	0.14	0.32
Double Low-E (e2=.029) Electrochromic Reflecting Bleached/Colored, 12.7-mm	2863	2	0.50	Air	0.29	0.41	0.33	0.31	0.14	0.16	0.12	0.07	0.08	0.22
Double Low-E (e2=.029) Electrochromic Reflecting Bleached/Colored, 12.7-mm	2864	2	0.50	Argon	0.23	0.33	0.26	0.24	0.48	0.56	0.64	0.32	0.14	0.32
Double Low-E (e2=.029) Electrochromic Reflecting Bleached/Colored, 12.7-mm	2865	2	0.50	Argon	0.23	0.33	0.26	0.24	0.13	0.15	0.12	0.07	0.08	0.22

Figure A1. DOE glass library [15]

APPENDIX B. eQUEST BUILDING SIMULATION WIZARD

With a few exceptions, all the default settings in eQUEST are used, as shown below:

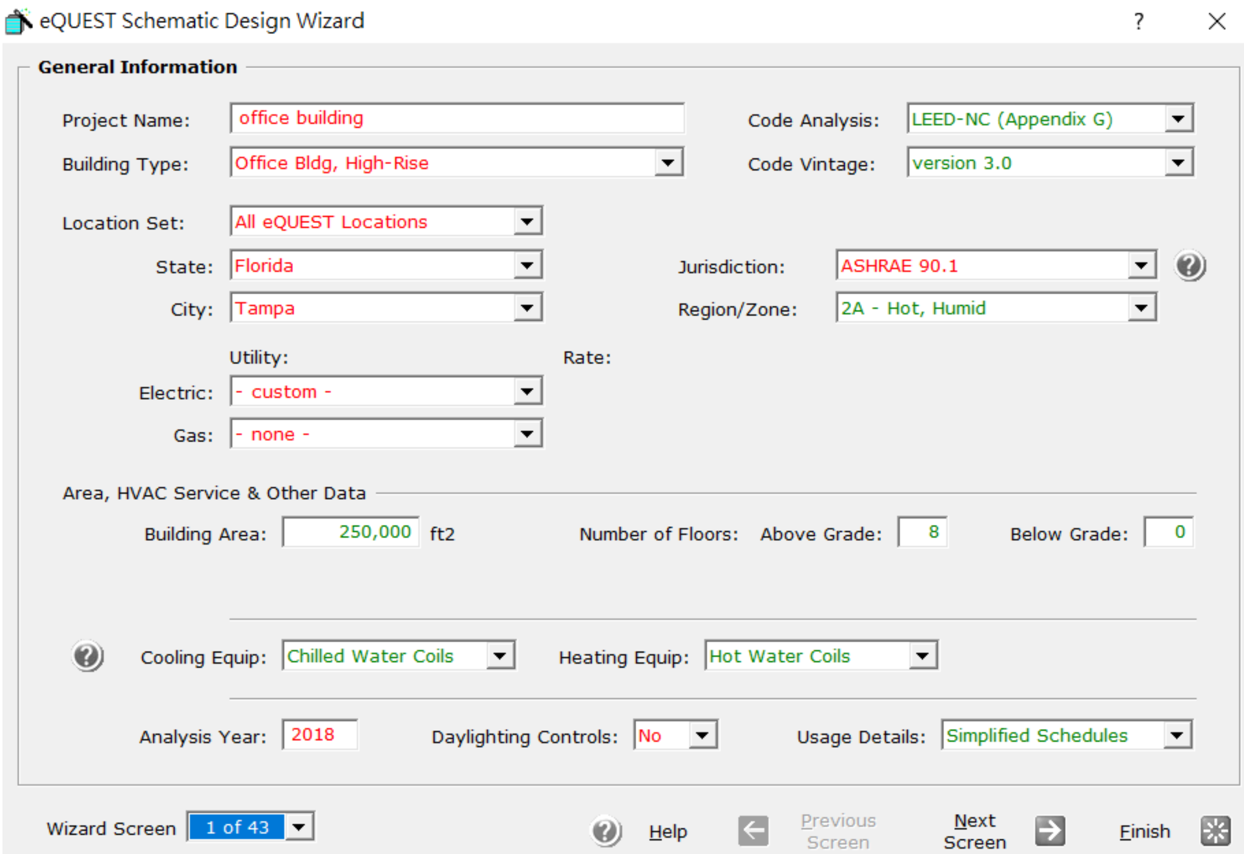

Figure A2. General information on the eQUEST Building Simulation Wizard

The picture shows the first screen of the Building Creation Wizard. In this window, the type of building, its location, utility rates, and analysis year were all adjusted. For example, the buildings used were Office Bldg, High-Rise. The location is in Tampa, Florida. Data files for these locations can be downloaded from the DOE2.com through eQUEST.

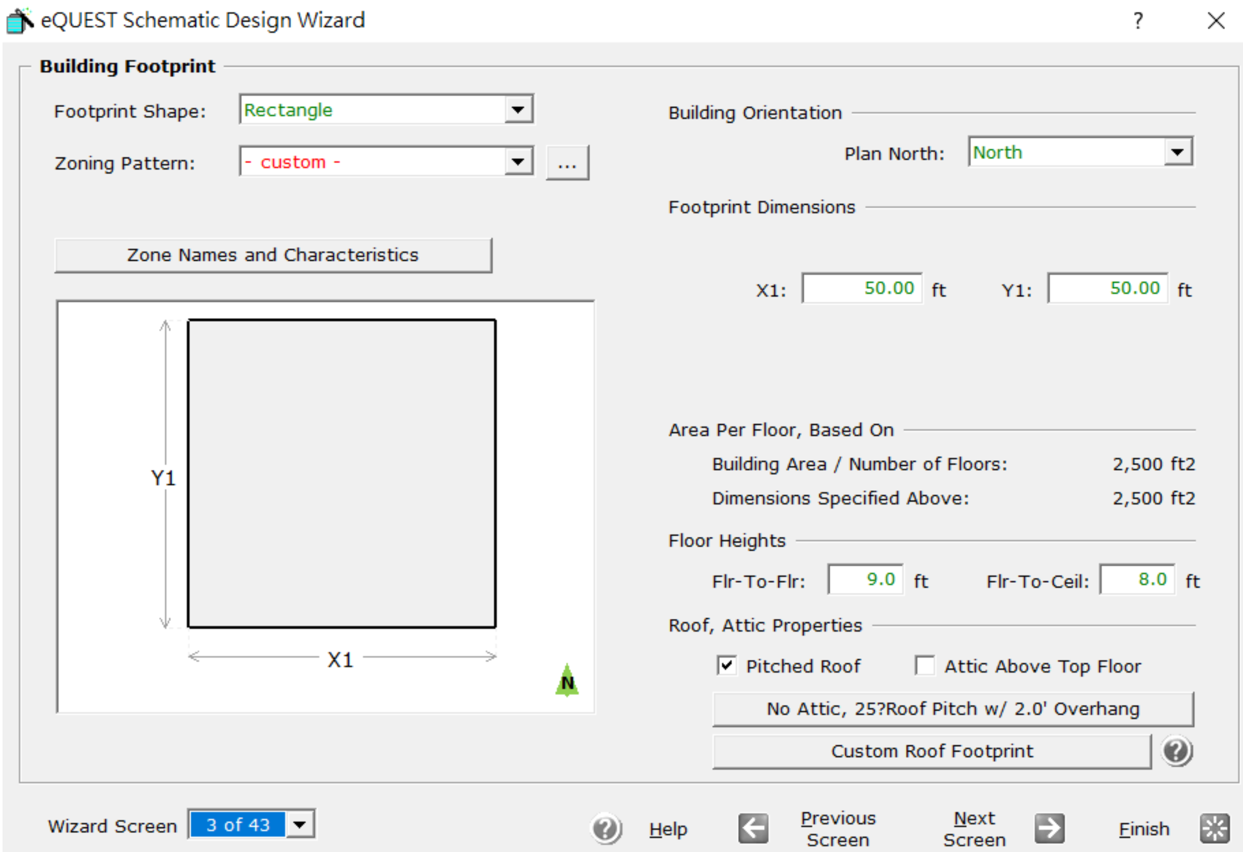

Figure A3. Building footprint on the eQUEST Building Simulation Wizard

This window can adjust the shape of the building. Roof area can also be calculated by multiplying the X1 and Y1 footprint dimensions. On the right hand side, people can select a flat roof or a pitched roof. The angle of the roof can also be controlled.

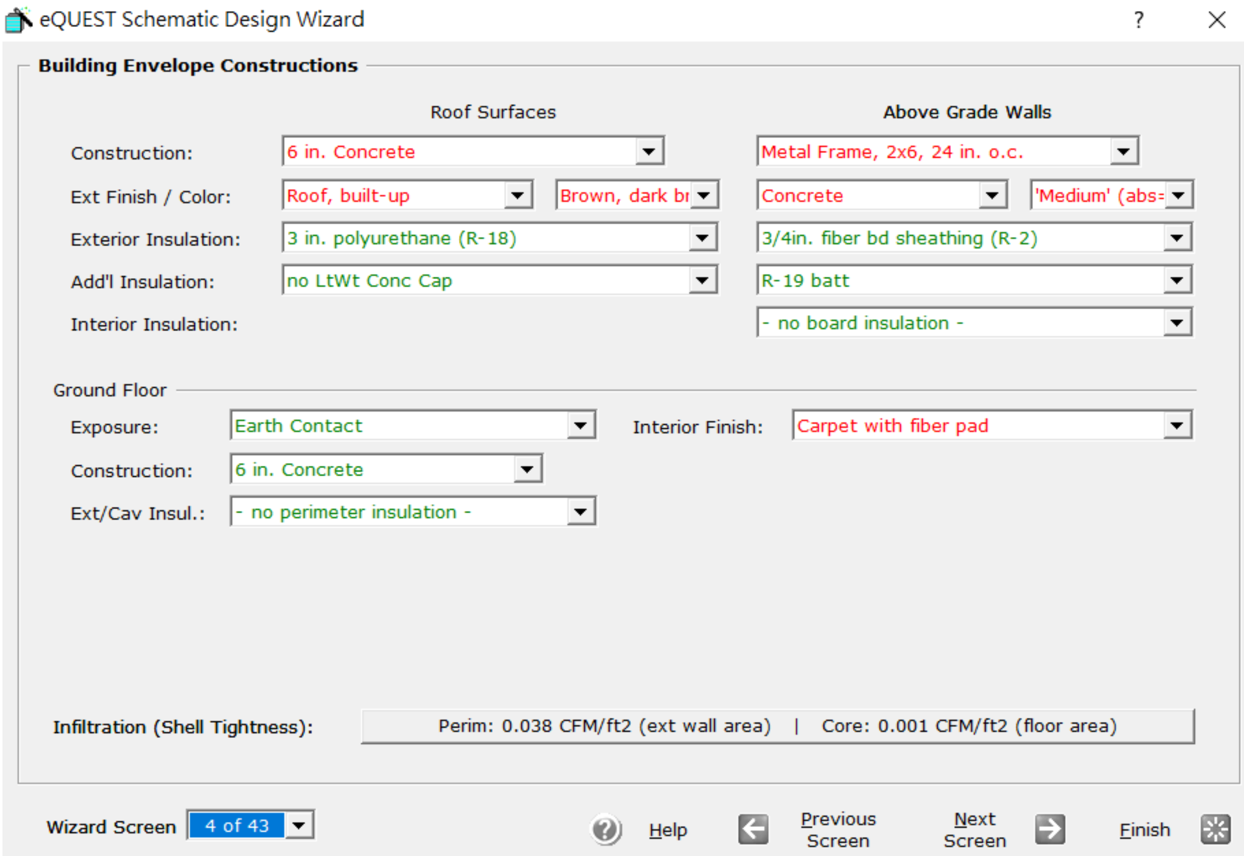

Figure A4. Building envelope construction on the eQUEST Building Simulation Wizard

In this window, the building envelope can be adjusted. For instance, the roof type is built-up roofing and the color is dark brown. The wall is made of concrete. In addition, R-value is 18 for this roof.