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APPLICATION OF WIDE-BAND LIQUID CRYSTAL REFLECTIVE WINDOWS IN BUILDING ENERGY EFFICIENCY: A CASE STUDY OF EDUCATIONAL BUILDINGS

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ABSTRACT

The purpose of this article is to study the impact of seven different window systems on overall energy consumption of educational buildings. In particular, four of the windows are non-traditional liquid crystal base, namely 1) Tunable, 2) Broadband Type 1, 3) Broadband Type 2, and 4) Broadband Type 3. For the purpose of simulation, a LEED Gold certified building located at a major university in the U.S. was modeled, benchmarked, and calibrated. Then several scenarios according to window choices haven been tested, both in actual and different climate zones. The results show, Broadband Type 2 and Type 3 can make a significant impact in reducing building energy consumption. Their contribution is higher for projects located in hotter climates.

1 INTRODUCTION

Having a significant share of total energy consumption and related emissions, buildings and their environment, among others, are the primary focus of sustainability assessment (Komeily and Srinivasan 2015). This is due to the fact that the benefits of energy efficiency go well beyond the simple scaling back of energy demand as it has the potential to support economic growth, enhance social development, advance environmental sustainability, ensure energy-system security and help build wealth (Figure 1).

According to US Energy Information Administration (EIA), in 2015, about 41 percent of total U.S. energy consumption was consumed in residential and commercial buildings, equating to about 39 quadrillion BTUs (Figure 2); commercial buildings represent just under one-fifth of U.S. energy consumption, with office space, retail space, and educational facilities representing about 50 percent of commercial sector energy consumption. In this regards, despite continuous advances in fenestration and windows technologies, they are still regarded as energy liabilities, accounting for about 30 percent of building heating and cooling loads, with an annual impact of 4.1 quads of primary energy (the term "Quad" is shorthand for 10^{15} BTU). Such a amount of energy loss is partially due to the impacts of unwanted conductive losses and gains (i.e. heat transfer due to temperature differences across the window), unwanted solar heat transmission, and infiltration. Moreover, windows even play a greater role as they have significant impact on major building performance indicators such as peak energy demand and occupants' comfort (Arasteh et al. 2006).

The use of daylight is one of the most important factors to be taken into consideration for window design. An additional 1 quad of lighting energy could be saved if buildings employed effective daylighting strategies. Daylighting affects heating and cooling loads of buildings in terms of solar gain as well as heat gain from artificial lighting when lighting control is installed. Bodrat and De Herde (2002) evaluated the impact of lighting energy savings on building's energy consumption by a combination of a daylighting simulation and a dynamic thermal simulation. The results showed that the primary energy saving due to daylighting was around 40%.

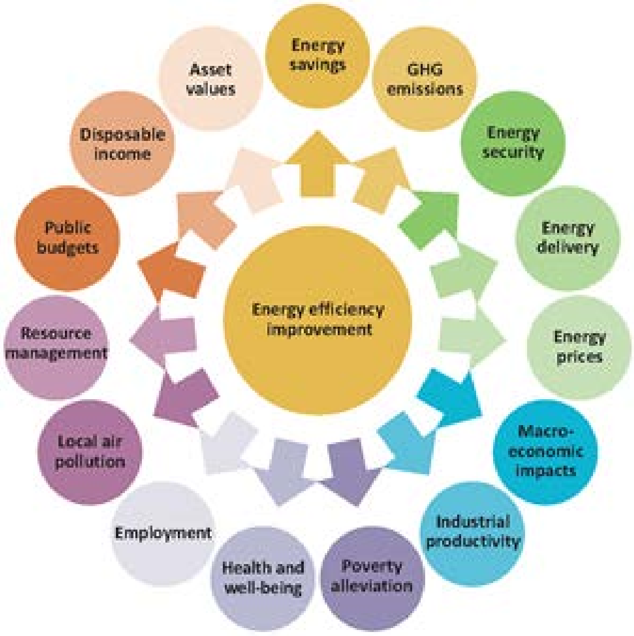


Figure 1: Energy efficiency improvements and its broad impact (International Energy Agency, 2014). Due the interconnected nature of factors involved in sustainable development, a change in one factor is not limited to one aspect of sustainability; it can have a broad impact on various factors (Komeily Srinivasan 2015).

The need for energy conservation has become a priority for many governments which has been translated in policies, regulation, assessment schemas, and etc. This could be seen , a wide range of innovative technologies have been spurred in the past two decades. Many devices such as shutters (Hashemi and Gage 2012), blinds (Tzempelikos and Anthienitis 2007), electro and photochromic windows (Shibaev, Bobrovsky, and Boiko 2003) and (Wang et al. 2014), thin-film solar cell windows, polymer dispersed liquid crystals (PDLCs), organic films (Miyake 2012), liquid crystal based windows (Debije 2012) and (Khandelwal 2014) and thin inorganic coatings have all been suggested or have already reached the marketplace.

This paper investigates the potential impact of tunable windows on educational buildings' energy efficiency. It is believed US educational building stock are among promising niche market for adopting advanced energy efficiency technologies. This is due to a) large potential market share: currently, there are approximately 5,300 colleges and universities throughout the U.S. with roughly $7 billion of annual utilities and energy costs, and b) congenial policies in place: many higher education institutions have already policies in place to decrease greenhouse gas emissions and have ethical commitments to sustainable development by , for example, construction of energy efficient buildings or retrofit of the existing buildings.

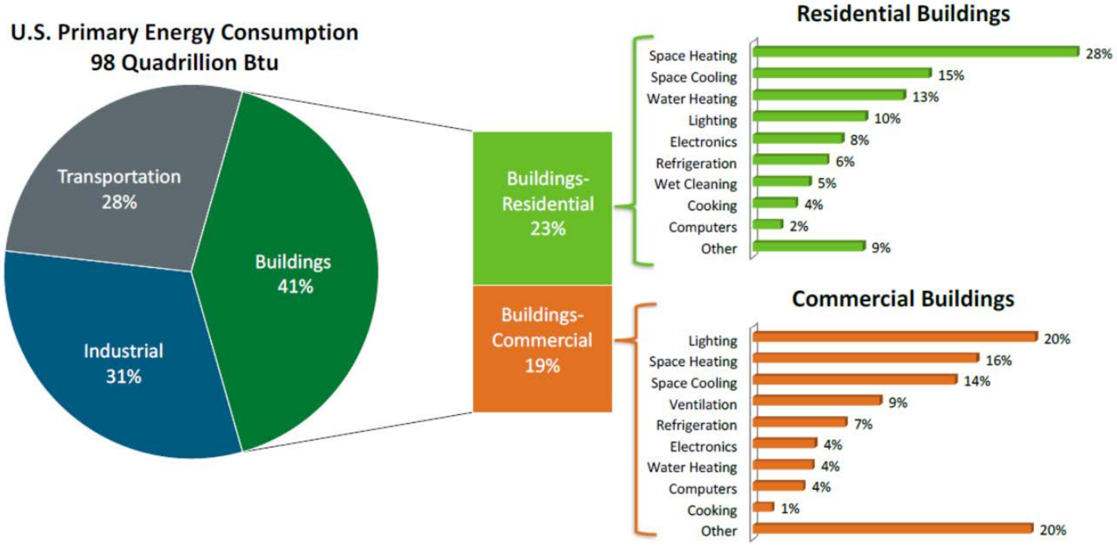


Figure 2: 2010 U.S. primary energy consumption in quads (DOE, 2015).

In this regard, this paper pursues following objectives: 1) to develop a building model for purpose of energy simulation and calibrate it, 2) to calculate tunable window's properties according to temperature, 3) to run the simulation based on different scenarios by changing the climate zone of the case study and measure the impact of windows choice on overall consumed energy, and 4) to perform a benefit analysis for each scenario. This paper is organized in 4 sections: a) Section 1 is the introduction and focuses on the importance of windows in overall building energy efficiency, b) Section 2 introduces advanced LC-based technologies and how to calculate their properties, c) Section 3 focuses on methodology and developing a calibrated model for performing energy simulations, d) Section 4 presents the results of the analysis in for each scenario, and e) Section 5 provides the discussion and summary.

2 LC WINDOWS

2.1 Liquid Crystals

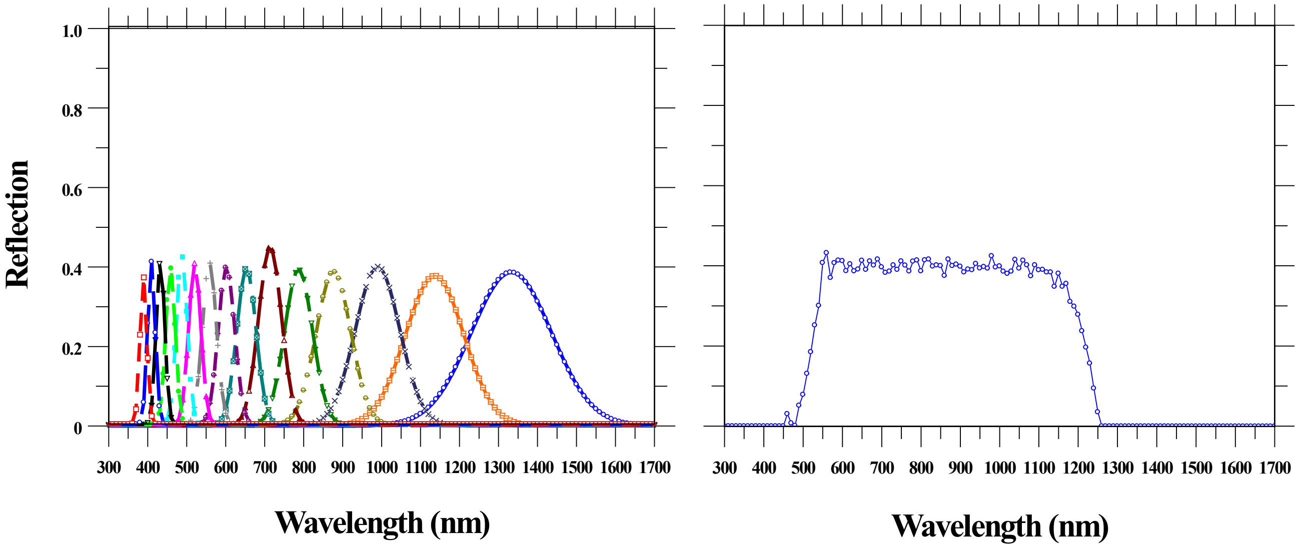
Liquid crystal is the fourth state of matter exhibiting properties between liquids and solids (Jákli and Saupe 2006). The constituent molecules of a liquid crystalline compound can freely flow analogous to fluids; however, they could be aligned in a particular direction and maintain a quasi-crystal structure. Liquid crystals has taken center stage due to their manifold applications such as: liquid crystal displays (LCDs), writing boards, lasers, lenses, biosensors, elastomers, and responsive fibers. One of the applications of liquid crystals is to utilize them in windows to control and tune their properties for improving building energy efficiency (Kamalisarvestani et al. 2013; Khandelwal et al. 2015).

2.2 Tunable Selective Reflection of Light

Helical structure of the cholesteric liquid crystals (CLC) results in selective light reflection. The reflection wavelength crucially depends on the CLC pitch. A CLC with a set pitch usually reflects light in a narrow band, e.g. 100 nm. The pitch of a CLC can be altered with temperature or depending on the material properties it can be accordingly configured. Another material which selectively reflects light is the heliconical cholesteric phase in which temperature, materials properties and the applied voltage can impact the selective reflection of light; altering any of these variables helps achieve a tunable selective reflection of light. Figure 3(a) shows 15 different selective reflection of light in the aforementioned materials; any of the reflection spectra is achievable by tuning the variables associated with CLC.

2.3 Wide-band Reflective Liquid Crystal Films

Broadening of the reflective band, gives opportunity for manufacturing of reflective filters capable of rejecting a great portion of solar IR spectrum and some visible light (White 2010; Xiao 2007; Mitov 2012; Broer, Lub, and Mol 1995). An example of that is shown in figure 3(b).



(a) (b)

Figure 3: (a) Selective light reflections of CLC. Typical reflection spectra of for different conditions. (b) Wide-band liquid crystal film reflecting a sufficiently large portion of the solar spectrum.

In a seminal work by Broer, Lub and Mol (1995), the reflective band of a CLC cell was drastically increased with introduction of a pitch gradient across the thickness. Diffusion of the reactive monomers and freezing of the pitch through their photopolymerization were used to render pitch gradient and fixed helical pitch, respectively. Also, use of a UV-absorbent dye creates a gradient of UV absorption along the cell thickness. Therefore, the side facing the UV light experiencing faster polymerization and depletion of CLC, leaving a gradient of concentration along the thickness. This manifests itself in gradient of pitch in transverse direction to the substrate. The reflective band was broadened from 50nm to 480nm. Naturally, prolonged polymerization by lower UV intensity, higher temperature during reaction and higher concentration of the UV-absorbent dye alleviate the diffusion and accordingly widen the reflective band (Schiff et al. 1995).

Aside from control of CLC polymerization kinetics introduced by Broer et al. (1995), numerous alterative approaches have been taken for broadening of the reflective bandgap. For instance Relaix et al. (2006) have used natural UV-absorption properties of LCs in PSCLC instead of using UV-absorbent dyes to generate a wide reflective bandgap. In an alternative approach, Nouvet and Mitov (2010) used spatial modulation of photoracemization reaction to create a broad reflective band CLC. They postulated that photo and thermo-racemization can take place on one side of the cell that is filled with a mixture of glass forming CLCs and a high (Helical Twisting Power) HTP chiral dopant. It was observed that, exposure to UV assists in racemization of the R-enantiomers to S-enantiomers on the side facing the light, which resulted in creation of a diffusion across the layer. Formation of a cell with gradient pitch and wider reflection bandgap was then followed by quench freezing of the structure. Photoisomerization is another technique for broadening of the reflection bandgap that can be conducted in several ways. For example, a photo-isomerizable chiral copolymer with UV-induced HTP change was mixed with a NLC and UV-absorbent dye, similar to Broer's method. Exposure to UV creates a distribution of intensity along the thickness through absorption by the dye. This led to gradual alteration of the HTP, pitch and broadening of the reflection band (de Witte, Brehmer, and Lub 1999). A similar technique was used by White et al. (2010), but this time without using the UV-absorbent dye. Instead, natural absorption of UV light by a bis(azo) chromophore along a thicker cell was exploited to produce a UV-tunable reflector. In another approach, inorganic templates with pitch gradient can be used for widening of the reflection bandgap. In a cell with gradient of helical column pitch, Nematic Liquid Crystal (NLC) molecules replicated the twisted structure and whole assembly reflected a broader light band (Robbie and Brett 1997). Another technique could be polymerization of heliconical cholesteric liquid crystals. This technology is based on the recently discovered twist-bend nematic liquid crystals (Salili et al. 2014; Xiang et al. 2015; Salili et al. 2016) . It is such that a certain voltage is applied such that it makes a certain selective reflection spectrum; we illuminate UV for a certain time that only the top part of the liquid crystal film gets cures. We repeat the same thing with a higher voltage that promotes a different selective reflection spectrum and we shine UV for a longer time such the part underneath the already polymerized layer gets cured. We repeat this with different voltages until different layers of the liquid crystal window show different reflection spectra; this way the broadband reflection spectra could be nicely achieved.

2.4 LC Window Parameters

2.4.1 Visible Transmittance (V_t)

V_t indicates the fraction of visible light transmitted through the window. Its value is between 0 and 1. The higher the V_t, the more light is transmitted. V_t is defined as shown in Equation 1

$$\mathbf{V}_t = \frac{\int T(\lambda)\, E_{S\lambda}(\lambda)\, V(\lambda)\, \mathrm{d}\lambda}{\int E_{S\lambda}(\lambda)\, V(\lambda)\, \mathrm{d}\lambda} \tag{1}$$

where T(λ) is the spectral transmittance of the window system, $E_{s\lambda}$ (λ) is the solar spectral irradiance distribution, V(λ) is the photopic spectral luminous efficiency function.

2.4.2 Solar Heat Gain Coefficient (SHGC)

The fraction of incident solar radiation admitted through a window, both directly transmitted and absorbed and subsequently released inward is defined as SHGC. Its value is between 0 and 1. The lower a window's solar heat gain coefficient, the less solar heat it transmits.

$$\mathrm{SHGC} = T_s + N_i A_s \tag{2}$$

$$T_S = \frac{\int T(\lambda) E_{S\lambda}(\lambda)\, \mathrm{d}\lambda}{\int E_{S\lambda}(\lambda)\, \mathrm{d}\lambda} \tag{3}$$

$$N_i A_S = N_i \frac{\int A(\lambda) E_{S\lambda}(\lambda)\, \mathrm{d}\lambda}{\int E_{S\lambda}(\lambda)\, \mathrm{d}\lambda} \tag{4}$$

where A(λ) is the spectral absorption and the other parameters are as defined for V_t. Before introduction of SHGC, window standards used to use Shading Coefficient (SC) which is the ratio of solar gain (due to direct sunlight) passing through a glass unit to the solar energy which passes through 3mm Clear Float Glass. SHGCS could be approximated as 0.87 of SC.

2.4.3 U-Factor

It indicates the rate of heat loss. The lower the U-factor, the better its insulating properties. Low U-factors are most important in heating dominated climates, although they are also beneficial in cooling dominated climates. The impact of liquid crystal film on this parameter is neglected.

3 METHODOLOGY

3.1 Simulation Program & Analysis Methodology

Annual energy savings presented in this report were analyzed by generating an hourly simulation of building energy consumption using the eQUEST® 3-65 software. eQUEST® is a sophisticated, yet easy to use, building energy use analysis tool that provides professional-level results with an affordable level of effort. eQUEST uses the latest DOE 2.2 building energy analysis software as its calculation engine. The program relies on the well tested and validated DOE 2.2 simulation engine and incorporates a state-of-the-art Graphic User Interface and features. Additionally, Window 6.3, the glazing simulation software developed by Lawrence Berkeley National Laboratory, was used to obtain the thermal properties of different glazing systems used in this study. The glazing library of Window 6.3 provides a variety of manufacturers' glazing properties from the International Glazing Data Base (IGDB).

3.1.1 Modeled Case Study

Given the focus of the paper is on energy efficiency in educational buildings, Rinker Hall, a 50,000 sqft three-story LEED gold certified building, at the University of Florida was selected as the case study. This selection was also impacted by availability of detailed metered data for consecutive years which is used for model validation and calibration. Rinker Hall includes classrooms, teaching labs, construction labs, several students lounges, faculty and administrative offices, and other student facilities. The eQUEST 3D model is shown in Figure 4.

Creating the 3D model initiated after the architectural drawings of the building were acquired and imported into eQUEST in *.dxf format. The project site, orientation and weather data were then defined. The next stage involved defining the all the thermal zones in the building as shown in Figure 5. The location of each VAV was defined subsequently. The further stages of model development included detailed definition of building shell parameters (wall type and material, roof design, windows, etc), building lighting systems, building schedules (annual, weekly, and daily), equipment schedule, etc.

3.1.2 Model Calibration

The error in monthly energy use is calculated as the percentage difference of measured kWh data and simulated kWh over the measured data for the month. The acceptable tolerance range for monthly data calibration per Federal Energy Management Program (FEMP) is +/-15%. This error is +/-25% based on International Performance Measurement and Verification Protocol (IPMVP). The monthly energy use model error percentage are shown in Figure 6.

3.2 Climate Zones

The project is located in Gainesville, FL. The ASHRAE 90.1-2004 climate zone for Gainesville, FL is Zone 2. This climate zone is characterized as "Mixed-Humid" with IP Units CDD50oF ≤ 4500 AND 3600 < HDD65oF ≤ 5400. Figure 7 shows the division of climate zones. In the second part of the simulation, we investigate the impact of climate zone on different window systems; hence, two cities of Boston, MA which is located in zone 5A with cool-humid climate, as well as city of Phoenix, AZ which has a hot-humid climate and located in zone 2B are considered as hypothetical project locations.

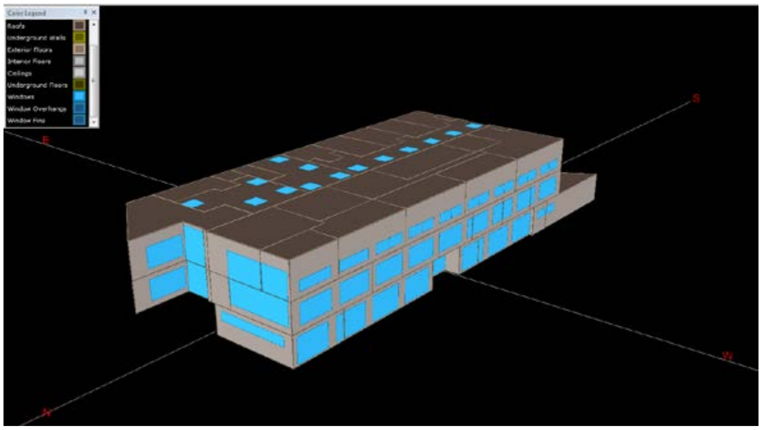


Figure 4: The 3D model of Rinker Hall, at the University of Florida which is used as the case study in this paper.

Figure 5: Thermal zones which are located in the first floor.

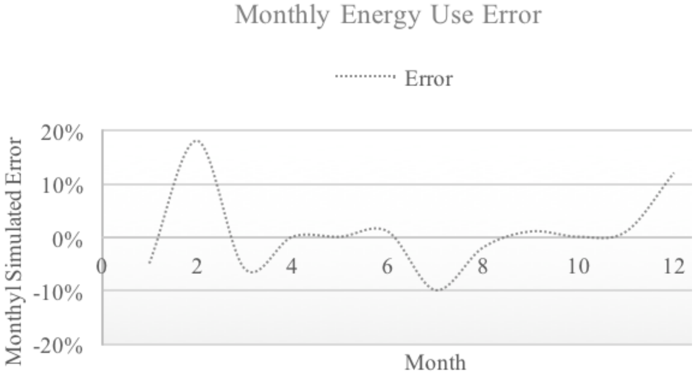


Figure 6: Error between simulated energy consumption and actual metered energy consumption in year 2011. The errors are within the acceptable range.

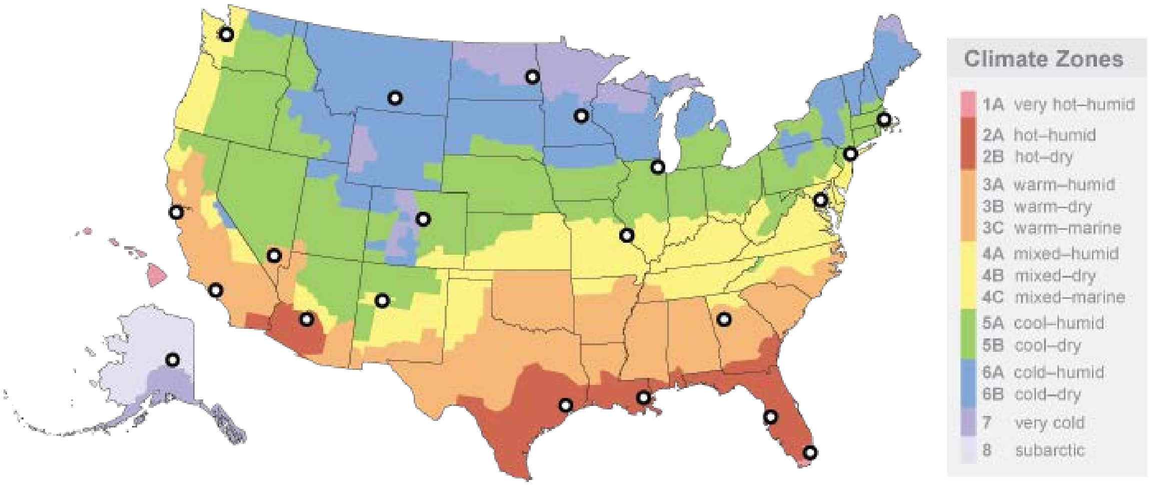


Figure 7: The climate zones of U.S. Phoenix, AZ is located in climate zone 2B, hot-dry, Boston, MA 5A, cool-humid, and Gainesville, FL 2A, hot-humid.

3.3 Window Selection

- **Regular single clear glass**: The clear glass manufactured by of PPG industries with ID number of 5012 in the glazing library of Window 6.3 was selected. The thickness of the glass was 5.7 mm. The properties are shown in Table 1.
- **Double clear glass (Air filled)**: Insulating double-pane clear glass used in this study included one 5.7mm clear glass with ID 5012 and interior glass of 2.3mm with ID 5008 filled with air. The properties are shown in Table 1.
- **Insulating double-pane low-E glass (Argon filled)**: This is according the exterior window schedule of Rinker Hall. It is a product of VIRACON® VE 7-2M. The property values listed in Table 1 are provided by the manufacturer; another study has shown these values match the result of simulated values from Window 6.3. The properties are shown in Table 1.

Table 1: Calculated properties for each window.

Glass Type	SC	SHGC	V_t	U-Factor
Single Clear Glass	0.939	0.817	0.886	1.025
Double Clear Glass (Air filled)	0.831	0.723	0.807	0.481
Insulating double-pane low-E glass (Argon filled)	0.31	0.26	0.55	0.24

- **Tunable Liquid Crystal Window**: This windows is designed to have a similar structural elements as the insulating double-pane clear glass but has an extra LC-based material. Using window 6.3, the U-factor is calculated as 0.481. It is assumed the LC material does not impact the U-factor value. The values of V_t and SHGC changes according to the outside temperature. For the purpose of this analysis, the average of daytime temperature is assigned to each month and the values of V_t and SHGC is the calculated.

Table 2: Calculated V_t and SHGC factors for each month according to Average Monthly Temperature (AMT).

Month	**Phoenix, AZ**			**Boston, MA**			**Gainesville, FL**		
	AMT	V_t	SHGC	AMT	V_t	SHGC	AMT	V_t	SHGC
Jan	69	0.681	0.496	36	0.760	0.513	66	0.681	0.496
Feb	72	0.637	0.494	39	0.760	0.510	70	0.681	0.496
Mar	78	0.673	0.492	45	0.758	0.508	75	0.637	0.494
Apr	86	0.736	0.490	56	0.754	0.502	80	0.673	0.492
May	95	0.760	0.494	66	0.681	0.496	87	0.736	0.490
Jun	104	0.760	0.501	76	0.637	0.494	90	0.758	0.489
Jul	106	0.760	0.501	81	0.673	0.492	91	0.758	0.489
Aug	104	0.760	0.501	80	0.673	0.492	90	0.758	0.489
Sep	100	0.760	0.497	72	0.637	0.494	87	0.736	0.490
Oct	89	0.758	0.489	61	0.735	0.497	81	0.673	0.492
Nov	76	0.637	0.494	52	0.754	0.502	74	0.637	0.494
Dec	67	0.681	0.496	41	0.760	0.510	68	0.681	0.496

- **Broadband Liquid Crystal Window**: This window reflects a larger portion of the solar irradiance spectrum as shown in Figure 3(b), compared to the tunable liquid crystal windows shown in Figure 3(a). This window has lower V_t and lower SHGC. For the purposes of this study, three different types of glasses were used along with the broadband liquid crystal window (Figure 8).
  - * Type 1: interior and exterior clear glasses
  - * Type 2: interior clear glass, and exterior Low-E
  - * Type 3: interior and exterior Low-E

4 RESULTS

4.1 Efficiency in Actual Climate Zone

The first part of the analysis is to investigate how different choices of window can contribute to energy efficiency of Rinker Hall. The results (Table 3) show while tunable windows have a better performance compared to the based case, they are not the best performing choice. Broadband window with Type 3 configuration has shown the best performance. Although, in it has caused an increase in Steam category, the savings in Chilled Water is very significant, making it a good choice for hot climate zones, where heating is not a priority.

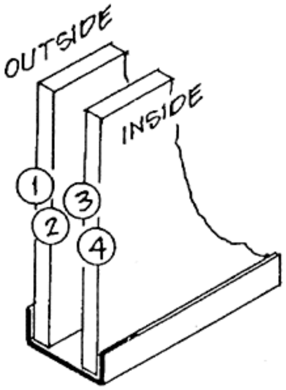


Figure 8: Windows in warm climates, where cooling is the primary concern, should have the low-E coating on surface 2; in cold climates, the coating should be on surface 3.

Table 3: Breakdown of simulated energy consumption for site location of Gainesville, FL.

Glass Type	Gainesville, FL, Climate Zone: 2A Hot-Humid				
	Electricity (KWH)	**Steam (MBTU)**	**Chilled Water (MBTU)**	**Total (MBTU)**	**Saving %**
Single Clear Glass	494163	23	3934	5643	Base
Double Clear Glass (Air filled)	494087	5	3913	5604	0.70%
Tunable	468990	2	3497	5099	9.64%
Broadband Window (Type 1)	446560	4	3128	4656	17.50%
Insulating double-pane low-E glass (Argon filled)	435049	6	2912	4402	21.99%
Broadband window (Type 2)	430932	8	2820	4298	23.83%
Broadband window (Type 3)	421050	14	2598	4049	28.25%

4.2 Efficiency in Different Climate Zone

The second part of the analysis is to investigate how different window choices can impact overall building energy consumption in different climate zones. Table 4, and 5 show the result of the analysis for Boston, MA and Phoenix, AZ respectively. It is clear the both broadband type 2 and 3 can significantly improve the building energy efficiency by decreasing the building's cooling load. Additionally, they have a much better performance in lighting efficiency, allowing the natural light into the building while filtering out the undesired IR in hot seasons.

Table 4: Breakdown of simulated energy consumption for site location of Boston, MA.

Glass Type	Boston, MA, Climate Zone: 5A Cool-Humid				
	Electricity (KWH)	**Steam (MBTU)**	**Chilled Water (MBTU)**	**Total (MBTU)**	**Saving %**
Single Clear Glass	463819	641	1741	3965	Base
Double Clear Glass (Air filled)	469206	338	1840	3779	4.68%
Tunable	454967	227	1661	3440	13.22%
Broadband Window (Type 1)	439155	270	1427	3195	19.40%
Insulating double-pane low-E glass (Argon filled)	428820	305	1293	3061	22.79%
Broadband window (Type 2)	426404	321	1232	3008	24.13%
Broadband window (Type 3)	421038	372	1114	2923	26.28%

5 DISCUSSION

This paper investigated the impact of different choices of window on energy consumption of educational buildings. For this purpose, Rinker Hall at the University of Florida was fully modeled in eQUEST and analyzed. Seven different choices of window systems were considered in the analysis, some of which are based on recent technological advances in the field of liquid crystal (LC). The analysis shows it is possible to save up to 30% on total building energy consumption by modifying windows properties.

Some of the limitations that existed in the current modeling are: 1) thermal zones are mostly divided through VAV systems, while the division of corridors is assumed to be separated and attached to different zones near each separated part, 2) occupancy is set by furniture plans, lighting density is decided by electrical plans, 3) it was assumed that the types of walls and roofs are fixed (Rinker Hall's green roof is not reflected in the model), and the properties of all the windows are the same, 4) schedules are not exact, and 5) forms and structures of all the VAV systems are considered to be the same. These limitations, among others, can explain certain error existed in the model (Figure 6); however, as it was discussed earlier, the error is well within the acceptable guideline.

From an economic perspective, application of energy efficient windows can have direct and indirect economic benefits. Table 6 shows the potential for direct savings in $ per annum. This could result in a significant lump sum over windows life cycle. Additionally, in the U.S., it is possible to receive tax credits for energy efficient windows. From indirect economic benefit, easier green building certification process could be noted, which has positive impact on marketability and the perception of the property.

Table 5: Breakdown of simulated energy consumption for site location of Phoenix, AZ.

Glass Type	Phoenix, AZ, Climate Zone: 2B Hot-Dry				
	Electricity (KWH)	**Steam (MBTU)**	**Chilled Water (MBTU)**	**Total (MBTU)**	**Saving %**
Single Clear Glass	532531	58	3758	5633	Base
Double Clear Glass (Air filled)	531610	17	3695	5526	1.90%
Tunable	500663	8	3202	4918	12.69%
Broadband Window (Type 1)	471599	13	2779	4401	21.87%
Insulating double-pane low-E glass (Argon filled)	455656	18	2530	4103	27.17%
Broadband window (Type 2)	449478	21	2421	3976	29.42%
Broadband window (Type 3)	434610	31	2155	3669	34.87%

Table 6. Energy Savings in $ amount for each scenario.

Glass Type	Average State's Electricity Cost		
	FL	MA	AZ
	11.42¢/kWh	14.91¢/kWh	11.29¢/kWh
	Savings Per Annum		
Single Clear Glass	NA	NA	NA
Double Clear Glass (Air filled)	$ 1,322	$ 6,211	$ 3,323
Tunable	$ 18,206	$ 17,543	$ 22,196
Broadband Window (Type 1)	$ 33,051	$ 25,744	$ 38,252
Insulating double-pane low-E glass (Argon filled)	$ 41,531	$ 30,243	$ 47,522
Broadband window (Type 2)	$ 45,006	$ 32,021	$ 51,458
Broadband window (Type 3)	$ 53,354	$ 34,874	$ 60,990

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