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GLAZING IN COMMERCIAL BUILDINGS - THE BALANCE BETWEEN COST AND ENERGY CONSUMPTION

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ABSTRACT

This paper explores the balance between reducing energy use and intial costs over the life cycle of glazing options. More specifically, this paper discusses the results of parametric analysis on a calibrated building energy model of a single-story office building with multiple glazing options, including: double or triple glazed insulated glazing units (IGU), low-emissivity (low-e) coatings, window-to-wall ratios (WWR), and gas fillers. The model was used to predict energy consumption; Skanska performed detailed cost estimates to provide upfront costs; and the model's results were combined with typical energy costs to estimate long-term costs.

INTRODUCTION

Architectural trends have evolved to include high WWRs on buildings. This is generally motivated by higher rental rates that developers can charge for views, but also encouraged by various voluntary "green" codes and standards that emphasize using daylighting to lower energy costs and improve occupant productivity (Edwards and Torcellini 2002). However, incorporating larger windows that insulate less than opaque walls can result in higher heating and cooling costs, so energy codes prescriptively limit WWRs. Increasing natural light while minimizing heat transfer through glazing systems often leads to selecting more sophisticated glazing systems with higher upfront costs.

Selecting a glazing system that meets cost and design criteria is not always straightforward. To aid in window selection, many studies have looked at the optimal window configurations including U-value, solar heat gain coefficient (SHGC), orientaion, and WWR; however, these studies are usually based on energy savings and do not incoorporate first costs (Ochoa, Aries, van Loenen, Hensen 2012; Grynning, Gustavsen, Time, Jelle 2013; Huang, Niu, Chung 2014; Harmati and Magyar 2015; Goia 2016; Misiopecki, Bouquin, Gustavsen, Jelle 2017). One study looked at costs in three climates (Jaber and Ajib 2011), but it did not include colder climates such as Boston, MA.

Another set of studies looked at cold climates and incorporated cost estimates from a manufacturer (Pikas, Thalfeldt, Kurnitski 2014 and Thalfeldt, Pikas, Kurnitski, Voll 2013), however, manufacturer's pricing does not incorporate the additional labor to install triple-pane windows over double-pane.

This study reviews how different glazing options affect the energy usage of the building along with the associated installation and long-term costs of each option.

SIMULATION

Baseline Model

We analyzed an 84,600 sq. ft. single-story office building located in ASHRAE Climate Zone 5 (Waltham, MA, just outside of Boston, MA) with a recently renovated building enclosure that includes new roofing, wall cladding, and glazing (Figure 1).

Figure 1 Building Geometry

- The roofing consists of the following from exterior to interior: black roofing membrane, 1/2 in. fiberboard coverboard, 3 in. polyisocyanurate insulation, and metal deck. The ceiling finish is 1 in. of rigid fiber glass insulation for noise reduction.
- The wall cladding consists of the following from exterior to interior: exterior insulation and finish system (EIFS - comprising a finish over 4 in. thick polystyrene insulation), brick, 2.5 in. metal studs with R-11 batt insulation in the stud cavity, and gypsum board.
- The glazing consists primarily of aluminum-framed, thermally broken windows with double glazed IGUs installed in punched openings at the first floor, and aluminum-framed curtain wall at the clerestory.
- Mechanical equipment consists primarily of 14 rooftop units (RTU). The RTUs use gas to heat and electricity to cool supply air to approximately 50°F year round; air terminals in each zone use electricity to reheat the air to approximately 72°F.

- Interior loads consist of lighting, plug and electrical loads typical for meeting and office spaces.

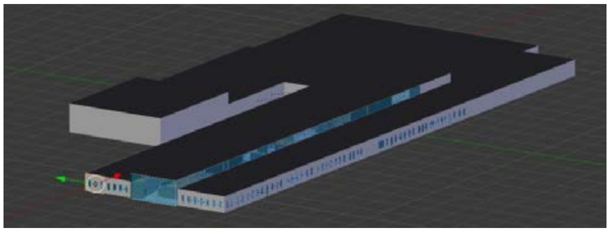

Figure 2 Model Geometry

The model includes 80 mechanical zones, and we used Blender, an open-source 3D modeling software, to model the building and adjacent building geometry (Figure 2); we used ODS Studio, a plugin for Blender, to convert the model into an EnergyPlus input file as well as for computational fluid dynamics (CFD) analysis.

Calibration

To assist with model calibration, we collected data from multiple sources: we performed a quantitative whole building air leakage test to measure the building's air infiltration; we sub-metered electrical consumption to separate mechanical and plug loads; and we installed an on-site weather station to collect local weather data including air temperature, relative humidity, wind speed and direction, solar radiation, barometric pressure, and precipitation at 15-minute intervals.

We coupled the results from the air leakage test with CFD analysis of the building's exterior to model air infiltration under different wind conditions.

These results were fed into the EnergyPlus model to create an airflow network incorporating the weather data and the measured air leakage rate. The EnergyPlus model was then manually calibrated to reduce the difference between the simulated and sub-metered electricity usages using the local weather file from the on-site weather station. The heating, ventilation and air conditioning (HVAC) and plug loads were calibrated separately to the sub-metered electricity loads, the temperature setpoints were adjusted, and the weekend occupancy was adjusted to match monitored entry (the calibration process is further described in Fu and Lyon 2018). The calibrated model has a coefficient of variation of the root mean square error (CVRMSE) of 5% with monthly data.

Parametric Analysis

We performed several studies on the calibrated model to understand the effects of different glazing options on the building's energy use. We selected the following glazing options to study, based on typical options available to designers:

- Number of glass panes: single, double, or triple pane (Figure 3)
- Low-e coatings (Figure 3)
- WWR: 22%, 26%, 31%, 37%, 44% and 51%
- IGU gas filler: air or argon

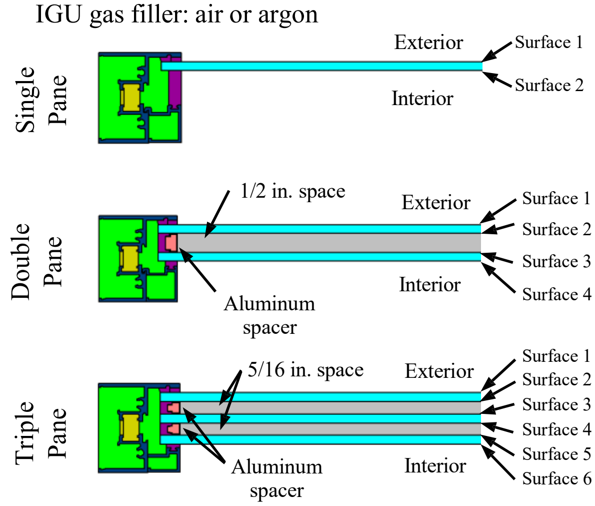

Figure 3 Number of glass panes

For all options, we modeled aluminum-framed windows with thermally-broken frames for the punched windows; the windows did not have sill receptors. We also modeled an aluminum-framed, thermally-improved curtain wall at the clerestory. To model the windows and curtain wall, we created the window and curtain wall components (including the head, sill, and jamb conditions) in Lawrence Berkeley National Laboratory's (LBNL) THERM 7.5 and WINDOW 7.5 programs (Figure 3); we analyzed the frame and glazing properties including material data for the glass and gas as well as spectral data and used this as input for the EnergyPlus model.

We used the Boston Logan Airport TMY3 weather file for the parametric glazing analysis (the airport is located apprioximately 11 miles from the Waltham office).

For low-e coatings, we compared the following options: double-pane glazing with no coating, a low-e coating on surface 2, and a low-e coating on surface 2 and surface 4; triple-pane glazing with no coating and a low-e coating on surface 2 (see Figure 3 for surface labels). For the double-pane glazing with a low-e coating on surface 2 and surface 4, we modeled a Viracon VRE 38 coating and a Viracon RoomSide low-E coating, respectively. For all other low-e coatings, we modeled a Solarban 60 coating.

Table 1 lists the center-of-glass U-factor and solar heat gain coeffeicient (SHGC) of each glazing option reviewed in this study.

Table 1 – Center-of-Glass Values

Glazing Options			U-factor $[\frac{B��}{h \cdot f^{2} \cdot F}]$	U-factor $[\frac{W}{m^2 \cdot K}]$	SHGC
# panes	**Gas Filler**	**Coating, Surface**			
1	n/a	none	1.025	20953	.818
2	air	none	.474	9689	.704
	air	low-e, 2	.291	5949	.392
	argon	none	.448	9158	.705
	argon	low-e, 2	.245	5008	.387
	air	low-e, 2 & 4	.235	4804	.361
3	air	none	.345	7052	.616
	air	low-e, 2	.266	5438	.331
	argon	none	.314	6419	.617
	argon	low-e, 2	.219	4477	.328

For WWR, we increased the area of the glazing units in punched openings in the model so the overall WWR for the building changed from approximately 22% to 51%. We did not change the size of the clerestory windows.

Cost analysis

For each glazing option, Skanska provided an approximate range of costs per square foot to procure and install the windows/curtain wall (i.e., materials and labor). We combined the average cost for each glazing option with the glazing area to calculate the upfront costs for the various glazing system and size combinations that we used.

To calculate the HVAC energy costs, we used the same process we use to predict energy costs from energy models for code compliance. We found the average monthly costs for commercial electricity and gas for Massachusetts from the Energy Information Administration (EIA, 2018a; EIA, 2018b). We used the time period from April 2016 to March 2017 because this included the most recent continuous data set (April 2017 gas data was missing). To calculate the average daily energy cost, we multiplied the average daily energy use in a given month by the average cost for that month. To calculate the annual cost of energy, we multiplied the average daily energy cost by the number of days in a month and summed the electricity and gas cost for each month.

RESULTS

Annual Energy Use

We used the model to predict the energy consumption for the building with various glazing options and sorted energy consumption into HVAC vs. non-HVAC energy use. We ignored non-HVAC energy use since this consists of plug and lighting loads that will not be affected by the glazing changes (there are no existing daylighting controls on the building). We divided the total HVAC energy use into four subcategories –rooftop unit (RTU) heating (gas), RTU cooling (electric), terminal reheat (electric), and fans (electric) (see Figure 4).

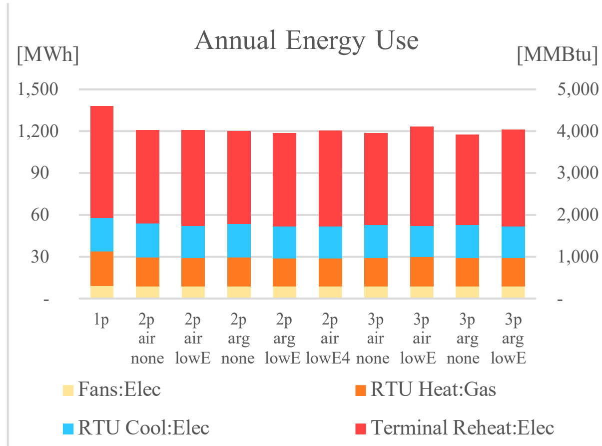

Figure 4 Annual Energy Use

For WWR, we compared the predicted annual energy use for each glazing option to the baseline glazing option of double-pane with air filler and a low-e coating on surface 2. We did this for the HVAC energy use, heating energy use, and cooling energy use (see Figure 5). We note the following:

- In term of overall HVAC usage, all glazing systems peformed worse with increasing WWR (Figure 5a).
- Single-pane glazing increased HVAC usage at the highest rate with increasing WWR.
- Double- and triple-pane glazing have similar usage increase rates with increasing WWR
    - Cooling loads increased mostly linearly with increasing WWR. Cooling loads for coated glazing increased at a slower rate than uncoated glazing (Figure 5c).
    - Heating loads increased in decreasing amounts and at a much lower rate than the cooling loads (Figure 5b). In many options, the increases were effectively flat.
- Triple-pane glazing with Argon and no coating was the best peforming system in overall energy usage (Figure 5a).

The heating load increases due to larger WWRs were effectively flat in most cases of the double- and triple-pane glazing. This is because larger windows allow more heat (solar) gain and heat loss due to their low insulation values. On the other hand, in cooling

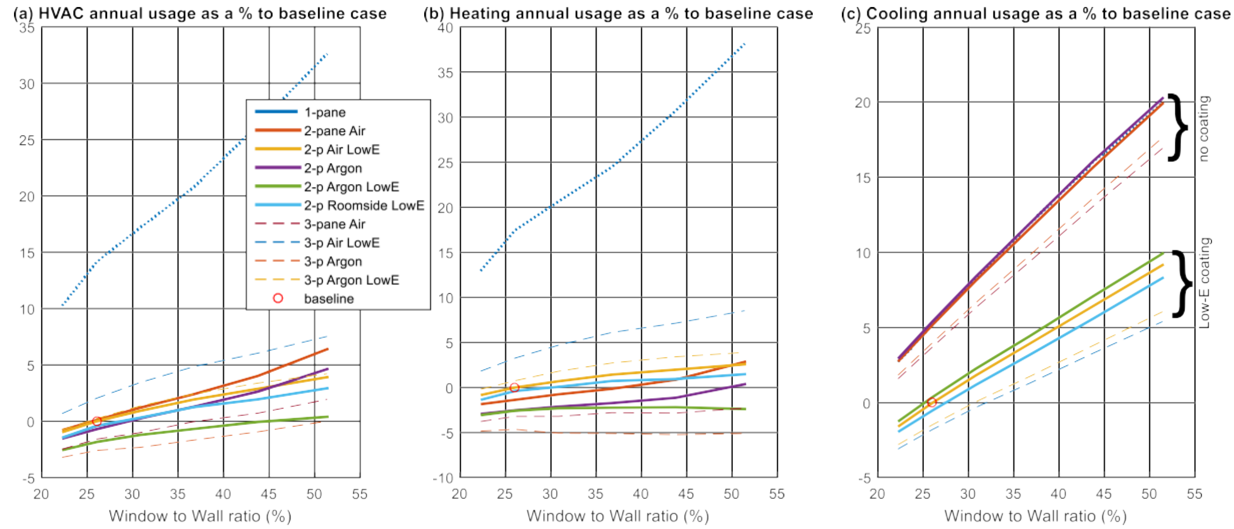

Figure 5 Annual HVAC usage related to WWR

seasons, larger windows always perform worse because of heat gains from both direct sunlight and warmer outside temperature.

Average Daily Energy Cost

We calculated the average daily energy cost for the different glazing options based on simulated energy predictions and Massachusetts' average monthly energy costs. From our analyses, we observed the following trends:

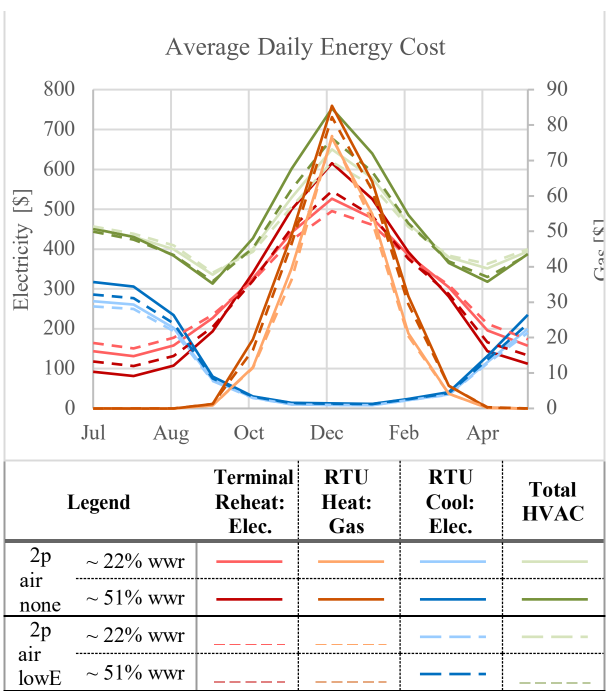

Figure 6 Energy Use - none vs LowE (2-pane)

Gas Filler

- Glazing with argon filler generally resulted in lower HVAC energy costs than their counterparts with air filler due to lower terminal reheat costs in the winter.

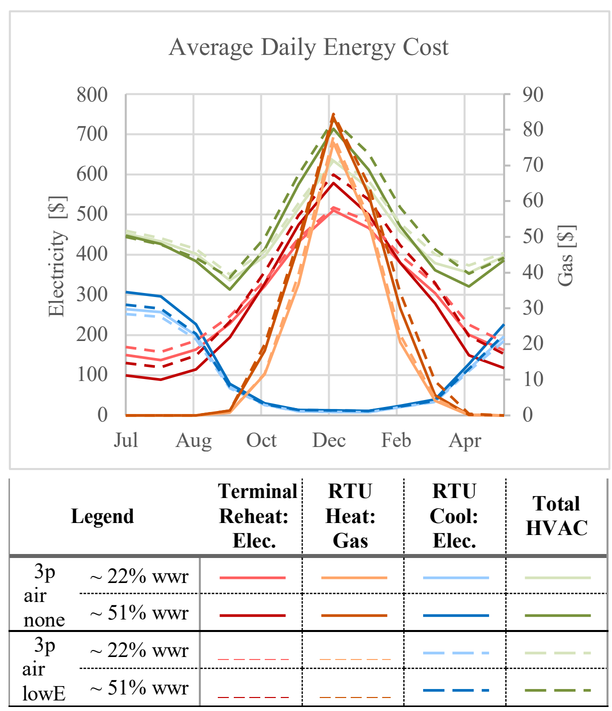

Figure 7 Energy Use – none vs LowE (3-pane)

Low-E Coating

- Double-pane coated glazing resulted in lower HVAC energy costs than uncoated glazing due to lower terminal reheat costs in the winter for the coated glass (Figure 6). While coated glass had higher terminal reheat costs in the summer, this was negated by lower RTU cooling costs.
- In contrast, triple-pane coated glass resulted in *higher* HVAC energy costs than uncoated glass due to higher terminal reheat costs in the winter for the coated glass. (Figure 7). While coated glass also had higher terminal reheat costs in the summer, this was negated by lower RTU cooling costs for the coated glass.

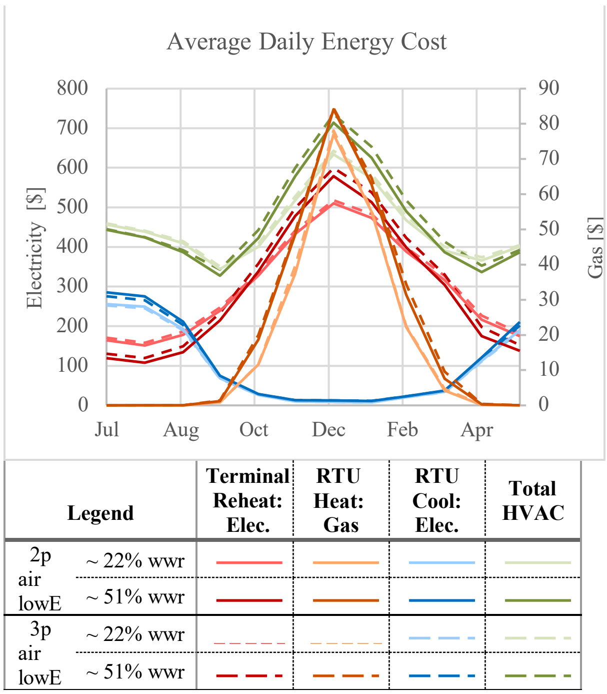

Figure 8 Energy Use – 2-pane vs 3-pane (lowE)

Number of Panes

- Single-pane glazing had the highest HVAC energy costs due to primarily higher terminal reheat costs in the winter.
- Triple-pane uncoated glazing resulted in lower HVAC energy costs than their double-pane counterparts (when both are uncoated) due to primarily lower terminal reheat costs in the winter for triple-pane glazing.
- Double-pane coated glazing resulted in lower HVAC energy costs than their triple-pane counterparts (when both are coated) due to primarily lower terminal reheat costs in the winter for double -pane glazing (Figure 8) . Double-pane glazing also has lower terminal reheat costs in the summer, but this is negated by higher cooling costs for double-pane glazing.

Annual Energy Costs

We calclulated the annual energy costs for HVAC as previously noted in the simulation section (see Figure 9). These results showed a similar pattern to the annual energy use, but the cost for single-pane glazing increased significantly relative to the other glazing options since it used the most gas heating (for the RTUs), which costs more than electricity.

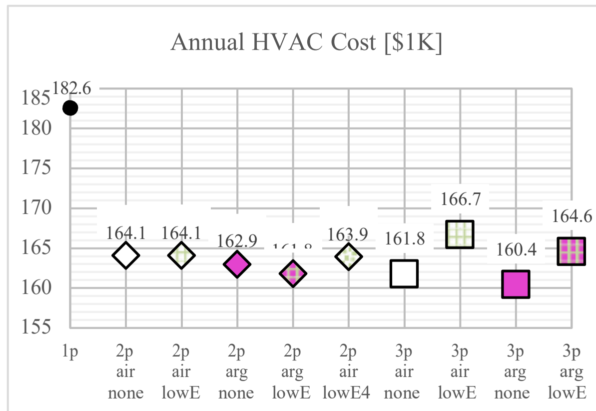

Figure 9 Annual Energy Cost (note: 2-pane air and 2-pan air with low-e had the same HVAC cost as the former option had a higher cooling load while the latter option had higher heating load)

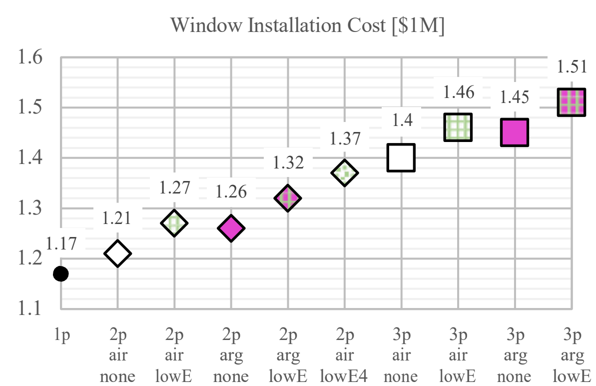

Figure 10 Total Window Installation Cost – Including Labor and Materials

Upfront Costs

Based on the cost per square foot we received from the contractor, we calculated the total costs for the glazing on the building for each glazing option, see Figure 10. In general, the cost increased for additional panes, the presence of a low-e coating (with a premium for the coating on surface 4), and argon filler.

Long Term Costs

We used the annual HVAC operating cost combined with 2.5% inflation to calculate the present value of the operating costs over time, up to 20 years (the typical service life of an IGU). We then combined the HVAC operating cost with the installation costs for the windows. This provided a cost over time that reflects the glazing's initial cost and its effect on the building's performance.

Assuming the glazing installation lasts for 20 years, we found the following based on Figure 11:

- Single-pane glazing and triple-pane glazing with low-e coatings resulted in the three highest glazing-related costs.
- Double-pane glazing with no coatings resulted in the lowest two glazing-related costs.
- The remaining options resulted in similar, but slightly higher glazing-related costs than the two options with the lowest costs.

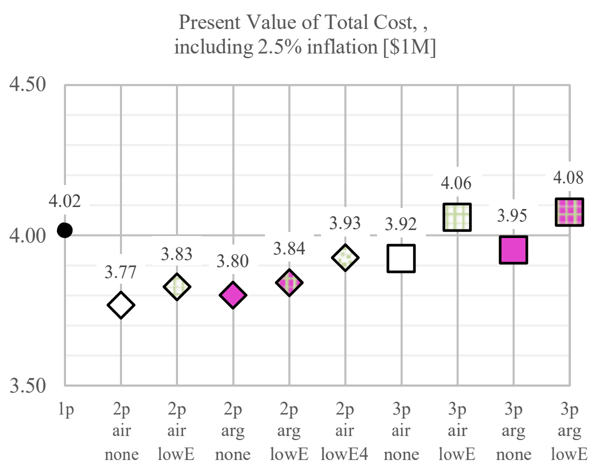

Figure 11 Combined Cost of Windows and HVAC over 20 years

Payback

For each glazing option, we also looked at the costs associated with upgrading from the least expensive option of single-pane glazing to other options. We calculated the additional installation costs and the savings on HVAC costs for each option as compared to single-pane glazing. We divided the additional upfront costs by the annual savings to get the payback (in years) for each option, not accounting for inflation (Table 2).

We found that four glazing options had a payback period of less than 10 years, and two had a payback period of less than five. The remaining options had long payback periods.

Table 2 – Glazing Performance over time

Glazing Options			Payback (yrs)
# panes	Gas Filler	Coating and Surface	
1	n/a	none	--
2	air	none	2.16
2	air	low-e, 2	5.41
2	argon	none	4.58
2	argon	low-e, 2	7.21
2	air	low-e, 4	10.71
3	air	none	11.05
3	air	low-e, 2	18.26
3	argon	none	12.63
3	argon	low-e, 2	18.88

Legend		
Payback < 5 yrs	Payback < 10 yrs	Payback ≥ 10 yrs

DISCUSSION

Typical office buildings often have energy use and costs that are cooling-dominated, usually due to the high internal loads. Buildings in temperate and warmer climates also have to manage large heat gains through the building enclosure. The building in this study is heating-dominated partly due to the cold climate, but mostly due to the mechanical system – with the RTUs heating and cooling air to around 50°F year round, and air terminals reheating the air.

General Comments – U-factor

The cold climate dominates the building's response to changing the glazing's U-factor. Glazing with higher U-factors, which allow more heat transfer through the windows, have higher heating costs in the winter because more heat from the interior is lost to the exterior. In the summer, minimal heat is gained from the exterior because the temperature difference between the interior and exterior is minimal.

The U-factor's effect on the building's HVAC energy cost is particularly evident through comparing the models of glazing with and without argon. Both double-pane glazing with and without argon as well as triple-pane glazing with and without argon each have U-factors that vary by approximately 5 - 9%; however, their SHGCs are within 1.5% of each other. Both double- and triple-pane glazing with argon, which have lower U-factor, have lower heating costs in the winter and similar cooling/heating costs in the summer.

General Comments – SHGC

The HVAC system dominates the building's response to changing the glazing's SHGC. In general, the glazing with higher SHGCs, which allows more solar heating, is beneficial year-round because it reduces the heating required by the RTU's and air terminal reheat in the winter, and it reduces the heating required by the air terminal reheat in the summer (although it also increases the cooling necessary by the RTU's).

It is more difficult to isolate the specific effect SHGC has on the HVAC energy use through comparing two specific glazing options in this study because the options that affect the SHGC also affect the U-factor. The two cases with the most similar U-factors are the low-e coated, double-glazing with air and the uncoated triple-glazing with argon. The two cases have U-factors that are within approximately 7.5% of each other, and SHGC's that vary by approximately 55%. The uncoated triple-glazing with argon, which has a higher SHGC, has lower terminal reheating costs throughout the year. The cooling costs increase slightly in the summer for the triple-glazing, but the winter savings dominates. This results in an overall lower HVAC energy cost for the glazing with a higher SHGC.

General Comments – U-factor vs. SHGC

While a lower U-factor and a higher SHGC are both associated with lower energy costs, the results showed different variables dominating if both are high or both are low. The single pane glazing with a high U-factor and SHGC, results in the highest energy costs of all options, predominantly from higher winter terminal reheating costs. Even with a SHGC roughly 16% higher than the next option, its U-factor is more than double the U-factor for all other glazing options. So although the high SHGC lowers winter heating demand, the higher U-factor dominates and results in very high HVAC energy cost for the single-pane glazing option.

With uncoated glazing, adding panes generally reduces the U-factor more than the SHGC (approximately 30% vs. 12%, respectively), so the lower U-factor dominates to reduce energy costs. However, for glazing with a low-e coating, adding panes has a smaller effect on the U-factor than the SHGC (approximately 10% vs. 15%, respectively), so, the lower SHGC dominates and additional panes of glazing increase the energy use.

Low-E Coating

Because all the low-e coated glazing options in this study have low SHGCs, they let in much less heat in the winter, generally resulting in higher winter heating costs. However, they also have lower cooling costs during summers due to the limited solar gain. As a result, in the studied Climate Zone 5 where heating is the primary concern, low-e coated glazing tends to result in higher overall energy costs.

Other Notes

This building includes a very high roof-to-wall ratio of 26%; the roof dominates the exposed enclosure area. Regardless of how the windows perform, they can only have so much of an effect on the building compared with the roof system.

This study also does not take into account depreciation of components over time, such as the loss of argon through the window seal. This will result in less saving in Year 20 than in the initial years, so the results may be overlyly generous for certain glazing options.

CONCLUSIONS

When looking at the costs as a whole – including both realistic upfront costs as well as long-term HVAC costs incorporating inflation, the better performance of more expensive windows may not be worth the upfront cost.

In this study, the mechanical system shapes how the building's energy costs change with the different glazing options. The results of this study apply mostly to heating-dominated buildings with a WWR of 26%, and a very high roof-to-wall ratio. For this type of building, double-pane systems with air or argon filler and no low-e coating will result in greatest cost savings over 20 years. Given argon's increased initial cost over air, its minimal value in long-term costs, and its depreciating effects as it escapes over time, it is reasonable to choose either gas filler depending on a project's goals.

For this type of buildings, single-pane glazing and triple-pane glazing with a low-e coating will be the least cost effective. Depending on project goals other than cost, other options include double-pane glazing with low-e coatings, and triple-pane glazing with no coatings.

Increasing the WWR will likely result in one of the double-pane with a coating options or the uncoated triple-pane option performing the best for overall costs, depending on the specific WWR chosen.

Using this information as a guide, building designers and owners can determine an approximate goal for the WWR, then analyze different options to meet code and their energy use and cost goals.

Recommendations for Future Research

The mechanical system and cold climate greatly affect the results. Studying how the energy use changes with different glazing options in buildings with different mechanical systems and climates would be helpful.

Low-e coatings also vary significantly in their emissivity. Studying coatings with a variety of emissivities to compare how they would perform in both cold and warm climates could provide further valuable information.

This building did not incorporate daylighting controls. While daylighting controls may not be as helpful on a building with a high roof-to-wall ratio, they could have a great effect on a building with a lower roof-to-wall ratio. Studying glazing's effects on a building with these controls and a low roof-to-wall ratio could result in significant differences on how energy use and costs change with a higher WWR. At the same time, with the advances in LED technology and prevalence of LED lighiting, the cost for lighting is becoming much lesss relative to the other loads in a building, so daylighting controls may have a minimal affect on the energy costss as a whole.

While the cost analysis in this study accounts for inflation, it is still relatively simplified. It would be beneficial to do a more detailed analysis, such as the ASHRAE cost-effectiveness calculation since many complex factors affect the cost.

ACKNOWLEDGEMENTS

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NOMENCLATURE

CFD – computational fluid dynamics

EIFS – exterior insulation and finish system

IGU – insulated glazing unit

low-e – low-emissivity

RTU – rooftop unit

SHGC – solar heat gain coefficient

WWR – window-to-wall ratio

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