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ABSTRACT

Heat transfer through the building envelope and associated air leakage comprise the largest HVAC loads in most climates, and windows, which are known as the weakest link in the thermal envelope, are responsible for about 5 Quads, or approximately 10%, of building energy use. Therefore, windows offer a significant opportunity for building energy savings. High performance windows, such as triple glazing, though comprised of less than 2% of all US window sales in 2016 and has remained stagnant because they typically require a full and expensive redesign of the typical window sash and frame. One potential low incremental cost solution to kick start the market is upgrading the glazing with a thin-glass triple-pane design that does not require modifications to existing frame and sash. In this work, we first define the characteristics and performance of current "typical" residential windows through an examination of the National Fenestration Rating Council (NFRC) Certified Products Directory (CPD). With knowledge of the typical window, we determine the potential thermal performance impact of replacing typical glazing with thin-glass triple-pane glazing. Finally, with an understanding of the potential improvements to traditional performance metrics, such as U-factor, we show the energy savings potential of the thin-triple glazing in place of typical low-e windows in residential buildings is 16% in heating dominated climates such as Minneapolis, MN, 12% in mixed climates such as Washington DC, and 7% in cooling dominated climates such as Houston, TX.

KEYWORDS

fenestration; windows; energy; retrofit;

INTRODUCTION

Buildings account for approximately 40% of total U.S. energy consumption, and 75% of electricity use. HVAC systems consume about 35% of total building energy use and are the largest end uses in most buildings. While much attention is focused on improving the efficiency of the heating and cooling hardware and systems that provide that thermal comfort, the underlying source of those thermal loads is often overlooked. Heat transfer through the building envelope and associated air leakage comprise the largest HVAC loads in most climates, and windows, which are known as the weakest link in the thermal envelope, are responsible for ~5 Quads or approximately 10% of building energy use. Therefore, windows offer a significant opportunity for building energy savings.

Low-emissivity (low-e) windows, which significantly increase energy savings potential over traditional single-clear and double-clear windows, have been a strong market success. Since their introduction in the late 1970's, low-e sales have steadily gained to nearly 90% of all insulating glazing units (IGUs) sold, see Figure 1 (Ducker 2018). While traditional low-e windows save significant energy, additional energy can be saved by more efficient products. Currently, there has yet to be a scalable and cost-effective follow-on technology solution to deliver additional savings. Typical triple-pane construction has been viable since the early 1980's, but there has been no market driver for its refinement and adoption. Thin polymer films with low-e coatings are one option that is sometimes used in place of one or more glass layers. While these products offer the same thermal performance as traditional triple-pane products, they were early market entries in the 1980s and they have only captured very small market share today due to the added complexity and cost of incorporating them into IGUs. Vaccum glazing and aerogel are two of the most discussed IGU techniques that could significantly improve thermal insulation, potentially

beyond the performance capable with triple or even quad-pane glazing. Aerogel, a microporous, transparent material with excellent themal properties, has shown promise in the laboratory but with over 30 years of R&D is not yet a commercially viable window option. Vacuum insulating glazing (VIG) is dual glazing with an evacuated gas space between the two layers of glass. Small spacers, or pillars, are placed to maintain separation between glass, and low-e coatings are used to reduce radiation exchange between glass layers. VIG maintains the weight of traditional IGUs but with reduced thickness. A single manufacturer has offered these products over the last 15 years but the performance is low compared to the theoretical capability of the technology, costs remain relatively high, and there is no existing production infrastructure in the US. Ongoing development in Europe, U.S. and Asia might produce more market viable products in the future.

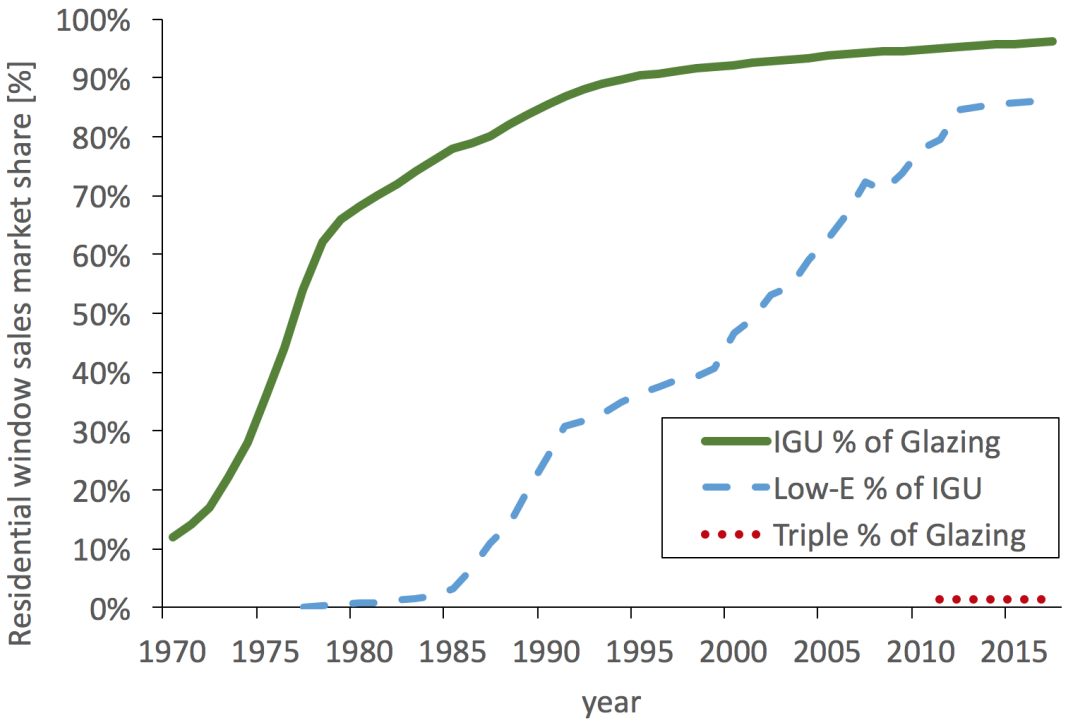

Figure 1. U.S. residential window sales historical market share by year. Low-e shows a rapid rise in market penetration, while triple-pane market share is stagnant at around 1.4 percent.

The thin-glass triple-pane concept was introduced in 1989 (Arasteh, Selkowitz, Wolfe 1989; Selkowitz, Arasteh, Hartmann 1991) to address window manufacturer technical, business, and market issues with the adoption of high-performance window technologies. This technology was ahead of its time though and only within the last couple years has the material technology caught up with the idea. As a technology solution, the thin-triple (TG) concept is a "drop-in" replacement IGU that 1) has the potential to reach low U-factors; 2) requires no significant investment in redesign on the part of the window manufacturer; 3) is based on cost-effective market-ready new technology; 4) can be supplied via the existing industry supply chain; and 5) is flexible enough to accommodate a variety of window types and sizes.

Starting with a conventional IGU, a piece of thin glass, approximately 1mm thick, is inserted in the center of a standard IGU cavity (Figure 2) and a second low-e coating is added to the glass facing the newly created second cavity. To simplify assembly, reduce costs, and improve durability the new center glazing is held in place in the cavity but is not part of the sealant and spacer structure.

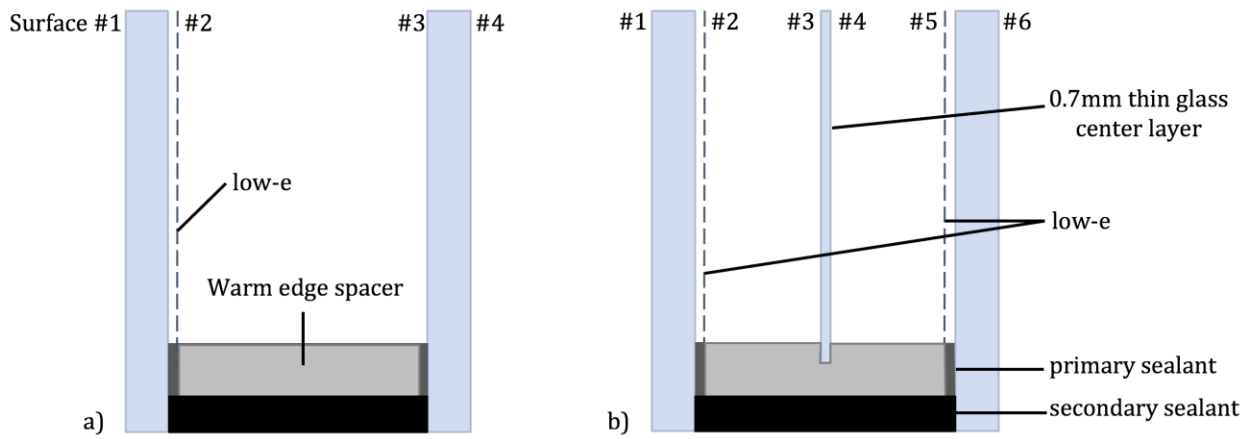

Figure 2. a) Typical double-pane IGU with 3mm glass and low-e on surface #2. b) Thin-glass IGU concept with 0.7mm center-pane and low-e on surface #2 and #5.

In this work, we first define the characteristics and performance of current typical residential windows through an examination of the National Fenestration Rating Council Certified Products Directory. With knowledge of the typical window, we determine the potential thermal performance impact of replacing typical glazing with thin-glass triple-pane glazing. Finally, with an understanding of the potential improvemnts to traditional performance metrics, such as U-factor, we examine the energy savings potential of the thin-triple glazing in residential buildings for three representative US climates.

THERMAL PERFORMANCE

We first define typical US residential windows and based on these windows determine the potential thermal performance of thin-glass triple-pane glazing retrofit into the typical frames.

Define Typical Window Construction

The National Fenestration Rating Council (NFRC) maintains a Certified Products Directory (CPD) of thermal performance metrics for US windows and doors. Products are certified in four year cycles so consideration of all the products within the CPD at a given time offers insight into market trends at that time. We accessed this directory in order to determine a representative, or typical, window being offered as of 2017 (Andersen 2017). Figure 3a and b show histograms of fixed and double hung windows binned into U-factors of 0.01 BTU hr^{-1} ft^{-2} F^{-1} and grouped by glazing type. The double-pane low-solar-gain (2P-LSG) product, which includes a 90% or greater Argon gas fill, is shown as the most commonly certified product for both window types. The performance of this product meets US ENERGY STAR and current IECC code minimums, so it's relatively high frequency in the directory is expected.

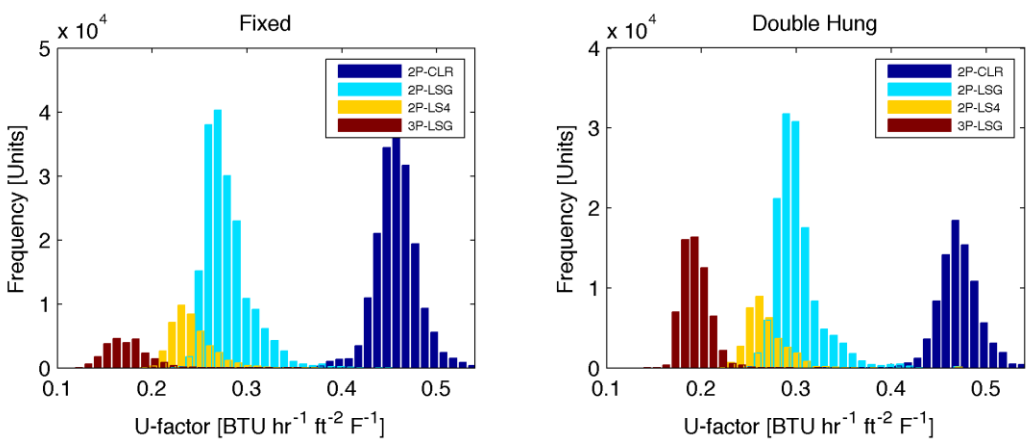

Figure 3. Histograms of (a) fixed and (b) double hung windows from the NFRC certified products directory (CPD) binned into U-factors of 0.01 Btu hr^{-1} ft^{-2} F^{-1} and grouped by glazing types of double-pane clear (2P-CLR); double-pane low-solar-gain low-e (2P-LSG); double-pane low-solar-gain with room-side (surface 4) low-e (2P-LS4); and triple-pane low-solar-gain low-e (3P-LSG).

We refine our review of the CPD to include only the 2P-LSG products as representative of typical construction. Figure 4 shows histograms based on frame type and spacer type of the 2P-LSG products. Vinyl frames and metal U-channel (U-type) spacers are the dominant constructions for both double hung and fixed windows. These window properties are therefore utilized for simulations in the following sections.

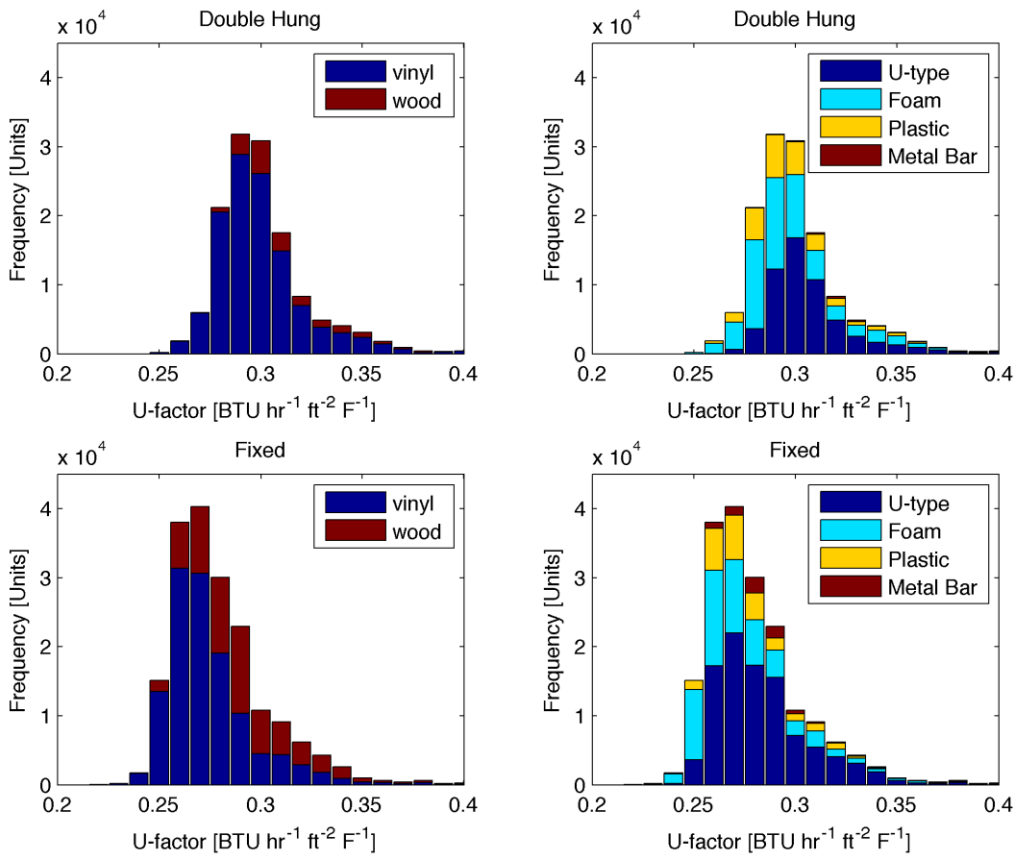

Figure 4. Histograms of NFRC certified products directory (CPD) certified fixed window and double hung products grouped by frame material type (a & c), and spacer types. Database accessed in 2017 (Andersen 2017)

The final piece we are able to define from CPD analysis on typical window construction is the gap between glass panes. A histogram of gap widths for double hung 2P-LSG products is shown in Figure 5. The results show that both the mean and median gap widths are approximately 0.50in. Thus, the 0.50in width is used in the following analysis. We were not able to obtain CDP data for fixed window gap width so the double hung results are utilized in our analysis for fixed windows as well.

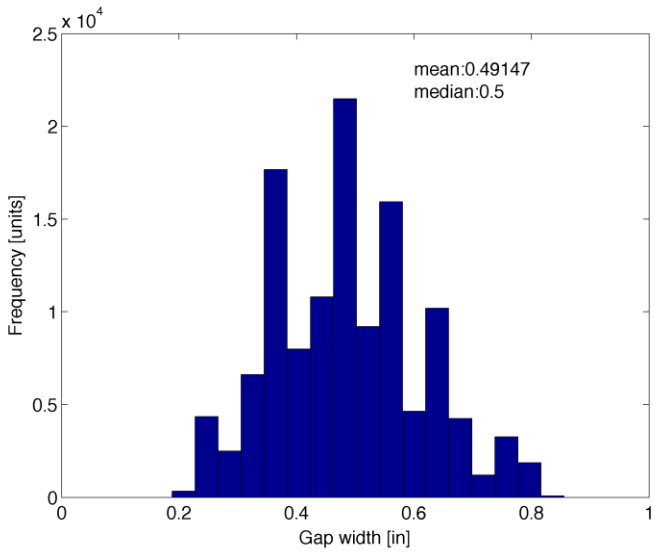

Figure 5. Histogram of gap width between glass for 2P-LSG Double hung products in the NFRC certified products directory (CPD).

The frame profile size and shape has a significant impact on overall window performance. The CPD does not contain information on either of these. For this reason, we have identified a vinyl double hung and picture window that we believe represent typical products in the US residential market. The sill profile of each frame is shown in Figure 6.

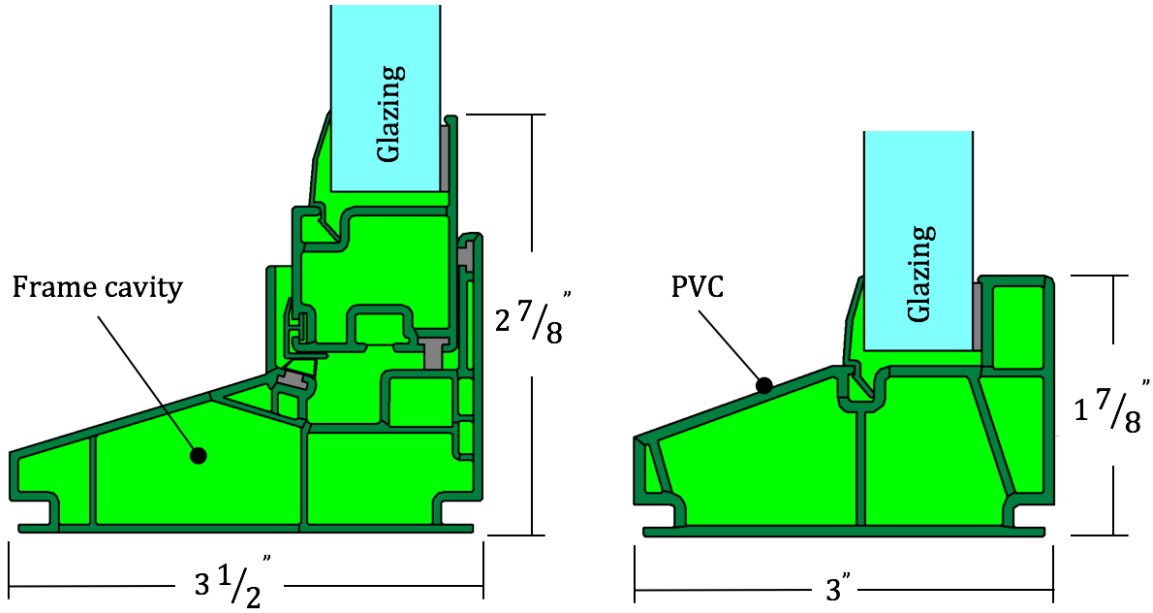

Figure 6. Sill profile of (a) double hung and (b) fixed vinyl (PVC) windows utilized in this study to represent typical products in the US residential market

The profiles shown in Figure 6 result in window component projected area break-downs of frame, edge-of-glass (EOG) and center-of-glass (COG) as shown in Figure 7. These areas are based on the NFRC standard window size of 4ft x 5ft. The EOG region is the area of glazing that is impacted by frame and spacer effects. It is defined as 2.5in into the glazing from the edge of frame.

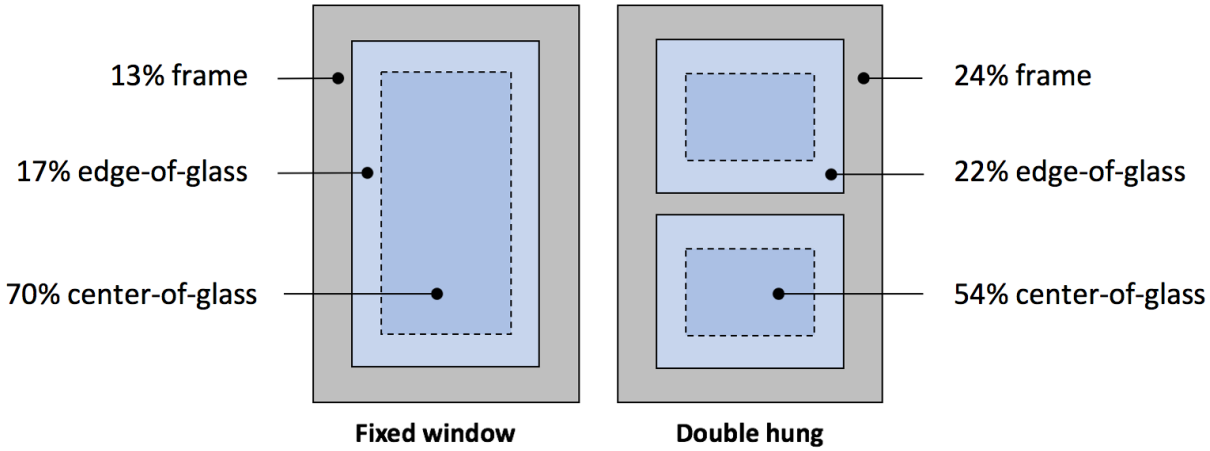

Figure 7. Window component area break-down for (a) fixed window and (b) double hung based on NFRC standard 48 in. x 60 in. window size.

A summary of the typical residential windows defined by our analysis of the NFRC CPD is given in Table 1. These windows are utilized as reference for the baseline performance and as the basis for determining the maximum potential performance with retrofit glazing systems.

Table 1. Summary of typical low-e residential window configuration

	Fixed Window	Double Hung
Size (W x H)	48 in. x 60 in.	
Projected area: Frame Edge-of-glass Center-of-glass	 13% 17% 70%	 24% 22% 54%
Frame material	Vinyl	
Spacer material	U-type	
IGU gap width	0.50 in.	
Glazing configuration	Double-pane low-solar-gain with 90% Argon gas fill (2P-LSG)	

Thermal Performance Potential

Several strategies for improving the COG thermal performance of typical windows are examined based on currently available technology. The baseline glazing of 2P-LSG Argon, as defined in the previous section, is typically sized at 0.74in IGU width. This size results from the typical 0.50in between-glass gap width and two layers of single-strength (1/8in nominal) glass. The parametric study of U-factor shown in Figure 8 demonstrates that triple-pane with thin-glass (3P-TG) and 95% Krypton gas fill offers the greatest performance potential over a wide range of IGU widths for all glazing configurations considered.

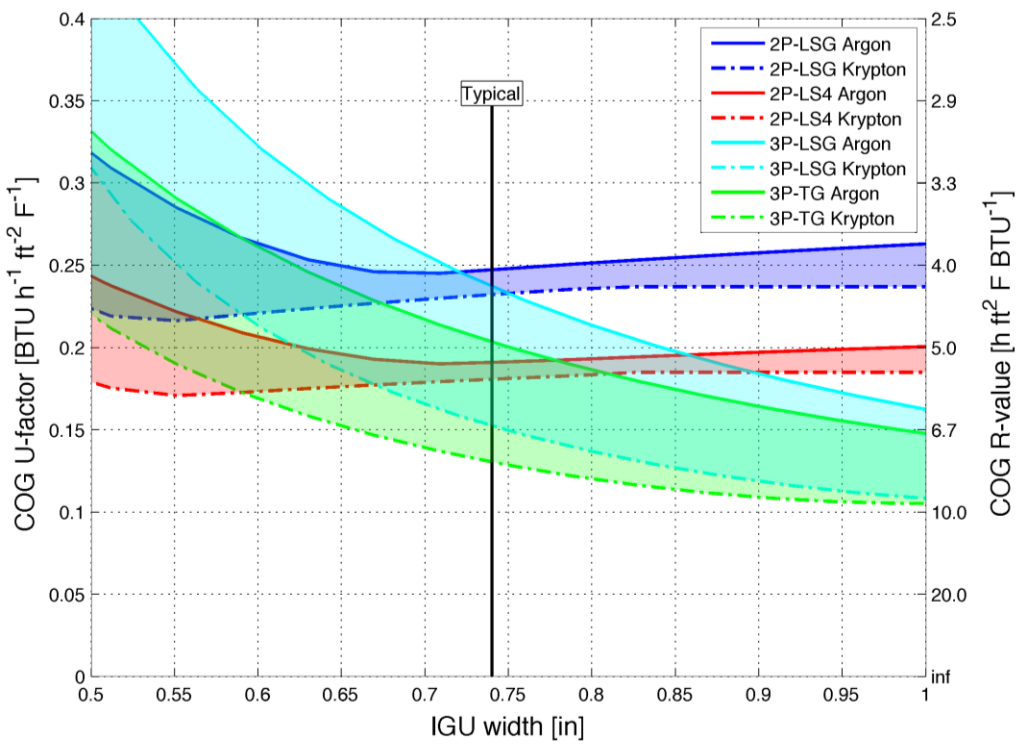

Figure 8. Center-of-glass (COG) thermal performance potential of glazing systems with between 95% Argon and 95% Krypton between-glass gas fill and single-strength (1/8in nominal) glass. 3P-TG uses 0.7mm glass thickness for center-glass.

Utilizing the spacer system and frame profiles defined in the previous section, the performance of whole window systems for a range of IGU widths is determined and shown in Figure 9 (a) fixed window and (b) double hung. This figure demonstrates the same trends as COG shown in Figure 8 but with performance impacts normalized by the framing and spacer systems. The thermal performance ranges of full windows were calculated assuming linear trends between COG and window performance, as described by the component modeling approach (Curcija 2008)

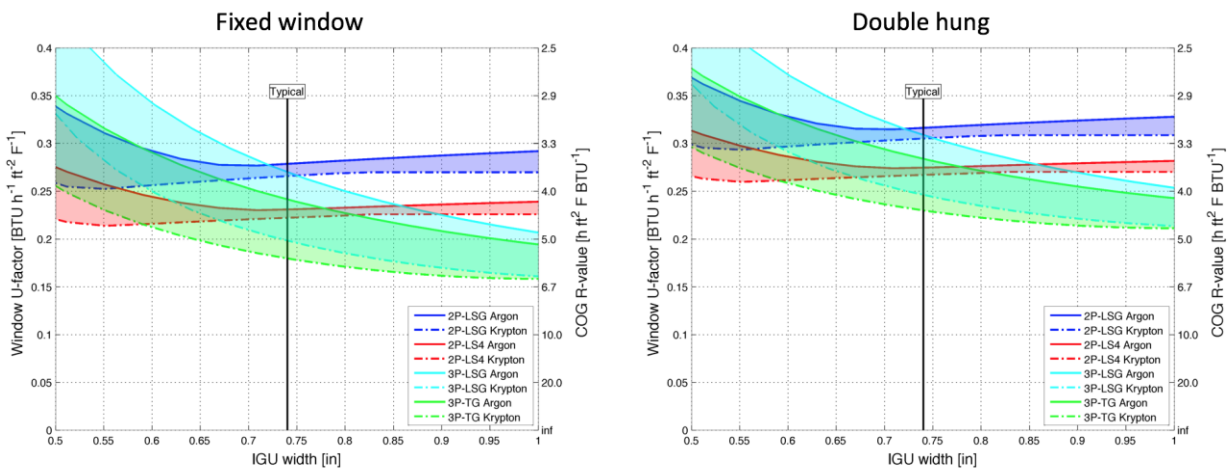

Figure 9. (a) Fixed and (b) Double hung full window thermal performance potential of glazing systems with between 95% Argon and 95% Krypton between-glass gas fill and single-strength (1/8in nominal) glass. 3P-TG uses 0.7mm glass thickness for center-glass.

There are several actions that can be taken for additional thermal performance improvements to typical windows without fundamentally altering the design of the frames themselves. Examples include foam filling cavities in vinyl frames, triple-silver low-e (emissivity less than 0.02) in place of the typical double-silver low-e (emissivity of approximately 0.04), and thermal low-

conductivity warm-edge spacer systems. Figure 10 shows the variations in average thermal transmittance of typical double hung and fixed windows to foam filling, low-e coating type (emissivities of 0.07, 0.04, and 0.02) with thin-triple glazing, and spacer type (aluminum bar, u-type, and foam). The variations in average demonstrate the sensitivity of each variable. Utilizing all of these techniques has the potential to decrease the U-factors shown in Figure 9 by up to 0.03 BTU hr^{-1} ft^{-2} F^{-1}. That means whole window U-factors of less than 0.14 for fixed and 0.18 for double hung are possible without any significant changes to current typical frames on the market.

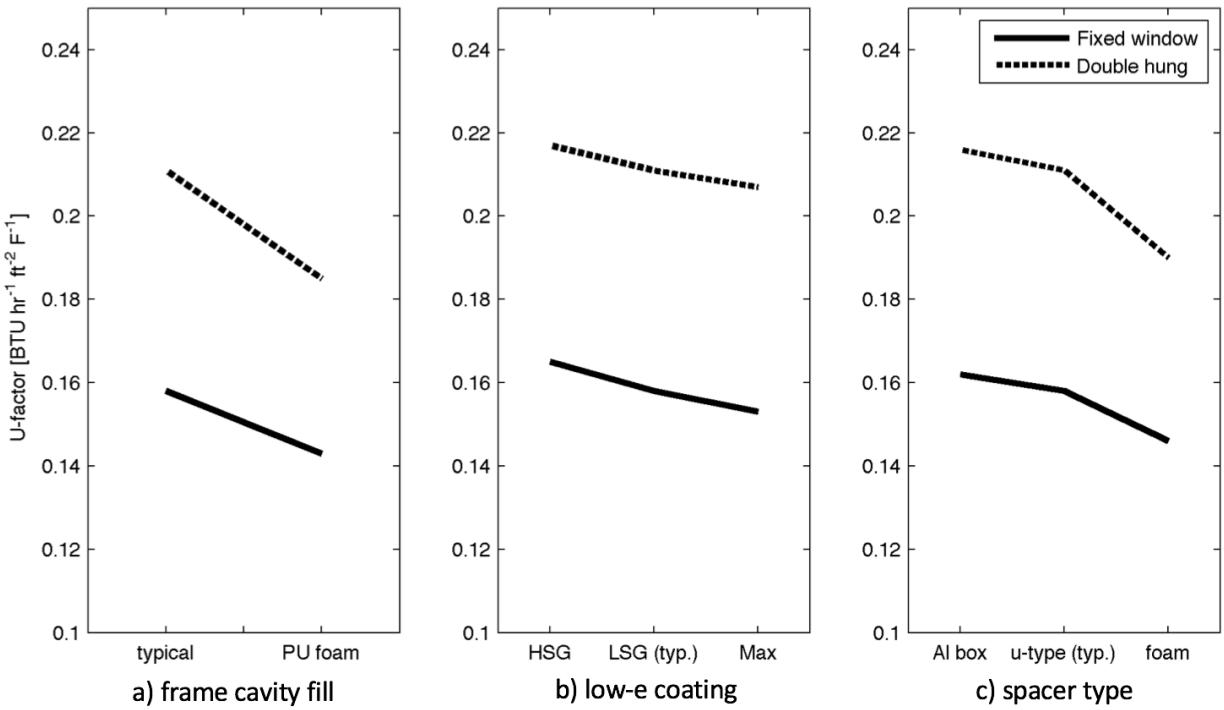

Figure 10. Average thermal transmittance of typical double hung and fixed windows with thin-triple glazing, displaying sensitivity to; a) frame cavity filling; b) low-e coating type (emissivity of 0.07, 0.04, and 0.02); and c) spacer type (aluminum bar, u-type, and foam).

ANNUAL ENERGY PERFORMANCE

U-factor is not the only performance metric of importance for building energy use associated with windows. Solar heat gain coefficient (SHGC) and air infiltration also play significant, if not larger, roles. Air infiltration is more associated with the type and build quality of the window, so is this section we assume a fixed air leakage area to isolate the synergies of window U-factor and SHGC on building energy performance. In addition to the intrinsic U-factor and SHGC of the window, measured annual energy use would also be impacted by the presence or absence of shades, and their use patterns. We address these issues in other related research (Burns, et. al. 2018 and Peng 2017).

Three different US climates are utilized to determine the energy savings potential of thin-glass window systems. Minneapolis, MN (4203 heating degree days (HDD); 417 cooling degree days (CDD)) is considered a representative heating dominated climate, Washington, DC (2537 HDD; 682 CDD) is a representative mixed climate, and Houston, TX (786 HDD; 1667 CDD) is a representative cooling dominated climate. For simplicity, we assume all windows in the simulated residential building are Double hung. This results in a "worst-case" scenario compared to Fixed windows since Double hung windows have higher U-factor and lower SHGC due to the relatively high frame-to-glass ratio. A summary of building model assumptions is given in Table 2.

Table 2. Detailed list of assumptions for model of typical house simulations in EnergyPlus

Parameter	**Residential building model**
Floor Area	2400ft^2 (223m^2) at 34.75ft x 34.75ft (10.6m x 10.6m)
House Type	2-story – one core and four perimeter zones

Foundation	Unheated basement (Minneapolis, MN) Slab-on-grade (Washington, DC & Houston, TX)
Insulation	envelope insulation levels are based on location (DOE 2012)
Infiltration	ACH_{50}=3 (Minneapolis, MN) ACH_{50}=5 (Washington, DC & Houston, TX) *ACH_{50} is defined as air changes per hour at 50 Pascal pressure difference
Window Area	15% (% floor area) 13% on North & South, 17% on East and West
Window Size	2.8m x 1.5m (windows divided vertically into two equal halves)
Window Distribution	4 windows per floor, distributed evenly and centered on the wall
HVAC System	Gas furnace & electric A/C (Minneapolis, MN & Washington, DC) Electric heat pump (Houston, TX)
HVAC System Sizing	Autosized for each window configuration
HVAC Efficiency	Annual Fuel Utilization Efficiency (AFUE) = 0.78 gas furnace, Seasonal Energy Efficiency Ratio (SEER) = 13.0 Air Conditioner
Thermostat Settings	heating: 72°F (22.22°C), cooling: 75°F (23.88°C) no setback
Internal Loads	number of people = 3 hardwire lights = 1.22 W/m^2 plug-in lights = 0.478 W/m^2 refrigerator = 91.01 W – design level misc. electrical equipment = 2.46 W/m^2 clothes washer = 29.6 W – design level clothes dryer = 222.1 W – design level dish washer = 68.3 W – design level misc. electrical load = 182.5 W – design level gas cooking range =248.5 W – design level misc. gas load = 0.297 W/m^2 exterior lights = 58 W – design level garage lights = 9.5 W – design level
Weather Data	TMY3 by location
Calculation Tool	EnergyPlus version 8.5

Figure 11 shows the impact of U-factor and SHGC on the combined heating and cooling source energy use (site-to-source conversion factors; Gas: 1.084, Electricity: 3.167) in the representative climates. Lines of constant total energy use in heating dominated and mixed climates, such as Minneapolis, MN and Washington DC respectively, are shown to be dominated by U-factor. Annual energy use in these climates is primarily heating. In these climates, the influence of SHGC is primarily seen when it exceeds 0.50. In cooling dominated climates, such as Houston, TX, both U-factor and SHGC significantly impact annual energy performance.

The performance of three double hung windows are indicated in the Figure 11 energy surface maps. These windows represent typical performance (2P-LSG), maximum performance with double-pane (2P-LS4), and performance with thin-glass triple glazing (3P-TG). The 3P-TG window shows potential total energy use reductions over typical 2P-LSG windows of 16% in Minneapolis, MN, 12% in Washington DC, and 7% in Houston, TX. This energy reduction comes primarily from heating energy savings. Greater energy savings is achievable by choosing glass coatings specifically designed to further reduce SHGC.

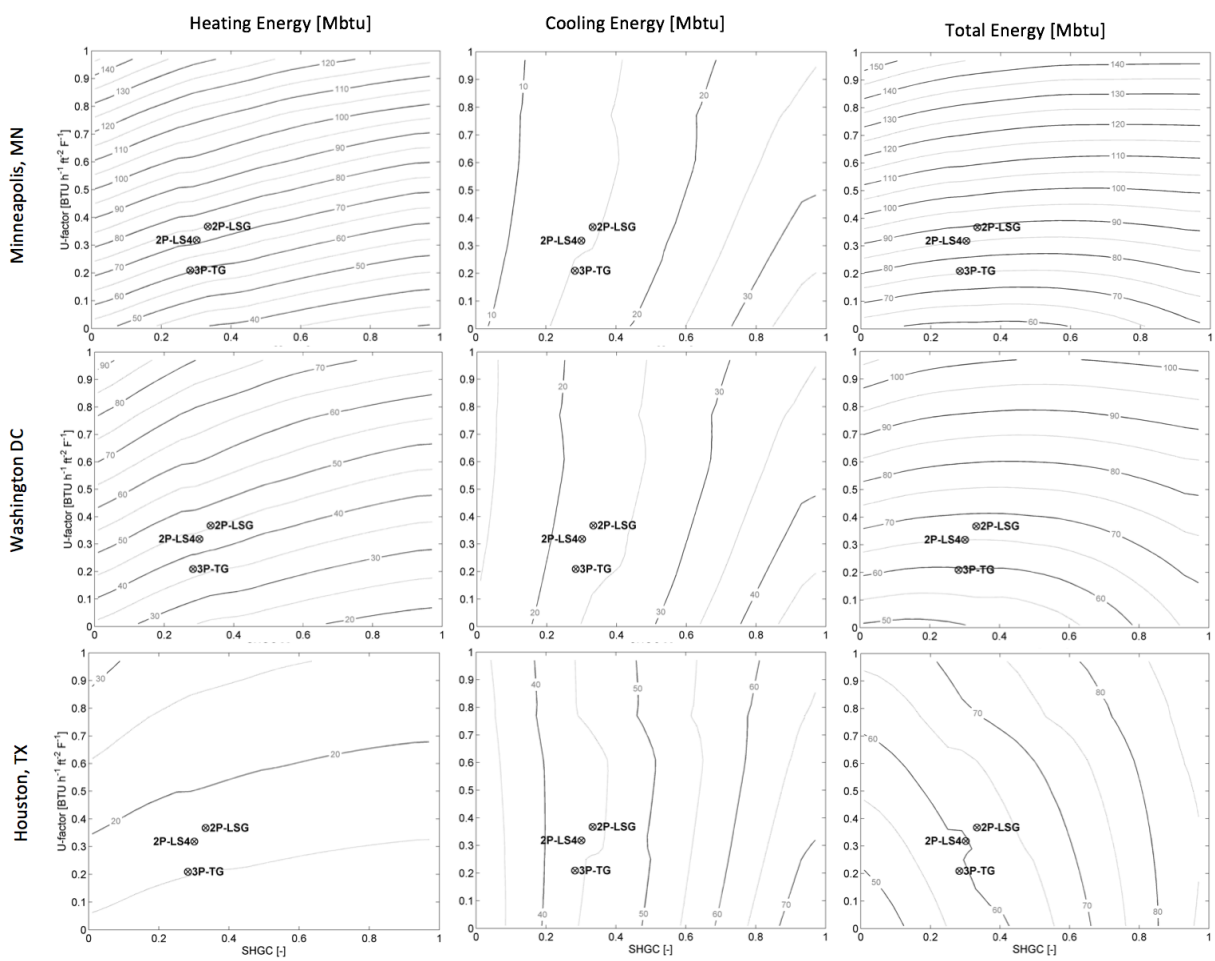

Figure 11. Heating, cooling, and total source energy use (MBtu) in; (a) heating dominated climate [Minneapolis, MN]; (b) mixed [Washington, DC]; and c) cooling dominated climate [Houston, TX]. Models are performed in EnergyPlus with the DOE residential prototype buildings and 2012 IECC building assumptions. The performance of typical (2P-LSG), surface #4 low-e (2P-LS4), and thin-glass triple pane (3P-TG) double hung windows are indicated.

CONCLUSIONS

Windows are often considered the weakest link in the thermal envelope, and are responsible for about 5 Quads, or approximately 10%, of building energy use. Therefore, windows offer a significant opportunity for building energy savings. One potential low incremental cost solution to increase window thermal performance is upgrading window glazing with a thin-glass triple-pane design that does not require modifications to existing frame and sash. In this work, we first defined the characteristics and performance of current "typical" residential windows through an examination of the National Fenestration Rating Council (NFRC) Certified Products Directory (CPD). With knowledge of the typical window, we determined the potential thermal performance impact of replacing typical glazing with thin-glass triple-pane glazing. Finally, with an understanding of the potential improvements to traditional performance metrics, such as U-factor, we showed the energy savings potential of the thin-triple glazing in place of typical windows in residential buildings is 16% in heating dominated climates such as Minneapolis, MN, 12% in mixed climates such as Washington DC, and 7% in cooling dominated climates such as Houston, TX.

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