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ABSTRACT

Windows account for about 5 Quads of US energy consumption or 12% of building energy use. After 20 years of public/private investment (from 1980 to 2000) in technology R&D, coupled with new rating and labeling organizations (NFRC) and with subsequent voluntary ENERGY STAR programs and tighter codes and standards, these windows using low-E/argon gas fill (~R3) gained a dominant market share and now account for >86% of all sales. This remarkable transformation of prior markets has stagnated, with triple glazing comprising less than 2% of all window sales in 2016. DOE estimates the national technical potential savings using triple glazed windows (~R5-7) at ~ 2Q annually, but manufacturers claim they would have to redesign their entire sash/frame inventory to accommodate the thicker, heavier insulating glass units (IGUs). R&D on vacuum glazing that could achieve these R values is not yet market ready. This paper describes a collaborative effort to transform window markets to the R5-7 insulating levels by introducing a novel packaging of existing technology elements, implemented as a "drop-in replacement" for current IGUs. The program involves working with supply chain partners (thin glass, low-E, new spacers, Krypton gas fill) with leading window manufacturers to initially deploy the technology and with market pull partners: building codes, utility rebate/incentive programs; builders targeting net zero and PassiveHaus designs, and with tighter northern climate zone ENERGY STAR criteria. The paper outlines the two-year program, now underway, to implement this transformation, with the goal of engaging other partners from amongst conference attendees.

Introduction – Problem Statement

It is well known that buildings account for ~40% of total U.S. energy consumption, and ~75% of electricity use. Therefore any attempt to dramatically reduce overall energy impacts, reduce carbon emissions and restructure the electric grid to a renewable energy future must necessarily understand and ideally change the role of the building sector in these end use patterns. Unfortunately, there is no single "silver bullet" solution in the building sector that will dramatically reduce energy use. The end use patterns change over time but are diverse with climate, building type and size. In support of the goal of providing thermal comfort for occupants in buildings nationwide, 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 ~4 Quads or approximately $40 billion in energy use. At the aggregate level this breaks down into the heating and cooling loads by sector shown in Table 1a:

Table 1a. Annual energy savings potential of residential and commercial window technologies (Arasteh 2006)

	Total Annual HVAC Consumption [2]	Window percent of HVAC Consumption, No Infiltration	
	Quadrillion Primary BTU (quads)[3]	% of Total	Window quads
Residential Heat	6.90	19%	1.30
Residential Cool	2.41	39%	0.94
Residential Total	9.31	24%	2.24

	Total Annual HVAC Consumption[4]	Window percent of HVAC Consumption, No Infiltration	
	Quadrillion Primary BTU (quads)	% of Total	Window quads
Commercial Heat	2.45	35%	0.85
Commercial Cool	1.90	28%	0.54
Commercial Total	4.35	32%	1.39

Table 1b. Annual energy savings potential of residential window technologies

Window Type	Energy Savings over Current Stock		
	Heat, quads	Cool, quads	Total, quads
Sales (Business as usual)	0.49	0.37	0.86
Energy Star (Low-e)	0.69	0.43	1.12
Dynamic Low-e	0.74	0.75	1.49
Triple Pane Low-e	1.20	0.44	1.64
Mixed Triple, Dynamic	1.22	0.55	1.77
High-R Superwindow	1.41	0.44	1.85
High-R Dynamic	1.50	0.75	2.25

Table 1c. Annual energy savings potential of commercial window technologies

Window Type	Energy Savings over Current Stock			
	Heat, quads	Cool, quads	Lighting, quads	Total, quads
Sales (Business as usual)	0.03	0.17	-	0.20
Low-e	0.33	0.32	-	0.65
Dynamic Low-e	0.45	0.53	-	0.98
Triple Pane Low-e	0.71	0.31	-	1.02
High-R Dynamic	1.10	0.52	-	1.62
Integrated Facades	1.10	0.52	1.0	2.62

This study also examined the technical potential savings of a variety of existing and emerging glazing and window technologies for the residential sector (Table 1b) and the commercial sector (Table 1c) and highlighted the conclusion that significant improvements in the heat loss of windows provided the path to the largest national energy savings.

Breaking the Logjam- the "Thin Triple" IGU

The "low-E window story" is a great technical and market success. Since its introduction in the late 1970's, low-e sales have steadily gained to nearly 90% of all IGU sales, see Figure 1 (Ducker 2018). The lack of a scalable and cost-effective follow-on technology solution for high-R windows to deliver additional savings, as outlined in Table 1, has been a nagging challenge for decades and state-of-the-art window technologies (Jelle, et al. 2012) have seen little adoption. Typical triple-pane construction has been viable since the early 1980's, but there has been no market driver for its refinement and adoption. We now describe a new program launched in 2017

with DOE support to address these issues and break this "logjam". As a technology solution, we have developed a "drop-in" replacement IGU that 1) has the potential to reach an insulating level of ~R10, 2) would require 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. This approach requires an additional layer of very thin glass, a Krypton gas fill and an additional low-e coating, each of which is market-ready and proven (see Fig 3). We review the technology involved and describe the program we have launched with window manufacturers to address the technical, business and market issues with the development and adoption of this approach, and the market pull activities we are working to align to further enhance the probability of success of the program.

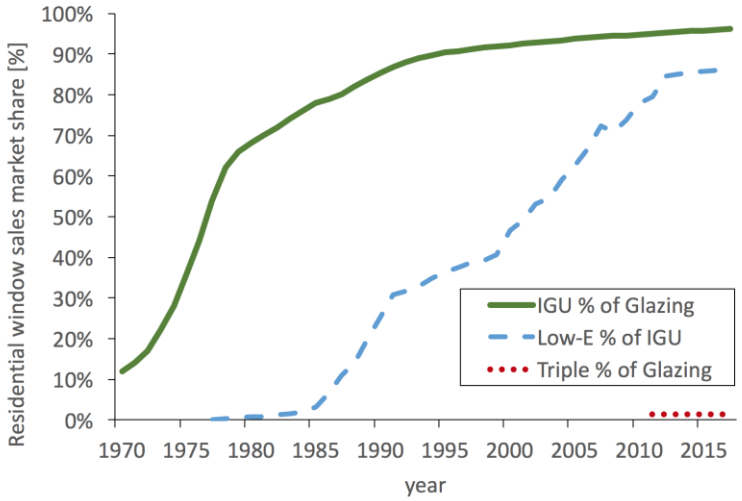

Figure 1. Residential window sales historical market share by year. Low-e shows a rapid rise in market penetration, while triple-pane market share is stagnant at around 1.4 percent.

Doubling Window Thermal Resistance: A Short Primer on Window Design

Overall window heat transfer is characterized by U-factor, a property that accounts for the intrinsic performance of the window construction (glass, spacer, sash/frame) and the effects of the air films on the indoor and outdoor surfaces. LBNL has developed software packages (Berkeley Lab WINDOW/THERM) that can accurately calculate the U-factor of a window with any glazing package inserted into any framing system. The software is usedly widely by NFRC and international code bodies. (WINDOW 2018). Insulating properties are also often referred to as thermal "resistance" values in R, where R = 1/U. We use this convention for convenience throughout this paper with two cautions; The R value of conventional insulations refers to the materials themselves, not including the inside and outside air resistance, which we include here. Furthermore; while the U-factor varies directly with heat loss and thus energy costs, the R varies as the inverse, so there are dimishing returns on energy savings, i.e. the energy savings from R3→R4 are similar to the savings from R4→R6 and from R6→R10.

Windows are complex assemblages of frame/sash, glazing systems, weatherstrip/seals and hardware. We focus here on two major components, frame/sash and the glazing system. The glazing system, includes an insulating glazing unit (IGU) with a spacer system with sealants, which separates the glazing panes. Because of the presence of the spacer and overlapping areas of sash/frame, the glazing is usually divided into the region that extends from the frame (edge of glass, or EOG) and the remaining part, center of glass (COG). For the purposes of calculating overall window thermal transmittance, U-factor, these three components of window (frame, EOG, COG) are calculated separately and combined into the overall U-factor using area weighting. In some parts of the world, such as Europe, glazing system area is not divided into EOG and COG, but instead linear thermal transmittance is calculated to account for the edge of glazing effects and its value is applied to the lenghth of the perimeter of glazing. Figure 2 shows typical area ratios of the three window parts for both fixed and double hung windows based on NFRC standard sizes. The large area ratios of frame to COG show that the performance of frame areas have a significant impact on the overall window performance. A drop-in replacement glazing can make a large improvement in the window thermal properties but is ultimately limited by the thermal properties of the existing sash and frame. Of course sash and frame can be redesigned with improved thermal properties but this is more costly and comples so in the short term our focus is on the IGU performance.

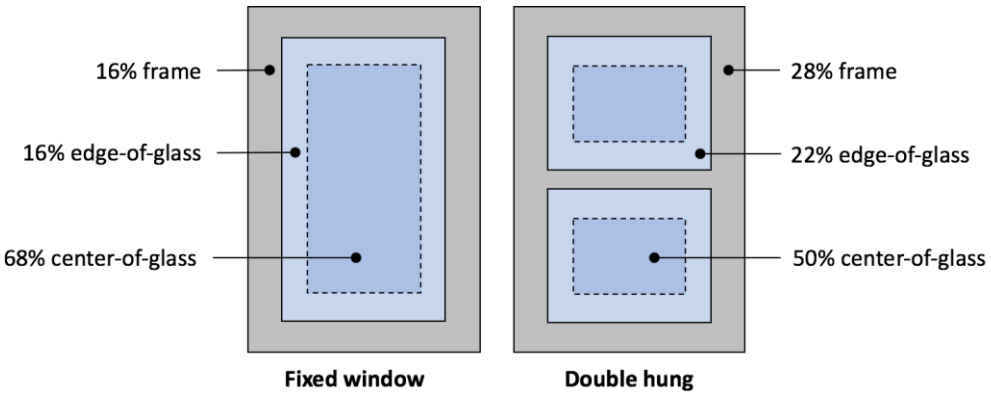

Figure 2. Typical area ratios for frame, edge-of-glass, and center-of-glass of NFRC sized fixed and double hung windows based on NFRC standard sizes. Note that as windows get larger, the COG glazing properties become more important.

COG thermal performance in traditional IGUs is determined by the combination of low-emissivity coatings, distance between glass panes, and the type of gas sealed between the glass. Some other options are the addition of glass layers with dynamic properties, such as electrochromic or thermochromic, however those are solar control technologies and do not affect the overall insulation value of the glazing. We do not discuss these “smart glazings” further in this paper although they could be added to the overall window and provide additional energy savings as noted in Table 1. Thin polymer films with low-E coatings are another option that is sometimes used in place of one or more glass layers. While these products were early market entries in the 1980s 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. 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. A complex glass-to-glass seal at the edge is needed to hold the vacuum over many years. VIG maintains the weight of traditional IGUs but with reduced thickness. A single manufacturer has offered these products over the last 15 years but costs remain relatively high, there are installation limitations, 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.

The "thin triple" concept proposed in this work can be thought of as a modified double, low-e IGU and its performance potential has been studied in depth. (Arasteh, Selkowitz, Wolfe 1989; Selkowitz, Arasteh, Hartmann 1991; Arasteh, Goudey, Kohler 2008) Starting with a conventional IGU, a piece of very thin glass is inserted in the center of the IGU cavity (Fig 3). Most residential glass is ~ 1/8 in (3 mm) thick; thin glass in our example is less than 1mm. A second low-e coating is added to the glass facing the newly created second cavity. The typical cavity with double-pane glazing is ~1/2 in (12mm) wide and filled with Argon, now the two thinner cavities, each ~1/4 in (6mm) wide, require a new gas, Krypton, to provide adequate insulating value. A final detail to simplify assembly, reduce costs, and improve durability is that the new center glazing is held in place in the cavity but is not part of the sealant and spacer structure.

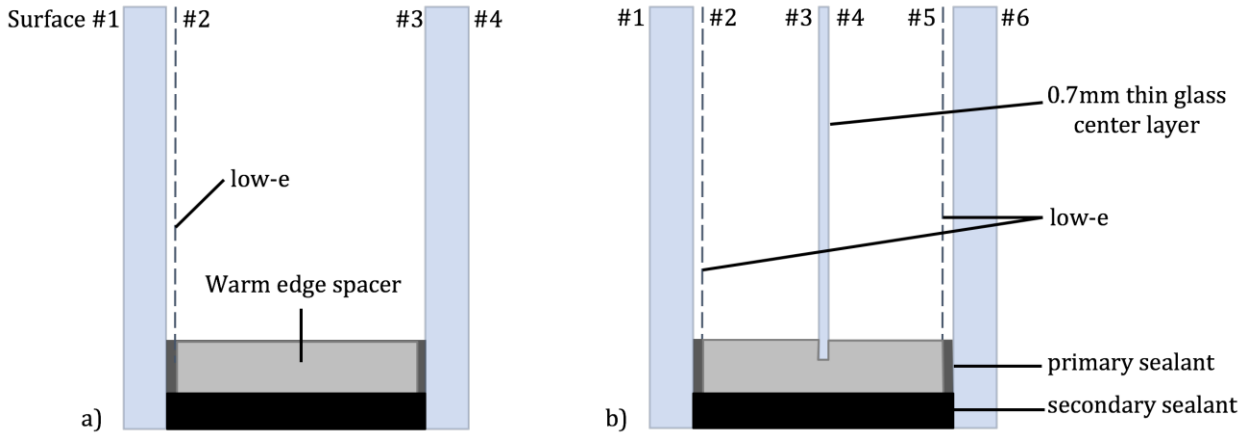

Figure 3. a) Typical double-pane IGU with 3mm glass and low-e on surface #2. b) Thin-glass IGU concept with 0.7mm center-pane and low-e on surface #2 and #5.

Figure 4 shows how the thin triple concept performs against the wide range of COG performance attainable with traditional IGU techniques, using the typical double-pane IGU width for reference. The majority of the market today is between the "2P-lowE" curves. These units have one low-E coating inside the IGU. The "2P-surf4" option adds a second low-E to the inner glazing on the room facing surface to provide modest additional insulating value. It is clear from the figure that manufacturers optimize the IGU width for double-pane with 95% Argon gas fill – the most commonly constructed IGU currently on the market. It is also clear from the data that a triple glazed unit with narrow gas spaces must switch from Argon to Krypton to provide the large, desired increase in R value, from R5 to almost R8.

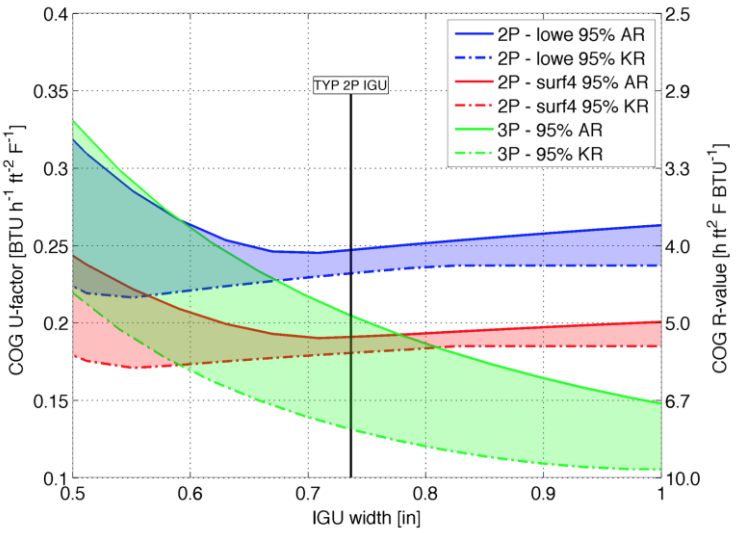

Figure 4. Center of glass thermal performance based on IGU width and gas fill. The performance ranges obtainable by double-pane low-e (2P-lowe), double-pane low-e with roomside low-e (2P-surf4), and thin-glass triple-pane low-e (3P) are shown. 3mm glass is used everywhere but center-pane of triple where 0.7mm glass is used.

As noted earlier the NFRC U-factor rating is a whole window value that includes sash/frame as well as IGU. The residential window market is dominated by two types of frame materials; wood and vinyl. Wood windows often incorporate an exterior facing cladding made from fiberglass or aluminum for weather resistance. The thermal conductivity of wood limits the thermal performance of wood frames to approximately R=2.5 [hr ft^2 F BTU^{-1}], while the construction techniques used to create vinyl products allows for a much wider thermal performance range, from approximately R=2.5 [hr ft^2 F BTU^{-1}] to highly-insulating foam-filled profiles with R=5 to 7 [hr ft^2 F BTU^{-1}]. Table 2 shows the thermal and solar performance of fixed windows utilizing a typical wood frame. Five windows are shown, ranging from low performing double-clear glazing to two high performance triple-pane low-e with differing IGU widths.

Table 2. Typical wood framed fixed picture window (PW) thermal resistance (R-value), solar-heat-gain-coefficient (SHGC), and condensation resistance (CR) from low performing double-clear to high-performance triple-pane low-e. The LSG option in window 5 shows that an R10 IGU can be achieved with a widening of each air gap in the IGU by .15”

						U-Factor [BTU hr^{-1} ft^{-2} F^{-1}]		PW		
Window	ID	Glass Panes	Glass Type	Gas	IG width (in) 3mm glass	COG	PW	R-value [hr ft^2 F BTU^{-1}]	SHGC [-]	CR [-]
1	2P-CLR	2	clear	Air	0.74	0.481	0.578	1.7	0.68	13
2	2P-LSG	2	low solar gain (#2)	Argon	0.74	0.239	0.270	3.7	0.24	54

3	2P-LS4	2	low solar gain (#2) high solar gain (#4)	Argon	0.74	0.194	0.226	4.4	0.24	45
4	3P-TG	3	low solar gain (#2, #5)	Krypton	0.74	0.128	0.173	5.8	0.21	63
5	3P-LSG	3	low solar gain (#2, #5)	Krypton	1.05	0.100	0.147	6.8	0.21	65

The concept of the "drop-in replacement" IGU simplifies adoption of the new technology but at some sacrifice in performance. As previously shown, windows incorporate three significant area types (frame, COG, and EOG). We explore here how use of existing frames will constrain overall performance. Figure 5 compares the COG thermal performance to the whole window thermal performance based on a typical wood frame with R=2.5 [hr ft2 F BTU-1]. The figure shows that a COG performance much better than that obtained by our triple-pane IGU designs will not result in much whole window performance improvement without further enhancements to the frame. As noted earlier, a larger window will show better results as the glazing area plays a more important role in overall properties.

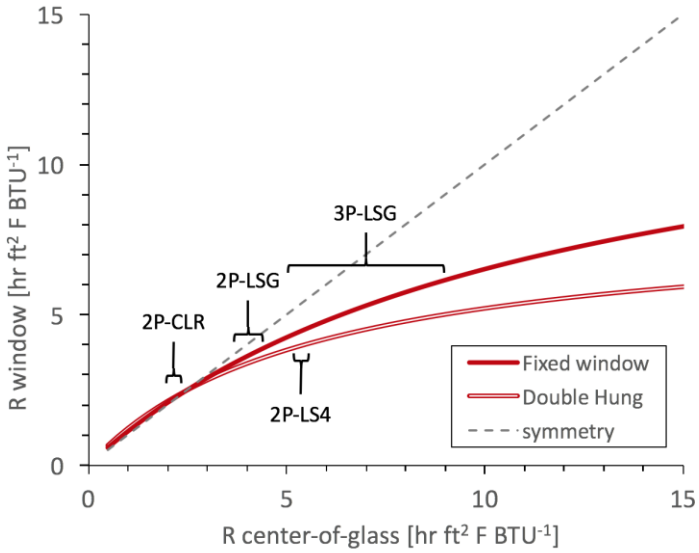

Figure 5. Center-of-glass thermal performance compared to NFRC standard sized fixed and double hung windows with typical wood frames. The center-of-glass thermal performance ranges of double-pane clear (2P-CLR), double-pane low-solar-gain low-e (2P-LSG), double-pane low-solar-gain with room-side surface low-e (2P-LS4), and triple-pane low-solar-gain low-e (3P-LSG) are highlighted.

Windows of varying materials and design are available from hundreds of manufacturers. Investigating the thermal performance of windows from the NFRC certified products database (CPD) demonstrates the above findings of performance ranges with actual manufacturer's products. Figure 6 shows frequency plots of NFRC certified fixed and double hung windows separated into the same four glazing types. Note that the CPD contains listings of all products certified for sale, but does not represent an accurate picture of actual sales. The peaks of each glazing type align with the performance ranges shown in Figure 5 above. The wider range of

performance from the CPD is explained by the wide variations of the glazing coatings and frame design/performance.

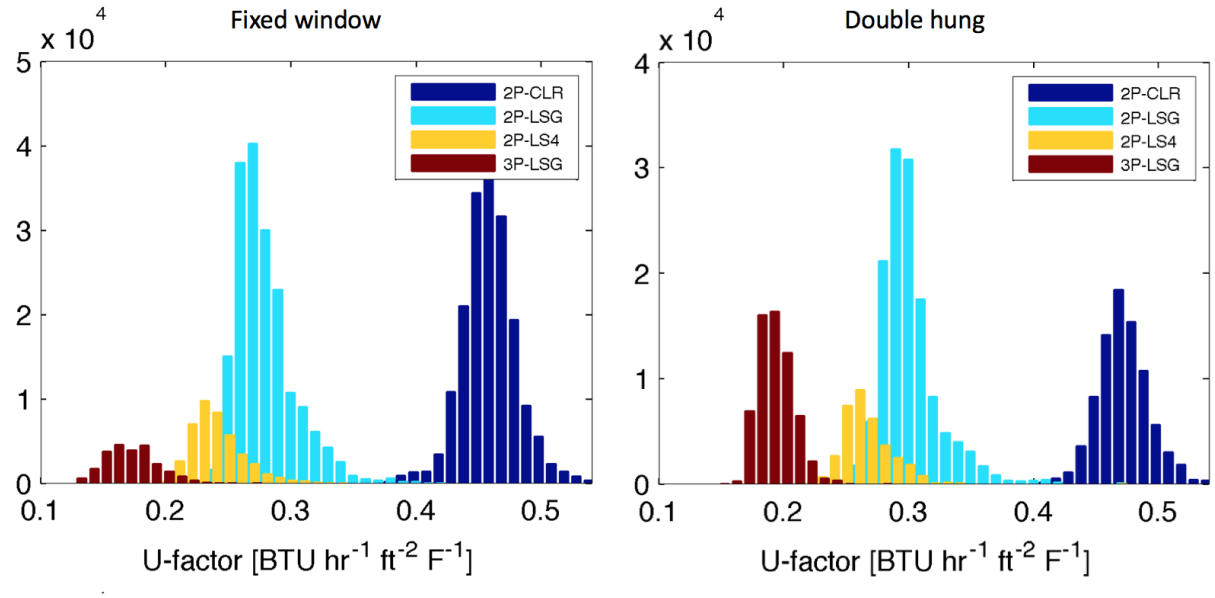

Figure 6. Frequency plots of NFRC certified fixed and double hung products based on the glazing type. 2P-CLR: double-pane clear, 2P-LSG: double-pane low-solar-gain low-e, 2P-LS4: double-pane low-solar-gain with room-side surface low-e, and 3P-LSG: triple-pane low-solar-gain low-e. Source: EPA

Energy Performance and Operating Cost

The energy use associated with windows in residential buildings can primarily be attributed to two performance metrics; thermal transmittance (U-factor) and solar heat gain coefficient (SHGC). (In this analysis we set aside air leakage through the window elements and the installation which can be estimated separately from the U and SHGC.) In heating climates, a higher SHGC allows more solar gain to enter the building thus reducing net heating energy use. In the summer the solar gain will contribute to increased cooling energy use. Figure 7 shows the impact of these two metrics on the heating energy use in the cold climate of Minneapolis, and the combined heating and cooling energy use in the mixed climate of Washington DC.

Lines of constant heating energy use in cold climates, such as Minneapolis, are shown to be linearly proportional to U-factor and SHGC. Reductions in energy use can be achieved over the entire range of U-factor and SHGC by proportional reductions in U-factor and increases in SHGC. The five windows presented in Table 2 are shown in Figure 7, along with a line indicating the IECC 2012 code compliant window performance. In addition to the intrinsic 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)

In mixed climates, such as Washington DC, lines of constant combined heating and cooling energy use are nearly independent of SHGC up to approximately 0.5. This results in reductions to energy use being solely dependent on U-factor. The minimally code compliant

window in this case has nearly constant energy in the typical range of SHGC obtained by the example windows. Note that the cooling impacts could be further reduced with other technologies not yet in common use, for example smart glass or active shading.

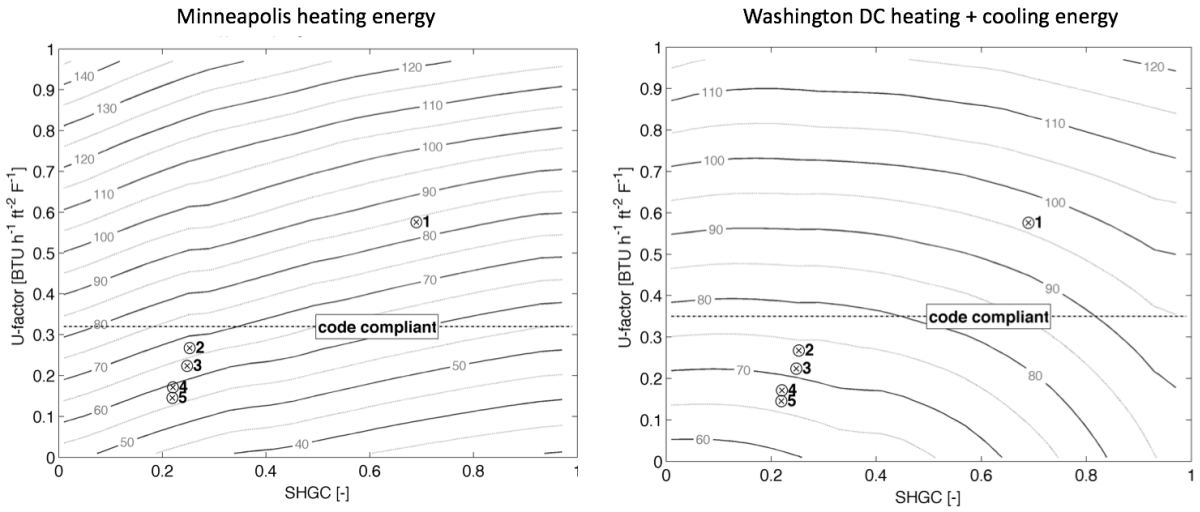

Figure 7. Energy use (MBtu) associated with heating in cold climate (Minneapolis) and heating plus cooling in a mixed climate (Washington, DC). Models are performed in EnergyPlus with the DOE residential prototype buildings with 2012 IECC building assumptions. The performance of code compliant windows is indicated along with the windows from Table 2.

"Cost effectiveness" and "paybacks" are often the first questions asked for new efficiency options, which we argue later is an unnecessary limitation that may be overcome by addressing other performance features but it is still useful to calculate "ballpark" values for these parameters. We have estimated the incremental manufacturing costs of various improvements to window thermal performance using the IGU designs described above. Glass, coatings, gas fill, and the assembly (including spacers) costs are each itemized in Table 3. The largest glass cost is in thin-glass at $1 per sf, and the largest coating cost is for surface #4, or room side facing low-e which is more costly that the sputtered low-E coatings inside the IGU. Argon fill costs are nearly negligible, while Krypton fill costs are relatively low and based on $0.50 per liter with waste of 3 percent. The thin-glass triple pane is shown to have incremental manufacturing costs/sf of $2.81 and $2.30 over 2P clear and 2P low-e respectively.

Table 3. Estimated IGU manufacturing costs from representative window configurations

	IGU construction			IGU cost per SF				
Window #	# Panes	Glass Type	Gas	Glass	Coatings	Gas	Assembly & Spacers	Total
1	2	clear	Air	$1.00	-	-	$2.00	$3.00
2	2	low solar gain (#2)	Argon	$1.00	$0.50	$0.01	$2.00	$3.51
3	2	low solar gain (#2) high solar gain (#4)	Argon	$1.00	$1.50	$0.01	$2.00	$4.51
4	3	low solar gain (#2, #5)	Krypton	$2.00	$1.00	$0.31	$2.50	$5.81
5	3	low solar gain (#2, #5)	Krypton	$1.50	$1.00	$0.81	$3.33	$6.64

*lsg: low-solar-gain low-e; hsg: high-solar-gain low-e

Thin-glass triple-pane windows (#4) are able to have a lower potential manufacturing cost than optimized conventional triple-pane (#5) because of the added investment for #5 required in frame re-design, additional frame and edge materials, manufacturing investment for new products, and additional inventory.

The heating and cooling energy use data from Figure 7 combined with the component costs from Table 3 allows us to begin to estimate the annual energy cost and simple payback of each window type. Table 4 shows the simple payback for each window type in heating dominated (Minneapolis, MN) and cooling dominated (Houston, TX) climates assuming a 1.9x markup from manufacturers to consumers and constant energy prices over time. Both the payback over 2P clear, typical of retrofits, and 2P low-e, typical of new construction, are shown.

Table 4. Simple payback of representative windows in a typical house based on energy savings in heating dominated (Minneapolis, MN) and cooling dominated (Houston, TX) climates

	Minneapolis, MN		Houston, TX	
Window #	2P clear baseline (Window 1)	2P low-e baseline (Window 2)	2P clear baseline (Window 1)	2P low-e baseline (Window 2)
1	-	-	-	-
2	1.3	-	1.5	-
3	3.6	25.8	4.4	71.0
4	6.0	25.0	7.5	48.4
5	7.4	27.4	9.5	56.9

Table 4 illustrates the importance of defining the base case condition. When the base case is clear double (typical of retrofits to existing stock) then the payback times are reasonable. The very short paybacks going from double clear to double low-E also helps to explain the market transformation one sees in Figure 1. The 7 – 9 year payback of an optimized conventional triple design (#5) is viewed by many as too long, but the 5-7 year payback of thin-glass triple IGU (#4) is more appealing. The paybacks using low-E as baseline, as one would find in much new construction, present a different set of challenges addressed in the next section. Performing the simple payback analysis in several other climates throughout the U.S. (Figure 8) with the clear double base case also looks promising across all climates.

Driving rapid market adoption can then be viewed as pursuing two parallel pathways: 1) improving the conventional “cost effectiveness” criteria outlined above, and 2) increasing the market value for product attributes that are known to have some degree of market recognition, e.g. thermal comfort. The estimated payback periods for highly insulating windows can be significantly reduced by a combination of strategies to reduce cost: by new technical innovations, by a learning curve in manufacturing, by changes in the supply chain and, while the market is maturing, by offering incentives based on energy savings. The most efficient use of those incentives would come at the manufacturer level, before their retail supply chain mark-ups are applied. This has proven effective with some efficient light bulb programs and storm window products so it might be examined for these products as discussed later.

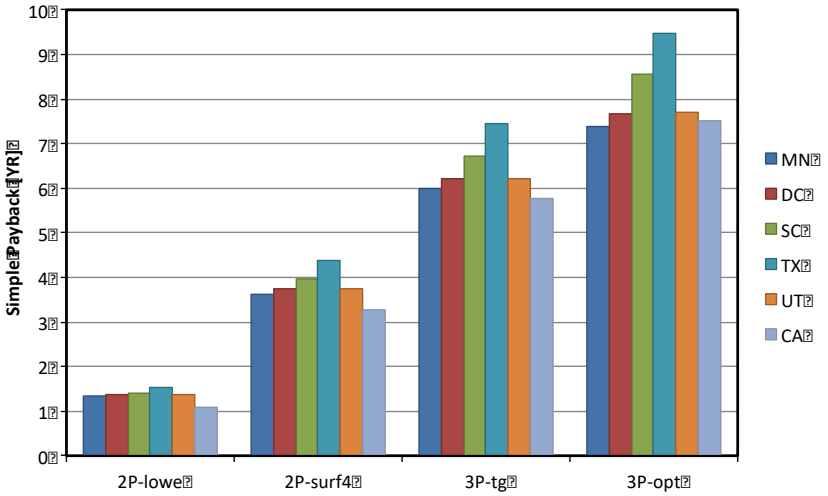

Figure 8. Simple payback over a double clear window based on current incremental cost estimates. MN: Minneapolis; DC: Washington DC; SC: Charleston; TX: Houston; UT: Salt Lake City; CA: Los Angeles.

Transforming Window Markets

In the almost 40 year trajectory of evolving window product offerings a variety of strategies have been used to advance the market for energy efficient. Most market transformation (MT) programs are built on the premise that there are existing commercially available energy efficient products, but due to a variety of "market failures" the purchase and utilization of those products occurs at a rate that is far lower than desired. The energy efficiency literature has many examples of the types of market failures that impede the widespread adoption of new energy efficient products and a range of strategies that have been used to address them. For example, transforming the residential lighting market to CFLs and then to LEDs has been the subject of many papers at ACEEE meetings over 20+ years. A much smaller number of papers have examined the challenges of transforming window markets. A series of papers beginning in 2000 (for example Ward, Suozzo, Eto 2000; Mihlmester et al 2000; Jennings, Degens, Curtis 2002; Cerce, Stanley, Johnson, 2002) studied strategies to increase market share of ENERGY STAR windows. Indeed, not only has the market share of ENERGY STAR windows increased since 2000 (note the rise in low-E market share after 2000 in Figure 1) but in some states tighter energy standards "locked-in" thermal performance properties that were even stricter than ENERGY STAR, driving further enhancement of those requirements in several regions in the U.S. Over 85% of windows sold nationally today are ENERGY STAR so it no longer represents a target to strive for. Those requirements can be met in every climate with variants on double glazed, low-E windows. An attempt in 2012 to tighten the requirements in the Northern Tier to effectively require triple glazing was halted by political pressure from the window industry, in part because it was still addressing the financial crises brought on by the recession and it argued it did not have the resources to update and retool manufacturing lines. The EPA "Most Efficient" program for windows requires R5 windows (triple glazing) but has not attracted significant attention as can be seen by the market share data in Figure 1. From the manufacturer's perspective, retooling to offer triple glazing is costly and risky. On the demand side, the decision-making processes in the "market" and the supply chain are complex, the energy impacts

are not always immediately noticeable and other benefits, e.g. comfort, are difficult to correlate to specific products. The result is a largely stagnant market dominated by double glazed, low-E windows as illustrated in Figure 1.

After analysis and exploration of these issues we developed a Market Transformation strategy that employs combined demand side and supply side measures. On the supply side we want to make it "easier" for a window manufacturer to transition from their current R3.3 double glazed window to an R5-7 triple glazed window using a high performance, affordable, drop-in replacement glazing element as described earlier. On the demand side we have attempted to marshal all the traditional MT program elements- training and education, rebates and incentives, demonstration projects, enhanced benefits, new ENERGY STAR targets, early adopter markets and enhanced codes and standards. While the initial focus is North and Central climate residential applications, both new and replacement, these approaches can be modified to have applicability for severe southern climates and for commercial buildings as well.

Integrated Program Strategy for a New Highly Insulating Window

What are the performance requirements for an "ideal" energy efficient window? DOE multiyear plans have referenced performance in two different ways – in terms of the thermal properties of the windows, e.g. R7, R10, R15, and in terms of an overall energy balance, e.g. energy neutral in winter heating mode where solar gain equals or exceeds thermal losses. This latter definition still requires a highly insulating unit as noted earlier.

While several different technologies have the potential to meet these requirements, the thin triple is the only one that we believe will meet the cost and acceptance requirements of our "drop-in" replacement approach. We fully expect that in a much longer time frame new innovations may appear and become market standards. But in the 5-10 year "near term" time frame we believe our drop-in replacement approach has the best chance to transform markets. The designs we described above have been simulated extensively and many have been built and tested in our laboratory to confirm their thermal performance attributes. However, a series of technical and business challenges remain that are the focus our ongoing project. We outline a sampling of these to illustrate the technical, business and cost challenges to launching the "thin triple" concept as a mainstream product.

Technology Push: Technical Challenges

Unlike the case of aerogels that require fundamental innovation on the intrinsic manufacturing process, or VIG that require further extensive production engineering and investment, further work on durability acceptance and some sash redesign, the "thin triple" concept is based on novel use of elements that are available today in price and volume to launch into early markets. We outline the three key technical challenges being addressed by the DOE-funded program at LBNL.

Thin glass: The design is dependent on volume availability of "thin" glass with price points and performance features that are suitable for mass production of the final IGU. This glass has been historically available for some time but largely for applications such as cell phones

where cost was not a market concern and in size and volumes that were very different from windows. However, the rapid market dominance of ever-larger flat screen TVs drove glass manufacturers to develop much larger and lower cost thin glass available in much greater volume. While there are new challenges with very thin glass – e.g. handling, cutting, shipping, etc., all of these have been solved by the LCD television industry and can be readily adopted by window companies. There are other challenges unique to windows such as tempered glass, that must be further explored, but we see no fundamental obstacles to use of thin glass in windows. The only way to fully resolve the remaining challenges though is to "learn by doing" and engage with manufacturers to build and test units.

Krypton gas: Krypton is required to replace some or all of the argon due to the smaller IGU gap sizes and the need to maintain low thermal conductivity. Krypton is extracted from air and is a commodity product but to date at relatively low volumes, as it is often a byproduct of oxygen/nitrogen gas production and cost has been unstable. Five years ago the costs were high due to competing uses such as Halogen light bulbs. LEDs have now replaced halogen lamps though, and other aerospace uses of Xenon generate Krypton as a byproduct, so costs have effectively dropped by a factor of 10 since our study 5 years ago, making Krypton economically viable for window use. Improved filling techniques (i.e. faster, less waste) are needed but can be developed once window companies show interest in the technology.

IGU design: The IGU design with thin glass "held-in-place" in the cavity is novel for the industry and there are a number of practical issues that must be resolved in design and for automated manufacture. We believe each of these is solvable with smart engineering once a commitment is made to address them. This is best done with the existing industry key players-window manufacturers who will commit to making the new products, trusted component suppliers and the companies who make today's automated IGU assembly lines.

Our goal is to see a new generation of high performance insulating windows reach the market place at scale and a cost that will promote widespread adoption. Thus, the resolution of each of these technical issues must be addressed from the pragmatic perspective of a window company choosing to offer a product for sale, not from the perspective of research team or even a utility incentive program. It takes a major investment in funding and corporate resources for a company to offer a new product line, and the reward/risk equation that guides those decisions must be carefully addressed. The program we have set up involves each of these supply side industry partners across the full supply chain, working both with a large national window company and a small specialty window company who each address both new and retrofit markets. The goal of these collaborations is to reduce the risk and cost of market introduction by rapidly addressing the remaining technical issues noted above, identifying any new challenges and addressing each with a market-viable solution.

Program Strategy: Market Pull

The last 20 years of trends in window sales makes a convincing case that in a "business-as-usual" environment without some "intervention" there will be no significant change in market sales of highly insulating windows and the ~2Q annual window heating cost will likely continue into the future. However, we want to design a market pull program that will create lasting change

in the market and not simply have sales of enhanced products disappear once the program is removed. The program we envision includes some shorter term market stimulation activities such as field demonstration projects and incentives by utilities, and/or government to build recognition of the value of the products, and longer term we expect that ENERGY STAR recognition and even new codes and standards based on the inherent cost-effectiveness of the approach will sustain growth without further incentives. This phase of the program also includes a focus on early adopters such as developers of Passive Homes and Net Zero Energy homes.

We outline below some of the activities now underway that we expect will help build market interest, recognition and demand for these new window products. Each of these is a task or project collaboration now underway or planned as part of the DOE-supported program.

Quantifying Energy, Demand and Carbon Savings from New Windows: Extensive energy analysis has been undertaken in the past for many climates. Further exploration of cost impacts including time of day rates, the effect of demand changes for winter peaking utilities, and carbon savings will have value to different potential institutional partners.

Cost Impacts: The window markets have complex and varied supply chains and are served by a small number of large manufacturers and much larger number of smaller manufacturers. The manufacture and sales costs of each of these vary widely. By further exploration each of these we can help utilities better explore the impact of potential upstream programs to reduce consumer costs. These should be feasible given the nature of the "drop-in" glazing replacement. Thermally improved windows can reduce HVAC system sizing as well as the layout and cost of duct systems. These may have first cost benefits, if they can be demonstrated to builders that impact construction cost and market value.

Thermal Comfort: People like large windows for view and connection to the outdoors but on the coldest days a large window presents a thermal comfort challenge. Even if average interior air temperature is acceptable the radiant effects of cold glass and thermal downdrafts can make space near the window uncomfortable and unusable, which sometimes results in the use of space heaters or turning up the thermostat to higher settings in winter. We will demonstrate with field tests that the R5-7 windows we envision would not have these problems, thus enhancing the marketing story for these investments.

Early Adopters: Builders of Passive Homes today require windows that typically in the R5-7 range. Finding suitable windows is a challenge in the U.S. and many are now imported from Europe so the thin triple product should provide new domestic options. Developers of new Net Zero Energy Homes also have an extra incentive to promote efficiency investments up to the marginal cost of installing solar power. We are exploring window performance in cold and moderate climates where the worst-case conditions will be cold, cloudy weather where minimal thermal loss windows can help achieve building performance targets. Modeling, field testing and demonstration houses will be studied to address these performance issues.

ENERGY STAR Requirements: The EPA ENERGY STAR program is in the process of reviewing the current specifications and plans to issue proposed new requirements by the end of 2018 for adoption in 2019. ENERGY STAR targets are based on what is commercially available

and cost effective. The designs we are developing should make it possible for ENERGY STAR to justify a significant tightening of thermal requirements in the Northern zone. Meeting ENERGY STAR specifications has been a key driver of technology adoption for manufacturers in the past.

Codes and Standards: Several entities are looking at tighter thermal requirements for windows to meet aggressive 2030 energy and carbon targets. We have worked with California teams who are considering tighter requirements and providing associated incentive payments. The California Association of Building Energy Consultants held meetings in 2017 (CABEC 2017) to explore the role that improved windows could play in meeting overall performance goals. One proposal under consideration was to make available up to $1500 per home to new home builders to achieve specific reductions in energy use. Simulation studies suggested that all new R5-7 windows could meet that whole house goal. For a home with ~300 sf of window area this translates into ~$5.00/sf window rebate which almost pays for the incremental cost of the windows (see Table 3). Canada has launched an aggressive program (ref) with the aspirational goal of reducing window U-factor to .21 Btu/hr-Ft^2 (1.2W/m^2K) by 2025 and .14 Btu/hr-Ft^2 (0.8W/m^2K) by 2030. The intent is to support R&D for new product development as well as market transformation activities. Workshops were help in 2017 and 2018 and a formal program is to be announced later in 2018.

Utility Programs: The Green Ontario Fund (GreenOn) has already launched a rebate program to promote window replacement to meet its carbon savings goals, offering a $500 rebate per "opening" (max $5000 per home) for windows that meet U < .14 Btu/hr-Ft^2 (0.8W/m^2K) performance targets. Needless to say, this rebate has attracted significant market attention. NEEA is studying the opportunities to launch a market transformation program in the Northwest, CEE has been sponsoring workshops and discussions to determine the level of interest by utilities, and other utilities in the U.S. have enquired about the status of the high-R window program we have launched.

Summary and Next Steps

The U.S. window market today represents a remarkable transformation to products that use about 50% of the energy that was typical of early 1980s products, but windows still account for ~4 Q of energy use at an annual cost of $40B. The technology to convert windows to net energy neutral products exists in prototypes and niche market products but is not available in volume at competitive prices. We outlined a DOE-industry partnership to capture the ~2Q of heating energy lost by windows. The partnership involves a technology push component based on refinement and market introduction of a novel, highly insulating "thin triple" glass product that can be incorporated into almost any existing window frame and can be fabricated at modest added cost. A companion market pull program engages a wide range of traditional market transformation actors and programs to build the demand that will encourage industry investment in the new designs. Two window manufacturers and four component suppliers are engaged, as are a number of utilities, energy efficiency organizations, and government entities with the goal of reaching mainstream markets in the next two years.

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