High-Performance Windows – More than just a Pretty Hole in the Wall

Katherine A Cort and Theresa L Gilbride
Pacific Northwest National Laboratory, Richland, Washington[1]

ABSTRACT

As more stringent building energy codes and better insulation products combine to yield better performing walls, window efficiency is coming into sharper focus. The U.S. Department of Energy has supported several projects through its national laboratories to improve the thermal performance of windows. At Pacific Northwest National Laboratory (PNNL) in Richland, Washington, the PNNL Lab Homes, two fully monitored identical side-by-side manufactured homes, have been used to test the performance of several window improvements including triple-pane windows, storm windows with low-emissivity (low-e) coatings, smart automated interior insulated shades, and exterior shading products. Findings will be presented on these studies, along with impacts. For example, PNNL's Lab Home research on low-e storm windows has helped to support a new ENERGY STAR certification, industry standards, and utility incentives. Preliminary findings will also be presented on current Lab Homes experiments focusing on exterior shades. The session will also present findings from related field studies and a market assessment of emerging high-efficiency windows technologies and discuss some of PNNL's planned field studies that will focus on validating the benefits and costs of the emerging thin triple-pane high-R window.

Introduction

Residential buildings in the United States currently require 8 quadrillion Btu/yr of energy for heating and cooling – that accounts for more than 40% of primary residential energy use (EIA 2015). Thermal transfer through residential windows accounts for approximately 10% of a building's energy use (Hart et al. 2019). Over the past 20 years, window replacement and window attachment retrofit technologies have been developed that significantly increase the options available to home builders, homeowners, and utilities when considering new windows or upgrades of existing windows. These options include high-R windows, including high-R thin triple-pane insulated glass units (IGUs), and various window attachment options like low-e storm windows (panels) which can be attached to the interior or exterior of the window, interior insulated cellular shades, and exterior shades.

This paper reviews past and current window-related research, including experimental evaluations conducted by Pacific Northwest National Laboratory (PNNL) at its PNNL Lab Homes in Richland, Washington, and discusses how results of these studies are supporting utility incentive and market transformation programs.

Photos of these technologies are provided in Figure 1 and the savings potential and application of these technologies are summarized in Table 1. The savings potential is based on a range of field, lab, and modeling studies, and is focused on heating, ventilation, and air-

[1] The mailing address for both authors is PNNL, P.O. Box 999, Richland, WA 99352, with respective e-mails: Katherine.cort@pnnl.gov, and Theresa.Gilbride@pnnl.gov

conditioning (HVAC) savings. These studies are discussed and referenced in the remaining sections of this paper.

Figure 1. High Performance Window Technologies include (from left to right) exterior low-e storm windows, insulated cellular shades, exterior shades, and thin triple-pane IGUs. *Sources*: PNNL, AERC, and LBNL.

Table 1. Savings Potential and Application of Windows Technologies Reviewed

Technology	Application	Annualized Savings Range
Low-e Storm Windows	Over single-pane or double-pane clear glass windows in all climate zones.	10-33% (annual HVAC savings)
Insulated Cellular Shades	Applicable with all types of new or existing windows in all climate zones.	10-34% (annual HVAC savings)
Exterior Shades	Best applications include unshaded south- and west-facing windows in cooling season (all climate zones).	12-25% (Cooling HVAC savings)[a]
High-R Thin Triple-Pane IGUs	New build or replacement windows in all climate zones.	7-16% (total energy savings)

[a]Not annualized and based on preliminary cooling season savings from 2019 Lab Homes study currently underway.

Glass alone is a poor insulator, with a thermal conductance of approximately 1 Watt per meter Kelvin (W/mK). Single-pane windows have an overall heat transfer coefficient (U-factor) of about 5.5 W/m^2K or 1 $Btu/hr\ ft^2F$, which is only R-1. The insulating properties of IGUs are described in terms of U value or its inverse, the thermal "resistance" value in R, where R = 1/U-factor. Sandwiching layers of trapped gas between layers of glass gives windows increased insulation value. Clear glass also transmits between 70% and 90% of its light and heat at all wavelengths, including infrared (IR) radiation so low-emissivity coatings that reduce radiation can improve a window's performance.[2] Several new windows technologies, including thin-glass krypton-filled triple-pane insulated glass units (IGUs) and vacuum insulated glass units, hold promise of greatly improving primary window efficiency.

[2] Lawrence Berkeley National Laboratory's International Glazing Database. Version 45.0. Accessed 3/7/2016 at https://windows.lbl.gov/materials/igdb/.

Window attachment technologies can improve the thermal and optical properties of the window via coatings (e.g., storm windows with low-emissivity coatings) or coverings (e.g., blinds or shades) that decrease solar heat gain, increase the reflectance of the window in IR wavelengths, and decrease the amount of thermal conduction or convection between indoor spaces and the outdoors. With automation or scheduled manual operation, operable shades and blinds can add a dynamic performance element to conventional windows, allowing solar gains when beneficial during the winter and reducing solar gains in the summer.

Previous Field Research and Case Studies

Table 2 summarizes findings related to high-R window and high-efficiency window attachment performance and associated energy savings based on recent case studies, energy simulations, and field studies. One of the most recent high-R window studies (Hart et al. 2019) includes a series of energy simulations that focused on assessing the energy-savings potential of a "drop-in" thin triple IGU in comparison to the "typical" double-pane residential window. The study demonstrated that, due to improvements in U-factor and other performance metrics, thin triple-pane windows have the potential to cut energy use in residential buildings by approximately 16% compared to typical double-pane low-e windows in heating-dominated climates such as Minneapolis, Minnesota. A number of field demonstrations and energy simulation studies focusing on low-e storm windows and insulated cellular shades have also demonstrated year-round savings in multiple climate zones.

Table 2. Summary of selected case studies focused on high-R windows and window attachments

Study	Description and Findings
Low-e Storm Windows/Panels	
Atlanta case study (2-year study) (EERE 2013) DOE, Quanta, Larson	A retrofit field study compared single-pane wood-framed windows with and without low-e storm windows in ten occupied homes. • ~15% heating energy reduction • ~2% to 30% cooling reduction (highly variable) • 17% reduction in overall home air infiltration
Philadelphia multifamily case study (EERE 2013) DOE, Quanta, Larson, NAHB, AGC Flat Glass, NSG-Pilkington	A retrofit field study compared old clear-glass storm windows with low-e storm windows over single-pane, metal- framed windows in two large multifamily buildings. • 18%–22% reduction in heating energy use • 9% reduction in cooling energy use • 10% reduction in overall apartment air leakage
Pennsylvania weatherization technical support (Zalis et al. 2010) DOE, Birch Point Consulting	An energy simulation modeling study compared 37 homes with range of window types in 7 climate zones • 12%–33% overall HVAC savings
Chicago case study (Drumheller et al. 2007) DOE, HUD, NAHB Research Center, LBNL	A retrofit field study compared single-pane wood-framed windows with and without low-e exterior storm windows in six low-income homes. • 21% reduction in overall home heating load • 7% reduction in overall home air infiltration • Simple payback of 4 to 5 years
Insulated Cellular Shades	
Modeling cellular shades in multiple climate zones	An energy simulation modeling study estimated savings from cellular shades covering multiple window types in 13 climate zones.

(Metzger et al. 2017) Silicon Valley Power, APPA	• 10-34% HVAC savings for small existing homes with large window area • 3-29% HVAC savings for larger homes with large window area • Savings similar for double- and triple-cell cellular shades
Denver case study (Zirnhelt et al. 2015) Hunter Douglas and RMI	An energy simulation modeling study examining residential savings from cellular shades covering multiple window types in Denver, Colorado. • Denver Max Cooling Savings – 25% • Denver Max Heating Savings – 10% • Peak electrical demand reduction of 9% for new homes
LBNL Modeled Estimates (Curcija et al. 2013) DOE	An energy simulation modeling study examining five cellular shade product types over single-pane and double-pane windows in 12 climate zones. • Savings vary by product types, climate zones, and baseline, but annual energy dollar savings ranged from $280 to $470 for cellular shades
Window Retrofit Solutions (Ariosto and Memari 2013) PHRC	An energy simulation modeling study that examined multiple window attachments, including cellular shades • Reduction in U-factor of 38% for cellular shades
High-R Primary Windows	
Thin triple-pane savings potential (Hart et al. 2019) DOE, LBNL	An energy simulation modeling study compared thin triple technology to common double panes in NFRC certified products database. • 16% annual savings in heating dominated climate • 12% annual savings in mixed climates 7% annual savings in cooling-dominated climate
Thin Triple Infrared Imaging (Fresno, CA, 2019) DOE, LBNL, CEC	Retrofit field study used IR camera to compare double-pane low-e, vinyl framed windows with thin triple-pane windows showing thermal improvements in windows with thin triple-pane IGUs (all else constant).
State-of-the-Art Windows Review (Jelle et al. 2011) NTNU, DOE, Research Council of Norway	An energy simulation modeling study comparing double pane, clear glass, aluminum-framed windows with high-r windows including: • Thin triple (with a stretched film center pane) and aerogel glazing had the lowest center of glass U-value of 0.28 and 0.30 W/m^{2}K, respectively. Commercially available vacuum-insulated glass has a center of glass U-value of 0.70 W/m^{2}K.

NFRC = national fenestration rating council; LBNL = Lawrence Berkeley National Laboratory; CEC = California Energy Commission; IR = infrared; NTNU = Norwegian University of Science and Technology; HUD = U.S. Department of Housing and Urban Development; NAHB = National Association of Home Builders; Quanta = Quanta Technologies, Inc.; Larson = Larson Manufacturing Company; RMI = Rocky Mountain Institute; APPA = American Public Power Association; PHRC = Pennsylvania Housing Research Center

PNNL Lab Homes Research

Although field data and case studies provide valuable insights related to the savings potential of window attachments in specific applications or climate zones, the variability that occurs due to home type and occupancy behavior can make it difficult to isolate the savings from the window attachment and project these savings to alternative circumstances. To address this, PNNL set up the Lab Homes to provide a side-by-side platform for precisely evaluating energy-saving and grid-responsive technologies in a controlled environment. The PNNL Lab Homes are two factory-built homes that have identical floor plans (see Figure 2) and were set up side-by-side with identical solar orientations on the PNNL campus in Richland, Washington, (Widder et al. 2012). Each Lab Home has seven windows and two sliding glass doors, for a total of 196 ft^2 of window area. HVAC conditions can be controlled in the Lab Homes to appropriately tailor and calibrate building simulation models to account for relevant interactions, occupancy, climate zones, and baseline characterizations. To be representative of typical existing residential homes, clear double-pane windows were installed as the baseline technology. The “experimental home” is retrofitted with the fenestration technology under evaluation, while the matching “baseline home” remains unaltered. The experiments listed in Table 3 were conducted in the PNNL Lab Homes. These include studies on low-e storm windows, insulated cellular shades, exterior shades, and triple-pane windows.

Figure 2. The PNNL Lab Homes consist of two manufactured homes with this identical floor plan set up side by side with the same solar orientation at PNNL’s Richland campus in eastern Washington state.

Table 3. Summary of Lab Homes Window and Window Attachment Studies

Study	Description and Findings
Low-e Storm Windows/Panels	
Exterior Low-e Storm Windows (Knox and Widder 2014) DOE, Larson	Clear glass, metal-framed, double-pane windows • 10.1% ±1.4, annual HVAC savings
Interior Low-e Insulating Panels (Peterson et al. 2015) DOE, Quanta, NEEA	Clear glass, metal-framed, double-pane windows; Panels covered 74% window area. • 7.8% ±1.5, annual HVAC savings
Insulated Cellular Shades	
Triple Cell Cellular Shades (Peterson et al. 2016) DOE, Hunter Douglas, NEEA	Shades over clear glass double-pane windows compared to uncovered windows and windows covered with vinyl venetian style blinds (varied shade settings/operations): • Cooling HVAC = 10-14% savings (±2-7%) • Heating HVAC = 11-18% (±3-8%)
Double Cell Cellular Shades (Cort et al. 2018) DOE, Hunter Douglas, BPA, NEEA	Cellular shades under various settings compared to vinyl venetian blinds (over clear glass double-pane windows). Shades/Blinds always pulled down or partially down (i.e., “typical use”) • Cooling HVAC = 6-13% savings (±1%) • Heating HVAC = 2-9% (±2%) West-facing shades optimally operated or all shades optimally operated • Cooling HVAC = 10-15% savings (±1-2%) • Heating HVAC = 7-9% savings (±1%)
Exterior Shades	

Exterior Roller Shades, 1% Openness Factor (PNNL preliminary 2019) DOE, Springs Fashion	Exterior shades over west- and south-facing clear glass double-pane windows compared to uncovered windows and windows covered with venetian blinds • 12-25% cooling HVAC (preliminary)
High-R Triple-Pane Windows	
Highly-Insulating Triple Panes (Widder et al. 2013) DOE	Triple panes compared to clear glass, metal-framed, double-pane windows • 16% annual savings in heating dominated climate • 12% annual savings in mixed climates 7% annual savings in cooling-dominated climate
(Larson = Larson Manufacturing Company; Quanta = Quanta Technologies, Inc; BPA = Bonneville Power Administration; NEEA = Northwest Energy Efficiency Alliance)	

Low-e Storm Windows

The traditional storm windows of the past consisted of a single piece of clear glass (or plastic) that was mounted in a wood or aluminum frame that was installed on the outside of an existing window. This window retrofit design focused on reducing thermal conduction and, to a limited extent, convection. Modern storm windows feature new designs that can be openable or fixed in place and are intended to be permanently mounted. In addition to conduction and convection, radiation is an important mechanism for heat gain and heat loss through windows. Low-e storm windows include a low-e pyrolytic coating that lowers the emissivity of glass for certain wavelengths, effectively reducing heat transmission through the storm window (see Figure 3). Uncoated glass typically has an emissivity of around 0.84, while low-e coated glass can have an emissivity of 0.16 or lower. When interior heat energy tries to escape to the colder exterior during the winter, the low-e coating reflects the radiative heat back to the inside, reducing the overall heat loss through the glass. The reverse transfer of heat occurs during the summer (Culp et al. 2015).

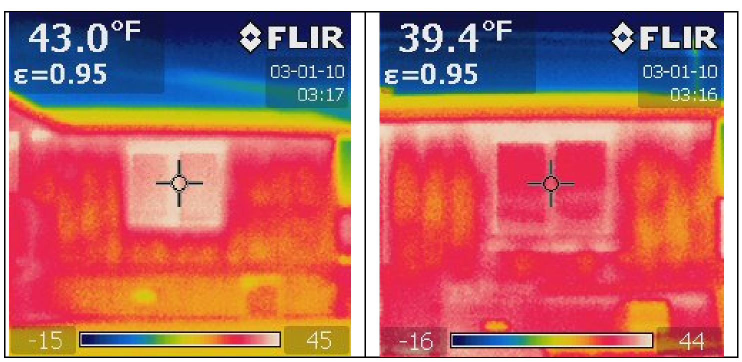

Figure 3. IR images of the exterior of a home without a low-e storm panel (left) and with a low-e storm panel (right); the light color of the window area in the home on the left shows significant heat transfer through the glass. Pictures were taken on February 2, 2015, when the average outdoor temperature was 34ºF.

Over a two-year period in 2013-2015, PNNL conducted a series of experiments in the Lab Homes to evaluate the thermal performance of both interior and exterior low-e storm windows when attached to a double-pane clear-glass window. Measured HVAC savings due to the exterior storm windows averaged 10.5% for the heating season and 8.0% for the cooling season for identical occupancy conditions (Knox and Widder 2014). Based on these seasonal experimental results, the annualized savings were simulated to be approximately 10% (see Table 3). For the interior panel testing, the annualized HVAC savings were estimated to be 8% based on seasonal experimental results. Note, however, that due to limitations on the manufactured size of the interior storm windows, the sliding doors were not covered during the interior storm windows experiment, which resulted in only 74% of window area coverage during the test. During these experiments, thermocouple sensors on the surface of the glass depicted significant temperature differentials between the windows with and without storm windows attached, as depicted with the IR images shown in Figure 3 (Petersen et al. 2015). Because the primary windows on the Lab Homes are very air tight to begin with (i.e., very little infiltration) the storm panels resulted in only a modest reduction in infiltration for these experiments. In contrast to these results, testing in the field (in occupied homes) has shown significant reductions in infiltration when storm panels are installed (see Table 2).

Insulating Cellular Shades

Within the interior window coverings category, honeycomb cellular shades (see Figure 4) typically provide the highest added R-values because of their layered or concentric designs. Introduced in the 1980s, cellular shades are designed to trap air inside pockets that act as insulators. This design can increase the R-value of the window covering and reduce the conduction of heat through the window that it covers. Insulating shades can also impact solar heat gains. The insulating air pockets can include a layer of metallized Mylar that lines the air pockets, which minimizes conductive and radiant heat transfer, similar to the effect that a low-emissivity coating has on windows. Savings can be increased if the coverings are managed properly, by raising and lowering the shades at the appropriate times of day using either manual or automated means.

PNNL conducted multiple Lab Homes experiments to evaluate the thermal performance of triple- and double-cell cellular shades under various operation scenarios during the 2015–2017 heating and cooling seasons. These cellular shades were equipped with the Hunter Douglas motorization and scheduling technology, which allowed researchers to evaluate the thermal improvement under different operation schedules. To evaluate the full functionality of the shades and associated automation schedules, PNNL tested the cellular shades in comparison to a residential building without window attachments and in comparison to a home with the windows covered with standard vinyl venetian blinds. Experiments were also conducted with shade operation scenarios designed to reflect baseline conditions and energy use in the home when shades are used in a manner typical of many residential users (i.e., “typical use” settings), as informed by D&R International’s 2013 behavioral study (Bickel et al. 2013). The savings are summarized in Table 3.

Figure 4. Hunter Douglas semi-opaque double-cell cellular shades which were tested in the PNNL Lab Homes, 2016-2017. Photo on right shows the amount of filtered natural light that enters the room when the shade is fully drawn down.

Some of the key findings from the studies are summarized below (Cort et al. 2018):

- High-efficiency cellular shades have significant energy-saving potential during the summer cooling season (25% HVAC savings compared to a home with no window coverings), but this savings decreases considerably if the larger view windows of a home remain uncovered during the day, particularly if these are west- or south-facing windows.
- High-efficiency cellular shades have significant energy-saving potential during the winter heating season, but at least some of the larger south- and/or west-facing shades should be operated (e.g., up during day and down at night) to fully realize these savings benefits.
- Cellular shades under typical use scenarios (i.e., some shades up and some shades down) do produce HVAC savings; however, when the high-heat-gain windows (i.e., large windows on west and south sides of a home) are left uncovered, the cooling season HVAC savings dropped from 25% to 5%.
- In all seasons and operation scenarios, cellular shades out-performed the typical vinyl blinds (2%–15% average HVAC savings attributed to cellular shades).
- Commercially available automation could be coupled with thermostat setbacks to enhance residential demand-response programs and improve occupant comfort.

Exterior Shades

Exterior shades can come in various forms, including louvered shutters and roller shades. Exterior shades can protect existing windows from weather and provide solar heat gain control in the summer months (i.e., cooling season). They often can be adjusted to provide both view and privacy, as well as glare control. Exterior shades can be effective at blocking solar heat gain before it hits the building envelope or window, which makes this technology an effective energy-saving measure in the cooling season months. To examine the performance and comfort implications of exterior shades, PNNL is currently conducting a series of Lab Homes experiments applying black fabric[3] motorized exterior shades with a 1% openness factor (see Figure 5). Shades were installed over two large west-facing windows and one large south-facing window in the experimental test home, while interior vinyl blinds were used to shade these same windows in the control home. The shades/blinds are kept down throughout the day. Experiments

[3] Graber Lightweaves exterior shades, Springs Window Fashion.

are ongoing, but preliminary results suggest that the application of exterior shades on these three windows resulted in cooling HVAC savings ranging from 12%-25% when compared to a home that uses interior vinyl venetian style blinds for these same windows.

Figure 5. Exterior shades are installed in the PNNL Lab Homes. The exterior shades provide privacy and reduce glare, while allowing views during the day. (Photo at right shows view through the shades from inside the home).

Triple-Pane and Thin Triple-Pane IGUs

The thermal performance of traditional primary window IGUs is determined by the combination of low-emissivity coatings, the distance between the glass panes, and the type of gas sealed between the glass panes. Adding layers of glass and gas can certainly increase performance. Triple-pane windows research by PNNL in the Lab Homes showed that conventional triple-pane windows can yield energy savings of about 12% annually (11.6% heating savings and 18.4% cooling savings in Richland, Washington) when compared with double-pane clear glass windows (Widder et al. 2012). The experiment also showed that the triple-pane windows provided more even temperatures throughout the home and warmer interior window surface temperatures during the winters (e.g., 76°F compared to 69°F in the baseline home). Standard triple-pane windows have been available for decades but have experienced very slow market uptake. Adding layers of glass adds weight and thickness to the insulated glazing unit (IGU) which can lead to costly retooling for the many window manufacturing plants who have production lines set up to manufacture window frames for double-pane IGUs.

Several options have been explored for developing higher performing windows without great increases in weight and thickness, including thin-glass triple-pane windows, thin film layers in the IGU, aeroseal gel, and vacuum insulated glass. While technically viable, production of many of these high-performance technologies has been limited and they have only captured a very small market share today due to the added complexity and cost of incorporating them into IGUs. To address this stagnation in both innovation and residential market uptake of the highest performance windows, DOE has undertaken a series of R&D efforts to address installation and market barriers.

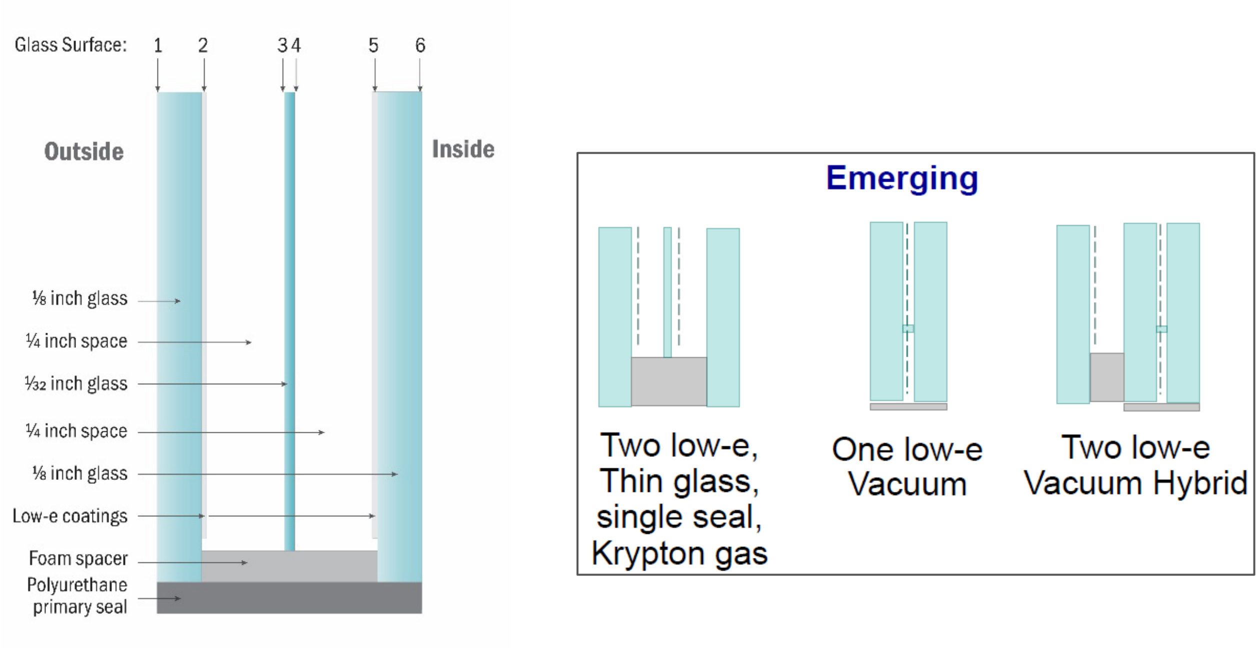

Figure 6. (Left) Thin Triple-Pane IGU; (Right) Three Emerging High-R Window Designs: the thin glass triple-pane IGU, Vacuum Insulated Glass, and a Hybrid design that integrates both VIG and conventional IGU design into a triple pane.

Aerogel and vacuum glazing are two of the most discussed IGU techniques that could significantly improve thermal insulation. Aerogel, a microporous, transparent material with excellent thermal properties, has shown promise in the laboratory but with over 30 years of R&D it is still 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 (see Figure 6). Small spacers, or pillars, are placed to maintain separation between the glass, and low-E coatings are used to reduce radiation exchange between the glass layers. A complex glass-to-glass seal at the edge is needed to hold the vacuum over many years. Commercial production of VIG is limited and, although there is ongoing development of this product in Europe, the U.S., and Asia, there is no existing production infrastructure in the United States (Selkowitz et al. 2018).

The "thin triple" IGU is another emerging technology that holds near-term promise as a cost-effective high-performance alternative, both from the supplier and consumer perspective. LBNL received a patent on the thin triple design[4] in 1991 and has worked to develop the IGU, which is ¾ inches thick like a double-pane IGU rather than the 1 ¼ to 1 ½ inch thickness of standard triple-pane IGUs. The thin-triple IGU uses two ordinary (1/8-inch) layers of glass sandwiching a thin (1/32-inch) layer of glass with a 1/4-inch gap on either side filled with krypton rather than argon gas. Krypton performs better at this narrow gap space than does argon. The thin triple also

[4] Selkowitz, S.E., D. Arasteh, and J. Hartmann. 1991. "Thermal Insulating Glazing Unit," U.S. Statutory Invention Patent Registration, H975, Nov. 5 1991.

has two low-E coatings (on the second and fifth surfaces) (see Figure 6). Some manufacturers have produced a thin-film version of the thin triple where the middle pane is a stretched polymer film rather than thin glass; however, this adds complexity to the production process and no manufacturer has undertaken production on a large scale.

Events over the past decade have increased the market viability of thin-glass triple-pane windows. The price of thin glass has dropped with its now widespread use in flat-screen TVs and monitors, cell phones, and tablets; the incremental OEM (original equipment manufacturer) cost for thin glass has fallen from $5/ft^2 in 2012 to about $0.60/ft^2 today. Krypton gas has also come down in price, from $3/ft^2 in 2012 to $0.50/ft^2 today, as supply has increased relative to demand now that halogen lights, which use krypton, are being replaced by LEDs. With these price reductions, the overall cost to manufacture thin-triple IGUs is estimated to be about $2-3/ft^2 more than for producing a conventional double low-e IGU (not including supply chain and retailer markups).[5] An analysis by LBNL showed a simple payback of 5 to 7 years in all U.S. climates for a retrofit when the base case was an older double-glazed clear window and assuming a decision to replace the window was already made so there was no extra labor cost (Selkowitz et al. 2018).

In addition to these R&D efforts, DOE has sponsored complementary market-pull strategies including working with key stakeholders to identify and address barriers to high-R windows, test and validate emerging technologies, and develop market-sustainable solutions to the identified challenges. Barriers to adoption of standard triple-pane windows were researched from the home builders' perspective in a recent survey of high-performance builders in hopes of informing adoption strategies for the thin-triple technology (Gilbride et al. 2019). The builders interviewed for the study all participate in DOE's Zero Energy Ready Homes (ZERH) program, a labeling program for high-performance homes that integrates energy-efficient design elements with renewable energy systems that offset most or all of the annual energy consumption. For these home builders, a higher efficiency window could improve their ZERH score and provide a tradeoff against other building components to help meet a project's target energy score.

Of the DOE ZERH builders surveyed for this study, 41% use all triple-pane windows and another 28% install triple-pane windows in most or some of their homes. For builders who choose to install triple-pane windows, the overwhelming majority said higher performance was the primary reason. The most mentioned secondary reason that builders gave for using triple-pane windows was noise reduction followed closely by increased comfort and condensation reduction. Among builders who chose to install double- rather than triple-pane windows, reasons cited included cost, availability, not enough energy savings, no consumer demand, installation issues, and design issues (Gilbride et al. 2019).

Builders were also asked what impact, if any, triple-pane windows had on their HVAC systems. Half said it allowed them to reduce the size of their HVAC system. Over one-fourth reported that they can use mini-split heat pumps and that, even with ductless heat pumps, temperatures are even throughout the home, including along exterior walls with windows. A Habitat for Humanity builder from Michigan who installs triple-pane windows in all his homes, said that "having better windows has allowed us to have center throws for the HVAC ducts and we do not notice it being cold near the windows." He noted that the insulating triple-pane

[5] For perspective, the average installed cost for a residential double-pane windows ranges from around $40 per square foot (vinyl frame) to $120 per square foot (or more) for wood-framed windows.

windows and highly insulated walls he uses have allowed him to go to a smaller 15,000-Btu high-efficiency furnace. This builder noted that performance and significant water damage from condensation around double-pane windows in the winter were the primary reasons his affiliate switched to triple-pane windows (Gilbride et al. 2019).

A greater percentage of builders in the northern heating-dominated locations used higher performance triple-pane windows relative to builders in the south, which implies the overall benefit-cost ratio of these higher performing windows was perceived to be greater in these cooler climates. These findings align with the energy simulation results reported by Hart et al. (2019), which found triple-pane windows yielded the highest energy savings in cold climates like such as Minnesota (Cort and Gilbride 2019).

Based on the assessment of barriers and potential consumer benefits, PNNL will be conducting studies in the PNNL Lab Homes to verify savings in comparison with double-pane clear glass windows. PNNL will also conduct field studies to validate benefits and address market barriers of the thin triple-pane windows. These will include field studies in occupied new and existing homes (single-family, multi-family, and manufactured homes) in Colorado, Michigan, Minnesota, Montana, and New York.

Demand Response and Peak Savings

All of the window technologies examined in the PNNL Lab Homes produced savings that were commensurate with the peak demand period during the day, particularly during the summer months. Many types of blinds and shades have automated operation and can be set to open and close via predefined schedules for optimized management of solar gains throughout the year. With automated integrated controls, high-efficiency shades could be coupled with thermostat setbacks to enhance residential comfort and energy savings. For example, the PNNL cellular shade study included a demand response experiment that demonstrated that pulling down the cellular shades in addition to 4°F thermostat increase (set up) during the hottest period of the day not only produced significant average HVAC savings but also reduced the average maximum peak demand by an additional 700 Watts when compared to a home that did not deploy shades and only setup the thermostat.

Energy Rating, Utility Acceptance, and ENERGY STAR

One market barrier to achieving more widespread market penetration of energy-efficient window attachment programs and utility incentives is the lack of standardized ratings for such products. To address this issue DOE helped launch a voluntary independent rating council for energy-efficient window attachments, which has become known as the Attachment Energy Rating Council (AERC).[6] The purpose of the council is to develop a comprehensive energy rating, labeling, and certification program for window attachments that offers independent and accurate information about the energy performance of window attachment products. As of January 2019, AERC energy rating labels are available for storm windows,[7] and cellular shades are slated for certification and energy labeling in December 2019.

Until recently, energy-efficient window attachments have received only modest support in utility energy-efficiency programs; however, that may be changing. Bonneville Power

[6] http://aercnet.org/
[7] https://aercenergyrating.org/product-search/aerc-product-search/

Administration now recognizes the technology on its list of energy-saving measures.[8] In addition, Efficiency Vermont[9] and Wisconsin's Focus on Energy[10] have both completed very successful retail pilot programs focused on low-e storm windows, and Xcel Energy in Colorado will soon be launching a rebate measure focused on cellular shades.

In September 2018, ENERGY STAR added a certification for exterior and interior low-e storm windows.[11] ENERGY STAR is also evaluating the Attachment Energy Rating Council's proposed automation rating as part of its Smart Home Energy Management System initiative.[12]

Conclusions

The standard double-pane low-E argon-filled window (~R-3 insulating value) comprises over 90% of U.S. residential market sales and is able to meet all residential energy code requirements as well as most of the high-efficiency energy ratings (e.g., ENERGY STAR, Zero Energy Ready Homes) in the United States. The triple-pane residential window currently represents the highest energy performance (~R-5 to R-7) among the most commonly available residential windows; however, the conventional triple-pane IGU is both heavier and about one-half-inch thicker than the standard double-pane IGU, which requires window manufacturers to re-design their standard double-pane frame and sash to accommodate the added weight and width. Even though most major window manufacturers now have triple-pane windows available for purchase in multiple residential-style configurations, the overall market uptake of highly insulated triple-pane products remains around 2%, with little growth in the market share over the past decade (Selkowitz et al. 2018).

High-efficiency window attachments and shades also show relatively limited uptake in the residential market. In 2013, D&R International conducted a residential window coverings study (Bickel et al. 2013), which estimated that 82% of all residential windows have some sort of window covering. Based on a review of shipment data however, the most predominant window attachment by far is the relatively low-performing, vinyl, venetian-style blind, which makes up over 80% of shipments. This same D&R study also examined how residential occupants operated their shades and blinds and concluded that home occupants rarely move or adjust their window coverings throughout the day and the position of the window coverings is primarily driven by privacy concerns rather than energy performance (Bickel et al. 2013).

The research described here highlights the energy savings potential of window attachments and high-R windows. Considering the energy-savings potential of these high-efficiency windows and window attachments, these findings suggest there is a large market opportunity to move consumers to higher-performance window technologies. For residential customers, the windows technologies highlighted in this paper offer a reduction in HVAC system energy consumption without sacrificing utility or comfort. On a broader scale, high-efficiency window technologies have great potential for reducing energy consumption in the residential sector and offer a cost-effective incentive option for utilities. The addition of energy ratings and

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[8] https://www.bpa.gov/EE/Technology/EE-emerging-technologies/Projects-Reports-Archives/Pages/Low-Emissivity-Storm-Windows.aspx

[9] https://www.efficiencyvermont.com/news-blog/whitepapers/low-e-and-behold-low-e-storm-windows-provide-a-new-way-to-solve-the-window-conundrum

[10] https://focusonenergy.com/low-estorms

[11] https://www.energystar.gov/products/storm_windows

[12] https://www.energystar.gov/products/spec/smart_home_energy_management_systems_pd

labels for window attachment and field-validation research for high-R windows should help consumers, designers, builders, and home performance contractors make informed decisions about window retrofit and replacement options. There is also an opportunity to improve efficiency by encouraging “smart” operations of these devices, whether through education or automation. Together these opportunities could help to save some of the vast amounts of energy we lose through windows each year.

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