Pacific Northwest
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PNNL-28823

Field Validation of High-R Windows

Market Assessment and Program Plan

July 2019

KA Cort
TL Gilbride

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Executive Summary

This report provides a market assessment for high-performance residential windows based on information gathered from key researchers and industry stakeholders including a series of interviews conducted with high-performance builders in 2019 (Gilbride et al. 2019). This report outlines the basic components and planned activities for implementing U.S. Department of Energy's (DOE) market-focused strategies related to high-R windows. The report references both supply-push and demand-pull R&D activities; however, the primary focus is on the planned "market-pull" activities including planned field validation studies that will be conducted in support of high-R windows. The primary intent of this report is to document market characteristics, barriers, and activities related to high-performance residential windows in order to assist with program planning related to the DOE sponsored Field Validation of High-R Windows project.

Lab testing and energy simulation modeling conducted by DOE demonstrate that a novel, highly insulating "thin triple" glass product can be incorporated into almost any existing window frame and can be fabricated at a modest added cost. The new thin triple-pane window has the potential to cut energy use in residential buildings by 16% compared to typical double-pane low-emissivity windows in heating-dominated climates such as Minneapolis, Minnesota. The energy savings in mixed climates such as Washington, D.C. is estimated to be 12% and annual savings of 7% are estimated for cooling-dominated climates such as Houston, Texas (Hart et al. 2019).

To assess the market adoption potential and identify field validation opportunities for thin triple-pane windows, this study examines and characterizes the benefits and costs of the technology, the size and characteristics of likely target markets, and the potential pathways to reach these markets. The market assessment identifies potential benefits as well as technical and market barriers to the market acceptance of thin triple-pane windows and identifies opportunities for field validation studies of high-R thin triple-pane windows.

In an effort to achieve sustainable market transformation outcomes, field validation studies are proposed within a framework that recognizes market drivers and focuses on validating the benefits of high-R windows to the relevant market stakeholders. The field studies focus on validating benefits and addressing barriers in order to prioritize efforts and identify the most promising pathways to broader and sustainable market acceptance.

Energy Savings:
Projected heating and cooling savings range from 7-16% per household.

Target Market:
New and existing homes with focus on:

- Cooling-dominated climate zones
- Regions with high energy costs
- High-performance homes
- Existing single-family and multi-family homes with lower-performing windows
- High-occupancy homes

Targeted Validation Studies:

- Validation of Benefits: reducing energy costs, utility incentives, noise reduction, increased comfort, decreased condensation, lower life-cycle costs, HVAC system sizing and distribution benefits, system tradeoffs.
- Addressing Barriers: first costs, installation costs, benefit-cost ratio, lack of consumer demand and recognition by energy-rating programs, lack of product availability, design limitations.

Acknowledgements

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Buildings Technologies Office of the U.S. Department of Energy (DOE). The authors would like to thank Marc LaFrance and Dale Hoffmeyer for guiding the technology development and market transformation of high-efficiency windows. A special thanks to Steven Selkowitz and Robert Hart, of Lawrence Berkeley National Laboratory, for their technical contributions and guidance throughout the planning process. Additional contributions and a review of the report was provided by Pacific Northwest National Laboratory staff, Cheryn Metzger and Walter Hunt. The authors would also like to thank Thomas Culp (Birch Point Consulting), Greg Sullivan (Efficiency Solutions), Pat Huelman (University of Minnesota) and Rolf Jacobson and Garrett Mosiman, both from the University of Minnesota's Center for Sustainable Building Research, for providing input to this program plan.

Acronyms and Abbreviations

BEopt	Building Energy Optimization Tool
BTO	Building Technology Office
DOE	U.S. Department of Energy
HERS	Home Energy Rating System
HOA	home owners' association
HVAC	heating, ventilation, and air-conditioning
IECC	International Energy Conservation Code
IGU	insulated glazing unit
LBNL	Lawrence Berkeley National Laboratory
NFRC	National Fenestration Rating Council
PHIUS	Passive House Institute U.S.
PNNL	Pacific Northwest National Laboratory
R&D	research and development
RESNET	Residential Energy Services Network
SHGC	solar heat gain coefficient
ZERH	U.S. DOE Zero Energy Ready Home program

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1.0 Introduction

Thermal transfer through residential windows accounts for approximately 10% of a building's energy use (Hart et al. 2019). The DOE's Research & Development (R&D) efforts, subsequent energy ratings, and tighter energy codes, have contributed to successfully moving the U.S. residential windows market from clear-glass windows to much higher-performing argon-filled double-pane windows that have low-emissivity (low-E) coatings and ~R-3 insulating values. The market share for low-E, argon-filled double-pane insulating glazing units (IGUs) has grown over a 25-year period from approximately 20% of residential window sales to approximately 90% of window sales today. However, more recent advances in the thermal performance of windows, in the form of triple glazed (~R5-R7) windows, have been slow to catch on in the U.S. market and currently account for less than 2% of all window sales in the United States (Selkowitz et al. 2018).

Improving building energy performance will require R&D to produce low-cost advanced materials and window technologies that can be easily and cost-effectively installed in new home construction and existing home retrofits. The mission of U.S. Department of Energy (DOE)'s Building Technology Office (BTO) is to accelerate the research, development, and commercialization of emerging, high-impact building technologies. To address the current stagnation in the residential market's uptake of these highest-performance windows, DOE has undertaken a series of R&D efforts to address the technical and market barriers to scalable and cost-effective technology solutions for high-R windows in the residential sector.

As part of its R&D efforts, DOE has adopted a "supply-push and demand-pull" strategy, whereby DOE and Lawrence Berkeley National Laboratory (LBNL) are partnering with the window manufacturing industry on the supply side of the market to develop innovative solutions to address the technical barriers and reduce the production costs of the most promising emerging technologies (Hart and Selkowitz 2018). In coordination with LBNL's innovation-push R&D efforts, Pacific Northwest National Laboratory (PNNL) is leading a complementary market-pull strategy centered on addressing barriers that are slowing the uptake of higher performance residential window technologies. PNNL is working with key market stakeholders in the residential buildings market to identify and address market barriers to high-R windows, test and validate emerging technologies, and develop market-sustainable solutions to the identified challenges.

In the context of this report, the term "supply" is in reference to the residential window supply industry, focusing on the manufacturing supply chain. This would include glass and coatings manufacturers, insulated glass unit[1] (IGU), frame and sash manufacturers, finished window fabricators, regional window suppliers and representatives. Because IGUs will often include inert gases for added insulation, such as argon or krypton, the producers of these gases would also be a part of the window manufacturing supply chain. R&D supply-push activities would focus on technological innovations that could potentially improve performance of the technology as well as reduce material costs and improve efficiencies and reduce costs in the manufacturing process. The demand-pull activities focus on the market for residential windows from the perspective of the consumers of these products. Demand-pull strategies are described in this report and generally refer to activities that assist in generating increased market demand for the higher-performance window technologies.

[1] Insulated glass units (IGUs) refer to two or more panes of glass sealed as a single insulated unit.

1.1 Report Purpose and Scope

This report outlines the basic components and planned activities for implementing DOE's market-focused strategies related to high-R windows. The report references both supply-push and demand-pull R&D activities; however, the primary focus is on the planned "demand-pull" or "market-pull" activities including planned field validation studies that will be conducted in support of high-R windows, based on economic and market research in the residential buildings sector. This report characterizes the current state of the residential windows market, identifies market barriers to high-R windows, and describes activities related to high-performance residential windows in order to assist with internal program planning for field validation, testing, modeling, and technical assistance efforts.

The market assessment provided in this report is based on information gathered from key researchers and industry stakeholders, including a series of interviews conducted with high-performance home builders in 2018–2019, the results of which were published in a corresponding report: *Double or Triple? Factors Influencing the Window Purchasing Decisions of High-Performance Builders* (Gilbride et al. 2019).

1.2 Report Contents and Organization

The ensuing sections begin with a description of the supply-push and demand-pull strategy for high-R windows (Section 2). The market assessment, presented in Section 3, is a compilation of the findings from a series of DOE and utility-sponsored efforts to characterize the market for high-performance windows in the residential sector. It describes the market potential for high-performance windows and identifies key stakeholders and drivers within this residential windows market. Section 3.4 of this report identifies market barriers and Section 3.5 describes sustainable market strategies to address demand-pull challenges in the residential windows market. Section 4 of this report describes a series of market-pull opportunities for field validation studies. Section 5 presents the associated program plan and goals for sustainable high-R windows R&D based on identified barriers and the existing market framework and partnerships.

2.0 Context for the Supply-Push and Demand-Pull Strategy

The triple-pane residential window has been a viable technology since the early 1980s and a typical triple-pane window today has an insulating value in the range of R5 to R7. The conventional triple-pane insulated glass unit (IGU) is both heavier and about one-half inch thicker than the standard double-pane IGU, which necessitates a re-design of the standard frame and sash to accommodate the added weight and width. The added weight and thickness, and the associated costs pose barriers to producing triple pane windows at scale and are often cited as the primary barriers to broader market acceptance of the technology. Meanwhile, the standard double-pane low-E argon-filled window (~R3 insulating value) dominates the U.S. residential market 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. From the manufacturer's perspective, retooling their production lines to offer triple glazing on a larger scale is costly and risky without significant market demand for the product, so there are few market drivers for triple-pane cost-reducing refinements and broader market adoption (Selkowitz et al. 2018).

To address the lack market uptake of triple-pane windows, DOE's BTO launched a series of market transformation activities focusing on highly insulating windows (U-factor no greater than 0.22) in 2009 to accelerate the adoption and reduce the costs of these windows in the residential and commercial buildings sectors. At the time, highly insulating, triple-pane windows were already commercially available in the United States, but they were not widely available, and the market uptake was below 2% based on a survey conducted by the National Association of Home Builders (NAHB) (Parker et al. 2013). DOE launched a Highly Insulating Windows Volume Purchase (WVP) Program that was carried out over a three-year period from 2009 through 2012 where the primary goals of the program were to: 1) reduce the incremental cost of highly insulating windows compared to ENERGY STAR (double pane) windows; and 2) raise the public and potential buyers' awareness of highly insulating windows and their benefits.

One outcome of the WVP program was the creation of the ENERGY STAR Most Efficient criteria for primary residential windows, which was adopted based on technical specifications set forth in the WVP program. At the onset of the WVP program, a federal tax credit had been in place that offered 30% off the product price (up to $1,500) in the form of a tax credit. The tax credit was reduced to 10% in 2012. Manufacturers participating in the WVP identified the higher tax credit combined with a higher-tier ENERGY STAR program as the most viable long-term strategy to significantly move the market for highly insulating windows (Parker et al. 2013).

As part of the WVP effort, DOE partnered with the window industry, government laboratories, universities, utilities, and consumer groups to develop voluntary performance and cost specifications and goals. These activities also involved executing agreements with manufacturers to meet the specifications and the creation of WVP website to list the windows and products meeting the cost and performance goals. Sales were tracked during the period of project. Overall, the availability of highly insulating triple-pane windows increased and the incremental cost between double-panes and triple-panes decreased from $7-10/ft2 to $6-7/ft2 at the conclusion of the program in 2012. The histogram, presented in Figure 1 of this report, provides, as an example, the number of triple-pane double-hung window products that are now registered in the National Fenestration Rating Council (NFRC) database. In 2018, triple-pane windows represented 11% of the double-hung window products in the NFRC database.

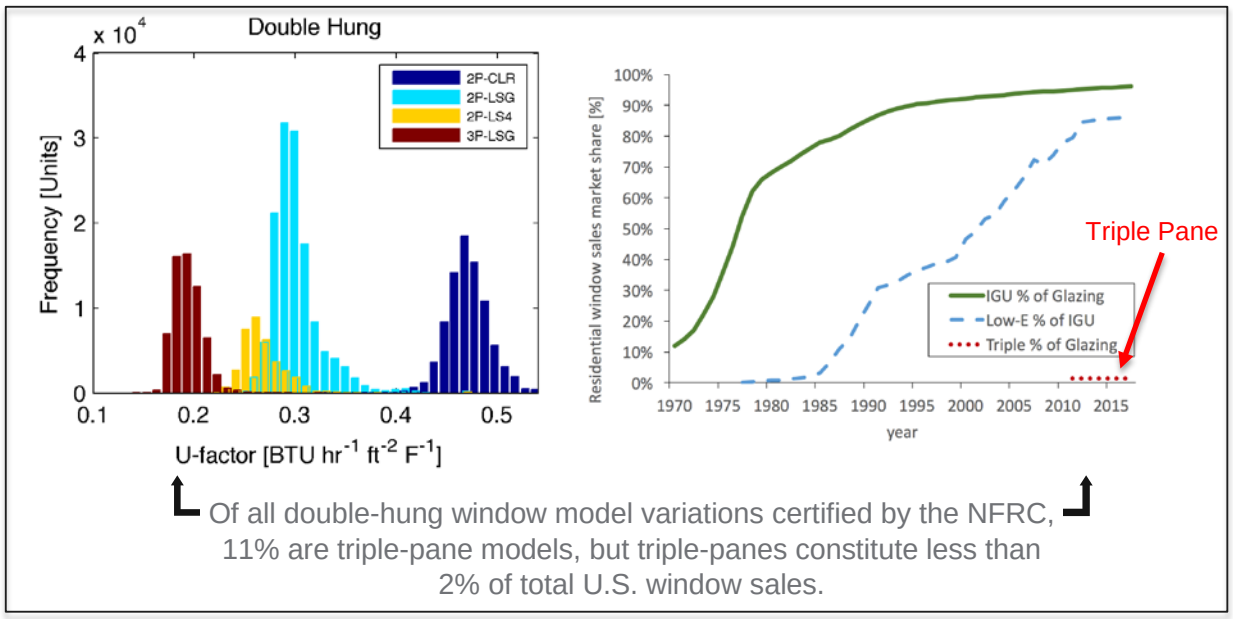

Figure 1. Market for High-Performance Residential Windows

Despite the reduction in cost and the increase in available products, however, overall market uptake of highly insulated triple-pane window products still remains around 2% (see Figure 1) with little growth in market share over the past decade. 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 related to the state-of-the-art "conventional" triple-pane windows. In particular, LBNL has focused R&D efforts on reducing the incremental cost between double-pane and triple-pane windows to $4/ft2 or less and addressing technical issues related to the weight and width of triple-pane windows, which pose significant market barriers and drive up the cost of triple-pane windows. DOE has adopted a "supply push-demand pull" strategy by which DOE and LBNL partner with industry on the supply side of the market to innovate solutions to address technical barriers and reduce production costs of the most promising emerging technologies (Selkowitz et al. 2018). Meanwhile, a complementary market-pull (i.e., demand-pull) strategy is centered on addressing barriers to consumers of residential windows by working with key market stakeholders in the residential buildings market to identify and address market barriers to high-R windows, test and validate emerging technologies, and develop market sustainable solutions to the identified challenges. PNNL is leading the market-pull efforts in coordination with LBNL's innovation-push R&D efforts.

2.1 Supply Push (R&D)

DOE's targeted outcome of DOE's supply push (or innovation push) for residential windows R&D is a cost-effective, highly insulating window that features a reduced installation cost. As a technology solution, LBNL has developed a thin triple-pane "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 (Selkowitz et al. 2018).

Thin triple-pane windows (Figure 2) use two ordinary-thickness (1/8-inch) layers of glass sandwiching a thin (1/32-inch) layer of glass with a 1/4-inch gap on either side of the thin glass that is filled with krypton. Together, these glazing components result in a thin triple-pane IGU measuring 3/4 inch thick, the same thickness as a double-glazed unit. In comparison, standard triple-pane windows use three panes of 1/8-inch glass separated by 1/2-inch gaps that are filled with argon for an overall IGU thickness that typically measures 1-1/2 inches. Argon performs best at a gap space of 1/2 inch but does poorly as the space becomes smaller. Krypton, on the other hand, performs well in a gap of 1/4 inch.

The thin triple krypton-filled IGU with a 1/32 inch (0.7 mm) center pane is the same thickness as the standard double-pane IGU, so it could “drop in” to a standard double-pane frame/sash.

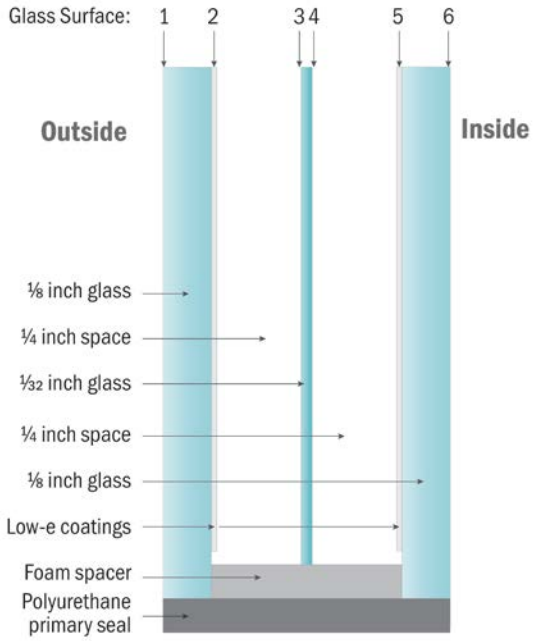

Figure 2. Thin Triple “Drop-In” IGUs

While the concept and technical viability of thin-triple windows has been around since the 1990s,[2] the cost of krypton and the cost to acquire, transport, and work with thin glass drove the resulting IGU costs too high for the residential windows market. However, the costs for glass and krypton combined have dropped by more than 75% (Selkowitz et al. 2018). With costs coming down, LBNL calculated paybacks of 5 to 7 years for thin triple-pane windows, which makes this technology more economically feasible for residential consumers.

2.2 Demand Pull (Field Validation)

Although DOE has invested in R&D to address technical barriers related to the weight and width of triple-pane windows, more nuanced market barriers exist related to cost, low demand, lack of availability, lack of code motivation, and industry inertia because manufacturers, vendors and

[2] LBNL received a patent on the thin triple-pane technology in 1991 (Selkowitz et al. 1991) for thin glass center pane triple-pane windows.

installers are too invested in current code-compliant designs. From the manufacturers' perspective, the lack of consumer demand related to these higher-efficiency technologies, leaves manufacturers with little incentive to invest and innovate toward newer higher-efficiency products and redesign production lines to potentially reduce the cost. As a result, the consumer price for triple-pane windows has remained out of the range of key players on the demand side of the market, such as production home builders and energy-efficiency programs with cost-effectiveness requirements (e.g., utility programs and ENERGY STAR).

A demand-pull strategy engages a wide range of traditional market transformation actors and programs to build the demand that will encourage industry investment in the new window designs to meet this demand. To develop a demand-pull strategy, we must first define and characterize the market actors and dynamics. The high-r windows demand-pull (i.e., market-pull) strategy is led by PNNL and is centered on targeted validation studies that will support implementation of higher-R windows in utility efficiency programs, ENERGY STAR, and energy codes, as well as by builders seeking trade-offs for performance-based code and program compliance. DOE will also build upon previous LBNL-led innovation-push activities to reduce payback periods for highly insulating windows through a combination of strategies to reduce cost, including new technical innovations, manufacturing innovations, and supply chain updates, and working with utilities and energy-efficiency organizations to build programs that incentivize the adoption of the highest performance residential windows.

DOE's market-pull strategy is designed to enhance market stimulation activities and create lasting change in the market. Shorter-term validation studies and field demonstrations can help build recognition of the value of high-efficiency thin triple-pane windows and potentially lead to longer-term changes in utility energy-efficiency programs, energy codes, and energy ratings, which could then lead to more sustained growth in market share without further government R&D support. While several other windows technologies have the potential to eventually meet the performance, cost and scalability requirements needed to stimulate market uptake over time (e.g., vacuum-insulated glass units and aerogel technology), DOE is focusing near-term field testing efforts on the thin triple-pane windows because this technology has the potential to meet the cost and acceptance requirements, particularly because the IGU could "drop in" to a conventional frame and sash without warranting any design modifications.

3.0 Market Assessment

DOE's BTO Residential Buildings Integration Program (RBI) activities are based on the use of collaborative, industry-based teams that integrate across supply chains, business practices, and stakeholders to deliver R&D that minimizes the overall costs and risks of emerging high-value energy-efficient products. The overall goal of market transformation is to increase the share of high-performance, cost-effective products and services within targeted markets. Field validation and technical assistance efforts must recognize the importance of working with key market players—manufacturers, distributors, retailers, utilities, and consumers—for any type of technology testing and demonstration efforts. The high-R windows demand-pull strategy should recognize both the technical and market potential of high-performance windows, and work within the current market structure for residential windows. The high-R window field validation efforts should lead to sustained increases in the adoption of higher-performing residential windows and be based on the following key principles (as documented by Nadel and Geller 1996):

- Work within the existing market structure to develop partnerships between government, private sector, energy utilities, and other stakeholders that influence the buildings market structure and function.
- Respond directly to identified market barriers.
- Focus efforts on benefits that are inherently sustained because the market and market drivers change. Competitive market forces drive energy-efficiency gains.

The following sections characterize the market with these key principles as a guide. To assess the market barriers and better understand the market for high-performance residential windows, PNNL conducted a market assessment that included a series of interviews with high-performance builders in 2018–2019. The findings of this market assessment were reported by Gilbride et al. (2019). PNNL's goal in undertaking this study was to determine what motivates builders to choose or not choose triple-pane windows, because better understanding of the motivations, experiences, and concerns of new home builders regarding window purchases would inform efforts to develop and deliver thin triple-pane windows and lead to their widespread acceptance in the marketplace. This report also draws from previous DOE- and regional utility-sponsored technology and market assessments related to emerging windows technologies.

3.1 Potential Energy Savings

Heat transfer through the building envelope and associated air leakage compose the largest heating, ventilation, and air-conditioning (HVAC) loads in most climates. 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 those that are triple glazed, represented less than 2% of all U.S. window sales in 2016, and their sales have remained stagnant over the past decade in part because conventional triple-pane windows typically require a full and expensive redesign of the double-pane window sash and frame.

Table 1 summarizes findings related to energy savings from recent case studies based on energy simulations, PNNL Lab Homes controlled experiments, and field studies. Most recently, LBNL completed a series of energy simulation studies focused on assessing the energy-savings potential of thin triple-pane windows in comparison to the "typical" residential window stock. 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 16% compared to typical double-pane low-e windows in heating-dominated climates such as Minneapolis, Minnesota, 12% in mixed climates such as Washington, D.C., and 7% in cooling-dominated climates such as Houston, Texas (Hart et al. 2019).

Table 1. Summary of Recent Case Studies Focused on High-Performance Windows

Study	Sponsor	Baseline Description	Findings
LBNL study of energy simulated savings potential of thin triple glazing (Hart et al. 2019))	DOE	Typical windows based on NFRC-certified products	• 16% annual savings in heating-dominated climates • 12% annual savings in mixed climates • 7% annual savings in cooling-dominated climates
Infrared camera imaging of thin triple-pane windows (2019)	DOE, LBNL, CEC	Double-pane, low-E, vinyl-framed windows	Replaced double-pane IGUs with thin triple-panes. Images show thermal improvements in windows with thin triple-pane IGUs.
PNNL Lab Homes side-by-side triple-pane study (Widder et al. 2012)	DOE	Double-pane, clear-glass, aluminum-framed windows	• 12% annual savings in Richland, Washington • 11.6% heating savings/18.4% cooling savings • > 20-year payback
Windows state-of-the-art thermal performance comparison by the Norwegian University of Science and Technology [NTNU] and LBNL (Jelle et al. 2011)	NTNU, DOE, Research Council of Norway	Various products delineated by U-values (glass, framing material)	• 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.

CEC = California Energy Commission; IGU = insulated glazing unit; NFRC = National Fenestration Rating Council.

3.2 Market Characterization

Triple-pane windows have been a viable product since the 1980s and most major window manufacturers currently have NFRC[3]-rated products. Figure 1 shows a histogram (on the left) of four types of double-hung window models (double pane clear in dark blue, double pane with one low-e layer in bright blue, double pane 2 low-e layers in gold, and triple pane with one low-e layer in rust). For each type, the chart shows how many models are listed as certified in the NFRC database. While 11% of the window models certified by NFRC are triple-pane products, sales data suggest that triple-pane products constitute less than 2% of the total sales for this window model (see Figure 1) (Hart et al. 2019).

The Energy Trust of Oregon (Energy Trust)[4] commissioned a window market study in 2018 (Apex 2018), and its findings align with those of LBNL (Selkowitz et al. 2018; Hart et al. 2019),

[3] National Fenestration Rating Council, www.nfrc.org

[4] The Energy Trust of Oregon is an independent nonprofit organization that collaborates with utilities, nonprofits, and government agencies to deliver clean energy benefits for Oregon. The Energy Trust offers services, cash incentives, and other energy solutions to customers of Portland General Electric, Pacific

but the Energy Trust study further delineates sales estimates by U-value (see Table 2), where the U-value category of 0.20 or less would constitute the triple-pane products.

Table 2. Windows Market Share by U-Value (source: Apex 2018)

U-Value Tier	2017 Market Share	Estimated 2022 Market Share
>0.35	4%	4%
0.31 to 0.35	30%	24%
0.25 to 0.27	11%	24%
0.20 to 0.24	3%	6%
<0.20	1%	2%
Total	100%	100%

The primary drivers of window purchasing decisions noted in the Energy Trust market survey include cost coupled with energy codes and ENERGY STAR specifications. As one manufacturer noted in the Energy Trust report, “Cost and code are the two main drivers unless something drastically changes on the buyers or technology side of the equation.” The Energy Trust survey participants concluded that builders and remodelers will try to find the lowest cost window product that meets code or ENERGY STAR specifications. However, they also acknowledged that marketing and education can also influence the market, and these marketing efforts today are primarily targeting consumers (rather than builders). Energy Trust survey participants also mentioned that federal tax credits and incentives influence the market for higher-efficiency products, including windows. Low energy costs also slow the market uptake of higher-efficiency products (Apex 2018).

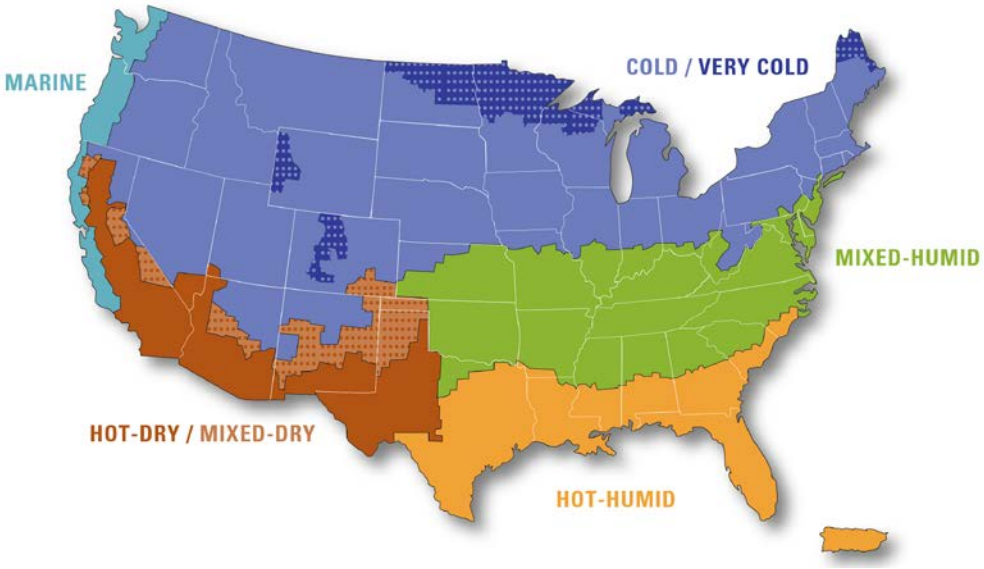

Figure 3. IECC and DOE Building America Climate Zone Designations

Power, NW Natural and Cascade Natural Gas in Oregon and customers in NW Natural Gas in Washington.

In terms of energy-savings potential for retrofits and remodels, the homes and buildings with single-pane windows would realize the greatest incremental benefit from replacing existing windows with high-performance triple-pane windows. DOE's 2015 Residential Energy Consumption Survey estimated that approximately 48.7 million (or ~40%) of existing homes have single-pane windows (DOE-EIA 2015). Even in the coldest climate zones (see Figure 3), where highly insulated windows and walls could provide the highest HVAC savings and comfort benefits, homes with single-pane windows make up over one-third of the existing residential building stock (DOE-EIA 2015). Overall, close to 60% of homes have double-pane windows. However, considering that over 90% of these existing homes were built before 2009, and that the 2009 IECC[5] code requirement for residential U-value for the coldest climates was 0.35, most of the existing double-pane windows would realize more than a 40% improvement in U-value rating if they upgraded to a thin triple-pane window with a 0.19 U-value.

3.3 Market Structure and Stakeholders

DOE buildings research and field validation are based on the use of collaborative, industry-based teams that integrate across supply chains, business practices, and stakeholders to deliver products of value and minimize overall costs and risks. The overall goal of demand-pull strategies is to increase the share of energy-efficient products and services in targeted markets. These market transformation efforts also must recognize the importance of working with key market stakeholders, such as manufacturers, distributors, home builders, and other window consumers. To identify and characterize market field validation opportunities and technical assistance activities for thin triple-pane windows, this market assessment follows the distribution "supply chain" depicted in Figure 4.

Figure 4. Market-Pull Structure and Key Stakeholders

[5] International Energy Conservation Code

On one end of the supply chain is the sales force for the technology, which could include any stakeholder with a business interest in promoting the market uptake of a given energy-efficient technology. For high-performance windows this could include IGU and window manufacturers, as well as certain home builders and developers. It could also include entities that are promoting energy efficiency and high-performance home construction and renovation, such as DOE Better Buildings or other RBI program teams (see Figure 4). On the other end of the supply chain are the end-use customers. The end-users of any windows-focused R&D would include home owners and home builders who are the primary decision-makers for most new home and replacement window decisions. The end-use customers could also include government agencies or affordable housing advocacy groups that own or subsidize housing (e.g., military or affordable housing, Habitat for Humanity homes). Based on the residential window market segments and the pathways identified for each segment, the "core customers" of the field validation include the segment of the market that work between end-users and manufacturers to promote energy efficiency and market uptake of energy-efficient products. These stakeholders include utilities (i.e., sponsors of regional energy-efficiency programs), regional window distributors who interface with end-users, energy-rating organizations (e.g., ENERGY STAR, Zero Energy Ready Homes), and weatherization assistance programs. On the supply chain (Figure 4) these would represent the core customers of research and deployment related to high-R windows field validation work because they act as the primary contacts with the end-users.

3.4 Sustainable Market Strategies

For the benefits of market transformation efforts to be sustained, there must be an inherent benefit of the energy-efficient technology to the consumer, a commercially viable market within which to work, and the potential to grow this market further. The commercial viability of the product should not be dependent on continuing market intervention by energy-efficiency research programs; rather, competitive market forces should drive energy-efficiency gains. Therefore, field validation efforts should be cognizant of the market drivers and focus on validating the benefits of high-R windows to the major market stakeholders: homeowners/occupants and homebuilders/remodelers. Field testing should also be identifying and validating where these benefits are greatest (i.e., building types and climate factors) in order to prioritize efforts and identify the most promising pathways to broader market acceptance.

3.4.1 Market Drivers

Based on the Energy Trust's recent market assessment and manufacturer survey (Apex 2018), the primary drivers noted for residential window purchases appear to be cost coupled with energy codes and ENERGY STAR specifications. It was noted that builders and remodelers will typically try to find the lowest cost window that meets code or ENERGY STAR specifications. Industry representatives also noted that marketing and education can influence the market, and noted recent campaigns that primarily targeted end-user (i.e., homeowners). DOE's Zero Energy Ready Home (ZERH) program and Passive House Institute U.S. (PHIUS) have been drivers for more efficient windows and building envelopes, but they affect a relatively small share of overall new building construction. Furthermore, only PHIUS has specifications that would require the installation of triple-pane windows.[6] While most DOE ZERH builders go beyond codes and standards, the minimum ZERH requirement specified for windows is to install

[6] The PHIUS recommends at least an R-4.5 window, up to R-7 in climates zones 5–7 (mixed and cold climates) and R-9 in climate zone 8 (very cold). See the climate zone map in Figure 3.

a window that meets ENERGY STAR specifications. Because more than 80% of the windows installed in the market already meet ENERGY STAR specifications, this acts as a non-binding requirement for most ZERH builders.

Federal tax credits and incentives influence the market for higher-efficiency products, including windows. Almost every state has utility-sponsored programs that incentivize window energy efficiency in some form or another and many are linked with ENERGY STAR, which offers a rebate for the purchase and installation of ENERGY STAR-rated windows.[7] There was no comprehensive reporting on the success and market uptake of these respective programs, but, anecdotally, some of the utilities in the Pacific Northwest that have directly incentivized the highest efficiency windows (i.e., U-values of .22 or less) have not seen a high market uptake of these products in their portfolios (Cort et al 2019). Low energy costs in the Pacific Northwest have also been cited as a reason for the slow market uptake of higher-efficiency products, in general (Apex 2018). Conversely, however, high energy costs are a major driver for advancing window energy performance in Japan and Europe (Selkowitz et al. 2018). Some of the high-performance builders interviewed (Gilbride et al. 2019) also indicated that high energy costs in places like New York tend to drive the market toward more thermally efficient designs, which includes higher-performing windows.

3.4.2 Benefits to Consumer

Although consumers will often identify energy savings as a reason for purchasing decisions, market research appears to indicate non-energy benefits often play a leading role in influencing consumer decisions. Builders interviewed confirmed that when it comes to "selling" the higher-performing triple-pane windows, they will often point to the non-energy benefits such as noise reduction, increased comfort, and reduction in condensation (see Figure 5) (Gilbride et al. 2019).

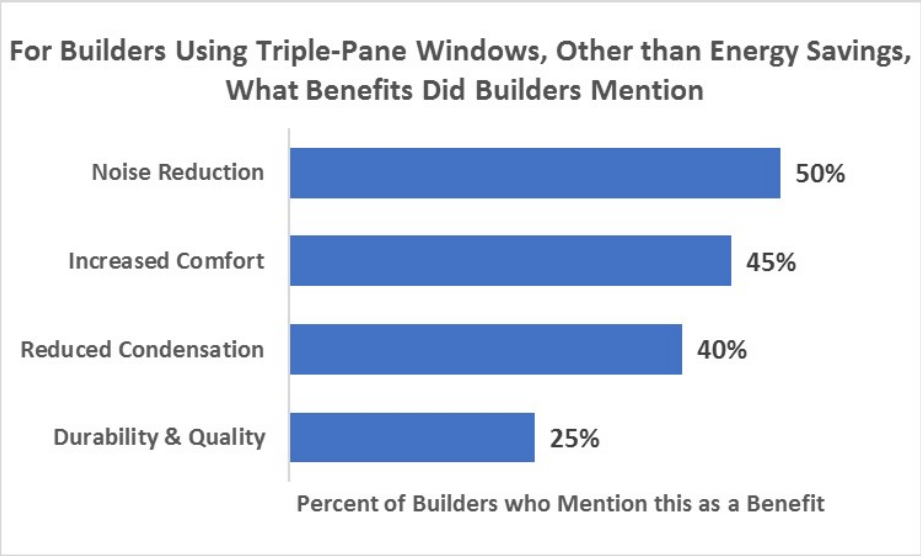

Figure 5. Benefits Builders Mention for Triple-Pane Windows

[7] See Efficient Windows Collaborative database search: https://www.efficientwindows.org/downloads/UtilityIncentivesWindows.pdf.

Because there are very few thin triple-panes in the market today[8], the technology associated with the benefits identified by consumers and builders in the survey (Gilbride et al. 2019) will almost always be conventional triple-pane windows. Most of these benefits, however, would also be generated with a thin triple-pane high-r window as well. One of the objectives of the High-R Window Field Validation project would be to validate these benefits in the field. The specific studies that would validate the benefits of a high-R thin-triple technology are discussed in detail in Section 4.1 of this report.

3.4.2.1 Noise Reduction

One of the most mentioned reasons that builders gave for using triple-pane windows was noise reduction (see Figure 5). A builder who constructs urban infill homes in Seattle promotes triple-pane windows as part of the high-insulation envelope that makes his homes so quiet. "When someone comes into the house and you shut the door, it's like getting into a Mercedes or BMW. It's so solid and quiet when you shut the door. We are building homes next to Boeing Field airport in Seattle. Planes are flying right overhead so close you can clearly see them from the houses, and it is so quiet inside you can't hear them."

Another builder in eastern Washington State also mentioned the sound-dampening effects. "A house with triple-pane windows is incredibly quiet. People always comment on how quiet my homes are. That cannot be accomplished without a U-value below 0.20. My standard for a window is U-value=0.18 and doors are U-value=0.24 because of that." He went on to say "Researchers are now finding health benefits (physical and psychological) to quieting the home. . . It's amazing how many people are sound sensitive."

3.4.2.2 Increased Comfort

A Midwest builder noted that triple-pane windows are a part of their marketing effort to position themselves as unique in the market. "We advertise that all of our homes have triple-pane windows for greater comfort, durability, and air quality." This builder said their home owners have noticed the "the pure comfort of sitting next to a triple-pane window."

Another builder commented that with triple-pane windows the comfort level is consistent across the room and close to the window. An upper Midwest builder said, "We are in the 20s and 30s here in the winter. You can stand in front of these windows and not feel any difference in temperature from the center of the house."

3.4.2.3 Decreased Condensation

Reduced condensation on the interior-facing side of the window was also a common reason for choosing triple-pane windows. A builder on Long Island, New York, noted that condensation formed on the double-pane windows he had used in the past leading to mold and rotting sills, which was one of the key reasons he switched to triple panes. One builder in Connecticut said, "We point out when you get windows with U-values that are low, even with very cold outdoor temps you are very unlikely to get condensation. Ten years ago we did a very expensive house, very elegant, with lots of windows. I suggested triple-pane windows; they went with double-pane. Last winter it got really cold and they got all this condensation. They called me asking about replacing all the windows." He noted the irony that putting in double-pane windows didn't

[8] A small number of manufacturers offer a thin triple-pane krypton-filled residential window with a stretched film acting as the center pane.

save the home owner any money and actually ended up costing much more, with the cost of two sets of windows and the labor to remove the double-pane and install new triple-pane windows.

One Habitat for Humanity builder in the Midwest said performance and condensation were the reasons his affiliate switched from double- to triple-pane windows. “Water destroys structures. We used to use double-pane windows but we would get so much condensation, we would get frost on the inside face of the windows, and mold, rotting of wood sills, even rotting of the drywall around the windows. It’s a real durability and health issue. Six years ago, we switched to triple-pane windows. Since we started installing them, there is zero condensation on the windows, even when it’s zero degrees outside and high humidity inside.” The builder noted their homes usually go to families with children and inside humidity can sometimes get up to 80% if there is a lot of cooking, bathing, and laundry happening. “And still we’re not seeing condensation issues. In my own home, with cheap double panes, I’m seeing ice on the windows inside the house in the winter” (Gilbride et al. 2019).

3.4.2.4 Other Features Mentioned

Three other features mentioned by builders were lower HVAC loads, less ultraviolet light and fading, and less heat coming through the windows. One builder mentioned that the difference in cooling HVAC use with triple-pane windows was a selling point for many of his clients. The Long Island builder noted that “windows had a bigger impact on our cooling load than on the heating load. We see much less summer heat gain if we use better windows. On the winter heating side, we have less condensation and dripping.” These are the impacts that are noticed by homeowners and can be a selling point for triple panes (Gilbride et al. 2019).

3.4.3 Benefits to Home Builders and Installers

In addition to the benefits that could directly translate to consumer benefits, as described in Section 3.5.2, builders referenced systematic business reasons for using triple panes in their home designs. Often these reasons could be translated into consumer benefits and selling points, but they also affect system design and cost, as well as marketing strategies for the builders (Gilbride et al. 2019).

3.4.3.1 Market Distinction

One builder surveyed said he uses triple panes in the Chicago area for “performance and to distinguish us in the market. We are the only builder in our market using triple-pane windows.”

Two builders specifically mentioned the HERS[9] score. One custom builder said he uses triple panes to boost his HERS score and demonstrate higher performance in the homes that he builds. A New York builder also mentioned that he uses triple panes to get the “lowest HERS score possible before solar.”

A Seattle builder said installing triple-pane windows is “the right thing to do” and it helps him get to the 5-Star Built Green program requirement of being 30% better than local code.

[9] Home Energy Rating System (HERS) is an index and industry standard by which a home’s energy efficiency is measured. See https://www.resnet.us/hers-index for more information.

A Long Island builder of homes for nonprofit agencies said, “The life cycle cost and sustainable savings is more important than immediate first cost. The simple payback doesn’t make sense. If I forecast the savings over 30 years, it makes sense. The math works for us more because we have such high utility rates. Our electricity is 18 to 21 cents/kWh.”

3.4.3.2 System Sizing and Cost-Reducing Trade-offs

Builders were asked what impact, if any, triple-pane windows had on their HVAC systems. Half of them said it allowed them to reduce the size of their HVAC systems. Over one-fourth reported that they can use mini-split heat pumps and have even temperatures throughout the home (see Figure 6).

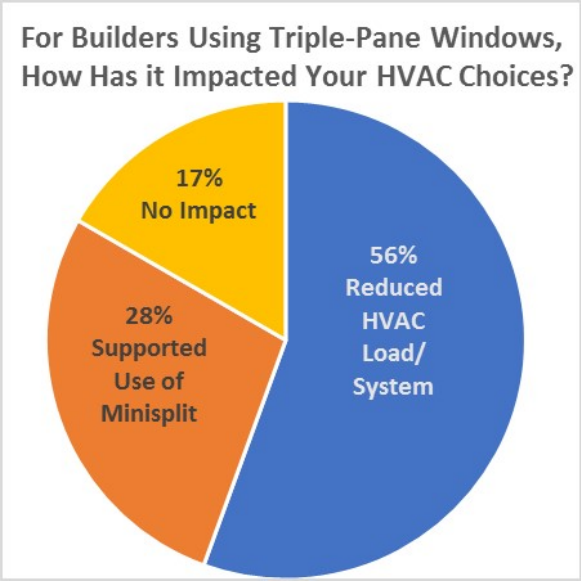

Figure 6. How Having Triple-Pane Windows Has Impacted HVAC Equipment Selections

A builder in Bellingham, Washington, noted that his loads “typically are in the 9,000 to 12,000 BTU/hr range. Bigger homes could be 14,000 to 17,000 BTU/hr. For bigger homes, we use a ductless air-to-water heat pump rated at 22,000 BTU. It ramps down for lower load times. For smaller homes, we use an air-to-air mini-split heat pump that is rated at 9,000 BTU. It also ramps down for lower load times.” These HVAC capacities are about one-fourth of the size of the heat pumps or air conditioners that would typically be recommended for a 2,000 to 3,000-ft^2 home using HVAC industry rough sizing estimates.

A Connecticut builder said, “Window performance is absolutely going to make a difference in HVAC sizing. You could go crazy with your walls and roof, and if you have poor windows, it will seriously undermine that. Your loads are a sum total of your exterior surfaces.” The Seattle builder was able to downsize the HVAC for his three-story, 4,000 ft^2 urban infill homes to ductless heat pumps, “and its comfortable everywhere, no cold spots.”

An upstate New York builder said the whole load for the homes he builds is “18,000 to 22,000 Btus for a 3,000 to 4,000-ft^2 house.” This builder noted “I definitely see it in the HERS modeling. If I were to switch to a regular ENERGY STAR double-pane window, it will probably increase my

HERS[10] score by 10%–20%. I don't need registers near outside walls because the triple-pane windows and ICF [insulated concrete form] walls perform so well I don't get cold walls."

A Habitat builder in Michigan said, "The furnaces we get are 15,000 Btus with a modulating burner and modulating fan and 2.5-inch ducts. The fan motor can modulate down to 5,000 Btus. 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."

A custom home builder in California noted that using triple panes "simplifies duct design and permits the use of mini-splits in some applications." He added "room loads are more even." A builder in Ohio who uses ducted and ductless mini-splits said, "I can do shorter duct runs when I have better windows. The registers don't have to be blowing directly on the windows."

3.4.4 Climate Factors

While the DOE ZERH builders interviewed (Gilbride et al. 2019) must install windows that meet the ENERGY STAR window criteria as a mandatory requirement for certifying their homes to DOE ZERH, many go beyond ENERGY STAR levels. The windows they specify may vary in U-value from project to project, but many builders identified a typical U-value they aim for. These typical values are shown individually for each builder in Figure 7. (Note: builders who build in more than one climate zone are represented by more than one data point.) A U-value of U = 0.20 is equivalent to an R-5; 18 of 29 builders are currently installing a window rated at R-5 or better (U = ≤ 0.20), and 12 of the 18 builders in the ENERGY STAR northern climate are meeting or beating an R-5. These findings align with the energy simulation results reported by Hart et al. (2019), which found that with an understanding of the potential improvements in traditional performance metrics, such as U-value, the energy-savings potential of the thin triple-pane windows in place of typical windows in residential buildings is greatest in the coldest climates, such as Minnesota.

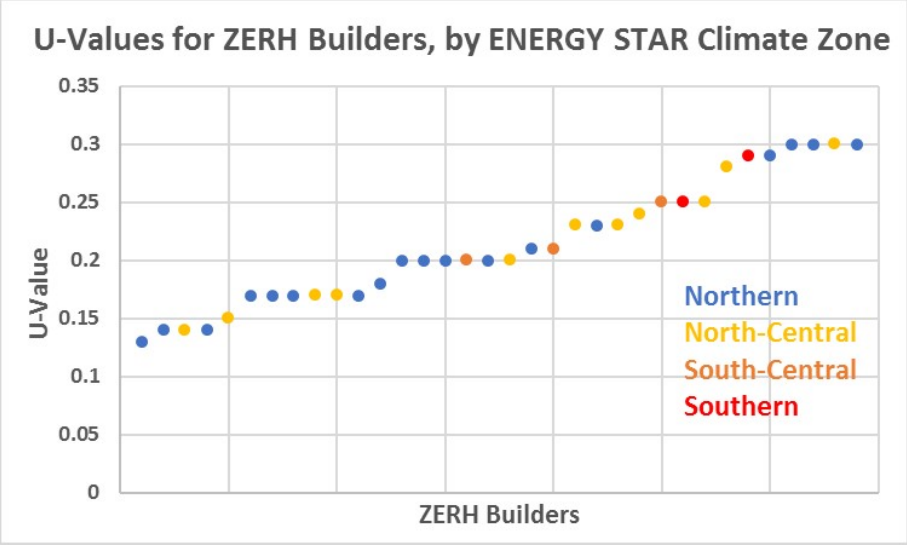

Figure 7. Typical U-Values for Windows Used by Each DOE ZERH Builder Interviewed (dot color indicates ENERGY STAR climate zone)

[10] Lower HERS scores are more efficient.

3.5 Market Barriers

Although the design of the thin triple-pane window is intended to address some of the key market barriers associated with conventional triple panes, in order to characterize current market conditions and assess some of the more nuanced market barriers related to cost, inertia, and product availability, this report relies on findings from the recent survey of high-performance builders (Gilbride et al. 2019). All of the builders surveyed actively participate in DOE's ZERH program, which is an energy-rating/labeling program for high-performance homes that integrate enough energy-efficient design elements such that renewable energy systems could offset most or all of the annual energy consumption. For these home builders, a higher-efficiency window could improve their ZERH score. ZERH builders are motivated to integrate higher-efficiency windows, but many are not integrating triple-pane windows into their designs. Thus, an assessment of the reasons why these builders are not integrating this technology provides us with an idea of some of the most problematic barriers related to thin triple-pane windows. In the survey, builders who currently do not use triple-pane windows were asked about why they do not install triple-pane windows and were given a list of reasons to choose from. The reasons included cost, availability, not enough energy savings, no consumer demand, installation issues, and design issues. Primary and secondary reasons for not installing triple-pane windows are graphed in Figure 8.

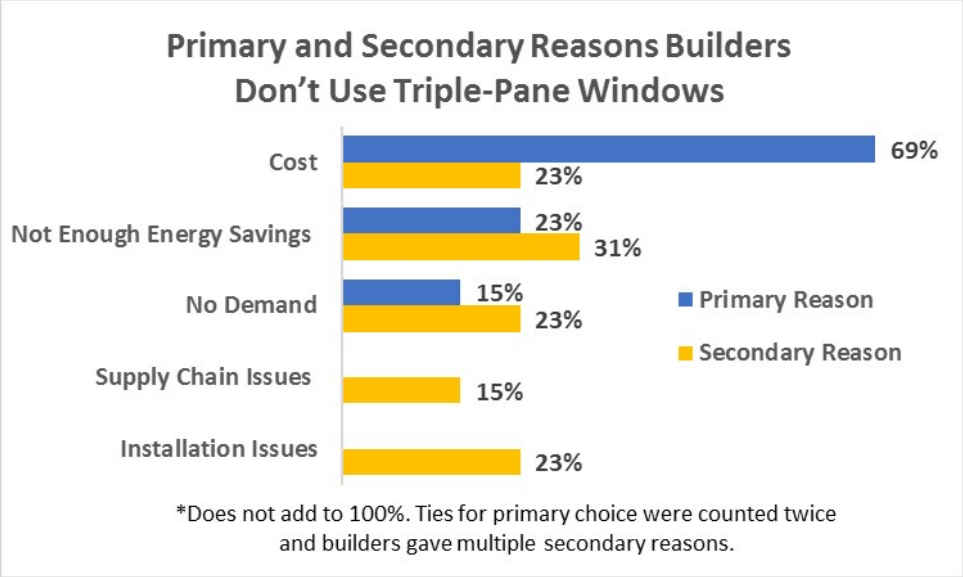

Figure 8. Primary and Secondary Reasons Builders Don't Use Triple-Pane Windows

Because there are very few thin triple-panes in the market today[11], the technology associated with the barriers and challenges associated with high-R windows that were identified by builders surveyed (Gilbride et al. 2019) are primarily associated conventional triple-pane windows, rather than thin triple-pane windows. In some cases, the noted barriers would be applicable to either thin or conventional triple-pane windows (see, for example, the discussion of first costs or consumer awareness below). For some of the factors, however, market barriers would be largely addressed with the thin triple-pane innovation. These would include barriers associated with the weight and thickness of conventional triple-pane windows (see, for example, the

[11] A small number of manufacturers offer a thin triple-pane krypton-filled residential window with a stretched film acting as the center pane.

discussion on installation cost below). In either case, further validation studies and field testing are warranted to either address the identified barrier or validate that thin triple-panes sufficiently address existing technical barriers associated with conventional triple-pane windows. These validation studies and R&D efforts are characterized in Table 4 of this report.

3.5.1 High Cost

As with many emerging technologies, one of the key market barriers to wide-scale market adoption of triple-pane windows is the significant cost premium associated with triple-pane windows relative to double-pane windows. Further issues cited (Selkowitz et al, 2018; DOE 2014; Parker et al 2013; Widder et al, 2012) with typical triple-pane windows include the need for a thicker sash, increased weight, and additional spacers and gas, which depend on labor-intensive manufacturing processes that not only add expense to production and drive up the incremental cost of this product, but also complicate and add costs to installation. Because of the wide variability in window costs, it is difficult to determine average trends in costs, but sampled data over the past few years suggest that the incremental cost between double- and triple-pane windows has not declined in any measurable manner in the past decade (Apex 2018).

3.5.1.1 First Costs

High-performance builders confirmed that the price premium for higher-performing triple-pane windows was by far the primary reason preventing them from installing this technology. One Ohio custom builder said triple-pane windows can cost twice as much as good double-pane windows. As an example, he provided two quotes for windows he had received for a very large home with 70 windows. The price quote for double-pane windows was $65,000, while the price quote for triple-pane windows was $120,000. This extreme price premium, noted by several of the builders, suggest that at least some triple-pane products are being sold as a “luxury” building components where the business model involves marketing triple-pane windows as a customized niche product targeting higher-end builders whose clients can afford this premium product. However, other builders who are focused on affordable housing and relatively lower-cost vinyl-framed windows have been able to find a consistent supply of triple-pane vinyl-framed windows at a cost premium of 40% over similar double-pane windows. In either situation, however, the cost premium between double- and triple-pane products is substantial and variable, ranging from 40% to over 100% (Gilbride et al. 2019).

Manufacturers participating in the Energy Trust survey (Apex 2018) also noted that consumers of residential windows were very price sensitive. One respondent noted that if there is “a difference of $1 between windows, builders will go for cheaper windows every time.” Costs need to be reduced on the supply side in order to meet these lower price points required for production buildings. There is currently a high degree of business risk trying to transform a market without sufficient support from consumers, and one manufacturer noted “most of the current low U-values [windows] sold are based on [utility] incentives. . . It is extremely costly and risky to design and retrofit our production to accommodate a triple-pane window, so if there was a way to make this transition trivial for them, including a drop-in triple-pane replacement, there will still be increased incremental cost, but if cost is low enough, this will open door for people to adopt.”

Technology Application

First costs present a significant market barrier to high-performance windows, in general, regardless of whether they are conventional triples or thin triple-pane windows. Several recent DOE efforts have focused on lowering the first costs of thin triple panes, including R&D efforts partnering with industry to innovate solutions and reduce production costs. These activities are called out in Table 4 under "Innovation-Push Strategies." There have been complimentary demand-pull efforts related to the Field Validation project that are directed toward reducing the first costs of thin triple-panes in the field, including teaming with multiple window manufacturers to integrate the higher performing thin-triple IGU with lower-cost frames and sashes to reduce the overall first costs of the thin triple-pane window. These efforts and the validation of performance of the resulting windows are also characterized in Table 4 under "Market-Pull Strategies."

3.5.1.2 Installation Costs

Installation issues related to the size and weight of the triple-pane windows and problems with incorporating them into the builder's standard design were also noted as barriers by builders interviewed. The additional pane of glass in a standard triple-pane window adds 1.6 lb/sf, which for a large 5 x 8 picture window could add around 60 lb to the window, warranting another crew member to assist with the installation, thereby driving up costs. While no builder cited installation issues as a primary reason for not installing triple-pane windows, nearly 40% cited them as a secondary reason. In general, more weight means more crew, more rented equipment, and higher construction costs.

Some builders expressed concern about the safety of their crews when lifting and carrying very heavy windows. A nonprofit builder in New York noted that with double-pane windows, one crew member can carry the window up a ladder by himself. With heavy triple-pane windows, it takes several crew members and longer to work out the logistics of lifting the window into place. For this reason, this builder switched from standard triple-pane windows to a thin triple-pane window that uses a stretched plastic film instead of glass as the center pane and noted that the installation was similar to double-pane window installation.

Technology Application

The installation cost barriers identified by builders are directly associated with the weight and width of conventional triple-pane windows. The thinner profile and lighter weight of the thin-triple window would presumably address this barrier. One objective of this project will be to validate this in the field (see Table 4).

3.5.2 Benefit-Cost Ratio

Many builders interviewed felt the savings for the triple-pane windows were not high enough to justify the initial cost of the window and several mentioned the long payback (Gilbride et al. 2019).

A production builder in Arizona said, "If the performance gains were high enough to save me money elsewhere, like in HVAC, then yes I could do it. If I could drop a half ton off HVAC, then

yes." A Fort Collins, Colorado, production builder stated that "Our rater ran BeOPT.[12] The BeOPT results are in reference to the price of solar. [To reach the HERS net zero goal] it was cheaper to put more solar PV [photovoltaics] on the house than to do triple-pane windows." A Denver production and multi-family home builder stated, "If it was $2,000 more per home to go to triple pane that makes sense. When the added cost is $7000 to $10,000 per home, that gets tough to justify."

But some builders suggested that they have weighed the trade-offs and determined that triple-pane windows are worth the additional costs. "The simple payback doesn't make sense," said a Long Island builder of nonprofit housing who said he uses triple-pane windows anyway because he felt the life-cycle costs do justify the expense.

Technology Application

The benefit-cost ratios referenced by builders in the survey (Gilbride et al. 2019) are associated with conventional triple-pane windows. One of the goals of the validation studies will be to assess how a "drop-in" thin triple IGU may change this ratio under various circumstances and climate zones.

3.5.3 Consumer Awareness and Demand

Some builders mentioned the lack of consumer awareness or demand for higher-R windows as a key barrier to widespread adoption of this technology. Others mentioned that their raters and energy modeling software could get them to the overall home performance target they were seeking with good double-pane windows and the consumers were satisfied with the double-pane windows as well.

Homeowners and occupants appear to want a window that looks good and keeps them comfortable, but few consumers are familiar with the energy specifications or other features of the window that could affect comfort. They tend to rely on code specifications or if they prioritize energy efficiency, they rely on ENERGY STAR specifications, which can be met with most of the double-pane windows available on the market. A custom and production home builder in New York uses triple-pane windows for their performance, but he said, "People don't ask for them. The education level of the people is low. They (home owners) don't care about the windows."

Nevertheless, there is some indication that consumers armed with appropriate information and education on the topic may care about window performance. In a 2019 National Association of Home Builders Survey[13] of home buyers, 77% of the respondents identified triple-pane windows as either an essential or desirable feature when buying a home; however, no price points were provided as part of the survey. One manufacturer interviewed as part of the Energy Trust Window Market Research Report suggested that manufacturers are starting to try to tap this potential consumer interest in high-performance windows by marketing directly to homeowners (rather than to builders). But this same manufacturer noted that marketing to homeowners requires considerable education, because few homeowners know what U-values are (Apex 2018).

[12] BEopt (Building Energy Optimization Tool) software is used to evaluate residential building designs and identify cost-optimal efficiency packages at various levels of whole-house energy savings.
[13] Information presented by Rose Quint at NAHB's Sustainability and Green subcommittee meeting, April 2019.

Technology Application

The consumer awareness barriers cited by builders (Gilbride et al. 2019) are not specific to conventional triple-pane windows and could be generally applicable to any high-R window. As a new and emerging technology, consumer awareness of thin triple-pane windows would likely be extremely limited; therefore, the demand-pull strategy should include additional efforts related to outreach and information dissemination to address this challenge.

3.5.4 Supply Chain Issues

Supply chain issues include limitations on what is available locally and concerns about long lead times and difficulty getting replacement parts. Lead times for the builders interviewed (the amount of time from placing the order to receiving the windows) varied dramatically, from 1 week to 4 months. Several of the builders surveyed buy their windows locally because they feel they are getting a good price, have a good relationship with the local vendor, desire locally produced products to reduce carbon footprint, or are buying from a vendor who is also their installer. However, this relationship can limit what choices are available to the builder because some window vendors only want to sell products from manufacturers with whom they have volume pricing arrangements, so they will often steer builders toward certain brands that sometimes may not even offer triple-pane windows as an option.

Some builders voiced concerns about longer lead times needed for triple panes. One concern is window breakage – if a window breaks during installation builders want to be able to replace it in days not weeks. Builders typically do not keep an inventory of windows on hand, due to lack of storage space and concerns about breakage, so if a window breaks, a replacement has to be ordered. Production builders also noted that when they put windows into a production environment, they have to be able to fill large orders quickly and efficiently, and get replacements in quickly if something breaks.

Five builders mentioned using European windows on at least one project. “I love the [European-manufactured] windows. We just can’t deal with the supply chain issues. We can’t handle an order being late or damaged in shipping,” said a production builder who buys his double-pane windows from a local manufacturer whose factory is less than 20 miles away. Two Canadian companies were among the 32 brands mentioned and four builders have used Canadian brands. Lead times were longer than for some U.S. brands but were not described as being problematic.

Technology Application

Although the supply chain issues cited by builders (Gilbride et al. 2019) are related to supply of conventional triple-pane windows, these same issues could pose issues with potential market uptake of thin triple-pane windows as well. Although supply arrangements for field demonstration are not necessarily reflective of the supply chain and distribution of full-scale production levels, both supply-push efforts (focusing on scalable, efficient processes) and demand-pull efforts (focusing on certification processes and distribution networks) should be considered to ensure sustainable market strategies.

3.5.5 Structural, Size, and Design Limits

Several builders noted design issues related to the weight and thickness of standard triple-pane windows. One production builder in the Southwest explained his company doesn't use triple-pane windows because, "We have design issues. Triple panes are a much heavier, larger, thicker window. On some of our homes we're doing a 2x4 wall so the triple-pane window is too thick. If it's not plug and play, it's not going to work."

One Seattle area builder who uses triple panes noted that he is limited in what sizes he can use. "We don't have a cherry picker or crane on site, so we have a maximum size limit. We don't install windows larger than 25 ft^2 above the first floor. Buildability is an issue, we have to design what we can build affordably." A Chicago builder also acknowledged that the weight and design limitation of the triple-pane window had posed problems for them. "We've had manufacturers tell us they could only make limited sizes on triples in casement and awning style windows because their hardware would only support so much weight."

A nonprofit builder in New York noted that, in addition to requiring more crew members, the heavier triple-pane windows also require different fasteners; they use screws instead of nails. A custom builder in Colorado who often uses large picture windows for the views said, "Our brand's largest triple window is 7 x 9 feet and weighs about 400 pounds. We use suction cups on it and five guys. We do have to think about what's feasible when designing window sizes for the second floors."

Technology Application

The structural, size, and design limitations noted by builders in the survey (Gilbride et al. 2019) are l directly associated with the weight and width of conventional triple-pane windows. The thinner profile and lighter weight of the thin-triple window would presumably address this barrier. One objective of this project will be to validate this in the field (see Table 4).

4.0 Market-Pull Opportunities

An effective market-pull strategy for the thin triple-pane technology should be centered on developing analyses, experiments, and field studies to address market barriers and validate potential benefits in the field. All efforts should involve key market stakeholders and focus on solutions and strategies that are sustainable in the market and not dependent on continuing technical assistance.

4.1 Validating Benefits of Thin Triple Technology

Based on the findings presented in Section 3.4 of this report, the technology benefits of thin triple-pane windows should be validated with analyses, case studies, and field testing. Table 3 summarizes the field tests and case studies that could directly validate the benefits identified in Section 3.4 of this report, and also identifies the research partners who would facilitate effective strategic engagement with key stakeholders within the market structure characterized in Section 3.3 to foster sustained benefits in the market.

Table 3. Recommended Research for Validating Benefits of Thin Triples

Potential Benefit	Field Validation and Study Design	Field Recruitment Targets and Potential Research Partners
Reducing Energy Costs	Design field studies and validate savings in regions with relatively higher utility costs.	Home builders and utilities in the U.S. Northeast
Utility Incentives	Design field studies in regions that have proactive utility programs geared toward weatherization and window improvements to take advantage of utility momentum in this area.	Northwest (e.g., BPA), California (e.g., CEC), Northeast (e.g., NYSERDA)
Noise Reduction	Design field tests to capture noise reduction benefits from installation of thin triple panes.	Urban builders and remodelers, airport noise mitigation programs, military bases (housing)
Increased Comfort	• Design field tests and PNNL Lab Home tests to capture temperature differences in and around the window. • Develop protocols to examine evenness of temperatures throughout the home. • Consider shading experiments in conjunction with triple panes	PNNL Lab Homes and potentially any home in the field; particular benefits to small homes and homes that have high window-to-wall ratios
Decreased Condensation	Design field test protocols to collect data on condensation differences between double-pane and triple-pane windows during the winter.	Smaller and higher-occupancy homes in heating-dominated climates
Lower Life-Cycle Costs	Field studies, PNNL Lab Homes, and follow-up simulation study results could be used to perform a life-cycle analysis of costs associated with installation of thin triple-pane windows.	PNNL Lab Homes. Field studies should include a cold climate location with high energy costs

Potential Benefit	Field Validation and Study Design	Field Recruitment Targets and Potential Research Partners
Market Distinction for Builders	Examine market data and develop case studies to assess marketing strategies that feature high-performance windows.	High-performance homebuilders (e.g., ZERH, PHIUS)
System Sizing and Distribution Benefits	Design Lab Homes testing to directly address differences in system sizing needs relative to thin triple-pane windows versus double-pane clear windows. Gather data and perform meta-analysis on existing data to assess system distribution benefits from triple-pane installations.	PNNL Lab Homes and high-performance homes (e.g., ZERH, PHIUS)
System Trade-Offs	Gather high-performance home building data and case studies to analyze system trade-off effects directly associated with triple-pane windows. Perform BeOPT or other simulation analysis related to system trade-offs.	PNNL Lab Homes and high-performance homes (e.g., ZERH, PHIUS)
Climate Benefits	• Design field studies in cold and/or very cold climates where both HVAC and comfort benefits from triple panes are maximized and the potential benefits of tightening energy-rating criteria in these climates can be validated. • Design experiments geared toward SHGC tuning.	Homes and home builders in northern cold and very cold climates

BPA = Bonneville Power Administration; CEC = California Energy Commission; NYSERDA = New York State Energy Research and Development Authority; PHIUS = Passive House Institute U.S.; SHGC = solar heat gain coefficient; ZERH = U.S. DOE Zero Energy Ready Home program.

4.2 Addressing Market Barriers

Based on the findings presented in Section 3.5 of this report, the following market barriers should be addressed by initiating supply-push/demand-pull strategies such as those suggested here and listed in Table 4 below.

1. **High first costs.** The drop-in thin triple-pane IGU has the potential to reduce first costs by utilizing the standard (and lower-cost) double-pane frame/sash. Several manufacturers in the Energy Trust manufacturer survey (Apex 2018) mentioned the continued importance of rebates, especially considering the reduced federal tax incentives, to drive behavior. A combination of supply-side and demand-side approaches could be employed to work with manufacturers and utilities to address high cost barriers.
2. **High installation costs**. Several builders surveyed (Gilbride et al. 2019) mentioned that a lighter weight, thinner thin triple-pane window could go a long way toward alleviating the burdens associated with installation of triple-pane windows. Field studies could help validate installation cost savings in the residential market.
3. **Benefit-Cost Ratio**. Builders recognize the thermal performance benefits of triple-panes. However, several did not find the overall benefits of moving to triple panes sufficiently high enough to outweigh the incremental costs. Nevertheless, several builders had made the case for triple panes in terms of life-cycle costs and HVAC system benefits and trade-offs.

Case studies, field testing, and controlled home experiments designed to validate these savings and trade-offs could help demonstrate the cost-effectiveness of these trade-offs and provide an overall positive benefit-cost ratio. These studies should be performed under varied regional and codes/standards conditions, including unique and ambitious state energy codes using building measure trade-offs, such as California's Title 24 Standard.[14] ZERH building measure tradeoffs could be modeled in BeOPT in various climate zones.

4. **Insufficient consumer demand and recognition of product benefits**. Consumer awareness of the life-cycle benefits of high-performance windows could be improved by conducting case studies that highlight the features that are important to consumers and by partnering with utilities and energy labeling organizations that directly engage with consumers.
5. **Recognition by energy-rating programs**. One manufacturer noted that if energy rating organizations can make it cheap to comply, then it can become easier for ENERGY STAR to lower the requirement (Apex 2018). ENERGY STAR- and NFRC-testing procedures, as well as energy modeling, were mentioned by one interviewee as being "outdated" and overlooking several critical attributes (including air-conditioning saturations, winter fan savings, proper fan sizing, and home orientation) (Apex 2018). Field validation planning efforts should involve energy-rating program representatives to ensure that the information that informs their procedures and specifications will be gathered as part of the field studies.
6. **Product availability and search costs.** Issues with long lead times associated with triple-pane orders was noted as a significant barrier to integrating triple panes into new building construction, especially for production builders. Builders often rely on regional window vendors to supply products and reduce their search costs for quality products. These vendor relationships are an important part of the builder business model, but may sometimes pose limitations on and potential barriers to getting new and emerging technologies integrated into new home construction. Field validation efforts should involve multiple window vendors and builders to assess and address issues related to product availability.
7. **Structural, size, and design limitations.** Several builders noted structural, size, and design limitations associated with integrating triple-pane windows into new home designs. Those who are building with triple panes have accepted or accommodated these limitations, but for others, these limitations present significant barriers to integrating triple panes into their construction plans. Field studies will be designed to validate that the thin triple-pane windows adequately address this barrier.

These barriers and potential supply-push and demand-pull strategies for overcoming them are summarized in Table 4.

[14] California's 2019 Building Energy Efficiency Standards – Title 24 – takes effect in January 1, 2020 and allows for tradeoffs between some wall insulation and window efficiency measures under the Energy Design Rating pathway to compliance.

Table 4. Recommended Research to Address Market Barriers

Barriers	Innovation-Push Strategies	Market-Pull Strategies
High First Costs	• Continue manufacturer engagement to examine incompatibility of thin triple-pane IGUs with production lines and frame/sash fabrication. • Provide direct technical assistance (e.g., testing, simulations) to manufacturers of thin triple-pane IGUs.	• Engage multiple window manufacturers, vendors and home builders in field validation studies. • Include lower-cost vinyl frame/sash in studies for broader applicability. • Work with utilities to design upstream rebates for manufacturing processes and programs that specifically incentivize consumers to move toward the highest efficiency products.
Installation Costs	Address installation costs by developing thinner, lighter IGUs manufactured in partnership with Alpen Windows and other manufacturers.	Validate installation benefits of thinner, lighter triple-pane IGUs in the field.
Benefit-Cost Ratio	Continue with strategies to reduce costs and conduct R&D to enhance the performance of thin triple-pane windows.	Analyze BeOPT envelope and system trade-off cases to determine price points needed to reduce payback and move toward a positive benefit-cost ratio for triple panes.
Insufficient Consumer Demand	• Provide direct technical assistance focused on NFRC certification of thin triple-pane windows. • Work with manufacturers to demonstrate variations in glazing options for thin triple pane windows (e.g., laminated, tempered glass, and varied coatings with range of SHGC).	• Design field validation studies that capture benefits that resonate with consumers, including non-energy benefits. • Consider demonstrations and field studies featuring special glazing options (e.g., laminated glass for noise reduction, tempered glass for sliding doors, and high SHGC coatings for window tuning). • Work with utilities to design and promote utility incentives for highest preforming windows. • Work with manufacturers and/or retailers to increase awareness of thin triples.
Recognition by Energy-Rating Programs	Provide direct technical assistance focused on ENERGY STAR “Most Efficient” certification of thin triple-pane windows.	Develop field and case studies that examine the HERS scores and cost-effectiveness of requiring a “Most Efficient” ENERGY STAR rating for ZERH windows in the cold climate zones.
Product Availability	Work with multiple manufacturers to encourage consideration of thin triple-pane IGUs in fabrication processes.	Incorporate multiple window frame/sash brands into field studies to validate “drop-in” feasibility of thin triple-pane IGUs with standard double-pane frame/sash (with multiple vendors).
Structural, Size, and Design Limitations	Address these limitations with development of thinner, lighter IGUs manufactured in partnership with Alpen Windows and other manufacturers.	Validate the feasibility and flexibility of thin triple-pane windows in multiple home types, including retrofit and multi-family applications.

IGU= insulated glass unit; BeOPT = Building energy Optimization Tool; NFRC = National Fenestration Rating Council; SHGC = solar heat gain coefficient; ZERH = U.S. DOE Zero Energy Ready Home program.

4.3 Field Validation Opportunities

Based on the barriers, existing framework and partnerships, and consumer benefits identified in the previous sections of this report, the following targeted markets and market transformation pathways and strategies are identified for high-R windows.

4.3.1 PNNL Lab Homes Experiments

To examine the energy and thermal performance of high-R thin triple-pane windows in a residential retrofit application, PNNL's matched pair of all-electric, factory-built "Lab Homes" could be used. The PNNL Lab Homes are located on the PNNL campus in Richland, Washington. The 1,500-square-foot homes are identical in construction and baseline performance and can be operated in an identical manner, which allows any difference in energy and thermal performance between the "control" and "experimental" homes to be attributed to the installation of the thin triple-pane windows in the experimental home. The PNNL Lab Homes allow for the windows year-round energy savings to be accurately measured in a controlled setting, and they facilitate experiments that are difficult to conduct in the field in occupied homes.

Experimental field validation opportunities that are well-suited for the PNNL Lab Homes platform include the following:

- **Thermal Performance:** Measurement of HVAC savings in all seasons in comparison to lower-performing double-pane clear-glass windows (common in existing homes).
- **HVAC sizing:** HVAC sizing implications using higher-performing windows. Testing could include validation of energy simulation studies including comfort implications (e.g., temperatures throughout the home) and distribution implications (e.g., ability to reduce length of ducts).
- **Installation Costs:** Validation of installation costs onsite.
- **Peak Demand Benefits:** Peak–load and experiments to examine peak-flattening effects. These experiments could potentially combine window shading technologies with thin triple-pane windows.
- **Non-Energy Benefits:** Validation of non-energy benefits such as temperature control and noise reduction.
- **Drop-in Feasibility:** Potential for completing validation of the "drop-in" feasibility of thin triple-pane IGUs in a standard double-pane vinyl frame/sash in the Lab Homes.[15]

The results of these experiments could contribute to analyses and energy simulations focused on life-cycle costs and system trade-offs.

4.3.2 High Performance New Homes

High-performance home builders that are participating in DOE's ZERH, PHIUS, or other energy-efficiency programs are relatively more driven toward efficient building products, including

[15] Although the Lab Homes could serve as a testing platform to validate drop-in feasibility of thin triples, it would involve costly modifications to both the baseline and experimental homes; thus, completion of these experiments would be dependent on time availability of Lab Homes for testing, funding, and availability of standard double-pane vinyl frames, which are not currently installed in the Lab Homes.

windows. Thus, field validation studies that partner with high-performance home builders could potentially provide sustainable results, because these builders have a vested interest in finding energy-efficient solutions that are cost-effective and potentially provide added market distinction for their homes. A number of field validation efforts would be well-suited for the high-performance home building market, including the following:

- **Costs in the Field:** Working with home builders in the field allows for validation of actual cost implications and helps determine whether the thin triple-pane windows are appropriately addressing the cost barriers relative to standard double-pane window purchases and installations. These barriers include installation costs improvements, relative first costs in different applications, and the search costs and lead time associated with thin triple-pane windows.
- **Thermal Performance:** Evaluating HVAC energy usage for homes with and without thin triple-pane windows could be collected for various homes types and climate zones for all seasons.
- **Peak Demand Benefits:** Peak-flattening and peak-load impacts of thin triple-pane windows could be collected in the field and compared for various base cases, home types, and climate zones.
- **Non-Energy Benefits:** Non-energy benefits, including temperature consistency and noise reduction could be validated.
- **Drop-in Feasibility:** Depending on the availability of appropriate products, field tests could be used to validate the “drop-in” potential of thin triple-pane IGUs in a standard double-pane vinyl frame/sash. Different combinations of frame/sash products and Alpen-produced IGUs could be considered to examine the applicability and scalability of the product.
- **Utility Incentives:** When possible, we can design field tests in coordination with utility envelope programs to further assess benefit-cost ratios and pathways to market and scalability in different regions and under varied utility programs.
- **Energy Ratings:** ZERH builder partners allow us to examine HERS ratings in the field to calibrate field data to BeOPT measurement trade-offs.

The results of various field tests could contribute to the analyses and energy simulations focused on life-cycle costs and system trade-offs.

4.3.3 Existing Homes Retrofits

Existing home remodels and window-replacement retrofits provide significant opportunities in terms of energy-savings potential. Existing homes with single-pane windows would realize the greatest incremental benefit from replacing existing windows with high-performance triple-pane windows and DOE estimates that approximately 48.7 million (or ~40%) of existing homes still had single-pane windows as of 2015 (DOE-EIA 2015). Also, as noted in Section 3.2 of this report, most of the existing homes with double-pane windows would realize more than a 40% improvement in U-value rating if they upgraded to a thin triple-pane window with a 0.19 U-value. A number of field validation efforts would be well-suited for the high-performance home building market, including the following:

- **Costs in the Field:** Window replacement is often a labor-intense endeavor, so ease of installation of thin triple-panes should be validated.
- **Thermal Performance:** Evaluating HVAC energy usage for homes with and without thin triple-pane windows could be collected for various home types and climate zones for all seasons.

- **Non-Energy Benefits:** Non-energy benefits, including temperature consistency and noise reduction could be validated.
- **Drop-in Feasibility:** The feasibility of “drop-in” triple-pane IGUs into a double-pane frame/sash has particular importance in the existing home setting where structural wall and window frame limitations would likely exist.
- **Utility Incentives:** When possible, we can design field tests in coordination with utility envelope programs to further assess benefit-cost ratios and pathways to market and scalability in different regions and under varied utility programs.

The results of various field tests could contribute to the analyses and energy simulations focused on life-cycle costs and system trade-offs, particularly for markets where building codes are set up with tradeoff compliance paths and are applicable to major retrofits and remodels.

4.3.4 Climate, Energy Costs, and Occupancy

Based on energy-savings potential studies of thin triple-pane windows (Hart et al. 2019), thin triple-pane windows have the highest energy savings potential in the cold and very cold climates in the northern Midwest and northeast regions of the United States. Based on input from home builders (Gilbride et al. 2019), some of the non-energy benefits of higher-performing windows, such as interior condensation reduction, are also most noticeable in these colder climates. It was also noted issues with interior condensation tend to be worse in higher-occupancy homes. The highest energy savings are also achieved in areas with the highest energy costs.

These two factors (cold climate and high energy cost) predominate in the Northeast where energy costs are among the highest in the United States. While the Northeast is considered a cold climate, summer cooling needs are also significant and are subject to some of the highest electric rates in the nation. Therefore, it would be ideal to find some field study opportunities in the Northeast to validate savings in these settings. If possible, it would be useful to find some higher-occupancy homes in the colder climates to validate both energy savings and condensation benefits. Field studies in cold- climate homes with high occupancy could also validate thermal performance, cost savings, and other non-energy benefits described in Section 4.3.2 of this report.

4.3.5 Multi-Family and Manufactured Homes

The standard wall construction of multi-family and manufactured homes has been identified as sometimes being incompatible with the width of conventional triple-pane windows. The thin triple-pane window conceivably addresses this structural barrier to higher performance windows for multi-family and manufactured homes—particularly in the retrofit setting. To validate these concepts, field studies specifically designed for these building types would be beneficial. These households are often smaller in size when compared to single-family homes and can be available for a lower monthly cost, which can be attractive for families with young children. One other potential benefit from having high-performance windows installed is that temperatures can be controlled throughout the home and in proximity to the windows. Issues with comfort and poorly performing windows can be particularly acute in smaller homes where you are never far from a window. In addition to validating the feasibility of installation, field studies in multi-family and manufactured homes could directly validate comfort benefits and also validate thermal performance, cost savings, and other non-energy benefits in a manner similar to that described in Section 4.3.2.

4.3.6 Other Opportunities

Other opportunities where the market drivers may align with consumer benefits in an optimal manner to validate window savings could include federal building stock or government-subsidized housing and/or community-supported affordable housing. Although the vast majority of the residential building stock is privately owned, a portion is owned by the government. Federally-owned residential stock primarily includes military housing and barracks. In an effort to reduce energy consumption in the federal sector, which is the nation's single largest energy consumer, a number of laws and Executive Orders have been enacted over the years to establish requirements and direct the reduction of energy and water consumption in federal facilities. The Energy Policy Act of 2005 and Title IV, Subtitle C of the Energy Independence and Security Act of 2007 provide the legislative foundation for guidance and Executive Orders that set goals for energy-efficiency improvements in federal facilities. Military housing, in particular, could be a good candidate for field validation of high- windows, because such housing would not only benefit from the thermal effects, but could also benefit from sound attenuation benefits and comfort benefits associated with smaller and higher-occupancy homes. In addition, when tenant or homeowners are paying utility bills, the lower heating and cooling bills would be relatively more beneficial to lower-income occupants, where a relatively higher percentage of their income goes toward heating and cooling bills.

Other opportunities could include larger homes with larger window-to-wall ratios where overall energy BTU savings and peak reductions from high-R windows would be expected to be greatest. Because of the potential noise mitigation benefits, homes that are exposed to sources of noise (e.g., urban centers, near airports, train tracks, etc.) may also be good candidates for field validation testing.

5.0 Program Plan and Goals

Based on the identified barriers and existing market framework and partnerships, the sustainable high-R window R&D strategies include the field validation modeling and technical support efforts targeting the market segments and "core customers" presented in Table 5.

Table 5. Field Validation Studies and Potential Pathways to Market Transformation

Experimental Questions/Topics	Validation Study Approach	"Core Customers" of Research (Pathway to Market Transformation)
Are thin triple-pane windows cost-effective (currently or near-term) for new construction and/ retrofit applications?	• Lab Homes experiments to quantify benefits and costs • Field validation studies to quantify benefits and costs • Life-cycle analyses based on field testing and energy simulation results	• Utilities (utility-sponsored window incentive and weatherization programs) • High-performance builders • Energy-efficiency organizations
Are thin triple-pane IGUs "drop-in" feasible with multiple brands of double-pane frames/sashes?	• Lab Homes and/or field testing to combine Alpen IGUs with multiple vendors' frames and sashes	• Multiple window manufacturers including regional window makers of relatively lower-cost vinyl frames/sashes
Do thin triple-pane windows reduce design limitations and facilitate more flexibility in high-efficiency homes?	Field experiments in multiple housing types including multi-family housing and retrofit applications	• High-performance builders • Energy-efficiency, weatherization, and affordable housing organizations
Are there cost-effective system sizing implications and/or system trade-off implications with the installation of thin triple-pane windows? In what applications/conditions?	• Lab Homes experiments to quantify system sizing implications using standard heat pump and mini-split heat pump • BeOPT and energy simulation case studies based on findings from Lab Homes and builder survey data	• High-efficiency builders in multiple climate zones and housing types • High-efficiency building energy-rating programs
To what degree are non-energy benefits associated with the installation of thin triple-pane windows? In what applications/ conditions?	• Lab Homes experiments to characterize comfort benefits • Field validation studies to characterize and quantify comfort, condensation, and noise benefits • Follow-up case studies with selected high-performance builders to characterize benefits in field	• Utilities (utility-sponsored window incentive and weatherization programs) • High-efficiency builders in multiple climate zones and housing types
Could thin triple-pane windows support the tightening of high-efficiency energy-rating standards?	• Provide direct technical assistance focused on NFRC, PHIUS, and ENERGY STAR "Most Efficient" certification of thin triple-pane windows • Case studies and energy simulations to assess the impact of tightening restrictions for identified climate zones	• High-efficiency builders in multiple climate zones and housing types • High-efficiency building energy-rating programs

IGU=insulated glass unit; BeOPT = Building energy Optimization Tool; NFRC=National Fenestration Rating Council.

In addition to the activities listed in Table 5, the program should develop a plan to effectively disseminate information to the “core customers” listed in Figure 4 and Figure 5: utilities, energy-rating organizations, regional window manufacturers, vendors, and distributors, and weatherization and energy-efficiency programs. These activities could include strategic workshops, training, and/or direct technical assistance in multiple forms.

6.0 Conclusion

The U.S. residential windows market has experienced dramatic improvements in performance over the past 30 years where argon-filled double-pane low-e windows (~R-3) now make up over 90% of window sales. Today's windows, however, still account for approximately 4 Quadrillion Btus of energy use at an annual cost of $40 billion (Selkowitz et al. 2018). A higher performing (~R-5-R-7) triple-pane window is readily available in the market; however, the conventional triple-pane IGU is both heavier and about one-half inch thicker than the standard double-pane IGU, which necessitates a re-design of the standard frame and sash to accommodate the added weight and width. The added weight and thickness, and the associated costs pose barriers to producing triple pane windows at scale and are often cited as the primary barriers to broader market acceptance of the technology. The thin triple-pane IGU technology has the potential to help address these barriers and transition the windows market to a significantly higher level of performance, but the technology is not available in volume at competitive prices. We have outlined a series of innovation-push and market-pull strategies, which includes a series of field validation studies. The field studies are proposed within a framework that considers key drivers in the residential windows market and focus on validating the benefits of high-R windows to the relevant market stakeholders. The field studies are designed to validate benefits and address market barriers of thin triple-pane windows in order to prioritize demand-pull efforts and identify the most promising pathways to transform the market for high-R windows.

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