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Thin Triple Pane Windows: A Market Transformation Strategy for Affordable R5 Windows

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Executive Summary

In many new homes windows represent just 7% of the envelope area but 48% of the total envelope heat loss. The typical ~R3[1] code compliant or ENERGY STAR™ window in common use in the Northwest is double glazed and has not changed significantly over the last 20 years. A shift from double to triple glazing, ~ R5, would reduce window heat loss and improve comfort. Unfortunately, this requires a potentially complex and expensive redesign of the entire window. Given the lack of market demand for triple glazing, there has been little to no motive for manufacturers to invest in making the necessary design changes and production investments.

More than two decades ago, the Lawrence Berkeley National Laboratory, LBNL identified a novel technology pathway to thermally upgrade windows by adding a thin third pane of glass into the traditional two pane insulating glass unit (IGU), adding a second low-E coating and replacing the argon gas fill with krypton.. **This results in a drop-in replacement R8 IGU that converts existing R3 windows to ~R5 without any redesign of the window, thus lowering risk, cost and time to market.** The thin glass needed has since become readily available and affordable because of high demand by the flat screen TV and computer monitor industry, dramatically reducing the incremental cost of this novel IGU. If built at scale this new "Thin-Triple" would have an incremental volume manufacturing cost of only $2-4 per square foot, and should result in a market cost far less than traditional triple pane windows. While the initial market opportunity is the residential sector, thin-triple pane windows would be applicable to the commercial sector as well.

This document outlines a plan to quickly introduce this thin-triple window to mainstream markets by removing key market barriers. The plan would require directly engaging window industry partners who make and sell windows in the Northwest and their critical supply chain partners. A key early challenge is solving the technical and investment challenges to make these new glazing units on a highly automated production line to reduce cost and enhance quality while simultaneously ensuring sufficient market demand that these product would sell with the necessary premium cost needed to recover the initial manufacturing investment.

The plan assumes the utility and educational/training/outreach partners that have served other successful market transformation efforts in the Northwest in the past could be leveraged with similar efforts in California and Canada. In order to reduce risk and provide the largest possible market stimulus, the plan suggests combining utility customer rebates/incentives with manufacturing investment support. The market transformation would be secured by establishing sufficient market demand

[1] We use U and R throughout the report to characterize window properties; U. conductance in Btu/hr-ft^{2}-^{0}F and R, resistance in hr-ft^{2}-^{0}F/Btu. Note that some refer to whole window properties and others to insulating glass (IGU) properties

that the current northern climate ENERGY STAR™ window specification can be moved from its current U value of 0.27 Btu/hr-ft^2-^{0}F to ~0.20 Btu/hr-ft^2-^{0}F where the ENERGY STAR™ "Most Efficient" specification level is currently set. Emerging code requirements in several states and Canada would create additional market demand, as would niche, but rapidly growing, markets delivering Passive House solutions and Zero Net Energy buildings.

A NEEA effort could leverage the active window transformation efforts in the Canadian and California programs. A coordinated effort with those evolving activities would maximize NEEA's chance of success since their combined window markets are six times larger than in the Northwest alone. The coordinated effort from all three regions will generate a much stronger positive investment reaction from the window industry than any one group or region alone.

The timing of this opportunity is also important for two reasons. First is alignment with new energy codes in California and Washington that go into effect in 2020. The presence of drop-in replacement R5 window will enable easier compliance paths for builders creating immediate demand for the product. The second reason is strong interest nationally by DOE which has launched a national field demonstration program and by the California Partnership for Advanced Windows (C-PAW) to promote rapid commercialization of this technology to meet their new 2020 codes.

Virtually all of the eight large window companies that dominate sales in the Northwest are also active in California and Canada. There are active cooperative technology development programs in place now between LBNL and two window companies, Andersen Windows and Alpen windows, with new discussions underway with other window companies and with active business relationships established with all the supply chain partners. Given the emerging availability of the "drop-in replacement" thin-triple technology, the timely related efforts already underway in California and Canada, and growing interest in the benefits of better windows, this is an opportune time for NEEA to launch a targeted effort in the Northwest, as outlined in this document.

Background and Context

Window energy efficiency has not advanced significantly over the last decade at a time when expectations for improvements in overall building energy use are changing dramatically. As concerns about climate impact of carbon emissions from energy use grows, more attention has been turned to redoubling efforts to increase energy efficiency in buildings as a proven cost effective strategy that has delivered results in the past. A variety of national, regional, state and local efforts have been formulated around the goals of zero net energy (ZNE) performance for new buildings by a 2030 timeframe and other similar aggressive goals in reductions in existing building energy use. In this report the authors focus on practice in the Northwest and focus on residential buildings, although data and findings are largely relevant nationally and to all buildings in varying degrees.

Much prior building policy and program effort has been focused on better lighting (incandescent → CFL → LED) and improved HVAC systems. These technologies and hardware systems are routinely updated and/or replaced on a periodic basis in most buildings. But the **building envelope, and specifically windows, are expected to last for 30, 50 or even 100 years without replacement. So ensuring that the "best possible" or at least "best available" windows are used in each new home or renovation/replacement ought to be a policy priority**.

Reaching more aggressive overall building performance targets will require a closer look at the building envelope that drives most of the HVAC loads in homes. Wall and attic insulation levels have risen over the years in building codes and standard practice to the range of R15 to R40 in conventional homes and higher in more efficient structures. Yet windows have lagged – a typical code compliant window today, and even an Energy Star window, is rated at R3 – R3.3. A few window products available for sale today can achieve thermal insulating properties as much as R10 and much of northern Europe has transitioned to R5 triple glazed windows, so there is no fundamental technical reason why thermally improved windows cannot be made and sold. **However, the market and associated supply and demand ecosystem is complex and has evolved slowly over time to its current state, and while the need for further change is clear, the complex processes that drive market charge are inherently very slow with no guarantees of specific outcomes on a scheduled timeframe**. This suggests the needs for a variety of technical and market interventions to accelerate that change process.

Virtually all change in the building industry is typified as slow and this is true for the window industry as outlined in more detail in this report. Transitioning the industry from double glazing (~R2) to double/low-E (~R3) took about 20 years from market introduction until 50% sales penetration was achieved. Over an additional 10-15 years sales of low-E have risen to over 85% of the market. Improving windows from ~R3 to ~R5 via the traditional route of switching to conventional triple glazing requires a complete redesign of the window to accommodate a wider, heavier insulating glazing unit (IGU), which thus incurs significant cost and risk on the part of the window manufacturer. This helps explain why these products exist today as niche products that represent only about 2% of current sales, a number that has not changed substantially in years.

Proposed New NEEA Window Initiative

This report focuses on actions that NEEA can take over the near term to transform window markets in the Northwest to include a mix of more affordable, high-performance insulating window products. The activities are focused around promoting an emerging technology option for a new "drop-in replacement" glazing that would initially allow a window manufacturer to convert their existing R3 Energy Star window to an ~R5 window without any window frame redesign. This would allow more rapid scale-up for higher volume production at less risk to the window manufacturers, reduce time to market and provide more options for consumers at lower cost. NEEA can facilitate and accelerate this effort by implementing a variety of proven strategies to change market behavior with the goal of transforming those markets to new self-sustaining operating business models.

While addressing a short term "tactical" need it also enables a longer-term broader market transformation. As the value of highly insulating windows becomes clearer in the marketplace, this should help "raise the bar" for window performance goals that should establish additional opportunity for investment in other high performance window products, such as redesigned windows with conventional triple glazing designs and later vacuum insulating glazing, VIG. It should also build support for tightening future performance requirements for mandatory codes and standards and for voluntary programs like Energy Star windows and utility incentive programs.

Learning from the Success of the Low-E Window Market

Based on historical precedent there is reason to be optimistic about the potential for significant change in window markets (Figure 1). In the 1970s the "oil crisis" and dramatic increase in energy costs precipitated an initial transition from single glazing, R1 to conventional double glazing, R2. But that was inadequate in cold climates, leading to the research and development of low-emissivity (low-E) argon filled glazings that improved the insulating value of the window to ~R3 without requiring a major redesign of the window. This approach, with a 50% reduction in heat loss, rapidly captured initial market share. Over a longer period of time the low-E coating technology evolved to include options that reduced SHGC for use in cooling dominated climates. This broader national applicability, with the help of a variety of market-based voluntary and mandatory programs, increased market share of low-E windows to the point where it now dominates the U.S. building sector with an annual sales market share of ~85%. The full transition took time, 30+ years, as can be seen in Figure 1 but the resultant national savings due to the market transformation of low-E vs a conventional double glazed window is estimated at ~$150B. (Selkowitz, 2018)

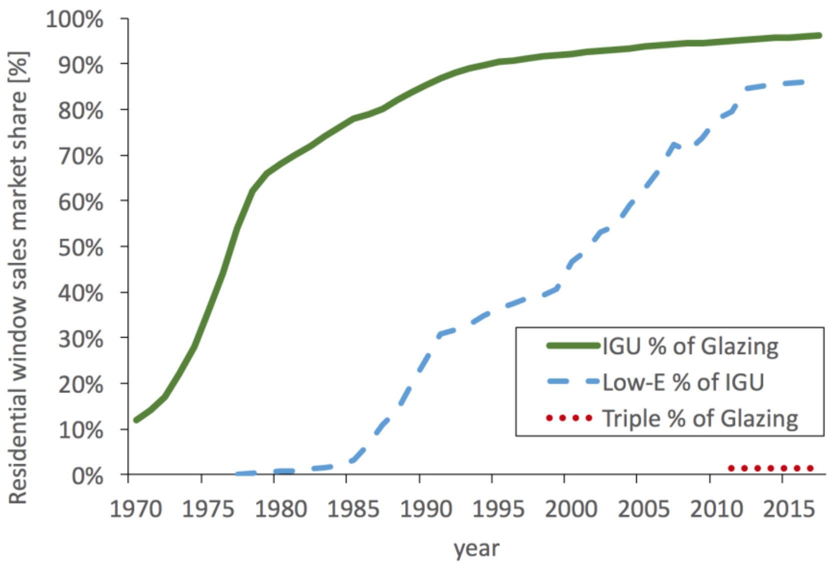

Figure 1. Residential window sales historical market share by year. Low-e shows a rapid rise in market penetration, while triple-pane market share is stagnant at around 2 percent. (Source: Ducker 2018)

History and market data as shown in Figure 1 reminds us that with focus, planning, effort, persistence and resources, significant change has occurred in window technology and markets in the past and we believe can be replicated again. **"Success" requires the understanding and simultaneous integration of two complex sets of actors and actions:**

1) the supply side, e.g. the window industry and the various technologies and supply chain/business practices involved, and
2) the market demand side, e.g. the consumers, contractors, builders, and the various voluntary and mandatory programs and standards that impact market behavior.

To create measurable progress in a very short time period, < 5 years, also requires a technology solution that:

1) is a drop-in replacement that improves overall window properties without a redesign of the window,
2) is affordable and scalable to supply growing markets, and
3) is not fundamentally disruptive to existing supply chains and market pathways.

A new variant on traditional triple glazing appears to meet these requirements and can form the core of a new NEEA effort to transform the market for energy efficient windows.

The new triple glazed window uses the prior low-E strategy of a drop-in replacement IGU. The "thin-triple IGU" (Fig 2) represents a new design for an R8 IGU based on a variant of triple glazing that uses an extra layer of very thin glass and other features (as outlined in more detail in Appendix 5) to meet these requirements and appears to be a promising candidate technology. While the technical concept for this R8 IGU was initially developed 30 years ago, it has only been in the last two years that scalable, cost effective solutions for the key elements became commercially available (Selkowitz, 2018).

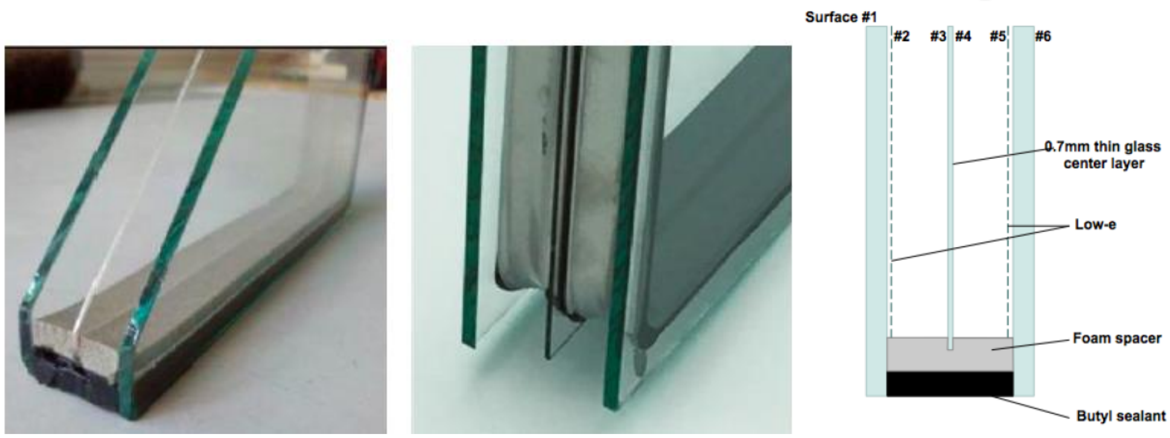

Figure 2: Two Edge Design Variants of the Thin-Triple IGU
Left: Single spacer, center thin glass is "floated" in the space
Middle: Conventional triple spacer design with 2 spacers, thin center glass is sealed to each spacer
Right: schematic section of (left) thin-triple IGU showing low-E coating locations (see Appendix 5 for more information on the "thin-triple" IGU concept)

The thin-triple IGU can be viewed as an "emerging technology". Extensive simulation-based optimization and prototype testing by LBNL have established the technical potential of the concept. **What is lacking is a market-focused program designed to accelerate the commercial availability of this proven window technology.** The proposed program would tackle the key market barriers with a series of activities that address the remaining technical and market adoption gaps. A comprehensive program addressing key barriers should provide an excellent opportunity for success. Launching such a program in the Northwest with its history of support for market transformation activities would create a nucleus for an emerging national effort, leveraging resources from other national and regional effort as outlined below. **The history of the successful low-E window development and market capture supports the notion that fundamental**

change in technologies and markets need both committed partners in the window industry working closely with a variety of public/private groups (NGOs, utilities, state agencies) to create broad market successes.

Market Transformation Logic Model for R5 Windows

The activities, pathways, and outcomes for such a program appear complex - because they are. To be successful, a program must address a range of concerns; 1) the window manufacturers and the supply chains that support them; 2) the designers, architects, homeowners and builders who specify and pay for them; and 3) the utilities, NGOs, state agencies and others with a stake in the outcomes with respect to broader societal sustainability goals.

A market transformation logic model has been developed that identifies the key technical and market barriers, outlines activities to address them, defines the expected outputs of those activities and then identifies the expected market outcomes (Figure 3). The outcomes are organized roughly by time frame, distinguishing a series of short-term (1-3 years) and mid-term (3-5 years) outcomes as well as to other desirable longer term market end states. The two essential short-term outcomes are highlighted in boxes 19 and 20: the implementation of manufacturing lines to fabricate the new insulating IGUs and the market availability of windows from window companies utilizing those IGUs. To further facilitate the initial launch and success of this effort a program of rebates and incentives (box 21) is designed to facilitate the transition to the new R5 windows.

The proposed NEEA effort is targeted to launch the products and build initial market share. The history of low-E reveals that a comprehensive series of follow-on activities and outcomes drove the market from its initial 5-10% market share to its eventual rise to 85+%. Additional desirable outcomes are also noted on the diagram for future consideration in a broader effort. These include:

1. Field data and user feedback that will support revisions to future codes and standards (boxes 24, 29, 30, 35, 36);
2. New design guidance to builders that support rethinking and downsizing HVAC equipment (boxes 24/25 and 30/31), which will partially offset the added cost of the windows;
3. Assisting EPA in updating Northern Zone Energy Star Criteria (box 22)
4. Estimating the impact of high performance windows on the electric grid as electric heating displaces gas in a decarbonized grid. (box 25)
5. Extending use of R5 glazings to the commercial sector, (boxes 24, 31, 37)
6. Extending the reach of the program to more cost sensitive purchasers and to retrofits markets using upstream rebates (boxes 27, 28, 34)

7. Building and validating the technology base for other triple and quad glazed windows as well as other insulating glass technologies like vacuum glazing for even more insulating future windows, (boxes 27, 28, 33, 34)

While these are potentially important to achieving broader and deeper longer range impact they are not all explicitly part of the current plan but are included here for completeness.

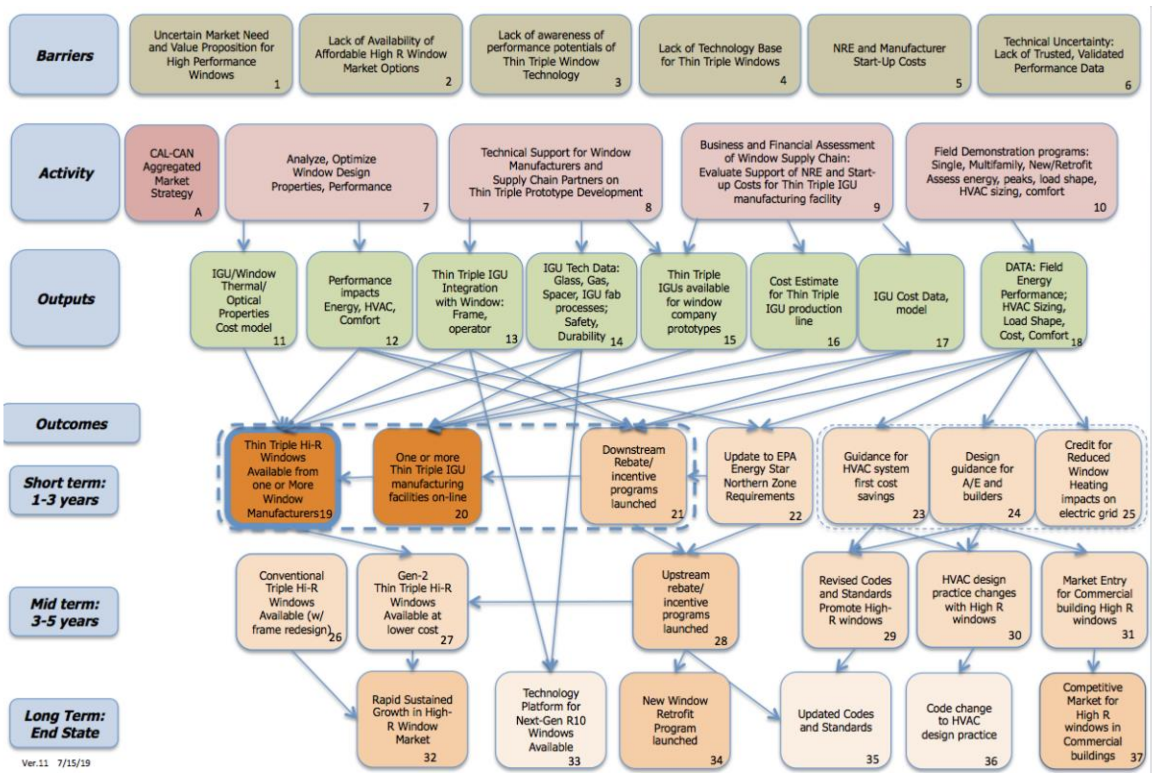

Figure 3: Logic Model to Drive Market Transformation for the Thin-Triple Insulating Windows Program

An Overview of the Logic Model to Introduce R5 Windows

We provide a technical, business and strategic framework for a program that NEEA can implement to transform the marketplace in the northwest for more highly insulating (~R5), energy efficient window solutions for buildings in a relatively short time frame. The initial focus is on window use in the residential sector, both new and replacement, although some of the findings and strategies may inform opportunities in the commercial sector. The residential and commercial markets are sufficiently different though that the applicability of technologies and programs outlined here might need to be altered. Even within the residential sector there are distinct market niches whose characteristics must be understood and addressed- e.g. developers building a subdivision vs a homeowner replacing old windows in an existing home. **The emerging technology goal is an R5 window:**

the pathway to achieve that is to utilize a novel R8 insulating glass unit (IGU) drop-in replacement that converts existing R3 windows to ~R5 without other redesign of the window, thus lowering risk, cost and time to market. This new "thin-triple" IGU concept, developed initially at LBNL and now being explored with several industry partners with research support from the U.S. DOE, is a variant of triple glazing as illustrated above in Figure 2 and explained in more detail in Appendix 5. A thin (~0.7 – 1.3 mm) layer of glass is inserted into a conventional ¾" wide IGU, a second low-E coating is added, and argon fill gas is replaced with krypton gas. These three changes double the insulating value of the IGU from about R4 to R8. When added to existing typical window frames, this raises the overall window insulating value from ~R3 to ~R5.

The interest in improving window energy efficiency is coming at a time when other opaque envelope thermal requirements for building performance continue to be tightened, while the changes in window thermal requirements have been modest. Window requirements to meet code or Energy Star have not changed significantly in many years. This represents potential low hanging fruit for NEEA to capture additional program savings. While one can find reports of new R12 evacuated glazings, there are only a few market options for windows with ratings of R5 or higher and they tend to be costly and difficult to find and procure. **The objective here is to focus on product options that are near-term, market ready, affordable, manufacturable by many companies, and deployable at scale over the next few years. Any longer term NEEA program would be performance based and technology agnostic so if this initial "thin-triple" design approach is successful it will open the door to other competing technology options that meet or exceed the energy performance and cost goals.** These longer-term options are identified in the Long Term/End State boxes of the Logic Model, (boxes 26, 32,33).

Forty years of experience in transforming building markets has taught us that any viable plan must address key intersecting issues on both the demand side and the supply side. The plan outlined in the logic model diagram combines a series of activities that advances supply side options as well as tasks that will drive progress on the demand side. The key is to coordinate and integrate the two efforts so the whole is more than the sum of the parts. **This must also be done in a manner that ultimately transforms markets on a permanent basis, not merely for the duration of the program activity.**

The Plan is organized as follows: The authors first outline a high-level strategy built around an assessment of the barriers (boxes 1- 6, referring to numbers in the logic diagram boxes) and then provide a description of the proposed program activities (boxes A, 7-10). This is then followed by a description of the expected outputs of those activities (boxes 11-18) and the broader market outcomes expected over the next 5 years, (boxes 19-30) and the longer term (boxes 31 – 36). Throughout the program description, additional critical window market assessment data is provided in the form of a series of Appendices that provides additional market data, technical data and window industry data that support the underlying business need and logic for these activities and expected outcomes.

Market and Technical Barriers

With a target performance level of R5 (U= ~0.2) few major window manufacturers are prepared to offer these products today as cost-effective mainstream options, as confirmed by the recent Apex Analytics study for Energy Trust of Oregon (Apex, 2018). The "thin-triple" concept outlined earlier has the potential to be rapidly adopted by window companies at cost levels that are more affordable relative to other options. While this concept has been proven in research labs it is not currently available in the market place. The reasons that affordable, highly insulating windows, and specifically the thin-triple version, are not readily available in key Northwest markets can be explained by six fundamental sets of barriers. The program outlined in this document is designed to address each barrier with a set of targeted activities. ("box #x" refers to boxes on Fig. 3,4,5)

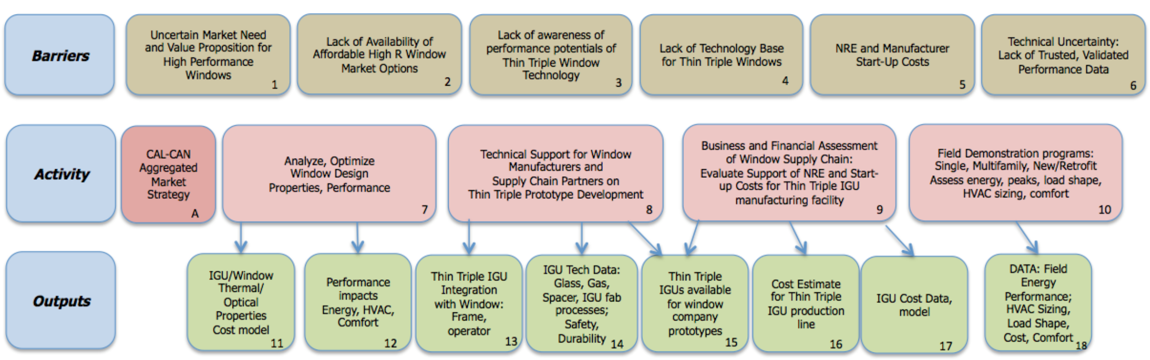

Figure 4: Program Barriers, with Suggested Activities and Outputs

In the section that follows each barrier is described; then in the following section the associated activities to address those barriers and the expected outputs of those activities design to address the barriers are outlined.

Barrier #1: Uncertain Market Value Proposition (box #1)

Thermal properties of windows and their relationship to household energy bills are confusing not only to homeowners but also to many builders and architects. The default selection is to meet building code and in most cases meet Energy Star requirements for the Northern zone which range from a U of 0.27 to 0.30. According to the recent Apex study (APEX, 2018) in Oregon about 70% of windows sold in 2017 meet the Energy Star values and 80% of those are in the U = 0.27-0.30 range with about 10% with even better thermal performance with U below 0.25, some of which are triple glazed. **The underlying unspoken logic is that a window that meets the energy efficiency codes and is Energy Star is an "efficient" window so there is little motivation to find a better performing product**. Furthermore, those better performing products may not be easy to find and when found, can add significant cost to the project. The energy savings paybacks for the owners faced with these large cost increments will not be attractive. There are other aspects to the overall value proposition related to thermal comfort, HVAC sizing and cost, but these are likely secondary to the market cost and are themselves complex since they vary with climate, design and operating details etc.

Barrier #2: Lack of Availability of Affordable R5 Windows (box #2)

Better performing window products are not easy to find from local suppliers and when found add significant cost to the project. Apex reports that while the cost increment to move from a non Energy Star to a U = 0.28-0.30 Energy Star window is small, ~ $2/ft^2$, the increment to get to 0.25 jumps to $9.00/ft^2$ and the cost increment to get to triple pane windows with a U below 0.25 is over $20.00/ft^2$. These data were obtained from home improvement retailers. A builder purchasing larger volume for a subdivision may buy direct from a window manufacturer at lower cost but because these products today are specialty, low production volume products, the prices will be high relative to high volume mainstream products. While many potential products are listed in the NFRC Certified Products Directory (CPD) only a small number are manufactured and sold in any volume (Appendix 4). Anecdotal information suggests that purchasing some of these products, even when identified in a catalogue, may be difficult. Because the overall sales volume for triples is very low, many are special order products that are available only after long delays and at significant extra cost. In some cases the triple IGUs are available only in a special higher cost frame system as well since the heavier IGU may not be suitable for standard frames.

Barrier #3: Lack of Awareness of Performance Potentials of the Thin-Triple Window Technology (box #3)

As noted under barriers #1 and #2, there are no "affordable" triple glazed windows with U ~ 0.20/ R ~ 5 on the market today and there has not been an easy path for a window company to migrate to such a product with a low cost, low risk strategy.

The “thin-triple” IGU now provides that option. Although the concept was developed and patented in 1990 (Selkowitz, 1990) for reasons explained below, until recently it has not been possible to obtain the key thin glass elements and the krypton gas needed to implement the solution at scale and at price points that make them attractive enough to address affordability, barrier #2. The concepts have been presented at window industry meetings over the last two years and summarized in two new published papers (Selkowitz, 2018; Hart, 2019) so window industry R&D teams are now generally aware of the technology. LBNL has worked closely with key industry partners in the supply chain, e.g. major suppliers of thin glass, to ensure that the performance seen in the laboratory can be delivered in a real product at scale. However, in discussions even with window R&D staff, the level of awareness of cost, availability, handling properties, etc. related to thin glass is well behind the actual state of the art. Since they believe- based on outdated precedent - that the costs are high, they see no market and little reason to pursue this line of inquiry. Absent a potential market (barrier #1) there is no drive internally in these companies for new R&D investments. Extension of the current R&D base and engagement with supply chain partners to raise awareness of the specific technical issues in concert with cost, availability, delivery times, etc. will help address these issues.

Barrier #4: Lack of a Technology Base for Thin-Triple Windows (box #4)

LBNL has modeled 1000s of variants of the thin-triple designs and tested prototypes, so it is confident of the underlying technical performance data. However, there are still technical and related business challenges that must be addressed in order to mass produce these products on a very large scale, which is important to minimize cost. The window industry is very experienced with handling, cutting, cleaning, transporting conventional single strength 1/8” thickness window glass and then assembling that glazing into an IGU with low-E coatings and adding argon gas fills. However, there are significant differences related to handling, cutting etc. once one shifts to a very thin glass layer. Issues related to production include a better understanding of the supply for key components, the ability to scale supply rapidly if the market grows rapidly, durability of seals for containing krypton gas, ability to fill an IGU on a production line with krypton with very low gas loss, etc. Some windows use tempered glass to meet special safety requirements when they break – it will be important to explore how can that be accomplished when the thin glass under discussion for this project is too thin to be tempered.

Barrier #5: Non-Recurring Engineering and Manufacturing Start Up costs. (box #5)

Shifting from a focus on thin-triple prototypes to the ability to mass produce windows with a thin-triple IGU will incur significant new start up engineering and investment costs on the part of an interested window company. In order to produce the most cost effective IGU they will have to be fabricated on high speed automated insulating glass production lines. The lines today can produce IGUs for about 1000 window sashes per day, can handle a wide range of IGU types, shapes and sizes, including the use of low-E coatings and gas fills. These lines will have to be modified to produce the thin-triple IGU design, initially incurring new engineering and prototyping costs and later the start–up investment needed to build that first automated line or modify an existing line. The cost range for building such an automated line is ~$1M-$3M. Without an assured market for the volume of output, about 250,000 sash units per year, the required investments are not likely to be made. The companies that produce the glass handling equipment for these lines are interested in adapting them to produce thin-triples. Some lines can already make units with a center glass as thin as 1.6mm, but additional engineering investment is needed to address all of the thin glass handling and low-loss gas filling challenges to make a range of thin-triple products.

Barrier #6: Technical Uncertainty with an Innovative New Product: the lack of trusted, validated performance data. (box #6)

The risks involved in new product introduction go beyond the financial costs associated with a new production line discussed in Barrier #5. There are other technical uncertainties related to durability of the new IGUs; the ability to fill them to greater than 90% krypton rapidly and with low gas loss; the maintenance of gas fill due to pressure differences when the IGUs are transported over different elevations; etc. All of these and other related issues have been faced by the window industry and “resolved” in the past due to the vast expertise gained over years as almost 100 million IGUs are fabricated each year. The cumulative production of thin-triples to date is less than 100, and these have been custom fabricated, so there is a body of validated knowledge that has yet to be gathered for this new window concept. Unlike the move to develop vacuum insulating glazing, the new thin triple IGU design is not a major departure from current IGU designs so this technical uncertainty can be addressed by extending existing practice and gathering the required validated performance data from additional lab and field testing.

Proposed Activities and Outputs

Five broad sets of activities must be undertaken to address the barriers outlined above with the **initial goal of having affordable, thin-triple windows available from one or more manufacturers in less than two years** (box 19). We first review the four recommended activities (boxes 7-10) and their associated outputs (boxes 11-18), then conclude with an overall emerging "partnership strategy" that we believe will leverage and accelerate NEEA efforts on this topic (box A).

Activity #7: Analyze and Optimize the Properties and Energy Performance of High Performance Windows with Thin-Triple IGUs

There are numerous thin-triple IGU design details that can be varied to achieve a range of different thermal properties and thus building energy impacts. Each of these design options also has cost impacts in terms of manufacturing cost but also cost impacts in terms of energy savings potentials. LBNL has already completed extensive modeling of the key variables of gas fill, gap width, spacer design and glass thickness but there are other design issues to consider in optimization such as novel designs for spacers. While most recent prototypes have been made with two spacers and 4 seals the original concept employed a single spacer that held the middle glazing in place but did not seal it. This concept should be further reviewed and optimized from the point of view of assembly, durability and cost as well as performance.

Identical IGU designs will have different overall thermal properties in different window frames and operator types, and will have different energy impacts in different climates in NEEA regions as well as with different house orientations, e.g. north vs south, and with different shading assumptions. The effects of all these parameters can be readily modeled to determine the sensitivities of outcomes to input parameters as illustrated in Hart (2018) for a range of climates. Of particular interest is further exploration of the effects of higher SHGC on reducing winter heating but increasing summer cooling loads. These energy optimization studies use a hourly annual energy model such as EnergyPlus and the model home base case designs that NEEA has used in past studies. These are all well understood, low risk activities that would directly support NEEA policy making as well as window industry partner design optimization.

→ Output #11: IGU and Window Thermal and Solar Optical Properties, and associated Cost Model

This output would constitute a "roadmap" as to how key design details impact the range of thermal properties achieved, both for the IGU and the overall window. **The engineering data can be coupled to a production cost model so that cost can be optimized or minimized as tradeoffs are considered.** The relationships between IGU design details and thermal properties have already been extensively documented in LBNL reports (Selkowitz, 2018, Hart, 2019) and are illustrated in Appendix 5 for the IGU and Appendix 4 for the overall window. The first shows the sensitivity of U to gas mixture as a function of the IGU gap width. As an example, if a specific target U is sought for a picture window and the gap is known the optimum mix of argon and/or krypton can be selected to minimize cost since the differential cost between the two gases is large. Similarly, for a given climate (and even orientation) the SHGC can be optimized for the window by proper selection of the two low-E coatings that will normally by utilized on the #2 and #5 glass surfaces. This technical data can guide both product design and optimization as well as program design for NEEA in connection with Output #12.

Output #12: Thin-Triple Performance Impacts: Energy, HVAC System impacts, Comfort Impacts

The design optimization outputs above in #11 will help provide guidance on program design depending upon their various building design impacts. These outputs are intended to be used for four main purposes. The energy savings outcomes can be used to assess the cost effectiveness of the new IGU design and the paybacks given data on first cost of the new glazing. **This data can then be used to help assess a range of allowable utility rebates if incentive programs are envisioned or perhaps the scope of an investment that NEEA might consider making in an IGU production line**. Initially a conventional downstream rebate could be used (Outcome #21) and this performance data, validated with field test data, could be used to determine the proper investment level. In addition, the data could be used to launch an upstream rebate program with its more efficient use of leveraging public funds (Outcome #28). Second, the modeling outputs can also assist developers in down-sizing or right-sizing their HVAC plant and distribution systems, with a potential for additional first cost savings. Third, the energy modeling outcomes can be used to assess the value of non-energy benefits, in particular improved thermal comfort due to the increased glass surface temperatures in winter. Assessment of potential acoustic benefits of the triple designs will be another beneficial output. Finally the data can also provide insights into the impacts on peak electric grid loads and on hourly load shapes, issues of interest to utilities across the Northwest as they address growing use of renewables and plan to meet new decarbonization goals.

Activity #8: Technical Support for Window Manufacturers and Supply Chain Partners to Advance Thin-Triple Prototype Development

This activity directly supports industry partners across the window supply chain working to develop viable window products incorporating thin-triple IGUs. Window companies have expressed interest in getting simulation support to explore design details that might be unique to their product lines. As part of a DOE funded program LBNL has worked directly with two window companies to help them explore, analyze and optimize thin-triple IGUs for their existing product lines. They are also interested in laboratory testing to validate performance of their prototypes. Supply chain partners include thin glass suppliers, krypton gas suppliers, low-E coating suppliers, spacer suppliers, sealant suppliers, manufacturers of automated gas filling equipment, manufactures of spacer assembly systems, manufacturers of automated IGU production lines, and window companies. Figure A2-1 from Appendix 2 is reproduced here to give a sense of the complexity of that supply chain and the technology elements involved:

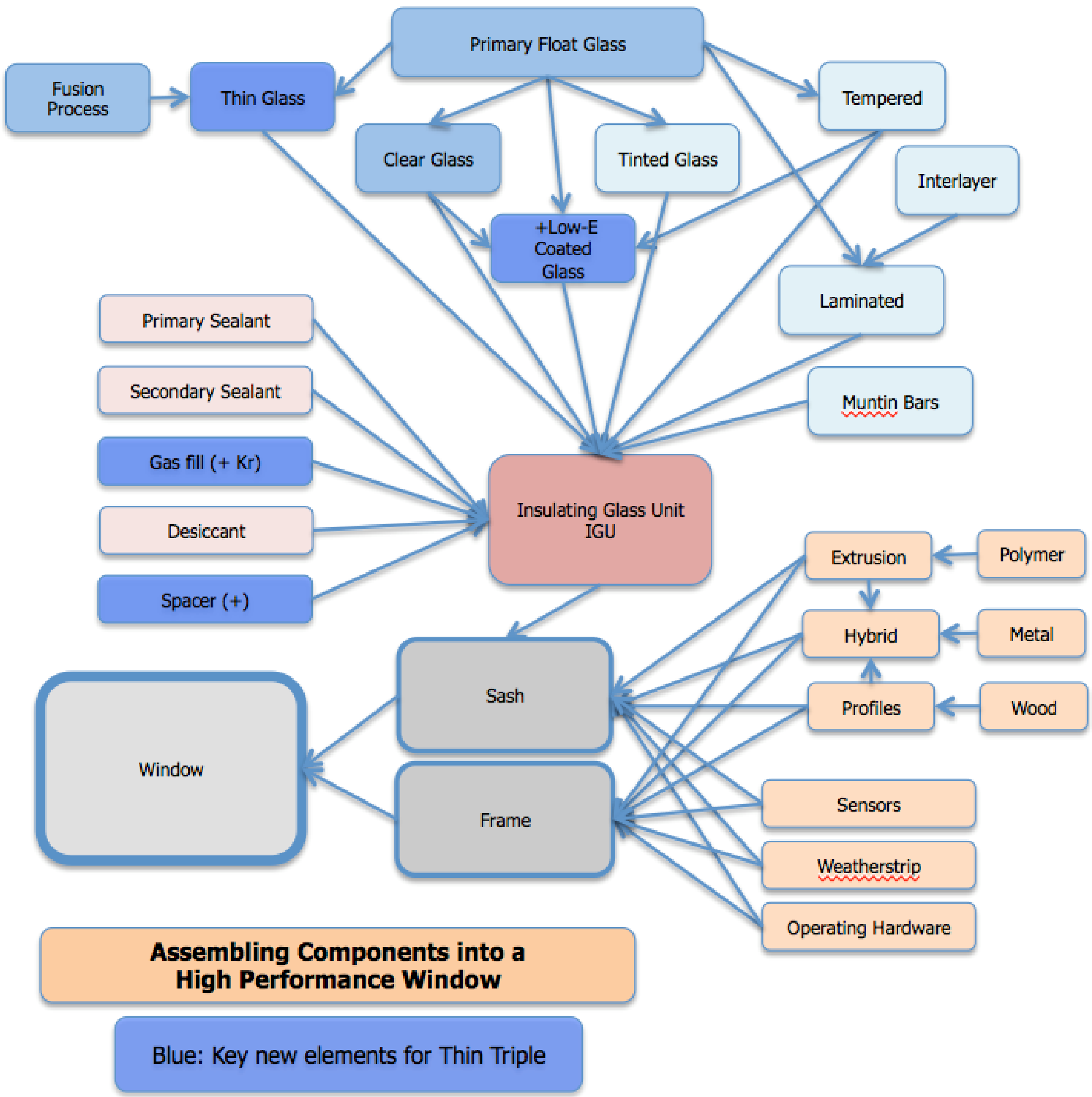

Figure 5: Window Industry Structure, from Appendix 2

This technical support activity addresses all aspects of IGU design and assembly, including durability over time. It also is intended to support not just the energy related issues but related marketability issues such as the safety glazing requirements. This will be a particular issue for patio doors and other windows subject to safety glazing requirements. It is generally agreed that it is not possible to produce tempered glass units thinner than 2mm. Very thin glass can be chemically strengthened so it is less likely to break but when it eventually breaks the breakage shards do not meet current safety codes. The options to be explored therefore are 1) use of 2mm glass with associate weight and performance impacts; 2) modification of thinner glass with applied coatings to meet safety requirements; 3) adjustments to properties of other windows in a code package since it is usually the area weighted average U that must meet code.

→Output #13: Thin-triple IGU Integration with Window Frame and Operator

The overall window U-value (and SHGC) is the "sum" of the properties of the IGU and the window frame. As we drive the U of the IGU lower and lower, the properties of the IGU become much better than the frames so the U of the overall window becomes worse than the IGU alone. The U of the IGU itself is composed of a center-of-glass component and an edge-of-glass, as explained in Appendix 4., Modern warm edge spacer design has improved the thermal properties of the edge to the point where optimal selection of the spacer can reduce overall window U by 0.01 – 0.03 compared to conventional designs. The impact of the operator type and its relative sash/IGU ratios are known but the details for participating companies must be worked out so that overall window properties are acceptable.

→Output #14: IGU Optimization with Glass, Gas, Spacer, Low-E and Assembly Process for thermal, durability and safety

LBNL has completed and published results of extensive optimization studies where the impact of most of the key design variables on properties of interest, e.g. U, have been explored to understand the sensitivities of IGU optimization with respect to those parameters. (Selkowitz, 2018; Hart, 2019) These new studies would refine and extend that work, if needed, to directly support new uncertainties or questions from the specific new industry partners working with NEEA.

→Output #15: Thin-Triple IGUs Available for Window Company Evaluation/Integration

Not all window companies interested in highly insulating window products will want to directly address the challenges of new IGU design and fabrication. Many window companies purchase IGUs from other companies. **NEEA should thus initially pursue a dual strategy of 1) encouraging those window companies with the interest and capability to make their own thin-triple IGUs to do so, and 2) encourage and support an IGU fabricator who could sell to any**

window company desiring to use the thin-triple approach. There is value in engaging with some industry partners with the ability to fabricate small quantities of thin-triple IGUs, so that these IGUs can be made available to window companies who do not have the capabilities or interest to fabricate IGUs themselves. The goal is for the window companies to understand the ease with which their conventional R4 IGUs can be replaced with the new R8 IGUs without any other manufacturing problems. Past observation of window companies suggests that they underestimate the ease with which they might be able to integrate the new IGU with their existing window product lines. The modeling outputs from #14 provide that data but this output provides the actual IGUs for first-hand experience with the new technology. This approach was proven in a thin-triple demonstration in California where IGUs were fabricated by one company in Colorado and then glazed into existing windows in a model home by a different supplier of windows to that developer.

Activity #9: Window Supply Chain: Business and Financial Assessment of Costs/Tasks for Automated IGU Manufacturing facility

Thin-triple IGUs can be manually fabricated and provide excellent performance when incorporated into any frame that will accept them. But to achieve the market breakthroughs on cost and volume that NEEA seeks, the technology must be incorporated into an automated IGU production line.(Appendix 3) LBNL has spoken with all the major global suppliers of automated IGU fabrication lines and each company has expressed some level of interest in adapting their machines to handle thin-triple designs. However, there are development costs involved and the IGU equipment manufacturers want to see interest from the window companies that purchase their equipment before investing in research and engineering to modify and adapt their equipment. This task is designed to explore in detail the tasks and costs needed to build an automated IGU line for thin-triples. As an interim arrangement we note that Output #15 is designed to provide low volumes of thin-triple IGUs to window companies by hand assembly. This activity specifically reaches out to the high volume equipment manufacturers to determine a path forward to get to outcome #20, one or more automated IGU lines in operation. Note that in one scenario a window company invests in the IGU line to supply their window production whereas an alternative outcome is for an independent IGU supplier to set up the line and sell to multiple window companies.

→ Output #16 and 17: Cost Estimate for Thin-Triple Automated IGU line and IGU Cost model and data

There are 6 manufacturers of automated IGU lines who may be interested in developing viable production line versions that support the thin-triple design. As noted above, their level of interest is proportional to the likelihood that a window company might buy one of their machines but this is a critical path element. Once the automated line cost (estimated at between $1-$3M for a new line with an output of ~ 1000 IGUs per day) is determined, the associated "fabricated IGU cost" can be determined based on amortization of the equipment, labor costs etc. It is also likely that an existing line can be modified at lower incremental cost. The outputs of this task will directly benefit NEEA and utilities as it will provide solid volume cost data on the cost that a window manufacturer will incur to upgrade their windows to R5 using the new thin-triple IGU. Our current estimate is that the full manufacturing cost is ~$3/ft^2 with a selling price that depends on the rest of the supply change to the final customer. (Appendix 6) The price they choose to charge customers will be different from their cost but ideally competitive market forces will constrain this. This cost data will be critical to NEEA in consideration of any type of rebate or incentive program, either upstream, midstream or downstream. If there is no immediate intrinsic market investment in a new IGU line likely, NEEA might consider financial subsidies as a start up strategy to "kick start" production as it has in the past with other energy efficiency production equipment.

Activity#10: Field Demonstration Programs to Assess Energy savings, peak and load shape impact, HVAC sizing opportunities and comfort impacts

Field studies should be conducted strategically in different areas with NEEA partners and addressing different building opportunities, e.g. single family, multifamily, new construction as well as replacement/renovation. Since willing partners are needed and these projects can interrupt the project development process, the timely availability of the "right" project is often a challenge. In addition, the timing of new construction can easily extend from 6 -12 months before a building is ready for testing and then another 6- 12 months to instrument the building and collect data over a full season, so a long term planning horizon is needed. The most powerful data comes from side-by-side testing of a house with the new windows vs one with conventional windows. In any such testing a critical decision is to test in occupied vs unoccupied houses. Planning and executing a field test program is complex but the outcomes can be highly informative for all parties. A simpler and faster option might involve sash or window replacement in an existing home. In that case "before" and "after" monitoring of the same building may provide a better indicator of the effect of the new windows.

NEEA can also partner with other programs in its region which may already have identified suitable test homes and add a window component. Utilities in California may be carrying out testing of thin-triple windows over the next year and NEEA should coordinate with PNNL who has support from U.S. DOE to carry out some field tests of thin-triple window installations in its test homes in Richland WA and in projects associated with the DOE Zero Energy Ready Homes program and other interested partners such as builders developing Passive House projects. While energy savings are a key element of a field test program it should also evaluate the opportunity to downsize HVAC central plant and associated distribution systems to understand the potential offsetting first cost. The test home activities could also document changes in environmental conditions that will improve thermal comfort and provide added market value.

→Output #18: Field performance data on energy savings, peak/load shape, occupant comfort, HVAC system downsizing opportunity

Measured energy savings are an obvious desired output from any field study program. While the main savings is expected to come from the lower U, the SHGC of the window (and associated shading) will also impact winter savings so efforts should be made to evaluate and disaggregate the effects of each. As the Northwest decarbonizes, the shift to electric heating displacing gas should accelerate, adding more pressure to reducing early morning peak electric loads. Documentation of changes in load shape and reductions in peak should be helpful in establishing the economic value of the new windows to the grid as well as to the building owners. For houses with mechanical cooling the impacts on summer cooling should also be assessed.

Field studies could also provide data on thermal comfort. New measured data on the impact of the new windows on thermal comfort has two potential values. The first is as a "selling point" to justify investment in the high performance products. The second is that when comfort is enhanced, thermostat settings could potentially be reduced without sacrificing comfort, resulting in further energy savings compared to conventional systems where higher air temperature settings on the thermostat are used to offset radiant discomfort near a cold window. Some initial LBNL modeling studies suggest this could significantly enhance savings under some conditions. The effects of radiant discomfort can be significant in the coldest climates but can be virtually eliminated with highly insulating glazings- see Appendix 7.

Activity A: "CAL-CAN" Aggregated Market Strategy

Activities 7-10 lay out the key program elements to be undertaken to transform the window markets in the NW. However successful execution of each of these may still fall short of the goal of Boxes 19 and 20 to invest in a fully automated IGU line producing low cost, high quality R8 IGUs for window manufacturers. **The key issue is whether NEEA program activities can generate sufficient potential market demand to justify the new business capital investments needed by an IGU fabricator or a window company in order to invest in an automated IGU line, with the needed production volume to bring costs down.** There are two high level approaches possible: 1) rely entirely on private sector investment decisions, or 2) subsidize the initial manufacturing investment as NEEA has done in the past with Heat Pump Water Heaters. **A third strategy alternative is to build sufficient demand for the thin-triple by coordinating efforts with two other currently**

independent activities promoting more efficient window products, one in California and one in Canada, thus the "CAL-CAN" nomenclature.

There is an alignment of interest, need and timing: 1) each of these regions is engaged in new energy efficiency programs that will demand more efficient window products, 2) each is fortuitously physically located in proximity to NEEA markets, which is important due to the nature of window industry supply chain logistics, and 3) each is served by an overlapping group of the same window companies and their associated suppliers. From a historical perspective we note that a NEEA window program launched in 2000 also built on a related program first launched in California to raise the efficiency levels of windows related to adoption of Energy Star performance levels.

The key value to NEEA is that aggregating demand presents a much larger potential market to the window companies, which in turn reduces the cost and risk to them for making investments in this new technology. Potential market size is a key factor in their willingness to make investments in new production equipment. A single automated IGU fabrication line which makes ~1000 IGUs per day produces ~ 250, 000 IGUs per year or enough for either 10-12,000 new homes or perhaps 20-30,000 renovation projects. One would logically turn first to early adopters e.g. Passive House, ZNE Ready homes, who are always an important target market to explore but their numbers are still small and would not appear to be encouraging to a major window company. We estimate the approximate size of these markets today as follows:

PHIUS Passive House: Passive house is a potentially important partner since they need windows that are much better than current code requirements. While the growth rates for new projects are high, the base rate of construction is still low. PHIUS reports that about 1,000,000 square feet floor area of Certified homes were added last year or roughly 500 homes (PHIUS, 2019); assuming an equal number were built and not certified, that translates into about 1000 homes nationwide or a demand for 20,000 windows in the entire US. With 4% of the national population, the numbers built in the Northwest are still smaller so the market for high performance windows to support them is small. Furthermore the national demand is scattered geographically making a market aggregation strategy more complex.

Zero Energy (ZE) and Zero Net Energy (ZNE) Ready Homes: this program also has impressive growth figures although the numbers are still modest in terms of overall market share. Both Oregon and Washington are in the top tier of state projects with 500- 1000 homes; (Team Zero, 2018) Unlike the Passive House program where triple glazing is essentially required only about 40-60% of these homes are designed with some or all triple glazing (PNNL, 2019). So while the developers are interested in overall thermal efficiency triple glazing is not yet seen as a "must have" option by many of them. This recent study by PNNL explores some of the reasons these homes are not yet using the best available windows, which includes availability, cost, supply chain, and other issues.

The recommendation to coordinate/collaborate with Canada and California is based on simple arguments of market size, which is a driver in a window company's assessment of investment in new technology. It is instructive to review relative market size for new home construction by builders, which absorbs about 50% of all window sales, the other 50% being renovation and replacement. Based on population as a proxy, the four NEEA states, Oregon, Washington, Idaho and Montana have an aggregated market share of 4% of U.S. window sales. By comparison California has 12% and Canada has sales equal to an additional 11%. So the combined market size of California and Canada is about 6 times larger than the Northwest market size. In terms of encouraging window company investment in new production equipment, this appears to be a ready made opportunity that should be exploited.

The argument for triple glazing in Canada makes intuitive sense given the cold climate. The basis for interest in triple glazing in California is more complex as outlined below.

The opportunity for collaboration with NEEA is even more advantageous because each of these large markets has already launched independent, but different, efforts that will likely result in radical restructuring of their respective window supply chains, each with a goal of supplying new highly insulating windows in the range of U = ~0.2 but with different drivers and different time lines. Since the existing window market landscape in both locations is fundamentally similar to that outlined in this document for NEEA territory, the case for the thin-triple appears to be equally compelling in all three regions, even if some of the existing conditions and market drivers are different.

Canada:
Canada has announced a new market transformation roadmap to 2030 and beyond to guide new program activities (NRCAN, 2018). The new energy efficiency goals include a variety of activities to reduce the national energy use in buildings, including a section on windows. The most recent roadmap document authored by NRCAN is the result of over 2 years of meetings between government and industry to better define goals and pathways to achieve a series of aspirational goals. Windows account for 35% of home heat losses and if the best available of today's technology was deployed widely, they estimate that total home energy use could be reduced by 9%. Their long-term goals are to see that high performance, next generation windows are standard in Canada, with performance targets for window U values of 0.14 by 2030, and with interim targets of 0.21 by 2025 and 0.28 in 2020. Some provinces are already enforcing tighter requirements on window properties that are driving some change in the Canadian markets. The Canadian process has already identified the thin-triple window concept as an option that may be useful in

Canada to achieve the 0.21 target by 2025. The Canadians have now settled on an updated Energy Star target with U = 0.20, which fits well with our effort.

California

California has enacted their new 2019 T24 code requirements that cover all new residential construction, effective for new plans submitted for approval after 1/1/2020. While the change in mandatory window properties are modest, a reduction from U = 0.32 to 0.30, there is a significant change in the mandatory requirements for builders to use High Performance Walls. This requires either a change to 2" x 6" insulated wall construction or use of an exterior continuous insulation layer over conventional 2" x 4" framing with other on site detailing changes that the builders argue will add cost and complexity in new construction. The California Energy Design Rating (EDR) approach allows alternative substitutions to mandatory requirements if the tradeoffs are energetically equivalent to the wall energy impacts. The CBECC-Res software tool produced by CEC allows those tradeoffs to be calculated for a specific building design in any of California's 16 climate zones. The use of windows with U = 0.20 or 0.21 (with some variation in SHGC) provides that equivalent tradeoff in all climate zones. The builder's cost to comply using the new insulated walls is estimated to be $2000-3000 per house. Since the U= 0.20 window package can eliminate the use of the insulated wall package this frees up that $2000-3000 to provide the triple glazed windows instead, without increasing the builder's overall costs. The California Building Industry Association (CBIA) estimates this translates into an incremental "allowance" of $4-6/ft^2 of window (Hodgson, 2019). Ongoing analysis at LBNL suggests that the manufacturing cost for the thin-triple is below these target levels. **Triple glazed windows with U ~ 0.20 thus appear to be a compelling choice for builders in all California climates for new construction beginning with plans approved after 1/1/2020 to meet the new 2019 building code**.

A recent meeting in Sacramento in July 2019 sponsored by the California Partnership for Advanced Windows (C-PAW) and including CEC, California Building Industry Association (CBIA) and LBNL engaged over 90 representatives from builders and window companies to explore this opportunity. The potential to meet a new mandatory code requirement with a design of equivalent or lower cost but less complexity in construction practice is appealing to the California builders. New building starts in California are now about 120,000 units per year, a construction level that equates to approximately 2.5 million window units per year. If even a small number of builders opt for the "U= 0.20 glazing alternative" to meet the new code requirements it could quickly generate a very large market for R5 windows. The thin-triple window option would be the easiest way for window companies which do not now offer conventional triples to add this capability to their product lines. **This could directly benefit NEEA since virtually all the top Northwest window suppliers are also active in California and because some plants in California already supply some Northwest markets.**

If the window industry begins to offer cost effective R5 windows for new markets in Canada, the Northwest and in California, it may also help to leverage change in EPA's Northern Zone requirements for Energy Star windows or more aggressively pursue the "Most Efficient" window program which currently promotes U </= 0.20 windows but has had little market traction to date. NEEA can play a critical role here since its territory is the Energy Star Northern Zone whereas California is not. In past window market transformation efforts in 2000, NEEA explicitly tied its incentive/rebate/educational programs to new Energy Star targets. (Jennings, 2000) So a NEEA decision about target values for the Northwest could add new urgency and impetus to changes in this national program which in turn should benefit the entire NEEA region. Energy Star target performance values have been widely adopted in all climate zones in the past. But in order to tighten criteria in any climate zone EPA requires that the target performance values be obtained cost effectively and that multiple manufacturers are able to supply the market. EPA announced in September 2019 the outline of its new Version 7 window update so NEEA activities as outlined in this document are timely and would contribute to that goal.

There appears to be a latent, timely, symbiotic opportunity for NEEA to partner with other organizations in transforming window markets. The immediate action for NEEA is to carefully evaluate the strategic value of aligning its emerging window program, as outlined in this Logic Model, so that it can influence the rollout of those two other regional activities where appropriate, and also be assisted and accelerated by these two related large scale window MT activities at the same time. After the recent CEC window forum several window companies have ramped up their level of interest in the thin-triple design. The recommendation is that both programs be pursued as they are well aligned with driving market forces that will directly benefit markets in the Northwest. Furthermore, the Canadian program is still in a formative stage so that NEEA needs and interests might influence the design details of their program. And while the new 2019 California T24 program is in place, the window companies are still formulating their response to it. **Their investment decisions might be favorably influenced by the emergence of a compatible program that rewards similar new high performance window systems in the Northwest, perhaps via incentives or rebates, or performance tradeoffs in codes, since there is no mandatory standards requirement at this time.**

Intended Program Outcomes

The activities and their outputs as described above are intended to have a series of critical path outcomes of two types over the short-term (1-3 yrs) and mid-term (3-5 yrs.).

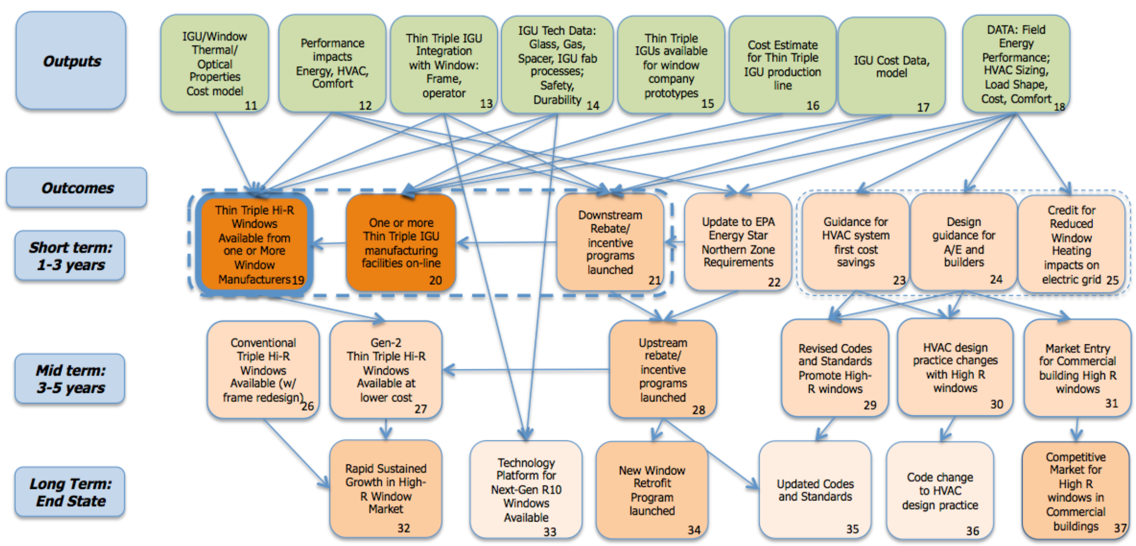

Figure 6: Activity Outputs and Program Outcomes

The most critical outcomes are shown in boxes 19 and 20- the initial commercial availability of thin-triple High R windows from one or more window manufacturers. These could be produced in low volume initially using manual assembly methods but to minimize cost, the box 19 outcome is a fully automated production line. This might be launched by an IGU company who sells to multiple window companies or could be a dedicated line in one window factory. The required capital investment could be accelerated and facilitated by the outputs described above in boxes 11-18 as well as the launch of the downstream rebate/incentive program (box 21) funded by utilities in the Northwest.

The first outcomes are changes to design practice in the form of new data, processes and tools that help promote the role and impact of new high performance windows as outlined in boxes 23-25 including training and education programs across the NW region to deliver program guidance. Over longer periods of time the information generated should impact future codes and standards, which eventually leads to greater market saturation of the compliant technology as updated codes and new design practice capture larger market share (boxes 29-30 and 35-36). In the shorter term the impact of voluntary programs like Energy Star windows has served to guide early adopters before new codes mandate the technology. NEEA should support national efforts to revise and update the Northern Zone Energy Star window requirements as noted in box 22.

For completeness, a potential extension of the program to the commercial building sector is shown in boxes 24, 31, and 37. Although some market paths are different, the market includes both windows and curtain walls, and the typical width of a commercial IGU and frame is wider than residential, most of the lessons learned in launching the thin-triple IGU for residential use could have value in many submarkets within the commercial building sector.

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APPENDICES

Appendix 1: **Residential Window Industry Companies**

Appendix 2: **Window Manufacturers and their Supply Chains**

Appendix 3: **Technical Potentials for Thermally Improved Windows**

Appendix 4: **IGU Properties → Window Properties**

Appendix 5: **Thin Triple Designs for R5 Windows**

Appendix 6: **Cost of Windows**

Appendix 7: **Windows and thermal comfort**

Appendix 1: Residential Window Industry

The residential window market delivers approximately 57 million windows each year for new home construction and to existing residential projects for replacement and renovation, in both single family and multifamily homes. The vast majority of these windows are fabricated by fewer than 50 companies and are delivered to the job site via several different market channels.

Window companies vary widely in terms of their size and their geographic reach or sales territory. The "Amazon warehouse model" where we expect overnight delivery of a myriad of gadgets and products does not apply to the window industry. Company size is also somewhat correlated to the physical extent of geographical markets. Window and Door Magazine (WDM) publishes an annual list of the top 100 window companies by size, a portion of which is shown below (Figure A1-1). As in many industries the overall sales are dominated by a small number of the larger firms. WDM reports that the top 20 firms out of 100 account for about 80% of the total industry sales. Not surprisingly, many of the larger firms have either a national sales market or sell to larger regional sales territories; smaller firms tend to be more regionally based.

The data below highlight the role of the largest window companies. We note that small companies play an important role in the window ecosystem- they can take risks and innovate more rapidly, they can address the custom needs of new markets in early stages, and in many cases can more readily serve the needs of custom builders or Passive Home developers. But large scale market transformation and decarbonizing the Northwest energy supply requires action at a much larger scale, and the engagement of market leaders in these programs. Larger companies have the market infrastructure and capital that are crucial to grow the market and they can add brand and advertising pressure that support the program goals.

Over $1 Billion
Andersen Windows & Doors*
Jeld-Wen
Masonite*
Pella Corp.*
Ply Gem
Velux USA
YKK AP America

$500 Million to $1 Billion
Harvey Building Products
Marvin*
Milgard*
Therma-Tru Doors

$300 Million to $500 Million
Alside*
Atrium Corp.
MI Windows and Doors
PGT Innovations
Woodgrain Millwork*

$200 Million to $300 Million
All Weather Windows
Champion*
Custom Windows Systems
Earthwise Group LLC
Polaris Windows & Doors
Sierra Pacific Windows
Weather Shield Mfg.*
Weather Shield Mfg.*

$100 Million to $200 Million
Atis Group Inc.
Cascade Windows
Four Seasons Solar Products*
Kolbe & Kolbe Millwork Co.*
Plastpro
ProVia
Quaker Window Products

Figure A1-1: Listing of top 30 US window companies by sales, a subset of a larger list of the top 100 (WDM, 2018). These 30 firms supply ~ 90% of all windows sold in the U.S.

Key manufacturers who have a sales presence in the Northwest have been identified in prior studies (Apex, 2018). In terms of the national companies listed above, the ETO survey identified what they termed as Tier 1 companies in the Northwest to be: Andersen, Jeld-Wen, Marvin, and Milgard, and a second tier that included Pella, Ply-Gem and Sierra Pacific.

Market structure contributing to lack of demand for high performance windows

Amongst the window companies listed in Figure A1-1, they operate with very different business models that depend on 1) company size and sales volume, 2) regional vs national scope, 3) target market (e,g, new sales to tract builders vs custom builders vs retrofit sales to homeowners), 4) average sales price and frame materials systems. Each of these factors impact a company's interest, willingness and ability to develop new technology and to provide new market options beyond their mainstream products.

These structural, institutional and financial aspects of window company manufacturing, marketing and sales impact their product offerings.
We highlight here two related issues: 1) the primary end use market and 2) the pathway by which product reaches that market.

Purchase Decisions in End Use Markets

Approximately half of all windows are sold to new home construction and half go to renovation, replacement and retrofit markets. The ratio has varied over the years with national economic conditions, as well as with region and with sector, e.g. single family vs multifamily. A key distinction is that in the new construction market the ultimate home owner generally does not have a direct input into the details of window package which is driven instead by the builder considering cost, building code and general market expectations. In the retrofit/replacement market, the homeowner is normally a key decision maker both in specifying features and deciding on cost, although an architect or contractor may fill that role.

For new home construction the targeted decision maker is the homebuilder/developer who will be purchasing in volume for expected construction and sales over the coming year. Builders are both regional and national, and they look to window manufacturers to deliver their products on both a regional and national scale. Furthermore some builders serve a single market with a limited price range per house whereas others operate in a variety of regions where they are building houses ranging from small starter homes to upscale houses in leisure communities. Not surprisingly, the details of the window package in a 1200 square foot starter home with a sales price of $180K might be very different from the window package in a 3000 square foot, $900K home. Most builders offer a variety of product lines with different features, e.g. "good", "better", "best", including some options that impact energy performance. A builder's window options will normally also be constrained by state and local building codes as well as by logistical requirements to limit the number of available options. The industry has made a continuous evolution over decades from a business model where a limited number of standard models and sizes were stocked in regional warehouses to a newer customized "build-to-order" business practice that provides more flexibility but requires "discipline" in managing the overall operation.

Channels to Market

Windows reach a customer's home via one of three primary pathways characterized by the number of actors between the manufacturer and the end user, and where, when and by whom the final decision is made.

1) **One step- Direct Sale**: Manufacturer to Customer
   e.g. direct sales to large customers, On-line sale to homeowner
2) **Two step- Manufacturer sale via distributor and/or Big Box retailer**; subsequent sale to Customer
3) **Three step**- Manufacturer sale to distributor and/or Big Box Retailer; subsequent sale to contractor, final sale to Customer.

These alternative pathways have two important impacts on how the decisions are made to purchase a high efficiency window product.

1: It impacts the options or choices that are presented to the final customer. When the customer is "buffered" from the manufacturer by "layers" of entities, the information about the range of available window options may be heavily filtered, unless that "layer", e.g. a contractor, is aware of and interested in high performance products. For a product that represents only a few percent of total sales (today), most people in the supply chain are not going to be promoters of products that are only occasionally specified.

2: This "information" gap is often exacerbated by pricing structures. Triple glazed windows are effectively "specialty products" today for most major manufacturers. Low volume and custom ordered products almost always become extra cost options, which further increases the final cost as seen by the consumer, beyond the intrinsic added product costs. There are often further time delays in procurement of special order products. Cost issues are discussed in more detail in the next section.

Window industry product lines and sales trends

It would be useful to have a detailed understanding of existing trends in window purchases and installed window stock in the Northwest and to be able to confidently assess the impacts of climate, building type (e.g. modular, single family, apartment), and other occupant parameters on purchase trends. While there are numerous data sources (utility rebate programs, big box store sales, EIA data, Energy Star data, window industry sales data, NAHB and other building industry trend data as well as several private studies), there is not sufficient comparability between them to confidently tease out these impacts and correlations with any degree of detail. **However it is still possible to extract enough useful information based on national industry trends to guide new policy**.

The window industry has the capability of producing thousands of variants of basic combinations of glass, gas, coatings and frames. (Fig. A2-1) A single company can offer a variety of product lines that are normally built around key features and styles and they also offer a range of operator types: e.g. fixed, single hung, double hung, horizontal sliders, casements, awnings, swinging doors, sliding doors and skylights. Operator types have a variety of characteristics and features related to ventilation capability, protection from rain and wind, infiltration etc. For example, casement and awning windows normally have compression seals and will normally have lower air leakage than a sliding window- either a hung window or horizontal slider. Windows also vary by the primary material of their frames, e.g. metal, vinyl, wood, wood-clad, and hybrid, and within these categories can vary with the type and quality of the primary material e.g. pine vs. oak, and the quality of hardware.

Several different industry organizations collect and publish market data on window operator type, frame type and glazing type. Most of this information is gathered at a national level and when examined at a regional level is often hard to disaggregate because of the way regional boundaries are drawn, e.g. “Western” typically includes California, Oregon and Washington, states that straddle distinctly different climate zones. EIA data also reports extensive data on windows by installed stock as a function of numerous other parameters such as house size, number of occupants, income level, etc. Although interesting, it is difficult to extract much actionable data related to window market strategy from these data.

To better understand window market characteristics we use national data published by WDMA (WDMA, 2015) on the key breakdowns of current sales by frame type, operator type, glazing type and glazing number as shown below in

Figures A1-2, A1-3, A1-4, and A1-5. These trends change only slowly over time so the four year old data is not an issue in understanding market forces.

Operator Type
Sliding windows (double hung, single hung and horizontal sliders) are the dominant operator type in the U.S., making up approximately 67% of sales and installed stock (Figure A1-2). This is important as this class of window operators typically has the "worst" U values for a given IGU due to the larger fraction of sash/frame.

Operation Type

2015 Shares and Units by Operation Type (Millions)

	2015	
	Units	Share
Double hung	15.21	26.5%
Single hung	15.20	26.5%
Casement	6.19	10.8%
Slider	7.73	13.5%
Awning	0.96	1.7%
Fixed	3.70	6.5%
Other	8.37	14.6%
Total	57.36	100%

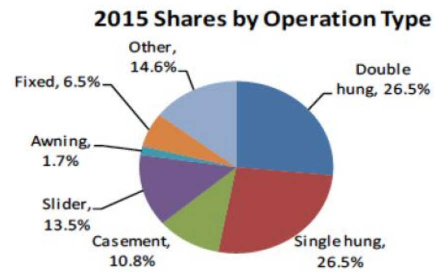


Figure A1-2: Market share by Operator Type: Sliding Windows Dominate, (WDMA, 2015)

Frame Material
Data on market share by window frame material type shows vinyl with a dominant market share of 64% of annual sales with wood and wood clad representing 27% and all others combined less than 10%. Vinyl has been gaining market share for over 25 years to where it is now the dominant frame type,

Material Type

2015 Shares and Units by Material Type (Millions)

	2015	
	Units	Share
Vinyl	36.65	63.9%
Wood	1.97	3.4%
Wood Clad	13.44	23.4%
Aluminum	1.75	3.0%
Fiberglass	1.04	1.8%
Composite	2.51	4.4%
Other	-	0.0%
Total	57.36	100%

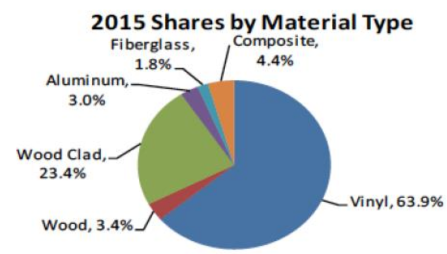


Figure A1-3: Market share by Frame type: Vinyl is the Dominant Material, (WDMA, 2015)

Glazing Number
As noted in earlier discussion, double glazing is the dominant glazing package with a market share of 98%, single glazing at 0.6% and triple glazing at 1.7% Some other sources report that triple sales may be 3-5% of all sales but data are not definitive.

Glaze Type

2015 Shares and Units by Glazing (Millions)		
	2015	
	Units	Share
Single glazed	0.36	0.6%
Double glazed	56.02	97.7%
Triple glazed	0.98	1.7%
Total	57.36	100%

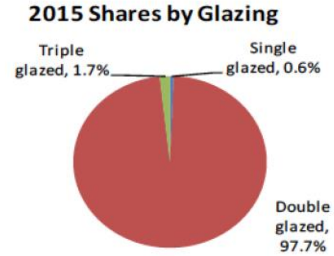


Figure A1-4: Market share by Glazing Number: Double Glazing Dominates, (WDMA, 2015)

Glass type

Glass type is the final parameter that WDMA reports and low-E dominates this parameter with a 96% share in this survey. (A different industry market source reports low-E at about 80%.) While laminated glass is shown, tempered glass is not which is surprising since some manufacturers report that about 10% of windows (mainly glazed patio doors) are tempered. We also note that these data are not representative of glass supplier sales since every low-E coated glass is paired with a layer of clear glass to form the IGU.

Glazing Type

2015 Shares and Units by Glazing Type (Millions)		
	2015	
	Units	Share
Clear	1.15	2.0%
Low-E	55.18	96.2%
Combination Low-E/Tint	0.11	0.2%
Tinted	0.03	0.0%
Combination Low-E/Reflective	0.00	0.0%
Reflective Coating	0.00	0.0%
Laminated	0.67	1.2%
Other	0.22	0.4%
Total	57.36	100%

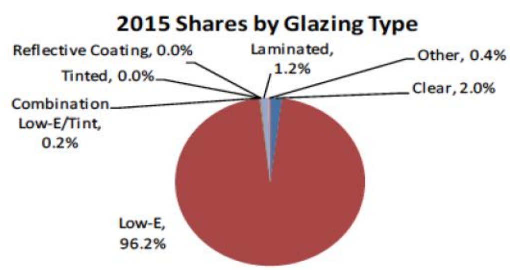


Figure A1-5: Market share by Glazing type: Low-E dominates, (WDMA, 2015)

We note that several different companies collect market share data in the window industry and it is widely understood that there are differences in the data collected. Although a common industry-wide data set would be useful, the discrepancies reported are not significant in terms of their impact on the conclusions of this task.

Appendix 2: Window Manufacturers and their Supply Chains

How the Supply Chain Impacts the Available Efficiency Options for Windows

The current residential window market sales snapshot portrayed in Figures A1: 2-5 is the result of a dynamic between what customers want, and what they will pay for on the one hand and what the companies are able to offer technically and what they think they can make and sell profitably. The opportunities and constraints on innovation in the window industry are determined in large part by the tension between the demand for new products from the customer side and the supply chain that supports the window manufacturers production and the pathways by which it delivers them to the end users.

In virtually all cases "cost" is an important issue, both to the suppliers and specifiers of new window products:

On the supply side, cost is an issue in terms of the new investment needed to create and launch a new higher performing window product (both R&D investment and investment in new manufacturing lines), and the risk associated with that investment in terms of the likelihood that it will be profitable. The larger regional and national window companies typically offer multiple product lines and have larger, more complex supply chains needed to support them.

On the demand side, any new housing feature that increase overall cost is scrutinized carefully by builders for their impact on final product cost and "affordability" in the target market. Those market demands and constraints vary widely. Upscale subdivisions with large million dollar homes will have a different window product line, mix of units and cost structure than the window package in a smaller, starter home. Retrofit and renovation markets, where the owner is more directly involved in the purchase decision, involve a different set of value propositions and are likely to respond to different price signals.

Market drivers are diverse and vary widely across customers. They include not just the energy use factors focused on here but also color/style/aesthetics, availability, warranty, thermal comfort, acoustics, installation and overall functionality and ease of use for operable windows, as well as cost and affordability. In new homes the window cost decision was made by the developer/builder and are typically buried in the overall cost of the home. For renovation, replacement and retrofit projects the cost of the window package can be substantial and may involve financing by the owner. Rebates and incentives, tax credits and lower cost loans can help promote purchase of more efficient products. In these cases the overall costs may also involve significant labor expenses connected with removal of the existing windows, installation of new windows and finishing with interior and exterior trim. It is within this complex set of parameters that the decision to "upgrade" to a thermally improved product at extra cost must be made.

In addition to cost, "availability" is often cited as a constraint in procuring high performance windows. Given that only about 2% of sales today are triple glazed, procuring a triple glazed product will often involve specifying a non-standard product, which may involve a special order, with additional time delays and costs. In almost any business "special orders" add costs beyond the intrinsic cost of the product itself. Some of this is the procurement process but some also relates to manufacturing where a standard product is made on a more efficient, high volume production line whereas a special order product is hand assembled at higher cost. "Mass customization", and the ability to deliver a wide range of design variants "on demand" is the market buzz and works well for example for the online order of a computer but is still yet not a routine option in the window industries although it is growing in market share as noted below.

Triple glazed windows cost more because not only are there more "parts" but the supply chain that provides them is more "complex" than that which supplies mainstream low-E, double glazed units. Part of the reason that low volume products or specialty products cost more is the detailed structure of the supply chain. Window manufacturers are "integrators" of a variety of key design and technology elements that they procure from other industries and then assemble into a variety of window designs for their end customers. A window is composed of two primary elements: 1) one or more insulating glazing units (incorporating glass, coatings, gas fill, spacers, sealants, desiccants, gaskets, muntin bars, etc), and 2) the sash and frame elements (metal, wood, vinyl, fiberglass, stiffening members, insulating elements, gaskets, weatherstripping, operating hardware, fasteners, cladding, sensors). These elements are shown diagrammatically in Figure A2-1 below**.** The result is a bewildering number of potential window products, each with different design details. The NFRC Certified Product Directory (CPD) lists and rates the thermal properties of millions of specific different window designs that could be built and sold, even if actual sales are a much smaller number of design options.

Many years ago when there were fewer low-E coating/gas fill options, the overall number of choices were smaller and many window companies stocked standard window types and sizes in regional warehouses. The proliferation of product options has complicated the supply chain and more companies now operate on a "build-to-order" basis, particularly in the retrofit/replacement market where there may be no standard sizes. No window companies make their own glass but many make their own IGUs as shown in Figure A3-4 for some or all of their window products, either using manual assembly or with the use of automated, high volume IGU production lines. A manual line has the flexibility of "easily" changing to a different IGU, e.g. a triple, if needed but the marginal costs are higher. An automated, high volume line requires investment in new equipment to make triples, which requires not just the financial resources but the assurance that the high volume market demanding the product is in place. Emerging markets generally do not supply that volume, at least initially, which is why new market transformation concepts such as supporting a new regional IGU plant that focuses on triples might help accelerate market change.

In order to change from a conventional double IGU to a thin triple IGU we note there are only four new or added key component elements (shown in blue in Figure A2-1) that are required to allow a doubling of the insulating value of the IGU from R4 to R8 and all are part of the IGU package, since no frame changes are needed. This "IGU-only" change simplifies the time and cost required by the window manufacturer to upgrade their products. Discussions with multiple manufacturers of automated IGU assembly lines confirm that the changes required for the thin triple IGU could be made easily but with some cost to set up the first line optimized for this design.

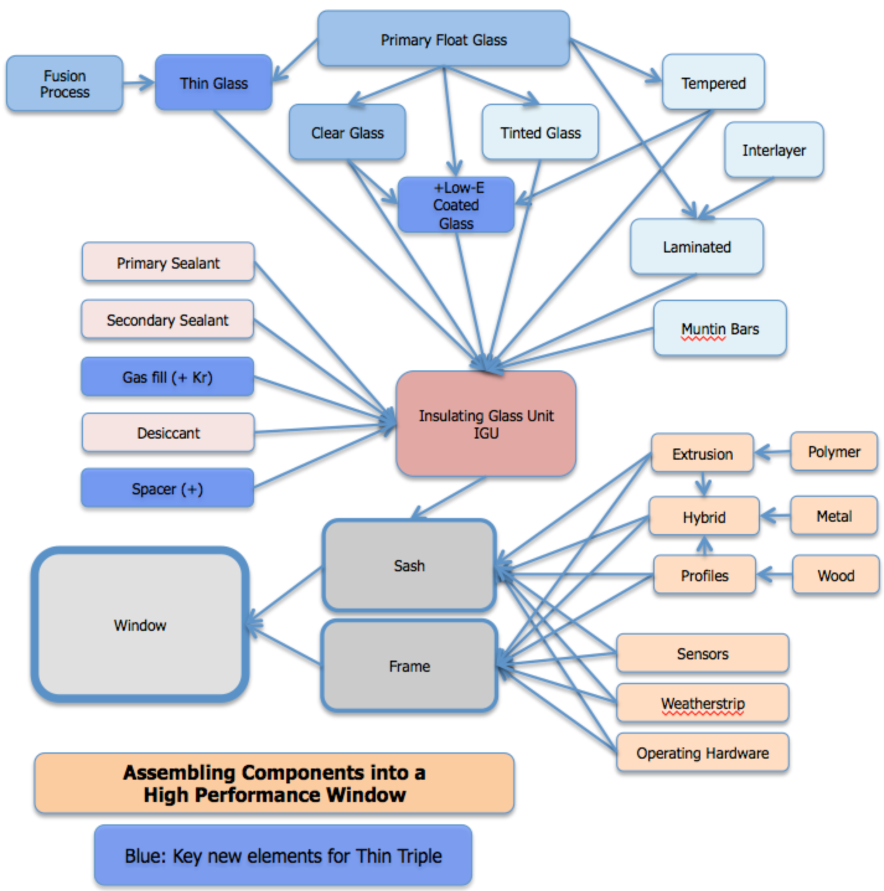


Figure A2-1: Supply Chain and Assembly of key components in a "Typical" Window, highlighting the new thin-triple elements in the IGU (blue)

Appendix 3 - Technical Potentials for Thermally Improved Windows

The essence of a window is a transparent view to the outdoors, but at the same time the transparency must protect occupants from sun, glare, rain, wind, dust, burglars, etc. so the glazing element is "the" essential and unique window component. Today virtually all windows have "insulating glazing units", IGU with multiple panes of glass and other features. The LBNL International Glazing Data Base (IGDB) (LBNL, 2019) lists ~5000 different glazings that are commercially available from the global glass industry but these are utilized in only about 10 major "IGU configurations" as a glazing unit, as illustrated below, with their associated U value.

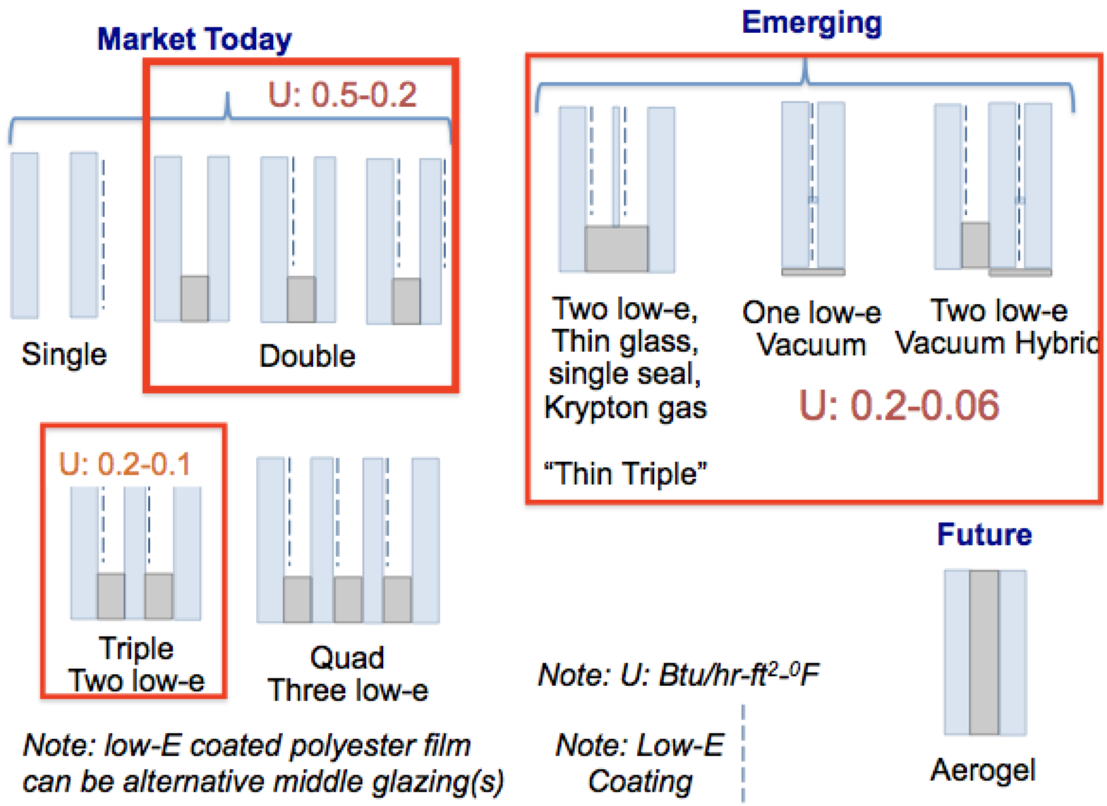


Figure A3-1: Primary glazing systems in use today and emerging options. Variants of double glazing make up about 90% of market sales

No window company makes its own glass. Glass is manufactured and sold by six global primary glass suppliers: Vitro, Guardian, Saint Gobain, AGC, Pilkington/NSG and Cardinal, who collectively have about 30 float plants located across the U.S. Each of the primary glass producers makes flat glass in a variety of standard thicknesses, clear and tinted, and provides one or more types of low-E coatings. Some primary glass manufacturers are more vertically integrated and will further process glass, offering tempered, heat strengthened, and laminated options, although these may also be created by other suppliers, e.g. glass fabricators. (Fig A2-1)

The "center-of-glass" (COG) U-value of these variants of double and triple glazing are the most critical factors for improving the insulating value of the overall window. The U_{COG} is a function of the gap dimensions, location, number and emittance of low-E coatings and gas fills. These are summarized in figure A3-2 below.

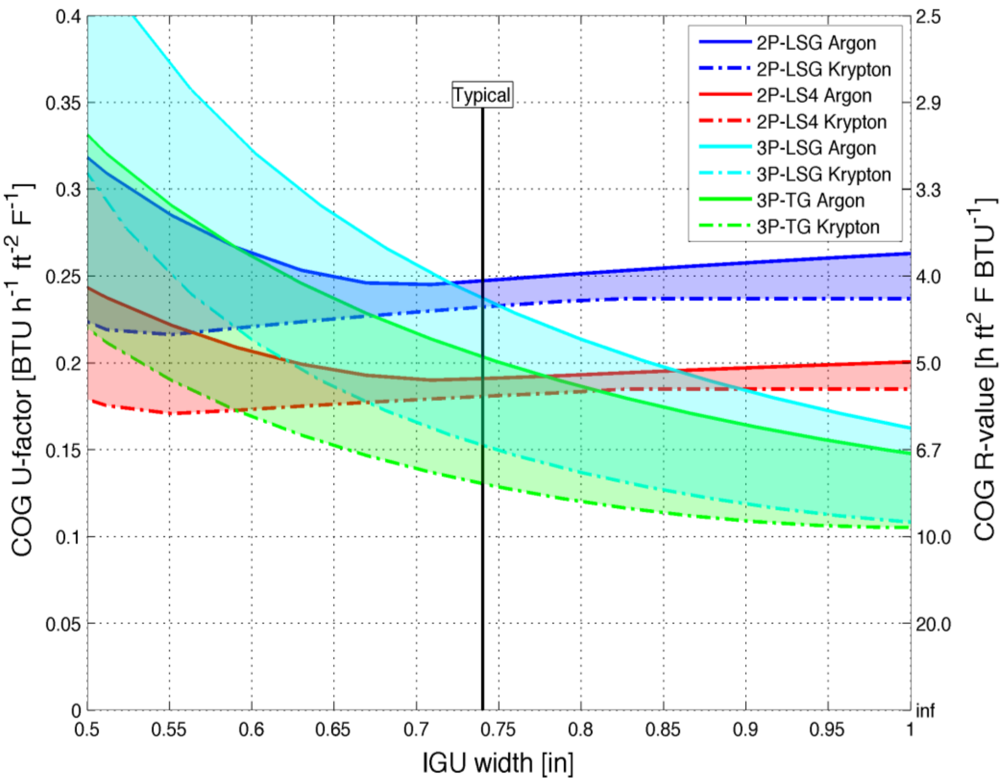


Figure A3-2: Center of glass thermal performance based on IGU width and gas fill. The performance ranges obtainable by double-pane low-e (2P-lowe), double-pane low-e with roomside low-e (2P-surf4), conventional triple (3P-LSG) and thin-glass triple-pane low-e (3P-TG) are shown. 3mm glass is used everywhere but center-pane of 3P-TG where 0.7mm glass is used. (Source: LBNL)

Conventional double glazed clear IGUs with ½" air gap were the initial standard for double glazing as the resultant ¾" IGU fits comfortably into most sash and ½ " is the optimal thickness for an air filled cavity. The next step to reduce U is to add a low-E coating on the #2 or #3 surface of the IGU, usually the #2 to reduce stress and lower SHGC in hot climates. Low-E coatings are made in several different manufacturing processes (off-line sputtering and on-line pyrolytic) which impacts durability and emittance and thus U, but since about 90% of coatings are sputtered for this study we assume a 0.04 emittance in the figure above and supporting discussion, typical of many available sputtered low-E products. Once this low-E coating is added to the IGU the effectiveness of changing the gas fill to Argon increases. Argon is cheap so the most common IGU is now an argon filled, low-E IGU. (solid blue line in Fig A3-2) The U of an argon filled, low-E window with 0.5" gap (0.7" IGU width) is approximately .25 and this has been a benchmark of window thermal properties for several decades. Adding a second low-E coating to the air space or changing the emittance has only a tiny impact with added cost.

The center-of-glass U factor of the overall IGU thus depends on the configuration (2 or 3 pane), the coating, the gas fill and the dimensions of the gap. But there are two additional thermal improvements that can be made to the .25 COG value for double glazing.

First, a more insulating gas like Krypton can be added in place of Argon (dotted blue line)– this has the effect of further reducing the U_{COG} to 0.22. Krypton has optimal performance at an even smaller gap as shown but has not been widely used since it was much more expensive than argon. The current cost of krypton has been lowered dramatically as is discussed later.

The second change is to add a durable low-E coating on the #4 surface – the surface of the window facing the room. This reduces the COG heat transfer to 0.19 for the ½" gap window with argon and potentially down to 0.17 with Krypton at smaller gap widths. (solid and dotted red lines) Since this low-E coating faces the room it is subject to a more challenging environment re durability than coatings protected inside the IGU and the manufacturing process is more complex and expensive. In principle a low-E coating could also be added to the #1 exterior surface but this is rarely done due to the exposure of that surface to exterior environmental conditions, and because the thermal effect is much smaller due to the presence of wind.

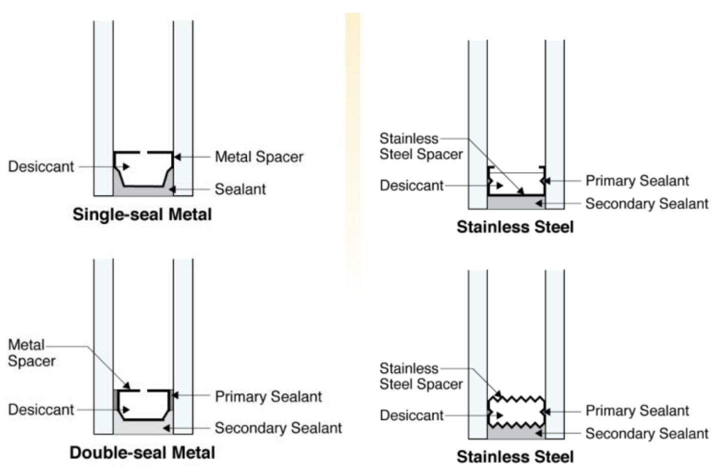
Two further options will further reduce heat transfer as shown in Fig A3-1- either 1) adding more layers of glass, gas and coatings, i.e. triple or quadruple glazing, or evacuating the air space to create a Vacuum Insulating Glass (VIG) unit. A well designed conventional triple glazed IGU (cyan solid and dotted lines) can reduce the U_{cog} to about 0.11 and a quad unit can go as low as 0.07. The thin-triple variant (green solid and dotted lines) can achieve the same values but with thinner IGU widths as discussed in more detail in Appendix 5. VIG units are capable of COG thermal performance in the same range.

Assembling the IGU: the role of spacers

Since effectively "all" residential windows are double or triple glazed, the assembly of sheets of flat glass into the IGU is a critical design element and manufacturing constraint. IGUs are assembled with a nominal ½" air gap which is created with a spacer that is sealed to the edge of the two glass sheets. A ½" gap is the optimal size for both air –filled and Argon-filled units. The sealing process is designed to keep moisture out so as to prevent condensation inside the IGU and to retain the Argon gas that is commonly used to fill the IGU since it thermally improves the IGU relative to air, particularly when a low-E coating is used. Spacers and their adhesive systems must meet structural requirements to handle the loads imposed by changes in atmospheric pressure, thermal expansion from solar energy, and other operating stresses induced by the window frame, and by operation.

Spacers have evolved over time and are categorized by material and design, and are available in a range of thicknesses. Traditionally, the best spacers used a dual seal system with a sealant bonding a metal or foam spacer to the glass to prevent gas transfer and a secondary sealant to add structural strength. (See Fig A3-3) Traditional metal spacers are thermally conductive and influence the heat transfer not just at the spacer but extend for a margin of 2.5 inches along the edge of the glass. This "edge-of-glass" conductance is calculated as part of the NFRC U value determination- see Fig A4-1). Spacers have evolved in both design and materials to reduce their thermal conductance, by 1) using less thermally conductive metals, e.g. stainless steel replacing aluminum, 2) enlarging the path length for heat flow, e.g. corrugated design, 3) changing the cross section, and 4) switching to non- metallic structural designs, e.g. foam, thermoplastics. Virtually all designs also include a desiccant load in the spacer whose purpose is to absorb any water vapor present at the fabrication step and any modest amount that might leak in over time. A major failure of the seal would overload the desiccant and result in visible failure due to fogging.

The pros and cons of each approach are complex and depend in part on the performance level desired, cost, etc. They also depend critically on the quality control of the IGU assembly process. IGMA and AAMA have "durability" standards that most window manufacturers reference. While experience with seal failures is still an issue in the industry the quality has improved markedly over the years. Many window companies now offer 20 year warranties against IGU failure.



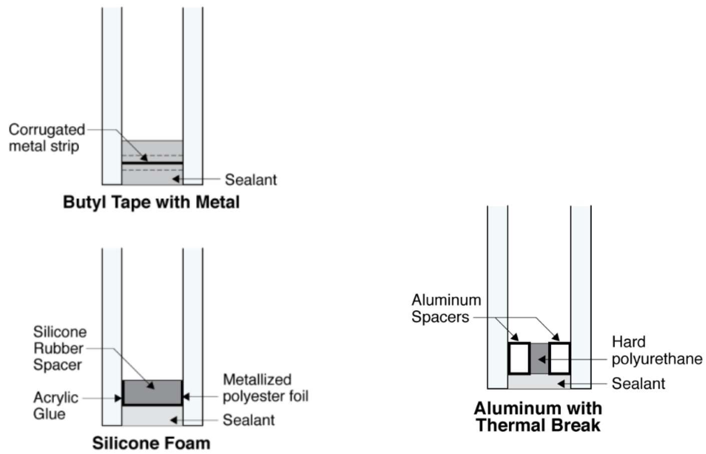


Figure A3-3: Common IGU spacer designs (source: EWC)

Automated IGU Assembly Lines

Coated and uncoated glass is assembled into IGUs by fabricators and then shipped to the window assembly plant or the glass is shipped directly to the window company and assembled into IGUs at the window assembly plant. For a window company the decision to purchase IGUs or build their own depends on many factors. Larger manufacturers tend to make more of their own units as they have the resources and staff to do so and can benefit from reduced costs of automated in-house production. DWM magazine reports that 78% of larger companies make some or all of their own IGUs whereas 54% of small and mid-sized companies take that approach.

Door and Window Manufacturers	Small/Mid-Sized (<$50M)	Large ($50M>)
Purchase IGUs from IGU manufacturers	46%	22%
Fabricate own IGU's	39%	45%
Combination thereof	15%	33%

Figure A3-4 Window Company IGU Fabrication: Make or Purchase (Source: DWM)

IGU's can be assembled manually with the spacers and glass cut to size, sealants and adhesives added, argon gas filled and the unit clamped to set the sealant. Increasingly IGUs are made on an automated assembly line that starts with stations to cut and clean glass panes and ends with a fully assembled IGU with low-E coatings and gas fill. Several companies build and supply fully automated IGU production lines with different options that carry out some or all of the steps above with robots in a fully automated assembly and inspection process. (Fig A3-5) These lines have the ability to assemble a wide range of different products in sequence.

Different lines are built around the specifics of different spacer system, e.g. a rigid metal spacer line will be different than a foam edge line. But they share the ability to produce as many as 1000 units per day of high quality IGUs. Some of these automated lines can be configured to offer triple glazed IGUs as well as double glazed units. These automated IGU lines typically cost 1-3 million dollars but with high throughput, reduced labor and better quality control there is growing interest in these solutions on the part of window companies. However the window company would require a significant annual sales volume to justify such an investment. An automated IGU line that makes 1000 window units per day would therefore make ~ 250,000 windows per year on a single line, or enough windows for perhaps 10,000 homes. Clearly production facilities of this cost and output require a significant sales volume to justify the investment. A further option is a line that can be switched between different products, e.g. double glazed IGUs and triples.

Before assembly into an IGU, as noted above (Fig A2-1), some glass undergoes additional processing, for example it may be tempered in a furnace or laminated to other glass, to provide properties that may be required by code. The processing facilities for these types of glass also have to be integrated into the work flow of IGU and window assembly if they are not supplied directly by the glass manufacturer.

Figure A3-5 : Example of Automated IGU Assembly Line (source: Bystronic)

Appendix 4: IGU Properties and Window Properties

While prior discussion has focused on the insulating glazing unit it is the overall window whose properties are most important. Annual window energy use is then a function of several overall window parameters as well as building location, orientation etc. The key energy- related properties of a window are the U factor, the Solar Heat Gain Coefficient, (SHGC), visible light transmittance, Tv and Air leakage. These properties are captured on the NFRC label which is used by virtually all manufacturers in the U.S. **In this effort we focus primarily on the U factor as it is a key determinant, particularly in colder climates, of annual energy impacts, it directly affects comfort, and it impacts peak heating system capacity and distribution system sizing and cost**. SHGC also impacts heating energy use (higher is better) but it is easily varied over a relatively wide range with existing coating technologies and has negative effects on cooling so is not an immediate constraint for decision making for thermally improved windows. The heating season tradeoffs with different SHGC are discussed later.

For many years the U factor was calculated and measured using a variety of different methods and assumptions, leading to confusion in the market place. Now virtually all codes and standards as well as Energy Star refer to the NFRC rating procedure to determine U factor. It is calculated using a suite of validated software tools developed by LBNL with support from the U.S. DOE. The NFRC U factor is a whole product value determined under a specific set of temperature and air flow conditions, for different operator types and for a specific standard size (48"x 60"). For this discussion the crucial issue is that the overall product U factor is the area-weighted average of three elements: 1) the center-of-glass (COG) properties of the insulating glass unit, 2) the edge thermal properties of the IGU, accounting for the effect of the spacer system, and 3) the sash/frame elements. These elements are shown schematically in Fig A4-1 below with the relative area-weighted-average based on NFRC standard size.

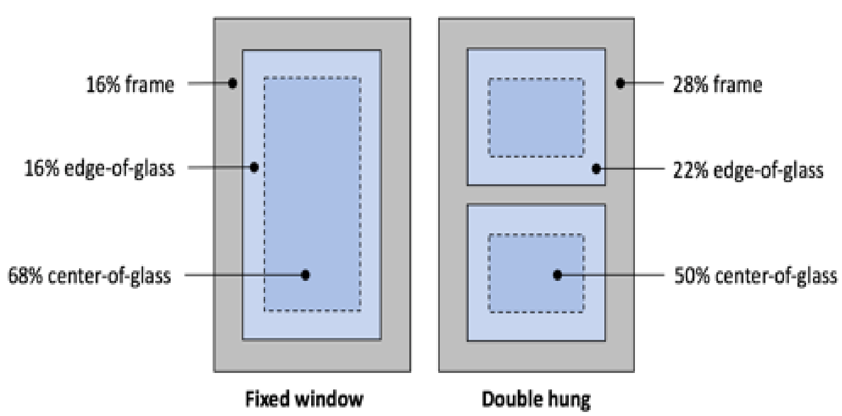


Fig. A4-1- Relative areas of frame, edge-of-glass and center-of-glass for a typical Fixed Window and Double Hung window

With an old single glazed wood window the sash/frame was more thermally insulating than the single pane of glass so the whole window U factor was lower than the COG value. But with today's low-E/Argon IGU the IGU is now more thermally insulating than most wood and vinyl frames with slim sections. If we assume a nominal value for the edge of glass for now, the relationship between the IGU COG U-factor and the NFRC whole window U factor is shown in Fig A4-2. The figure demonstrates two conflicting design directions. **A drop-in replacement IGU (no frame changes) must achieve ~ R8 COG to deliver a window with whole window properties of about R5,** assuming no change is made to today's typical frame**.**

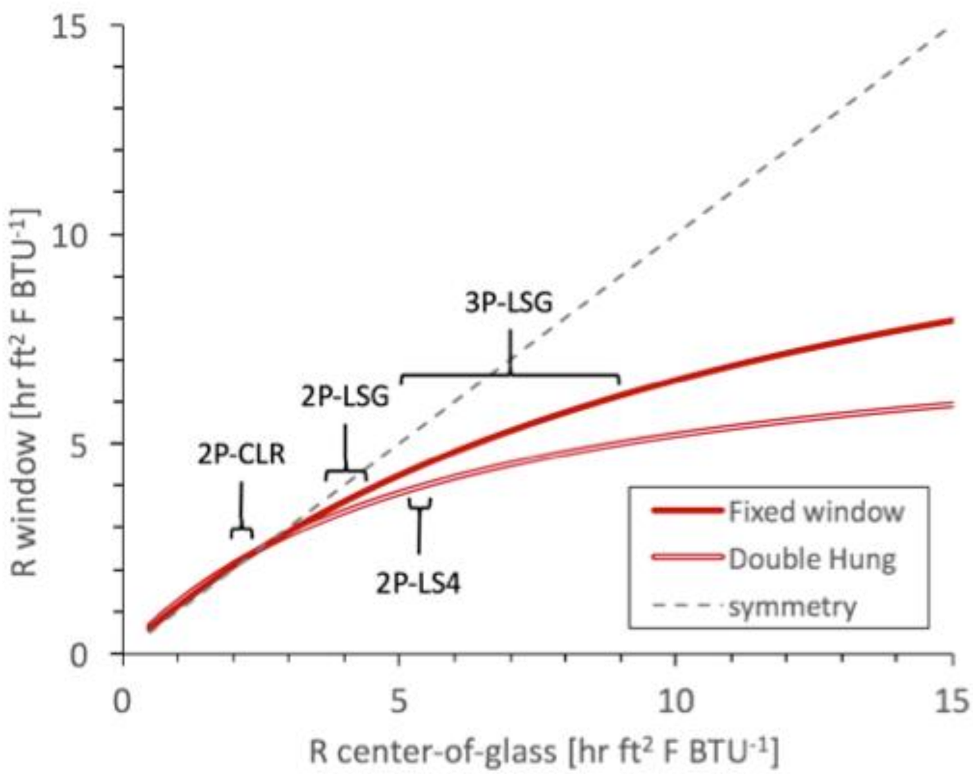


Figure A4-2: Total Window R value as a function of COG R value, for two operator types: fixed and DH. The captions describe the IGU type: 2P-CLR = double pane, clear; 2P-LSG= double, low solar gain low-E, argon; 2P-LS4= double, lowE argon w/ surface 4 low-E; 3P-LSG = triple, 2 low-E, gas fill. Assumes typical edge spacer.

This insight now helps explain the whole window properties data gleaned from the NFRC Certified Product Directory**.** Figure A4-3 looks at CPD data from all double hung windows with any glazing package and any frame material. This provides a snapshot of what the US window industry offers today (but not necessarily what is being sold). The mean window properties are given in Figure A4-4: the mean U is 0.33 (R3) which is consistent with the fact that about 80% of all windows sold today are Energy Star certified with target values in the 0.3 to 0.35 range. The mean IGU gap is 0.49 inches and the mean IGU total width is 0.74 inches, consistent with an IGU composed of two 1/8th glass layers and a .5 inch cavity. Other window operators have similar data so **this informs us that a drop-in IGU replacement with enhanced thermal properties must be built around a ¾ inch IGU dimension so as not to have to redesign window sash and frames.**

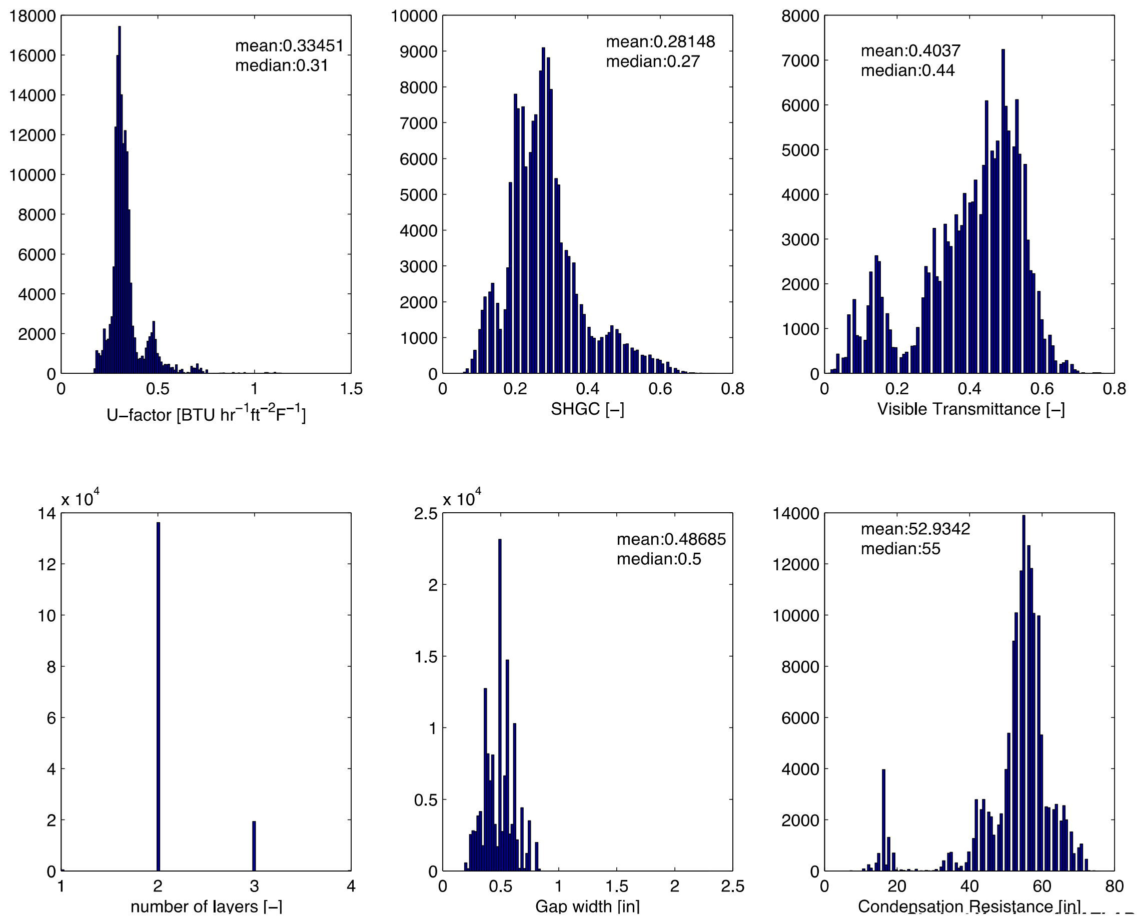


Figure A4-3. Frequency plots of U-factor, SHGC, VT, number of layers, gap width, and CR for single hung and double hung windows from the NFRC CPD.

The mean properties for these products is given in the table below:

Metric	mean	Unit
Window U-factor	0.33 [1.87]	BTU $hr^{-1}ft^{-2}F^{-1}$ [$Wm^{-2}K^{-1}$]
Window SHGC	0.28	-
Window VT	0.40	-
Window CR	53	-
IG Gap width	0.49 [12.4]	in [mm]
IG Total width	0.74 [18.7]	in [mm]

Figure A4-4: Mean properties of data from Figure A4-3

We can then explore in more detail the impact of operator type and IGU configuration. Figure A4-5 shows histograms for fixed and double hung windows binned by U factor and grouped by glazing type as explained in the captions. The market "standard" is the double pane, low-E with Argon fill which generally meets all codes and Energy Star requirements. Figure A4-6 adds more insights into the effect of the two major frame types, wood and vinyl, and the effect of spacer type. Vinyl continues to grow in market share as noted earlier and Figure A4-6: a, c shows that it represents a proportionately larger fraction of the lower U factor products. Figures A4-6: b,d show that foam and U-type metal spacers dominate the options listed in the NFRC CPD.

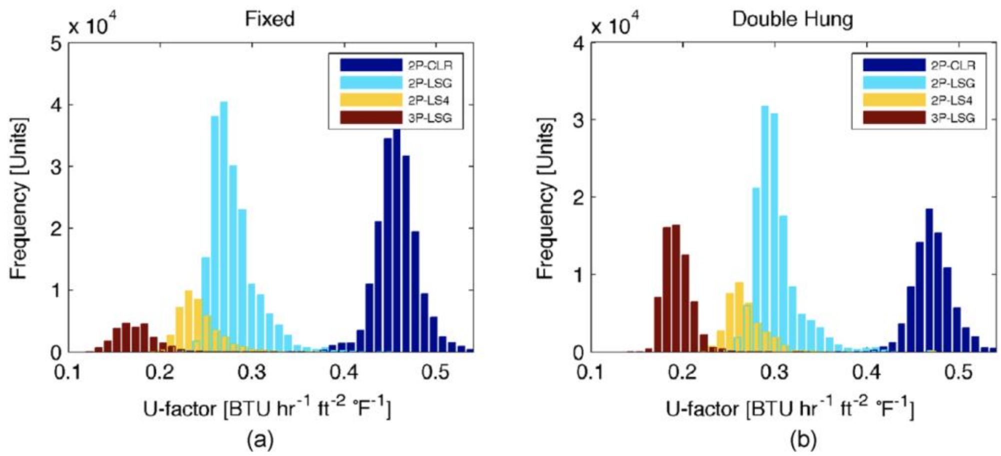


Fig. A4-5 Histograms of (a) fixed and (b) double hung windows from the NFRC certified products directory (CPD) *binned into U-factors of 0.01 BTU hr^{-1} ft^{-2} $^{0}F^{-1}$ and grouped by glazing types of double-pane clear (2P-CLR); double-pane low-solar-gain low-e (2P-LSG); double pane low-solar-gain with room-side (surface 4) low-e (2P-LS4); and triple-pane low-solar-gain low-e (3P-LSG)*

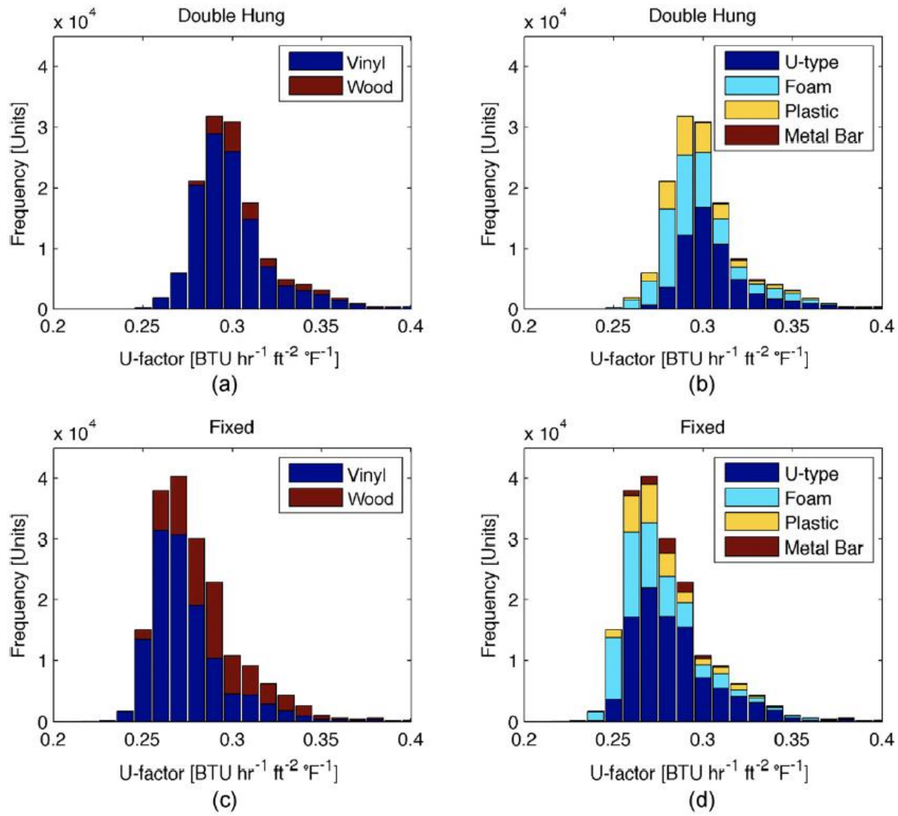


Fig. A4-6 Histograms of NFRC certified products directory (CPD) *certified fixed window and double hung products grouped by frame material type (a & c), and spacer types (b & d). Database accessed in 2017 (Anderson, 2017)*

We note again that while the NFRC data provide useful insights into technologies and capabilities, they represent products that "might be built and sold" but not actual sales volume. Referring to Figures A4-5, there are significant numbers of triple glazed products in the CPD but actual sales are less than 2% of total market volume. Similarly the double pane clear (dark blue) shown in the figure appear to have market share approaching that of low-E windows but the WDMA data in Figure A1-5 indicates that these actual sales are small.

Appendix 5: - The "Thin-Triple" Potential Solution

Appendices 1 and 4 establish the technical thermal performance limits of existing window solutions and their constraints. In this appendix we present more details on the thin-triple IGU design that we believe will address NEEA's market needs for an R5 window. A key attribute is that this "drop-in replacement" IGU allows a window manufacturer to meet aggressive new thermal performance targets without costly redesign of their window system.

This data on the sales and structure of the window industry and its supply chain helps to understand what will be needed to help transform the window industry. We have selected a target value of R5 for the thermally improved window for several reasons:

1. It provides a significant energy benefit compared to existing code compliant products;
2. It is achievable by many conventional triple glazed windows, as evidenced by sales data and code requirements in northern Europe;
3. It has been used as the target properties of the EPA Most Efficient window criteria, is being proposed as a mandatory 2025 target in Canada and a code compliance option in California in 2020;
4. It has been the subject of several utility rebate and incentive programs
5. It is not easily achievable by any simple modification of a conventional double glazing so will require either a conventional triple glazed IGU with a redesigned window frame or a new technology for the IGU that allows a drop in replacement to an existing frame.

To move the mainstream R3 market to R5 we define the following requirements based on the "barriers" discussion at the beginning of this report and based on reviews of other window market transformation programs over the last 30 years:

- drop in replacement- no sash redesign
- existing infrastructure
- capacity to expand volume quickly
- minimal technical risk
- affordable cost
- automated manufacturing
- consistent with existing industry business models
- acceptable aesthetics

The Thin-Triple Window - A High Performance, Low Cost, Low Risk Business Solution for Highly Insulating Windows

Progress on better windows has slowed because the technology platform that drove "innovation" over the last 20 years, the addition of low-E coated and gas filled IGUs, has maxed out its performance. Adding a surface 4 low-E drops the window U factor down to the range of .23-.27 but also increases condensation indoors and is expensive compared to other low-E coatings. Most importantly there is no easy pathway to further improvements- a surface one coating is even more expensive and makes a miniscule improvement in U. **Redesigning the window dimensionally and structurally to accommodate a conventional triple IGU provides the opportunity for a substantial improvement and has low technical risk but it has high business and market risk since a large expense would be incurred in the redesign and manufacturing setup to go after a market that does not yet exist in terms of explicit demand**.

Since the technical pathway to a wider, heavier sash for a conventional triple glazed window is clear but a profitable business pathway is less so, it makes sense to explore other options. The market opportunity for a narrower insulating window that delivers the same performance level as a conventional triple emerges from the confluence of three factors: 1) a thin standard wall design for most U.S. houses based on the 2x4 stud walls, 2) a historical preference for thin, minimal sash with more glass and vision, and 3) the fact that the most common window operator is a sliding window which means that the frame has to accommodate two sashes sliding in parallel making the overall width twice that of a single sash. The result is that the majority of existing US windows can not be easily converted to a standard triple glazed IGU that is 50% wider and 35% heavier than a double glazed window. Builders report that heavier triple glazed windows may also require extra contractor crew for installation and potentially some wall framing changes. The relative width of US vs European windows is illustrated in Fig A5-1 and it is easy to see that that the traditional slim sash cannot accommodate a conventional triple IGU without redesign.

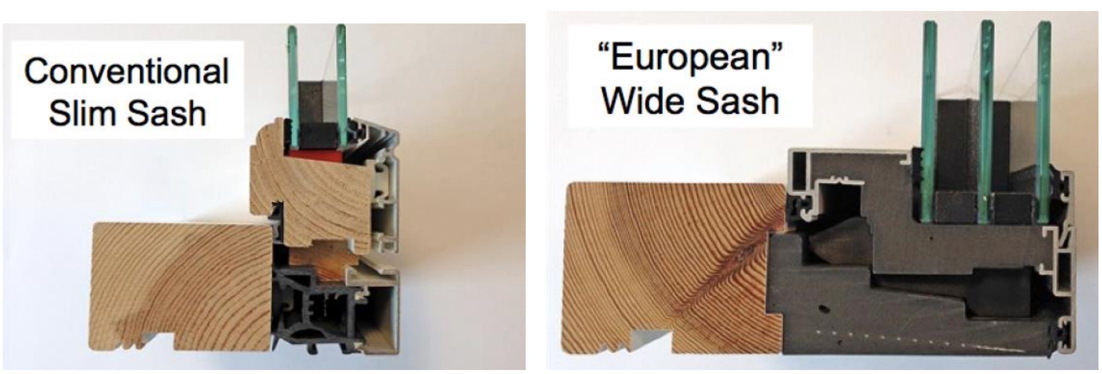


Figure A5-1: Conventional U.S. slim sash as part of a sliding window(left) and European Wide sash as part of a tilt and turn window (right).

The ideal solution would then be an IGU platform that allows significant further thermal improvements – e.g. doubling the insulating value of the IGU from ~R4 to ~R8 in order to improve the window to ~R5 - but without requiring expensive new glass technology, e.g. vacuum glazing, or a redesign of the window sash. **This performance level and set of features is available using the "thin-triple" IGU, -**

resulting in a window of conventional frame design that incorporates a new IGU platform (same weight/same thickness as conventional double low-E) but with R8 insulating levels.

The translation of the R4 conventional double IGU to the R8 thin-triple IGU is illustrated in the figure below, which is one example using a foam edge spacer. Three key features are added: an additional layer of glass, an additional coating and substitution of Krypton gas for Argon.

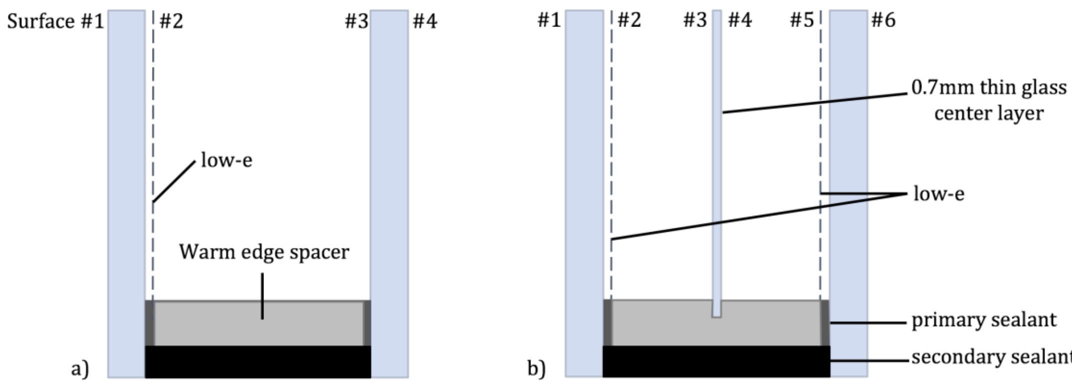


Figure A5-2 Diagram of thin-triple IGU vs conventional double IGU

The thin-triple design can be implemented in two different variants. The option illustrated in Fig A5-2 shows a single spacer with the new third glazing layer simply held in place in the IGU. Using a single spacer rather than two limits the potential for air leakage since there are only two edge seals, not four as in a conventional design with two spacers. In addition the two air spaces can "pressure equalize" which should reduce stress on the center glazing. The other option is to use two spacers in an edge design that is similar to most triple IGUs - this is shown on the right of Figure A5-3 below. Several companies already offer other types of single spacer designs that can accommodate a middle glazing layer as shown in Figure A5-4.

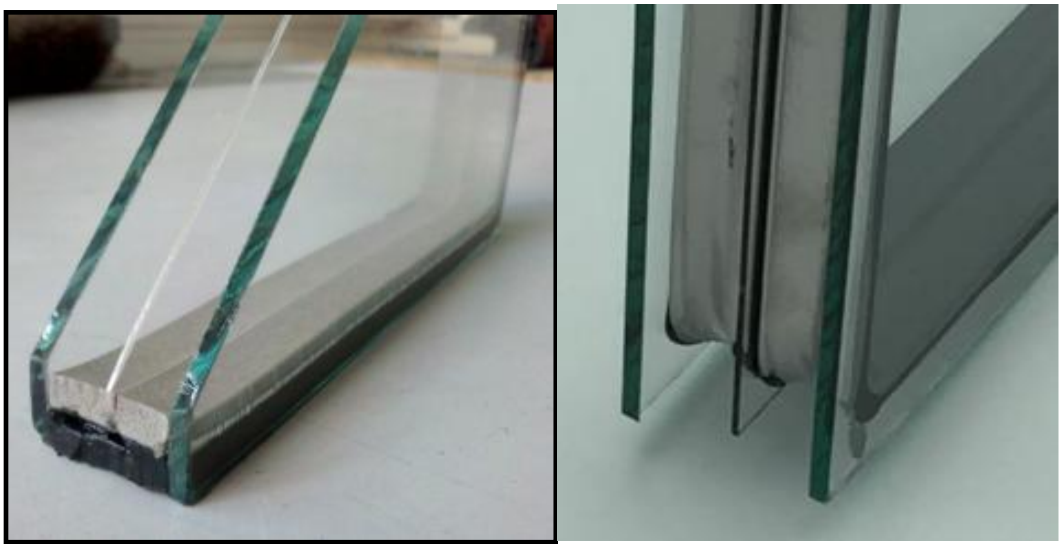


Figure A5-3 Photos of two versions of the thin-triple IGU; left- single spacer; right- two spacers.

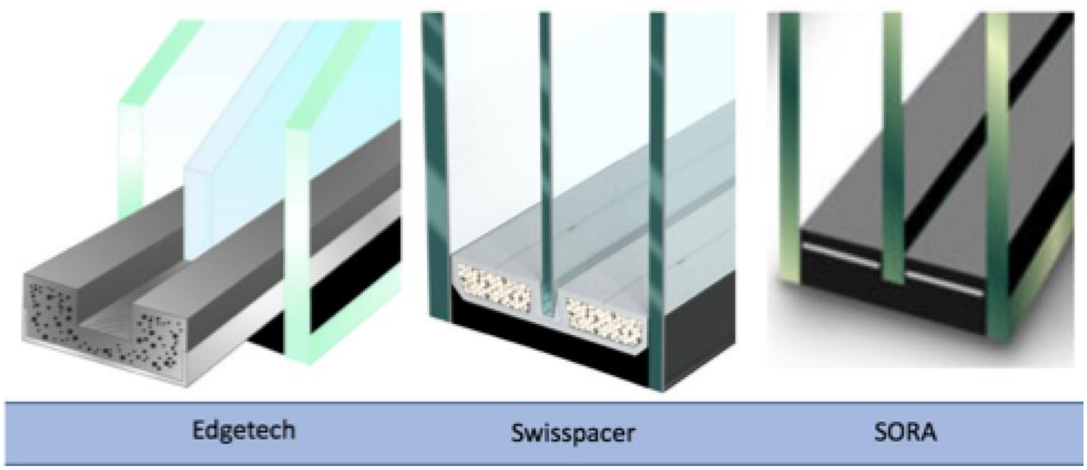


Figure A5-4: Examples of Commercially Available spacers that could be modified to support the thin-triple IGU concept

The thermal properties of the key thin-triple IGU have been modeled, optimized, built and tested at LBNL (Hart, 2018; Selkowitz, 2018) and are well understood. Summary results are presented below for fixed windows and double hung windows

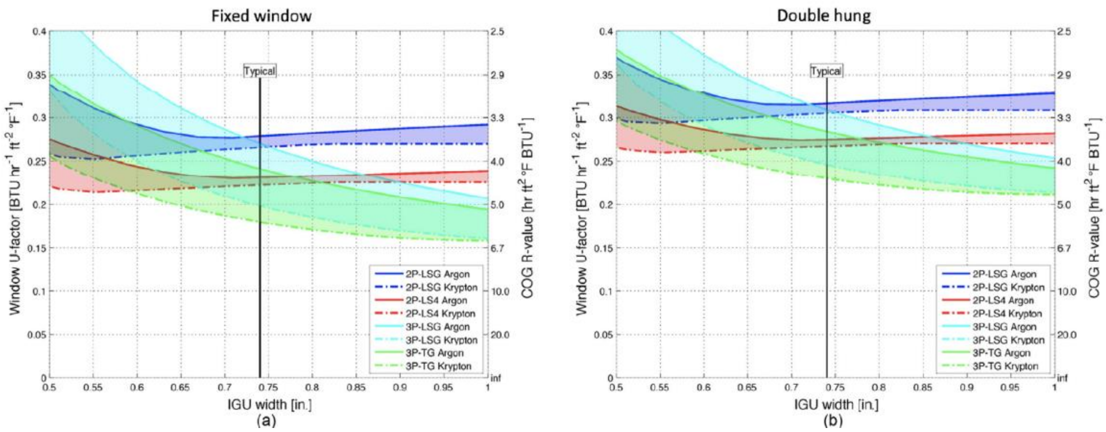


Figure A5-5: U factor for (a) Fixed and (b) double hung full window thermal performance potential of glazing systems with Argon and Krypton between-glass gas fill and single-strength (1/8 in. nominal) glass. 3P-TG uses 0.7 mm glass thickness for center-glass

Small numbers of versions of these prototype windows with the thin triple IGU have been built by Alpen High Performance Windows in Colorado. They report no significant design challenges after learning how to handle the thin glass. They have fabricated triples and quad versions (Fig A5-6) and have made prototype units as large as 5' x 10'.

Several questions have been raised regarding aspects of commercial readiness of this emerging technology. These are discussed at the front of this report as elements of the planned activities needed to address barriers to commercialization. But two specific supply side issues are noted here regarding availability of the essential thin-triple design elements: thin glass and krypton gas.

Thin glass: Two suppliers have been working with LBNL over the last year, Pilkington/NSG and Corning, and two others make thin glass in volume, AGC and Schott. The global production of thin glass for flat screen televisions exceeds 2 Billion square feet per year; by comparison the annual U.S. residential window market represents added window area of about 600M square feet. Cost is discussed in Appendix 7 but is acceptable now and has been falling over time. Supply can be increased if needed with the addition of new float plants.

Krypton gas: The two major global suppliers Linde and Praxair, merged last year. Costs have been falling and supply is adequate to launch new window products. If demand grows substantially over time new air separation plants can be added to increase production capacity.

Figure A5-6 Photos of two window corner samples showing a quad unit (l) and a triple unit (r); the quad unit utilizes a 1 ¼" wide IGU and can be optimized to achieve ~R15 COG (Courtesy Alpen)

Appendix 6: Cost of Windows: Understanding and Challenging Market Trends

When trying to understand the overall lack of market demand for thermally improved windows, the very high added cost appears to be a major barrier to adoption. Triple glazed windows are a conventional, proven solution that is widely used in Europe but uncommon in the US largely because the cost signals delivered to the potential user community are very high. Cost was studied extensively in two recent studies by PG&E in California (Hendron, 2018), and Energy Trust of Oregon (Apex, 2018). These studies identified a variety of challenges that we briefly discuss here. Both looked at the incremental cost to reduce window U factor to a range of lower values. The specific cost conclusions of each were different and signal a fundamental challenge to understanding how to deliver a cost effective product to the market. In addition, the overall cost structure of windows is complex and confusing, so this is discussed after a review of the two studies. The Energy Trust study tried to extract from sales data a continuous "cost per unit thermal improvement". This approach is difficult because the correlation of design features and performance is complex (see Appendix 4) and at some point in the pathway to reduce the window U there are discontinuous steps that dramatically impact cost. The PG&E study collected case study data from about 30 sources.

The cost structure of the window market is inherently complex. As in many markets "cost" and "price" can often be very different for reasons of marketing, promotion, brand, business strategy, volume, etc. Also price may be based on volume, and sometimes has other costs included such as installation if the purchase is from a contractor.

A bigger issue perhaps is that the overall range of cost per unit area for a window varies dramatically over a range of 5 to 1. A consumer can buy a basic vinyl window that is Energy Star compliant for ~$10/ft^2. In the same window section of a big box store, a consumer might also spend ~$50/ft^2 for a higher end, clad wood window with other features but that one that also meets Energy Star thermal requirements. Clearly the cost of enhanced thermal properties is only one of the many cost drivers that is involved in consumer decision making. Furthermore if the incremental cost of a thermally improved window is $5/ft^2, that "adder" is a large proportional increase to the $10/ft^2 window but is a much smaller adder to the $50/ft^2 window. Note that these cost differentials are not unique to windows. One can buy a 30 mpg car for $15K or for $75K- needless to say there are numerous other features that drive both the cost and willingness of the consumer to buy across that spectrum. The same should be expected in window markets. **The challenge is then not only to deliver improved performance at "modest" incremental cost but also to build the "value proposition" for the enhanced products that will increase the market interest and likelihood of sales. Building the value proposition was discussed earlier in terms of topics like enhanced comfort, HVAC downsizing, code equivalents, etc**.

Energy Trust undertook an initial study in 2014 and a more recent study in 2018 (Apex, 2018) that included an examination of costs of thermally improved windows by looking at cost data from big box retailers as a function of U factor.

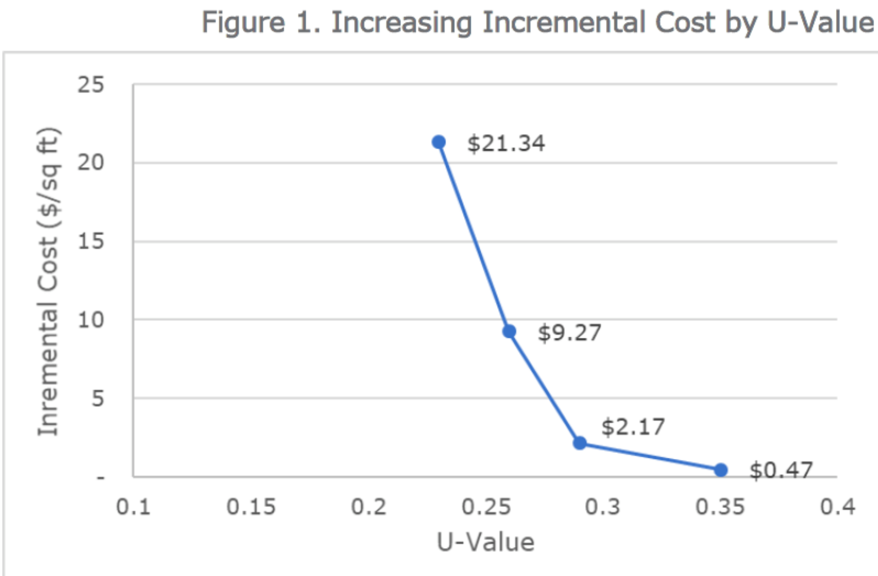


Figure A6-1: Incremental Cost of Thermally Improved Glazing (Apex, 2018)

The very high costs of over $20/ft^2$ do not even result in U values as low as 0.2 which one would expect from a good quality triple glazed window. The problem with this pricing approach is that there are many variables that impact price and many more that impact performance and they are not necessarily well coordinated, as discussed above.

PG&E also looked at cost data as part of the 2019 Title 24 code revision exercise and came to rather different conclusions about the incremental cost. But in the final analysis they did not find that the incremental savings were cost justified to support a mandatory upgrade to the 2019 building codes. As a result the 2019 T24 code made only a small reduction in the U factor from 0.32 to 0.30 but did mandate a significant tightening of the overall opaque envelope requirement. However lower U factor windows are available as an alternative compliance path. This is discussed in more detail in an earlier section. As noted earlier the reason why this is important to NEEA is that a shift in the California new home construction market could generate significant market demand that could encourage major window manufacturers who serve both California and Northwest markets.

One of the cost survey data tables from the PG&E study is shown below. While there is a wide range there are a number of survey results bunched in the middle at an incremental cost of about $7.00/ft^2$ to go from a double to triple pane window. We note again here that "triple pane" does not guarantee any specific performance level in terms of U.

THIRD PANE COST

Source	% Increase for 4ft x 4ft Window*	Incremental Cost per 2,700 ft² House (540 ft²)	Incremental Cost/4ft x 4ft Window	Total Cost for Triple Pane ($/ft²)	Incremental Cost for Double to Triple Pane ($/ft²)*	Notes
BEopt	30%	$3,699.00	$109.60	$29.92	$6.85	Vinyl frames, installation included
BEopt	78%	$13,975.20	$414.08	$58.94	$25.88	Insulated vinyl frames, installation included. NREL has proposed revisions for the upcoming version of BEopt that reduce large cost interactions.
Builder 1 estimate	5%	$650.00	$19.26	$26.20	$1.20	Builder price, installation included
Manufacturer 1 estimate	14%	$1,518.75	$45.00	$28.38	$3.38	List price, 20% installation and markup assumed, upgraded coatings and spacer
Manufacturer 2 estimate	17%	$1,856.25	$55.00	$29.13	$4.13	Triple Glazing, LowE(2), Argon, undiscounted, 20% installation and markup assumed
Farese et al. 2011	20%	$973.44	$81.12	$30.07	$5.07	R-5 windows vs code minimum
National Residential Efficiency Measures Database (NREMD)	20%	$3,780.00	$112.00	$42.00	$7.00	Vinyl frames, installation included
NREMD	144%	$35,100.00	$1,040.00	$110.00	$65.00	Insulated vinyl frames, installation included
Expert 1 estimate	35%	$4,725.00	$140.00	$33.75	$8.75	Double pane to 1-3/8" argon filled triple pane
Expert 2 study	26%	$3,504.60	$103.84	$31.49	$6.49	Average for argon filled windows (sample of 2)
Expert 3 estimate	33%	$4,387.50	$130.00	$33.13	$8.13	Standard double pane to triple pane estimate
Builder 1 estimate	35%	$4,725.00	$140.00	$33.75	$8.75	Standard double pane to triple pane recollection based on an actual project
Builder 2 estimate	30%	$4,050.00	$120.00	$32.50	$7.50	Standard double pane to triple pane estimate. Estimated $1000/home as well, but window area is unknown.

Figure A6-2: Incremental cost of Triple Glazing; (Hendron, 2018)

It is clear from these and prior studies that market based data collection on pricing must be reviewed and interpreted carefully. It should also be correlated to a bottoms up energy cost analysis as a sanity check for the cost numbers reported.

Cost Estimates for Thin-Triple IGUs:
Excellent thermal performance is only relevant in the business world if the associated costs are reasonable. **An initial bottoms up cost analysis based on inputs from key industry supply partners has been promising, suggesting the overall manufacturing cost would add ~ $3/ft² to the IGU cost with a selling price that would be somewhat higher**.

The thin-triple requires three additional elements: a second low-E coating, krypton gas replacing argon and a layer of thin glass. In addition there will be some added cost for a spacer and the amortized cost of the automated line that assembles the IGUs with a low-loss gas fill system. The two most expensive elements are the thin glass and the krypton gas. In 2014 when an earlier cost estimate was made, the glass cost was ~ $5/ft² and the equivalent cost of krypton was ~ $2/ft², which when added to other materials and assembly costs would have pushed the total cost to well over $10/ft².

Markets have changed dramatically for the key components of a thin glass IGU. Current estimates with volume pricing are:

1. 0.7mm glass: ~$0.65/ft^2
2. krypton gas fill: ~ $0.50/ft^2
3. low-E coating: ~ $0.40/ft^2.
4. added IGU costs (spacer, sealant): ~ $0.20/ft^2
5. amortized cost of a high speed IGU assembly machine, including labor is estimated at less than ~ $0.50/ft^2.

Thus an OEM target incremental manufacturing cost of ~ $3.00/**ft^2 **may be achievable. Further exploration of these cost figures in the context of pricing out a low and high volume production scenario is an early goal of the project.

Appendix 7: Assessing Non-Energy Benefits: Windows and Thermal Comfort

Home owners care about their utility bills and efficiency investments that will lower those bills. In a house with thermally poor windows, those bills are reminders of poor performance only once a month when the bill arrives. But thermal discomfort is a direct outcome of use of conventional windows and they remind the homeowner on a daily basis that something needs to be done with their windows.

Unshaded windows may have comfort impacts in the cooling season; for this report we focus on thermal discomfort in winter with outdoor cold conditions. Thermally poor windows (old single glazing and conventional double glazing) and even some of today's code compliant windows create discomfort via two mechanisms. (Fig A7-1) First, since their surface temperature will be well below the indoor air temperature on a cold winter night a person standing next to such a window will experience the cold surface since due to the unbalanced radiant heat flow - from your warm body to the cold window. A secondary effect is that the cold surface of the glass cools the air adjacent to it, which then forms a plume or cold air current that descends to the floor and outward as a cold draft. The impact of both of these effects is a function of the type of glazing, the occupant's distance from the window, the size of the windows and the outdoor conditions.

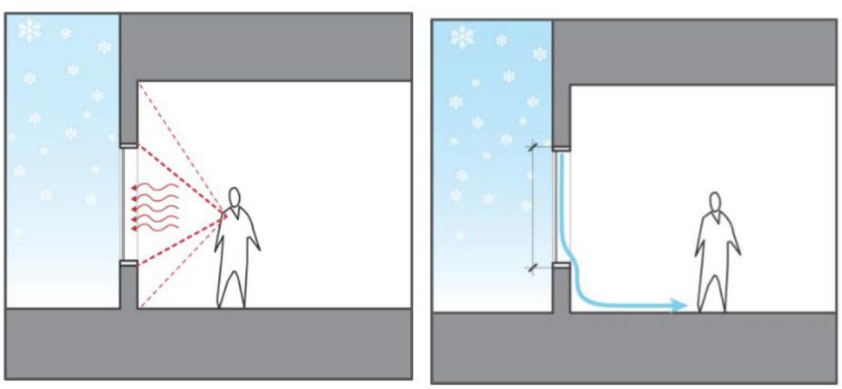


Figure A7.1: Two Sources of Window Thermal Discomfort
Left: Radiant effect on full body
Right: Down draft on ankles Source: EWC

Fig A7-2 below provides a graphic illustration of these effects for a living room with windows on two walls for a design day in Minneapolis. The dark color shows the location of the worst thermal comfort. It is clear that the triple glazed product provides comfort throughout the space, even with wall to wall windows on two sides of the room. These thermal effects are generally known to home owners. Translating these non-energy benefits into willingness to spend more for the thermally improved window is the challenge that remains.

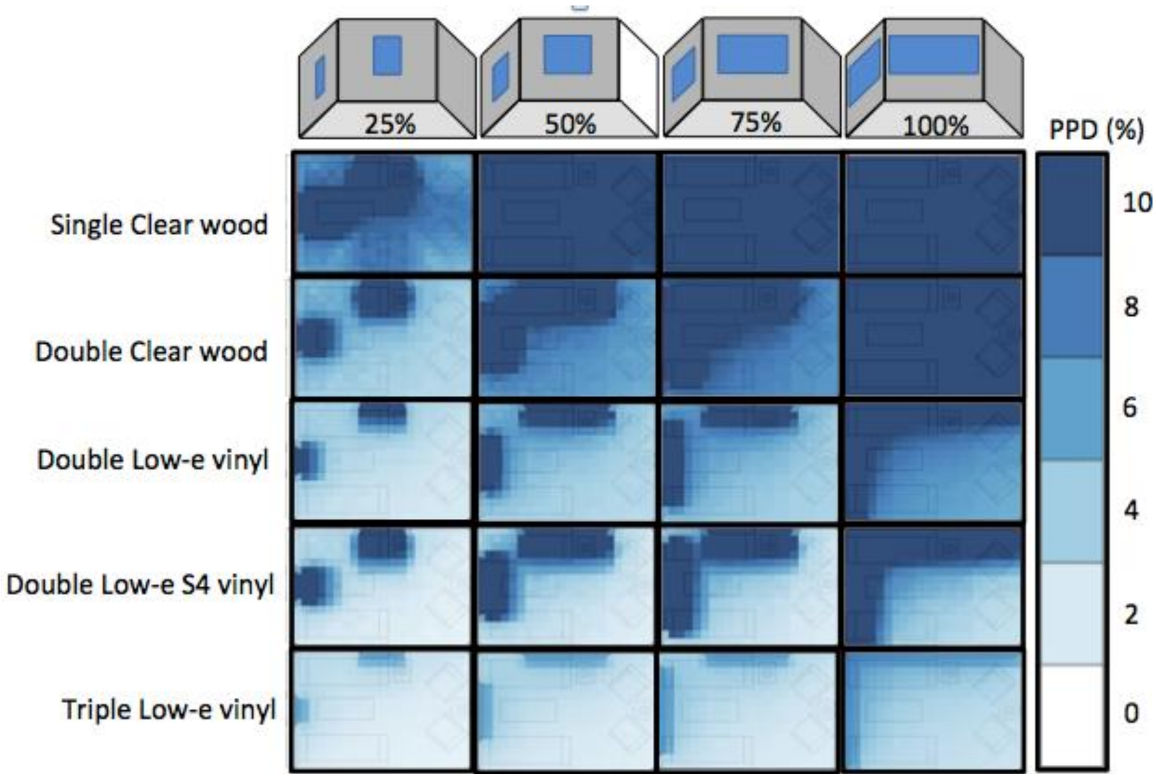


Fig: A7-2 Chart showing areas of discomfort in a room with windows on 2 walls, with 5 different glazing types as a function of window size (25% to 100%), in Minneapolis.(Source: R Hart, LBNL)