

Thin Triple Pane Windows – a View from the Field

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ABSTRACT

The U.S. Department of Energy (DOE) has supported the development of a thin triple-pane window that uses an ultra-thin center pane of glass with krypton gas fill to produce an insulated glass unit (IGU) with the same thickness and similar weight as a double-pane IGU, but with performance that can match many heavier, thicker, triple-pane windows. DOE funded the Pacific Northwest National Laboratory (PNNL) and research partners to identify and address technical and market barriers to wide-scale adoption by validating energy savings and other benefits associated with the thin-triple technology. Sample windows were evaluated at the PNNL Lab Homes, a matched pair of buildings on PNNL's campus in Richland, Washington, and more than a dozen demonstration sites around the country. This paper presents findings from these field validation studies including measurements of thermal performance, acoustics, temperature distribution throughout the home, and condensation potential on the window. Field observations related to cost, acquisition, and installation will also be discussed.

Introduction

Thermal transfer through the building envelope and associated air leakage makes up the largest HVAC loads in most climates, and windows alone are estimated to be responsible for approximately 10% of the building energy use (Hart et al. 2019), despite their proportionally small area. The U.S. Department of Energy (DOE) estimates a ~2 Quad energy savings potential by utilizing triple glazed windows at R-5 (U-0.20) to R-7 (U-0.14) performance in place of current residential building stock (Arasteh 2006). Typical triple-pane construction has been available since the early 1980's, but there have been limited market drivers for large scale adoption to date and triple-panes make up less than 3% of market sales. The conventional triple-pane insulated glass unit (IGU) is both heavier and about one-half inch thicker than the standard double-pane IGU, which necessitates a re-design of the standard frame and sash to accommodate the added weight and thickness of a conventional "thick-triple"; the associated costs pose barriers to producing triple pane windows at scale and are often cited as the primary barriers to broader market acceptance of the technology. Meanwhile, the standard double-pane low-E argon-filled window (~R-3 insulating value) dominates the U.S. residential market and is able to meet all current residential energy code requirements as well as most of the high-efficiency energy ratings (e.g., ENERGY STAR¹, Zero Energy Ready Homes) in the United States.

¹ In July 2021, U.S. Environmental Protection Agency (EPA) published Draft 1 Version 7 specification revision to the windows, which would propose to change the prescriptive U-Factor requirement in the Northern climate zone from ≤ 0.27 to ≤ 0.22 (specifications available online: https://www.energystar.gov/sites/default/files/asset/document/ES_Residential_WDS_Draft%202_Spec.pdf).

From the manufacturer's perspective, retooling their production lines to offer conventional thick triple glazing on a larger scale is costly, and risky without significant market demand for the product, so there are few market drivers for triple-pane cost-reducing refinements and broader market adoption (Selkowitz et al. 2018). As a technology solution, the thin-triple concept – made possible with an ultra-thin center pane of glass similar to a cell phone screen – is a “drop-in” replacement IGU using the existing double-pane frames and sashes that has the potential to reach very low U-factors; requires no significant investment in redesign on the part of the window manufacturer; is based on cost-effective market-ready new technology; and can be distributed via the existing industry supply chain.

To address the technical and market barriers to broader adoption of high-R windows, DOE has adopted a “supply-push and demand-pull” strategy where on the “supply-push” side, Lawrence Berkeley National Laboratory (LBNL) is partnering with energy efficiency organizations and manufacturers in the window industry to support technology innovations to reduce high-R window production costs. In coordination with LBNL's support of product innovation, Pacific Northwest National Laboratory (PNNL) is leading a complementary market-pull strategy centered on addressing barriers that are slowing the uptake of higher performance residential window technologies by engaging with construction industry stakeholders to identify and address market barriers to high-R windows, field test and validate emerging technologies, and feed back market-sustainable solutions to the identified challenges. This paper presents the findings from field validation studies of high-R thin-triple windows conducted in both PNNL's Lab Homes and at occupied field sites throughout the U.S.

Thin-glass IGU Technology

Multiple versions of the thin-glass triple-pane IGU have been developed, NFRC certified, and released into the market in the past 2 years with NFRC-certified windows now manufactured by such industry leaders as Alpen HPP, Andersen Corporation, and Ply Gem. In addition, Alpen HPP has provided IGU's to glaze into multiple product lines from additional manufacturers participating in demonstration projects of the technology. The most common construction approach with these units is shown in Figure 1 and consists of two spacers, a center glass thickness of 1.6 mm, and a mixture of Krypton and Argon gas as needed to meet specific thermal performance targets. The frames and exterior and interior glass panes used are identical to those in typical double-pane configurations, which is a primary goal of the thin triple-pane technology. These certified units are a first iteration of the technology and do not fully optimize the potential cost advantages associated with material choices and manufacturing processes and the expected economies of scale of the thin-glass technology (Hart, et. al. 2020).

Overall window heat transfer is characterized by U-factor ($\text{Btu/hr}\cdot\text{ft}^2\cdot\text{F}$), or its inverse R-value (resistance to heat flow). These properties account for the performance of the window construction (glass, spacer, sash/frame) and the air films on the indoor and outdoor surfaces. The thin-triple IGU approach has notable thermal improvement over current industry standard double-pane IGUs, while leaving room for significant future optimization of triple-pane window performance. The performance ranges for NFRC certified thin triple-pane fixed picture window available in today's market ranges from U-factor of 0.18 to 0.14, which is on par with standard triple panes (e.g., IGU width of 1 - 1.25 in.) and a significant performance improvement over the traditional double pane low-e fixed picture window, rated with U-factor of 0.30-0.27 (Hart et al. 2020).

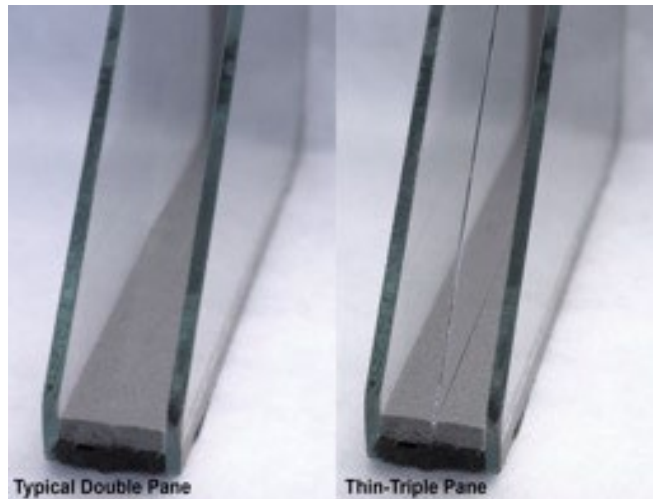


Figure 1. Thin-triple IGU technology utilizing thin glass as a non-structural center layer enables raising IGU thermal performance from R-5 to R-8 hr ft² °F/Btu. *Source:* LBNL.

Validating the Performance Thin Triple-Pane Windows in the Field

Based on the observed technical and market barriers, as well as the existing market structure and potential consumer benefits of high-performance triple-pane windows, a series of field validation demonstrations and studies were designed to address market barriers and validate the benefits of thin triple-pane technology. The selection of experimental studies and field-testing sites was based on the energy savings potential (as described in Hart et al 2019) and market assessments (Cort and Gilbride 2019), which were informed by interviews conducted with industry partners and builders of high-performance homes (Gilbride et al. 2019). Table 1 summarizes a series of some of the key experimental questions and topics that were examined in these studies.

Table 1. Experimental Questions and Field Validation Studies (Source: Cort and Gilbride 2019)

Experimental Questions/Topics	Validation Study Approach
How much energy do thin triple-panes save when compared to double pane clear glass windows?	Side-by-side PNNL Lab Homes study.
Are there peak demand savings and grid benefits associated with the energy savings from thin triple-pane windows?	PNNL Lab Homes daily savings profiles.
Are thin triple-pane IGUs “drop-in” feasible with multiple brands of double-pane frames/sashes?	Combine Alpen IGUs with multiple vendors’ frames and sashes and demonstrate in the field.
Are thin triple-pane windows cost-effective for new construction and/or retrofit applications?	Quantify benefits and costs through life-cycle analyses based on field testing and energy simulation results.
What co-benefits are associated with the installation of thin triple-pane windows?	Characterize comfort, condensation, and noise benefits. Follow-up case studies with selected high-performance builders to characterize benefits in field.

Field Testing Platforms

To answer the range of experimental questions described in Table 1, field studies were planned for both a controlled Lab Homes testing platform as well as in occupied home field sites across the U.S.

PNNL Lab Homes. The 1,500-square-foot Lab Homes are identical in construction, baseline performance and operation, which allows any difference in performance between the “control” and “experimental” homes to be attributed only to the thin triple-pane windows. Each lab home contains nine double pane clear glass aluminum-framed windows (seven operable windows and two sliding glass doors) totaling approximately 196 ft² of surface area, approximately 20 % window to wall ratio. The fenestration load for the homes is largely influenced by the five south- or west-facing windows (which include the two 72-inch x 80-inch sliding glass doors). Figures 2 and 3 show an exterior view of the two buildings and a floor plan with windows highlighted, respectively. Figure 3 shows the home layout, home orientation, and window dimensions at each lab home. The PNNL Lab Homes are located on PNNL’s Richland, Washington campus, which is in Southeastern Washington state at 384 ft above sea level in climate zone 5B. The city of Richland has slightly lower temperatures than the US average with above average sunshine in mid to late summer (see Figure 4). In 2012, these PNNL Lab Homes were used to examine the side-by-side performance of conventional vinyl-framed triple-pane windows with 1-inch thick IGUs (Widder et al. 2012). Apart from the design and overall thickness of the triple-pane windows, the 2019-2020 Lab Home study tested thin triple-pane windows using similar protocols and evaluation processes.

The homes are all-electric and an underfloor ductwork distributes heating from a 15 kW single-stage furnace and cooling from a 13 SEER single-stage A/C, both controlled with an Ecobee 4 Smart Thermostat set to 75°F with a dead band of 0.5°F and a minimum run-time of 5 minutes. Homes were kept dark and no additional internal loads were generated during testing.



Figure 2. PNNL Lab Homes with conventional double pane windows (left) and thin triple pane windows (right).

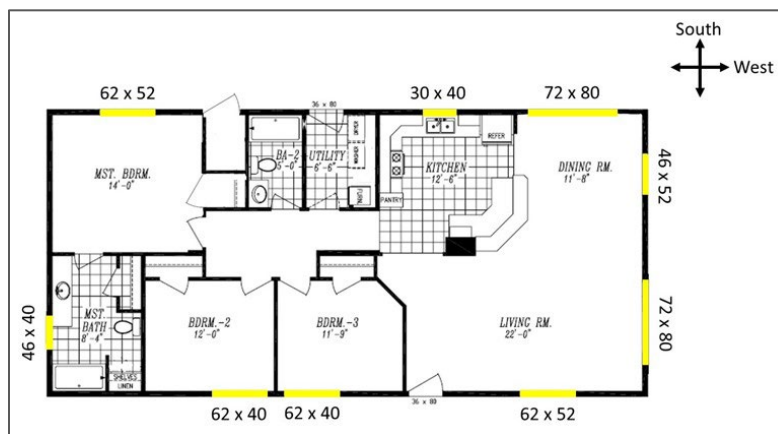


Figure 3. Window and Home Layout at the PNNL Lab Homes

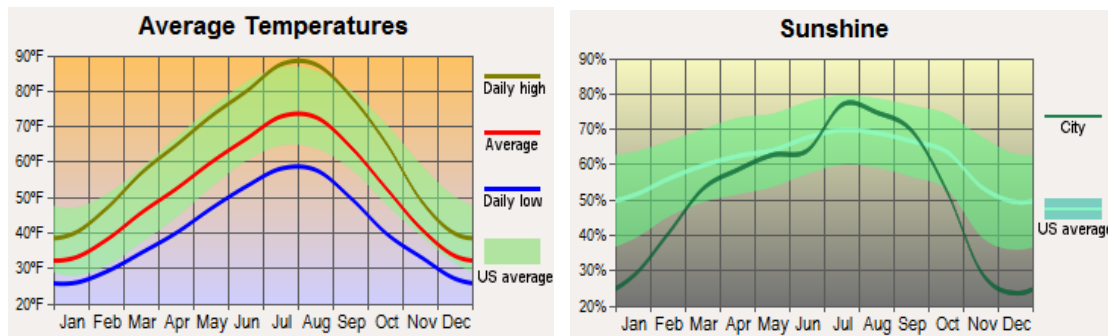


Figure 4. Average temperature and sunshine profiles for PNNL Lab Homes (*Source: City-Data²*)

Case Studies. Field-testing protocols were also developed for occupied homes at field sites throughout the country. Candidate homes were enrolled by recruiting local builders with projects

² <http://www.city-data.com/city/Richland-Washington.html>.

that met the criteria developed based on findings from a related market analysis (Gilbride et al. 2019) and program planning efforts (Cort and Gilbride 2019). These early research efforts called for a sampling of new and existing single-family, multi-family, and manufactured homes to evaluate the range of thin triple-pane applications and associated benefits and installation costs. All field-testing recruitment was completed in 2019 and thin triple-pane windows have been installed in 14 build sites across the country (7 newbuilds and 7 existing home retrofits – see Figure 5). In addition to thin triple-pane field test sites, parallel studies included one thin quadruple-pane window case study in a new build site in Anacortes, Washington, and a conventional triple-pane evaluation in collaboration with the Home Performance with ENERGY STAR program in a single-family retrofit home in St. Joseph, Michigan.



Figure 5. Locations of Current and Planned High-R Window Field Demonstration Sites

Findings from Lab Homes and Occupied Field Sites

Thin triple-pane windows manufactured by Alpen HPP were evaluated in the PNNL Lab Homes during the 2019-2020 winter heating season and then again during the 2020 summer cooling season. One Lab Home contained a complete test set of nine thin triple-pane windows, while the other Lab Home contained the same number, size, and location of baseline double-pane windows. The experimental design isolated the windows as the single difference between the two Lab Homes.

In addition to the Lab Homes testing, thin triple-panes are currently being evaluated in fully instrumented occupied home field sites. Monitoring and data collection at the occupied field sites is ongoing, but the installation process at the 14 sites provided valuable insights regarding the market potential of thin triple-pane windows. The following field study findings address the key questions identified in Table 1.

1. **How much energy do thin triple-panes save when compared to double-pane clear glass windows?**

To consider the HVAC savings associated with the examined thin triple windows, results from the twin lab homes on the PNNL campus are presented in Table 2 as both a range of daily savings and an average daily savings across the data collection periods for both the heating and cooling seasons. In addition, daily HVAC savings from both a kWh savings and a percent savings perspective are presented in subsequent figures for heating and cooling seasons.

Table 2. Daily HVAC Energy Savings with Thin Triple-Pane Windows

Metrics for the reporting period		Winter Heating Season	Summer Cooling Season
DATES ³	Start	1/18/2020	6/20 /2020
	End	3/23/3030	7/20/2020
AVG	Outdoor temperature, °F	43 °F	78 °F
	Solar Irradiance, W/m2	66.5 W/m ²	276 W/m ³
	Daily energy savings, percent	12%	27%
	Daily energy savings, kWh	7.8 kWh	5.3 kWh
RANGE	Average Daily Outdoor temperature, °F	33 - 55 °F	71 - 83 °F
	Solar Irradiance, W/m2	5 - 154 W/m2	107 - 324 W/m2
	Daily energy savings, percent	3% to 18%	23% to 41%
	Daily energy savings, kWh	0.2 to 18.7 kWh	2.5 to 8 kWh

The overall savings of the thin triple-pane windows were found to be similar to those achieved by conventional 1-inch think IGUs, which were tested against the same baseline windows in the Lab Homes in 2012 (Widder et al. 2012). Daily HVAC savings associated with the thin triples varies based on both the outdoor temperature and outdoor solar irradiance.

For the cooling season, the daily HVAC savings varied from 2.5 to 8.0 kWh and solar irradiance was generally uniform across the data collection period. During the cooling season, the reduced temperature-driven heat transfer and the reduced solar radiation-driven heat transfer of the thin triple-pane windows provided an energy-savings benefit. (Hunt et al. 2021).

For the heating season, the daily HVAC savings varied from 0.2 to 18.7 kWh, or approximately 3% to 18% on the days evaluated (see Figure 6). The highest daily HVAC savings for heating season were observed on test days with minimal solar irradiance (i.e., heavy cloud cover). During the heating season, increased solar radiation heat transfer is an energy benefit during the daytime as it offsets the temperature-driven heat transfer and the overall heating load. On heating test days with high solar irradiance, the HVAC savings observed with the thin triples was lower due to this energy tradeoff.

³ Heating test days included 1/18-1/19, 1/22-1/30, 2/1-2/11, 2/13-2/17, 2/22-2/25, 2/27-3/1, 3/6-3/8, 3/18-3/23. Cooling test days included 6/20-7/1, 7/18-7/20, 7/22-7/23.

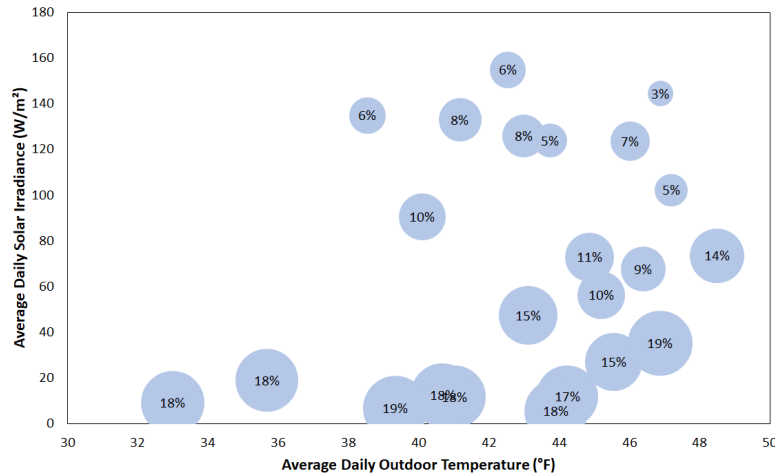


Figure 6. Heating Season Daily HVAC Savings (kWh)
for Thin Triple-Pane Windows

2. Are there peak demand savings and grid benefits associated with the energy savings from thin triple-pane windows?

Electrical load shapes for the HVAC system were evaluated in the Lab Homes study and were developed for the heating and cooling seasons. Figure 7 provides a comparison of the HVAC load shapes for the “Baseline Home” and “Thin Triple-Pane Lab Home” for heating season period. Highest energy use during the winter heating season is typically during cold overnight temperatures. Figure 7 shows the hourly peak HVAC power demand during the heating season occurred at the Lab Homes at ~6 AM. During the cold, early morning hours, the thin triple-pane windows offered improved thermal resistance, significantly reducing energy use compared to the baseline double pane windows, with an average HVAC peak power reduction of approximately 17% (~650 W) (Hunt et al. 2021). This timing of the peak savings is coincident with electric system peaks for the region, suggesting that grid system benefits could be realized with largescale use of triple-pane windows. In addition, triple-pane windows could help reduce the auxiliary resistance heat needed by heat pumps during the morning hours when the home is heating up, as the savings are concentrated during this same time period.

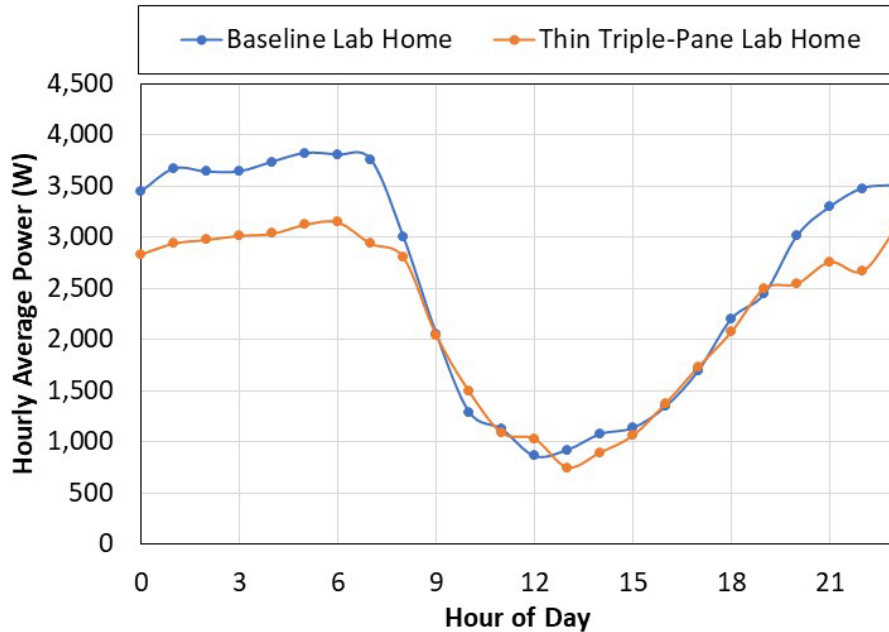


Figure 7. Heating season HVAC Load Shapes for the Baseline and Thin Triple-Pane Lab Homes (average). *Source: Hunt et al. 2021.*

For the cooling season period, Figure 8 illustrates the peak flattening effect that triple-pane windows have on the HVAC load during the hours of noon to 6 PM. An average HVAC peak power reduction of approximately 33% (~1,200 W) was observed for the Thin Triple-Pane Lab Home compared to the Baseline Lab Home during the cooling season (Hunt et al 2021). The well-timed energy savings offered by triple-pane windows could help grid operators manage the power balance challenges associated with a transmission network that includes high amounts of variable renewable power generation, especially solar photovoltaics (PV) which only produce energy during sunlight hours. PV generation tailing off coincides with increased residential demand as families return home and begin to use ore electricity such as cooking, cleaning, use of electronics in the evening. Regions where solar electricity generation makes up a larger proportion of grid-transmitted electricity experience the challenge of the “duck curve” power profiles (Figure 9), triple-pane windows can shorten the “neck” of the duck by reducing power consumption just as PV power is dropping (between 4pm and 6pm in particular).

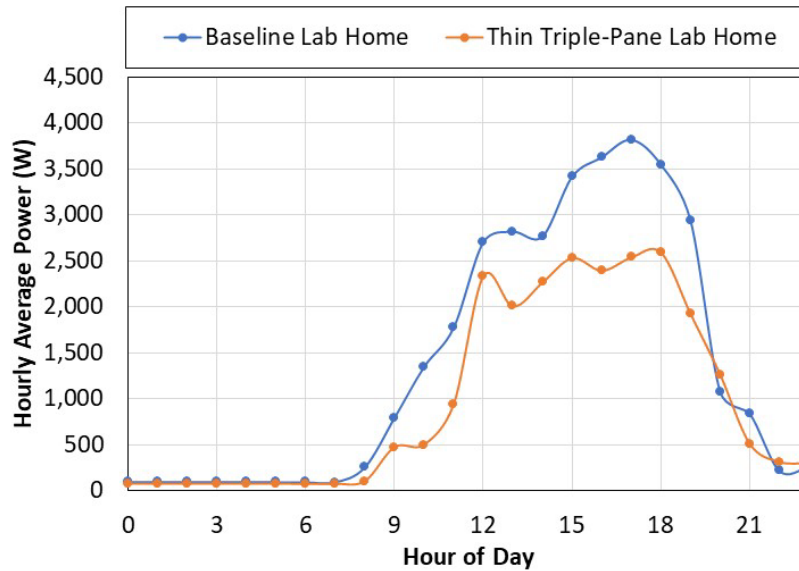


Figure 8. Cooling Season HVAC Load Shapes for the Baseline and Thin Triple-Pane Lab Homes. Source: Hunt et al. 2021.

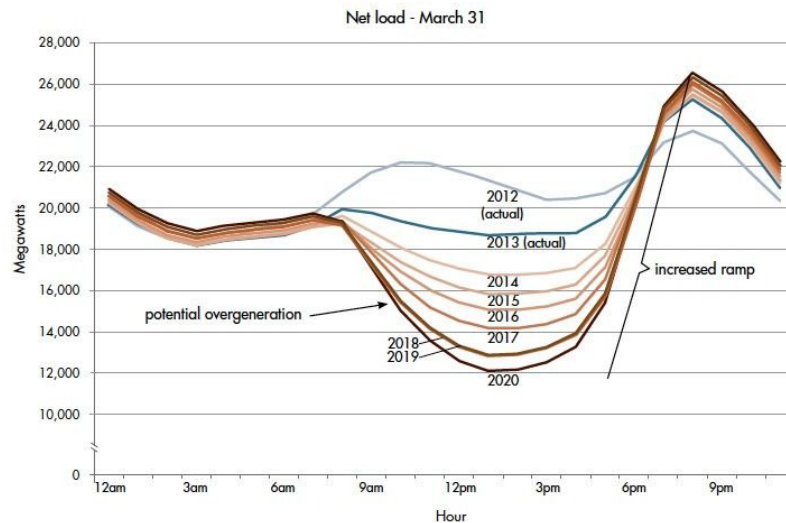


Figure 9. The “duck curve” Source: Office of Energy Efficiency & Renewable Energy⁴

3. Are thin triple-pane IGUs “drop-in” feasible with multiple brands of double-pane frames/sashes?

While Alpen HPP was the sole manufacturer of the thin triple-pane IGUs in the study, the research protocol ensured a variety of IGU/frame pairings. As previously discussed, the ability to “drop-in” a higher performing IGU into a standard double-pane frame has the potential to reduce production costs of high-performance triple pane technology as well as increase the options for window retrofits. This approach was validated with two different orders of thin-triple IGUs sent

⁴ Accessed from: <https://www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy>.

to window manufacturers who did not themselves have an existing process to produce thin-pane insulated glass units using thin glass as the center pane. Instead, they installed the “thin triple” IGUs provided by Alpen HPP into their own proprietary double-pane vinyl frames. These hybrid windows were installed in two different field demonstration homes, both new construction – one in Minnesota and one in New York (see Figure 10). To demonstrate this approach as a field modification, two separate orders of thin triple IGUs were glazed into *existing* vinyl double-pane windows in a single-family home in California and in four similar manufactured rental homes in Washington state (see Figure 11). Replacement of IGUs in the field is a standard practice well-known to window installers and typically takes less than half the time as a full window replacement.

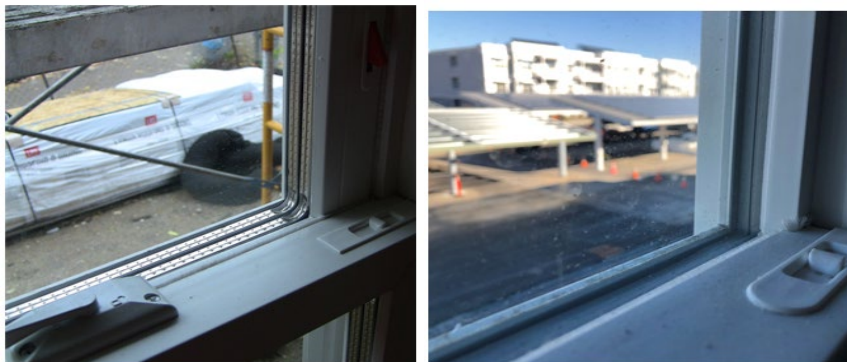


Figure 10. Left: Thin triple windows with vinyl frames and stainless steel spacers are installed in a new home site (Twin Cities, MN). Right: Thin triple with vinyl frames and a foam spacer are installed in a new home site (Rotterdam, NY).

4. Are thin triple-pane windows cost-effective for new construction and/or retrofit applications?

When lower cost vinyl frames were used, the tested thin triple-pane windows were manufactured and delivered for an incremental cost of \$6/s.f. relative to the double-pane equivalent window, which is a potentially cost-effective price point. Further, installers found the windows as easy to install as double-panes; thus, no installation cost premium was associated with the thin triple-pane window. However, there were a number of factors identified that could potentially hinder cost reduction goals including the rising cost of krypton and the limited scale of production, which slows down delivery and replacement time when needed.

One particularly cost-effective retrofit application was validated in the mobile home site in Pasco, Washington, where 4 manufactured homes with vinyl double-pane windows (with roughly a U-factor of 0.45) were retrofit with thin triple-pane IGU. Because the frames were in reasonable condition, only the IGUs were replaced with a thin triple-pane version, which reduced the whole window U-factor to ~0.20 (see Figure 11). Both the lower material cost and lower labor expense reduced the cost of this retrofit to less than half of the cost of a full window replacement.



Figure 11. Thin triple-pane IGUs glazed into existing double-pane vinyl frames (Pasco, WA).

5. What co-benefits are associated with the installation of thin triple-pane windows?

For the retrofit homes, significant differences in interior surface temperatures on and near the window were logged at multiple field sites, which resulted in noticeable comfort improvements to the home occupants. In the Lab Homes study, during the winter season the home with thin triple-pane windows experienced 2°F warmer room temperatures than the home with double panes and temperatures were much more evenly distributed throughout the home. The thin triple-panes also noticeably reduced the condensation on the interior surface of the window in homes that had experienced significant condensation buildup before the retrofit. Figure 12 shows the condensation and ice buildup on an existing home site window before the retrofit. After the retrofit, the condensation was limited to only the coldest evenings and no icing has occurred since the retrofit.

Sound infiltration was examined at the Lab Homes using a set of sound meters and a sound generator at 90 dB and three frequency levels. The windows in the Thin Triple-Pane Lab Home demonstrated a reduced sound infiltration of 8 dB to 10 dB over the baseline double-pane windows in the Baseline Lab Homes. It has been established that a 6 dB to 10 dB reduction in sound level generally results in an individual's perception of sound being reduced by half (Warren 1973).



Figure 12. Left: Condensation and ice buildup on interior surface of Helena, MT field site (double-pane windows, vinyl frame). Right: Same window location after replacement with the thin triple pane window (fiberglass frame). Both photos are taken in March 2021 at a similar time of day, but outdoor and indoor conditions vary between photos.

Conclusion

The Lab Homes experiments demonstrated that replacing clear glass double-pane windows with thin triple-pane windows provides year-round energy savings and reduces peak demand both in the heating and cooling seasons. Both the Lab Homes experiments and field testing also validated other performance benefits of the thin triple-pane windows including reduced condensation potential, more even temperatures throughout the home and near the windows, and reduced sound attenuation through the windows, leaving the home quieter and more comfortable for the occupants. Field demonstrations also validated the feasibility of dropping in thin triple-pane IGUs into lower-cost double-pane frames, providing triple-pane performance at a more competitive price point. The thin triple-pane IGU technology has the potential to help address market barriers that have hindered market uptake of higher performance triple-pane windows.

Because thin triple-pane technology has not fully entered the marketplace, these windows were all custom-manufactured; pricing is considered reasonable, but not necessarily reflective of final industry targets. Due to strong energy and acoustic performance and the uniform lack of constructability challenges, thin triple-pane windows should be explored further with respect to pricing and market adoption opportunities. The U.S. Department of Energy (DOE) has joined forces with regional energy efficiency alliances and national labs to launch the Partnership for Advanced Window Solutions (PAWS) to continue work on market maturation to scale the adoption of this technology. As ENERGY STAR and other home energy rating and labeling programs move toward advancing window performance specifications, the increased availability of affordable high-performance window products could help move the residential sector toward meeting nationwide decarbonization goals.

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