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PNNL-31165

Evaluation of Thin Triple-Pane Windows in the PNNL Lab Homes

April 2021

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U.S. DEPARTMENT OF ENERGY

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

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Richland, Washington 99354

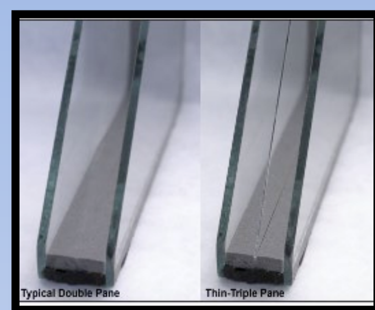
Summary

Heat transfer through windows accounts for a significant percentage of a building's energy use and adds substantially to the peak cooling load of a home. In recent years, improvements in glass manufacturing have enabled the production of thin triple-pane windows, which are manufactured with a thickness similar to standard double-pane windows. Because this highly insulating "thin triple" glass product can be incorporated into almost any existing window frame and can be fabricated at a modest added cost, the U.S. Department of Energy is sponsoring laboratory and field demonstration testing of thin triple-pane windows to validate thermal performance and installation requirements in real-life field settings.

To examine the performance of thin triple-pane windows, the Pacific Northwest National Laboratory (PNNL) evaluated the windows at the PNNL Lab Homes, a matched pair of homes located on PNNL's campus in Richland, Washington. In this study, one Lab Home contained a complete set of nine thin triple-pane windows, while the other Lab Home contained baseline double-pane windows. The experimental design isolated the windows as the primary difference between the two Lab Homes. The experimental results include a comparison of heating, ventilation, and air-conditioning (HVAC) energy usage, condensation potential, occupant comfort, sound infiltration, and thermal performance.

HVAC energy savings with the thin triple-pane windows varied daily across the heating and cooling season based on the outdoor temperature and solar irradiance. Across the experimental test days, the daily HVAC savings ranged from 0.2 to 18.7 kWh (3%–18%) for heating season data collection and from 2.5 to 8.0 kWh (23%–41%) for cooling season data collection. The higher thermal performance of the thin triple-pane windows also reduced the condensation potential on the interior surface during winter months and provided more even distribution of temperatures throughout the home in comparison to the Baseline Home. In addition to the added thermal performance, the thin triple-pane windows demonstrated significant acoustic benefits, reducing sound infiltration by 8 dB to 10 dB over the baseline double-pane windows at the Lab Homes.

Technology:
The thin-glass triple-pane insulated glass unit allows for performance of R-5 (U-factor 0.20) or better.



Application:
New and existing homes where the Lab Homes testing platform provides validation of:

- existing single-family and/or manufactured home
- full-frame window replacement of double-pane clear glass aluminum-frame windows.

Whole Home Energy Savings:

- Heating savings (Daily HVAC): 0.2 kWh–18.7 kWh (3%–18%, average 12% over testing period operating conditions)
- Cooling savings (Daily HVAC): 2.5–8.0 kWh (23%–41%, average of 28% over testing period operating conditions)
- Annualized HVAC savings (based on energy simulations): 18.6%

Other Benefits:
Validation of non-energy benefits included:

- reduced utility costs for homeowner
- increased occupant comfort
- decreased condensation potential on window
- noise reduction.

Acknowledgments

The PNNL research team would like to acknowledge Craig Maierhofer of Alpen Windows for support in the procurement of thin triple-pane windows examined at the PNNL Lab Homes and Greg Sullivan of Efficiency Solutions for capturing thermal images of the thin triple-pane windows at the Lab Homes. We would also like to thank Yan Chen and Karthikeya Devaprasad of PNNL for simulating the energy use of the Lab Homes to calculate annual energy savings from the application of thin triple-pane windows. Thanks also to Edward Louie of PNNL for providing a technical review of the report.

Acronyms and Abbreviations

dB	decibels
DOE	U.S. Department of Energy
F	Fahrenheit
Hz	Hertz
IGU	insulated glass unit
HVAC	heating, ventilation, and air-conditioning
kW	kilowatt
kWh	kilowatt hour
LBNL	Lawrence Berkeley National Laboratory
NFRC	National Fenestration Rating Council
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
PV	photovoltaics
R&D	research and development
SHGC	solar heat gain coefficient
SEER	Seasonal Energy Efficiency Ratio
TMY	Typical Meteorological Year

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1.0 Introduction

Heat transfer through windows is a significant contributor to a building's thermal load and the associated heating, ventilation, and air-conditioning (HVAC) energy usage. There are a variety of measures that can improve the thermal performance of windows for residential applications. One measure includes expanding the double-pane window design to a triple-pane window design, which improves the insulating properties (i.e., U-factor) of the insulated glass unit (IGU). Triple-pane windows have been commercially available for many years and are often considered in high-performance residential applications and home designs. Compared to a standard double-pane window, conventional triple-pane windows have been characterized by a thicker IGU. The added weight and thickness of the IGU with conventional triple-pane windows increases installation cost and complexity in both new and retrofit applications. In recent years, improvements in glass manufacturing have enabled the production of thin triple-pane windows, which are manufactured with a thickness similar to double-pane windows. To examine their performance, the Pacific Northwest National Laboratory (PNNL) evaluated thin triple-pane windows at the PNNL Lab Homes, a matched pair of homes located on PNNL's campus in Richland, Washington. In this study, one Lab Home contained a complete set of nine thin triple-pane windows, while the other Lab Home contained baseline double-pane windows. The experimental design isolated the windows as the primary difference between the two Lab Homes. The experimental results include a comparison of HVAC energy usage, condensation potential, occupant comfort, sound infiltration, and thermal performance.

2.0 Background

The triple-pane residential window has been a viable technology since the early 1980s and a typical triple-pane window today has an insulating value in the range of R4 to R6 (i.e., U-factors of 0.22 to 0.17)[1]. The conventional triple-pane IGU is both heavier and about one-half inch thicker than the standard double-pane IGU, which necessitates a redesign of the standard frame and sash to accommodate the added weight and width. The added weight and thickness, and the associated costs pose barriers to producing triple-pane windows at scale and are often cited as the primary barriers to broader market acceptance of the technology. Meanwhile, the standard double-pane low-E argon-filled window (~R3 insulating value) dominates the U.S. residential market and is able to meet all residential energy code requirements as well as most of the high-efficiency energy ratings (e.g., ENERGY STAR, Zero Energy Ready Homes) in the United States. As a result, double-pane low-e windows make up more than 80% of window sales, while triple-pane windows make up about 2% of window sales with little growth in the market share over the past decade (Cort and Gilbride 2019).

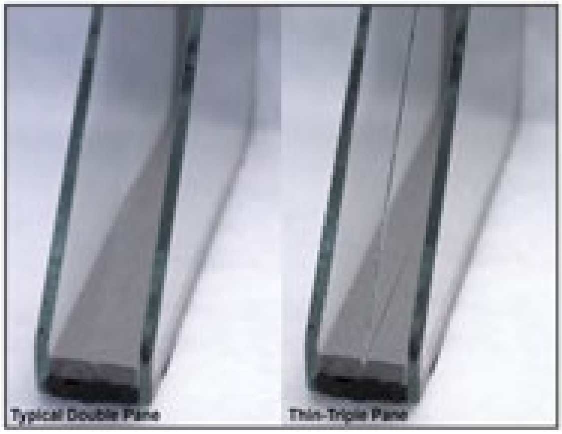
2.1 Thin Triple-Pane Window Technology

To address this stagnation in both the innovation and residential market uptake of the highest performance windows, the U.S. Department of Energy (DOE) has undertaken a series of research and development (R&D) efforts to address installation and market barriers related to the state-of-the-art "conventional" triple-pane windows. In particular, Lawrence Berkeley National Laboratory (LBNL) has focused R&D efforts on reducing the incremental cost between double-pane and triple-pane windows while addressing technical issues related to the weight and width of triple-pane windows, which pose significant market barriers and drive up the cost of triple-pane windows. The thin triple-pane "drop-in" replacement IGU is a high-performance technology that does not require significant investment or redesign on the part of the window manufacturer, because the thinner IGU can "drop-in" to the conventional double-pane frames and can be supplied via the existing industry supply chain.

Thin triple-pane IGUs (Figure 1) use two ordinary-thickness (1/8-inch) layers of glass sandwiching a thin (1/16-inch) layer of glass with a 9/32-inch gap on either side of the thin glass that is filled with krypton. Together, these glazing components result in a thin triple-pane IGU measuring 7/8 inch thick, the same thickness as a double-glazed unit.[2]

[1] Where R-value = $hr\ ft^2\ F\ BTU^{-1}$ and the U-factor = $BTU\ hr^{-1}\ ft^{-2}\ F^{-1}$.

[2] The IGUs in the two 72 x 80 inch sliding patio doors were also 7/8 inch thick however the center pane utilized a stretched heat mirror film instead of a pane of thin glass due to the size limitations of thin glass.



The thin-glass triple-pane IGU allows for R-5 (U–0.20) or better insulating performance using a combination of thin glass (0.7–1.6 mm) for the center layer, 2 low-e coatings and krypton gas fill.

Figure 1. Thin Triple "Drop-In" IGU Technology

2.2 PNNL Lab Homes

The PNNL Lab Homes (Figure 2) are side-by-side homes located on the PNNL campus in Richland, Washington, and serve as a residential buildings research platform. One home serves as the Experimental Lab Home, and the other as the Baseline Lab Home. The Experimental Lab Home is used to evaluate emerging residential technologies and control strategies, while the Baseline Lab Home serves as an untouched baseline comparison. This research platform is used to examine technologies from the perspective of existing U.S single-family residences. Each home contains a central, 13 SEER air-conditioner with comparable ductwork. Envelope air leakage and duct leakage are regularly evaluated at the Lab Homes to make sure levels remain comparable in the two homes. The Lab Homes contain nine windows—three south-facing windows and two west-facing windows. One of the south-facing windows and one of the west-facing windows are sliding glass doors. For this study, the Experimental Lab Home contained the thin triple-pane windows, and the Experimental Lab Home is referred to as the Thin Triple-Pane Lab Home throughout the report.

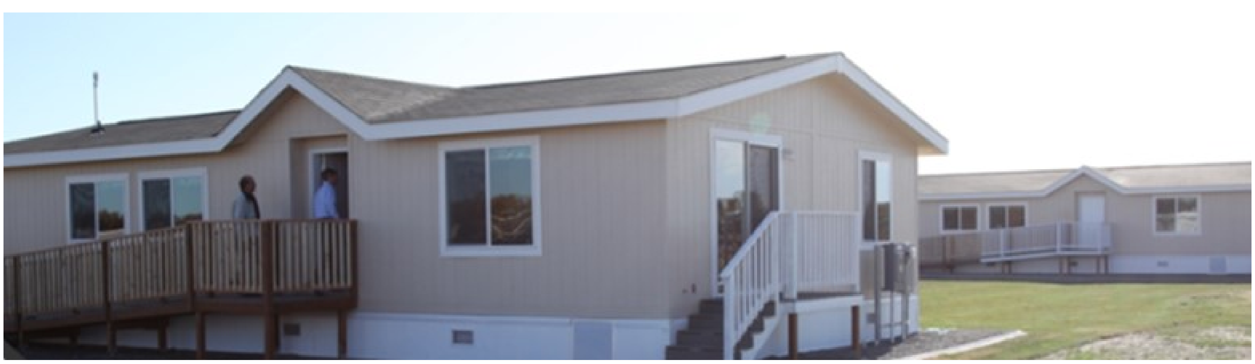


Figure 2. Side-by-Side PNNL Lab Homes

2.3 Related PNNL Lab Home Studies

In 2012, the PNNL Lab Homes were used to examine the performance of conventional vinyl-framed triple-pane windows with 1-inch thick IGUs, which was compared to the performance of clear glass double-pane windows with aluminum frames (Widder et al. 2012). Apart from the design and overall thickness of the triple-pane windows, the 2012 Lab Home evaluation of traditional triple-pane windows is comparable to the Lab Home evaluation of thin triple-pane windows. The Baseline Lab Home's overall building envelope and the double-pane windows used for both the 2012 and 2021 Lab Home studies are identical. The triple-pane windows examined in the 2012 Lab Home study were designed with a U-factor and a Solar Heat Gain Coefficient (SHGC) of 0.20 and 0.19, respectively, while the thin triple-pane windows examined in this study were designed with a U-factor of 0.19 and a SHGC of 0.26 to 0.27, respectively. The traditional triple-pane window evaluation at the PNNL Lab Homes included a heat pump for space heating and an internal heat gain load generated by electric heaters. In contrast, the thin triple-pane evaluation included an electric resistance furnace for space heating and no internal heat gain generation. These differences are largely attributed to best practices developed over the years by the PNNL research team to allow for the most reliable and repeatable operation of the PNNL Lab Homes for experimental evaluations.

2.4 Other Related Research

Table 1 summarizes findings related to energy savings from recent case studies, energy simulations, and field studies. Most recently, LBNL completed a series of energy simulation studies focused on assessing the energy-savings potential of thin triple-pane windows in comparison to the “typical” residential window stock. The study demonstrated that, because of improvements in U-factor and other performance metrics, thin triple-pane windows have the potential to cut energy use in residential buildings by 16% compared to typical double-pane low-e windows in heating-dominated climates such as that of Minneapolis, Minnesota, 12% in mixed climates such as that of Washington, D.C., and 7% in cooling-dominated climates such as that of Houston, Texas (Hart et al. 2019). Both experimental Lab Homes studies are located in Richland, Washington, which is a “Cool Dry” climate zone (i.e., 5B) based on the International Energy Conservation Code climate zone map.

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

Study	Sponsor	Baseline Description	Findings
LBNL study of energy simulated savings potential of thin triple glazing (Hart et al. 2019))	DOE	Typical windows based on NFRC-certified products	• 16% annual savings in heating-dominated climates • 12% annual savings in mixed climates • 7% annual savings in cooling-dominated climates
Infrared camera imaging of thin triple-pane windows (Hart et al. 2020)	DOE, LBNL, CEC	Double-pane, low-E, vinyl-framed windows	Replaced double-pane IGUs with thin triple-panes. Images show thermal improvements in windows with thin triple-pane IGUs.
PNNL Lab Homes side-by-side triple-pane study (Widder et al. 2012)	DOE	Double-pane, clear glass, aluminum-framed windows	• 12% annual savings in Richland, Washington • 11.6% heating savings/18.4% cooling savings
Windows state-of-the-art thermal performance comparison by the Norwegian University of Science and Technology [NTNU] and LBNL (Jelle et al. 2011)	NTNU, DOE, Research Council of Norway	Various products delineated by U-values (glass, framing material)	• Thin triple (with a stretched film center pane) and aerogel glazing had the lowest center of glass U-value of 0.28 and 0.30 $W/m^{2-°}K$, respectively. • Commercially available vacuum-insulated glass has a center of glass U-value of 0.70 $W/m^{2-°}K$.

CEC = California Energy Commission; IGU = insulated glazing unit; NFRC = National Fenestration Rating Council; NTNU = Norwegian University of Science and Technology.

3.0 Experimental Setup

This chapter contains details of the experimental setup for the thin triple-pane window evaluation at the PNNL Lab Homes. It describes the window and home layout of the PNNL Lab Homes, designed characteristics of the examined baseline and thin triple-pane windows, operation of the Lab Homes during the study, data collection and instrumentation utilized, a strategy for examining sound infiltration, and baselining approaches for the study.

3.1 Window Layout of PNNL Lab Homes

The PNNL Lab Homes consist of two side-by-side identical 1,500 ft^2 homes with three bedrooms and two bathrooms. Each home contains nine windows (seven operable windows and two sliding glass doors) totaling approximately 196 ft^2 of surface area. The fenestration load at 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). Figure 3 shows the home layout, home orientation, and window dimensions at each of the PNNL Lab Homes.

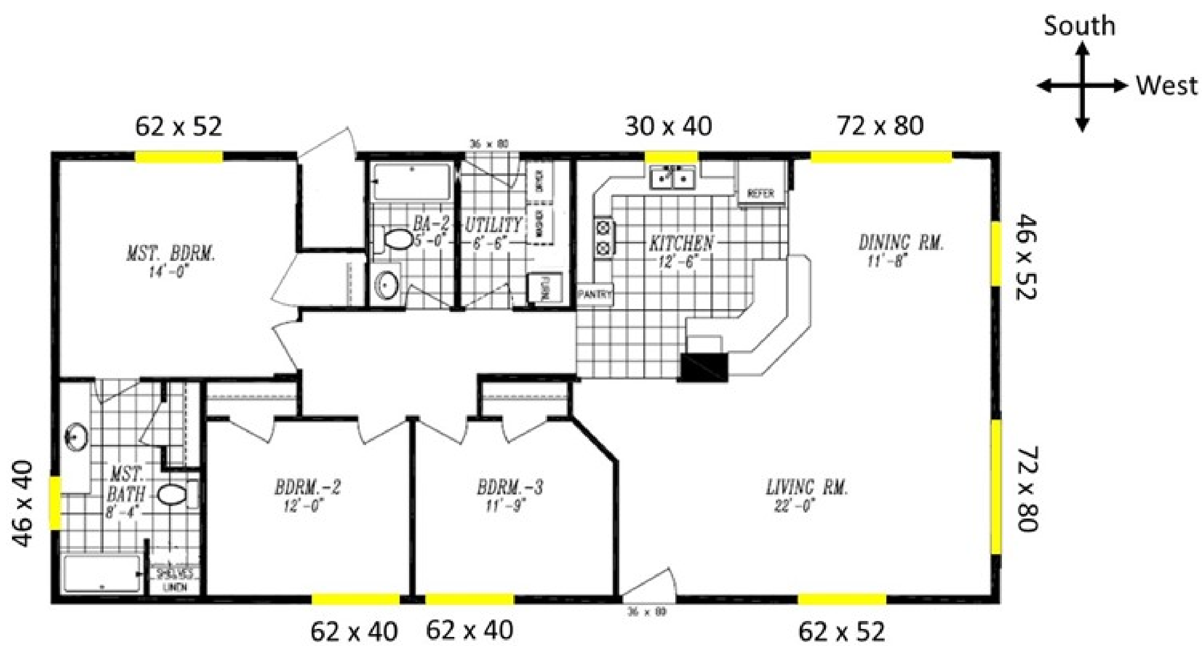


Figure 3. Window and Home Layout at the PNNL Lab Homes

3.2 Baseline and Thin Triple-Pane Window Characteristics

During this study, the Baseline Lab Home contained double-pane, aluminum frame, clear glass windows, while the Experimental Lab Home contained thin triple-pane low-e windows with fiberglass extruded insulated frames. Table 2 provides the full-frame National Fenestration Rating Council (NFRC) U-factor and SHGC for the baseline and thin triple-pane windows. The thin triple-pane windows have improved insulation, reducing heat transfer caused by a thermal gradient, and an improved SHGC, reducing heat transfer from solar radiation. Multiple values are provided for the U-factor and SHGC where applicable because the window properties varied slightly based on the window sizes at the Lab Homes and the manufacturer design.

Table 2. Product Design of Baseline and Thin Triple-Pane Windows

	Baseline (Double-Pane)	Thin Triple-Pane
U-Factor (Btu/hr-ft2-°F)	0.68 / 0.66	0.19
Solar Heat Gain Coefficient	0.70 / 0.66	0.27 / 0.26

3.3 Operation of Lab Homes

Each Lab Home consisted of an identical central HVAC system with under-floor ductwork. The HVAC system consisted of a 2.5 ton, 13 SEER (Seasonal Energy Efficiency Ratio) air-conditioner and a 15 kW electric furnace. Each HVAC system was operated in cooling only or heating only mode by an Ecobee 4 Smart Thermostat. The intelligent functionality of the smart thermostat was not activated during the testing. The thermostat controlled the homes temperature within a threshold of 0.5 °F with a minimum ON and OFF time of 5 minutes. For a given test day, the HVAC system conditioned each Lab Home in either the heating or cooling only operational mode. During the experiment, no internal loads were generated within the load homes (i.e., no lights, no appliances, no occupancy simulation). Internal loads would be expected to have a minimal impact on the HVAC energy (kWh) difference between the two Lab Homes, but internal loads would change the HVAC savings from a total percent perspective. For winter and summer data collection periods, interior vinyl blinds were used for a portion of the test days, while no interior shading was present on the remainder of the test days. Table 3 provides a summary of the operating state of the Lab Homes during the thin triple evaluation.

Table 3. Operating Summary of PNNL Lab Homes for the Experiment

Space Heating Equipment	15 kW (1-Stage) Electric Resistance Central Furnace
Heating Thermostat Setpoint	70 °F
Space Cooling Equipment	13 SEER, 3-ton, 1-Stage Central Air-Conditioner
Cooling Thermostat Setpoint	75 °F
Internal Load Simulation	Simulated occupancy and plug loads were not active during this study.
Interior Shading	Winter and summer data collection included test days with no interior window shading and with interior vinyl blinds closed on all windows at the Lab Homes.

3.4 Data Collection

Table 4 provides an overview of the data collection methods and instrumentation used at the Lab Homes for the thin triples study. Outdoor temperature and outdoor solar irradiance were collected using an onsite weather station. Solar irradiance was obtained using a horizontally mounted pyranometer. For this experiment, the daily average solar irradiance was determined and used as a metric for capturing the available solar irradiance for a given test day. Interior space temperatures and both interior and exterior window surface temperatures were monitored with T-type thermocouples. An example of the window surface-mount thermocouples is provided in Figure 4. For each of the nine windows at the Lab Homes, a surface-mount thermocouple was placed on the center of the glass, and for the dining room window additional surface-mount thermocouples were placed 2 inches from the bottom of frame to explore condensation potential. Sound meters were used for sound infiltration testing discussed in the following section and an infrared camera was used to examine heat loss patterns for the study.

Table 4. Measurements and Instrumentation Used at the Lab Homes

Measurement	Monitoring Method	Monitored Variables	Data Application
HVAC Energy Consumption	Electrical panel metering	Energy (kWh), Power (kW)	Support HVAC energy comparison.
Interior Space Temperature	Ceiling-hung, T-type thermocouples throughout home	Temperature (°F)	Examine occupant comfort. Support energy comparison.
Outdoor Temperature	Packaged meteorological station (thermistor)	Temperature (°F)	Support HVAC energy comparison.
Outdoor Solar Irradiance	Packaged meteorological station (horizontal pyranometer)	Irradiance (W/m^2)	Support HVAC energy comparison.
Window Surface Temperatures	Surface-mount thermocouples (interior/exterior of dining room window 2 inches from bottom).	Temperature (°F)	Window surface condensation potential.
	Surface-mount thermocouples (interior/exterior surface) at center of glass on all windows.	Temperature (°F)	Examine occupant comfort.
Radiant Temperature	Black Globe Temperature Sensor. One in dining room and one in master bedroom.	Temperature (°F)	Examine occupant comfort.
Sound Infiltration	Two sound meters: exterior meter for control and interior meter for infiltration measurement	Sound Level (dB)	Examine sound infiltration.

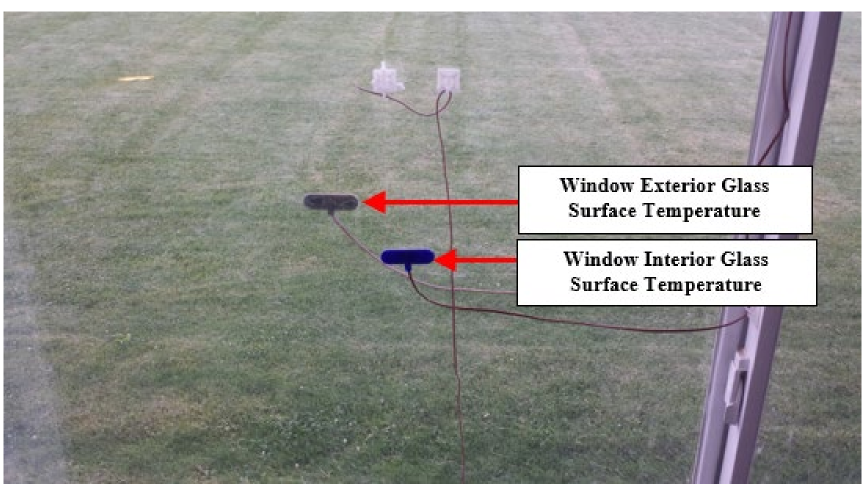


Figure 4. Example of Window Surface Temperature Measurements

Data collection occurred in 2020 over a timeframe of approximately 2 months during winter and approximately 1 month during summer. During winter data collection, average daily outdoor temperatures ranged from approximately 30 °F to 50 °F and hourly outdoor temperatures ranged from approximately 20 °F to 65 °F during that timeframe. During summer data collection, average daily outdoor temperatures ranged from approximately 70 °F to 85 °F and hourly outdoor temperatures ranged from approximately 60 °F to 100 °F during that timeframe. Solar irradiance values commonly range from ~0 W/m^2 during nighttime hours to ~1,000 W/m^2 during daytime hours during summer data collection. The average daily solar irradiance was greater during summer data collection than during winter data collection. The average daily solar irradiance was near zero for a portion of the winter data collection period. The regional climate where the Lab Homes are located is dry, and thus window condensation potential was considered from a theoretical perspective and not based on actual humidity measurements at the Lab Homes.

3.5 Sound Infiltration Protocol

Triple-pane glass windows have traditionally been selected not only for their energy efficiency advantages, but also for their perceived ability to reduce exterior noises. A potential disadvantage to using thinner glass and a thinner profile IGU in triple-pane windows could be a reduced ability to block exterior noise. To evaluate sound infiltration through the double- and thin triple-pane windows, the PNNL research team adapted procedures developed for DOE's Solar Decathlon Competition. The sound infiltration test setup included an adjustable speaker, a tone generator, and two identical sound meters, as shown in Figure 5. At the Lab Homes, the sound infiltration evaluation was conducted at the dining room sliding glass door of each home. The adjustable speaker was located at the center of the sliding door approximately 4 feet from the glass. A controllable tone was played through the adjustable speaker at 90 decibels (dB) and frequencies of 200 Hertz (Hz), 1,000 Hz, and 4,000 Hz. The sound meter located on the exterior of the sliding glass door was used to calibrate the adjustable speaker to 90 dB. The sound meter inside the home was used to measure the sound infiltration at each of the three frequency levels. The sound infiltration evaluation procedures were conducted similarly at both the Thin Triple-Pane Lab Home and the Baseline Lab Home (containing double-pane windows). The results of the sound infiltration evaluation are provided in Section 4.0.

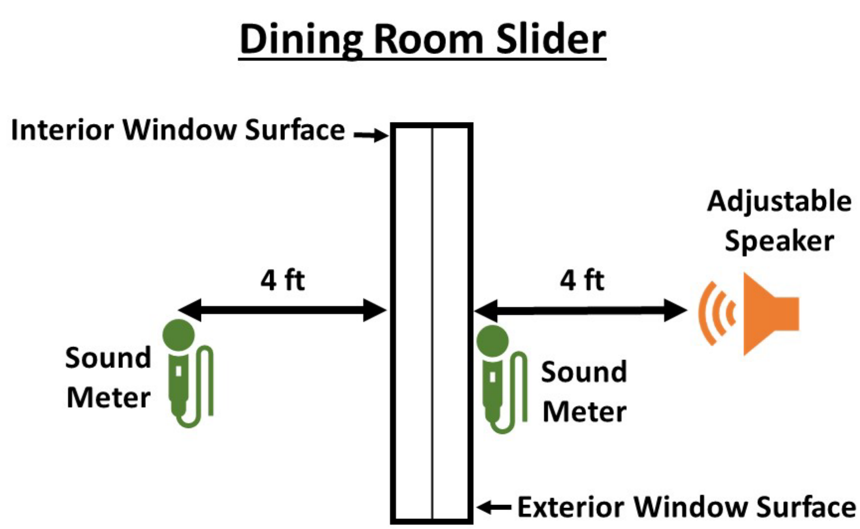


Figure 5. Equipment Setup for Sound Infiltration Testing

3.6 Baselining of Lab Homes

Baselining refers to examining the agreement between the two Lab Homes before an experimental evaluation or before a modification is made to one of the Lab Homes. For this study, baselining included examining the agreement between the HVAC cooling energy usage, HVAC heating energy usage, and home air leakage. Prior to the installation of the thin triple-pane windows, the two Lab Homes consisted of comparable building envelopes with identical double-pane windows, and the two homes were operated under identical conditions for a baselining period to determine and compare HVAC usage. For a cooling and heating baselining period of five consecutive days, the two home's HVAC systems exhibited comparable energy usage, as shown in Table 5. Because of the comparable HVAC energy usage of the two Lab Homes during baselining periods, no adjustments were made to the experimental results when examining the HVAC savings associated with the thin triple-pane windows in this study.

Table 5. Cooling and Heating Season Baselining at the PNNL Lab Homes

	Baseline Lab Home HVAC Energy Usage over 5 Days	Thin Triple-Pane Lab Home HVAC Energy Usage over 5 Days
Cooling Operation Baselining (5 days in fall 2019)	48.4 kWh	50.2 kWh
Heating Operation Baselining (5 days in winter 2020 just prior to installation of thin triple-pane windows)	411.5 kWh	414.2 kWh

Both before and after the thin triple-pane windows were installed at the selected Lab Home, a blower door test was performed on each Lab Home. The test indicated that the two homes had similar home air leakage, as shown in Table 6. Based on the HVAC baselining agreement and comparable blower door test results, the thin triple-pane windows were considered the primary difference between the Lab Homes from a building envelope perspective during this experiment.

Table 6. Home Air Leakage Evaluation before and after the Thin Triple-Pane Installation

	Baseline Lab Home (Double-Pane)	Thin Triple Lab Home (Thin Triple-Pane)
Home Air Leakage @ 50 Pa before Thin Triples Were Installed (Summer 2019)	834 cfm	797 cfm
Home Air Leakage @ 50 Pa after Thin Triples Were Installed (Summer 2020)	828 cfm	850 cfm

3.7 Installation of Thin Triple-Pane Windows at the Lab Home

Installation of the nine thin triple-pane windows at the PNNL Lab Home occurred over a series of days during winter 2020. Figure 6 provides a series of images of the installation process but is not intended to be a step-by-step guide for installation. The figure includes the removal of the existing double-pane windows (Images 1 and 2), prepping the border for a new window (Image 3), and the installation of the thin triple-pane window (Images 4 and 5). As highlighted in the Introduction, thin triple-pane windows are available with a thickness comparable to traditional double-pane windows and are therefore a suitable candidate for retrofit applications as well as new construction applications. Additional images and details of the installation process are provided in Appendix A.

Figure 6. Installation Process of Thin Triple-Pane Windows at the PNNL Lab Home

During the installation process, an interior pane was cracked in the north-facing thin triple-pane window located in Bedroom 2 of the Lab Home because of an installer error. The interior pane crack was approximately 6 inches in length and was sealed with tape immediately after its discovery, while the middle and exterior pane of the triple-pane windows were undamaged. The crack in the interior pane of the thin triple-pane window was present for most of the heating and cooling season data collection. Toward the end of the study, the triple-pane IGU was replaced for the bedroom 2 window. Appendix B provides a series of images documenting the IGU replacement for the bedroom 2 window. In addition, Appendix C provides analysis that concludes that the cracked interior pane did not have a discernable impact on the overall assessment of the thin triple-pane windows at the PNNL Lab Homes.

3.8 Energy Modeling

The energy modeling and simulation for the PNNL Lab Homes was conducted using EnergyPlus version 8.9.0. The PNNL Lab Home geometric characteristics presented in Figure 3 and physical parameters presented in Table 3 were used in the energy model. The window specifications for U-factor, SHGC, and visual transmittance were based on the NFRC full-frame performance ratings for each window configuration as provided by the manufacturer and modeled using the simplified window model object in EnergyPlus. Building geometry, envelope leakage parameters, internal gains, and HVAC equipment characteristics were specified to be consistent with the experimental parameters. To carry out annual simulation typical meteorological year (TMY) data from the nearest location (Pasco, WA) was used.

4.0 Results

This section provides the experimental results of the PNNL Lab Home evaluation of thin triple-pane windows including impacts on HVAC energy consumption, window condensation, indoor comfort, sound infiltration, and the thermal performance of the building envelope.

4.1 HVAC Energy Savings

To consider the HVAC savings associated with the examined thin triple-pane windows, results are presented as both a range of daily savings and an average daily savings across the data collection periods for both heating and cooling seasons. For each test day, HVAC energy usage, outdoor temperature, and outdoor solar irradiance data were collected and used to examine the results. A test day was considered to be from 12 A.M. to 12 A.M. Table 7 provides a summary of the HVAC savings for the heating season for the thin triple-pane windows with and without interior shading. In addition, daily HVAC savings from both an actual energy savings (kWh) and a percent savings perspective are presented in subsequent figures for the heating season with and without interior shading. For heating season data collection, Figure 7 provides daily energy savings (kWh) with and without interior shading, while Figure 8 and Figure 9 provide daily energy savings without interior shading using percent savings and actual energy savings, respectively.

Table 7. HVAC Energy Savings for Heating Season with Thin Triple-Pane Windows

No Interior Shading	**Range of Daily Average Outdoor Conditions**	Outdoor Temperature = 33.0 – 55.0 °F Outdoor Solar Irradiance = 5 – 154 W/m^2
	Range of Daily HVAC Savings	3% – 18% 0.2 kWh – 18.7 kWh
	Overall Averages for Test Period	HVAC Savings = 12% or 7.8 kWh Outdoor Temperature = 43.4 °F Outdoor Solar Irradiance = 66 W/m^2
Interior Blinds Closed	**Range of Daily Average Outdoor Conditions**	Outdoor Temperature = 39.7 – 49.2 °F Outdoor Solar Irradiance = 24 – 187 W/m^2
	Range of Daily HVAC Savings	8% – 18% 3.6 kWh – 13.3 kWh
	Overall Averages for Test Period	HVAC Savings = 13% or 6.9 kWh Outdoor Temperature = 44.3 °F Outdoor Solar Irradiance = 139 W/m^2

Daily HVAC savings associated with the thin triple-pane windows vary based on the outdoor temperature and outdoor solar irradiance. This occurrence is due to the windows affecting the temperature-driven heat transfer and solar radiation-driven heat transfer. The average daily HVAC savings presented in Table 7 were determined based on the Lab Home data collection periods and associated weather conditions.

For the heating season, the daily HVAC savings varied from 0.2 to 18.7 kWh without interior shading and from 3.6 to 13.3 kWh with interior shading. The highest daily HVAC savings for the heating season were observed on test days that featured minimal solar irradiance (i.e., significant cloud cover). During the heating season, increased solar radiation heat transfer is an energy benefit during the daytime because 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 were less due to this energy tradeoff and the thin triple's lower SHGC relative to the Baseline Lab Home windows. For test days on which the available solar radiation was larger on average, greater energy savings were observed with the interior blinds closed. This occurrence can be attributed to the reduced impact of solar radiation and associated space heating on the Baseline Lab Home when interior blinds are closed. The thin triple-pane windows designed with a lower SHGC are less affected by the available solar radiation.

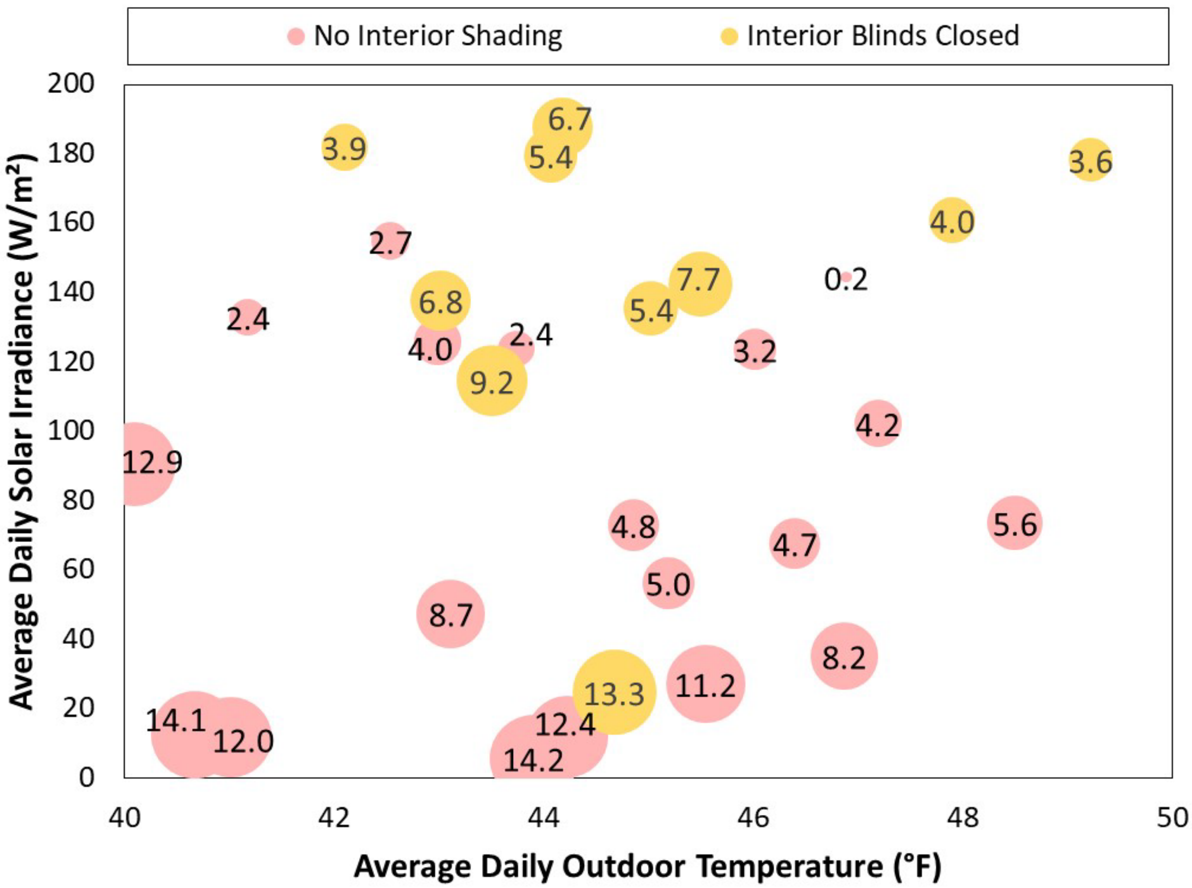


Figure 7. Daily HVAC Savings (kWh) for Thin Triple-Pane Windows during Heating Season with and without Interior Blinds

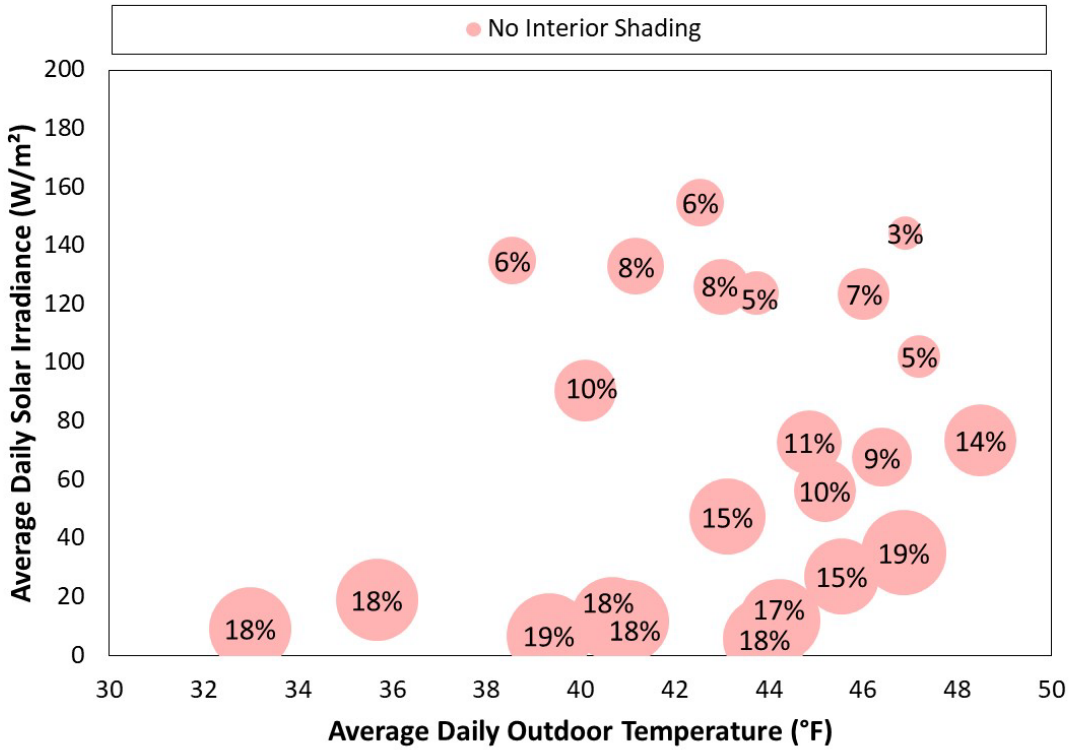


Figure 8. Daily HVAC Savings (%) for Thin Triple-Pane Windows during the Heating Season with No Interior Shading

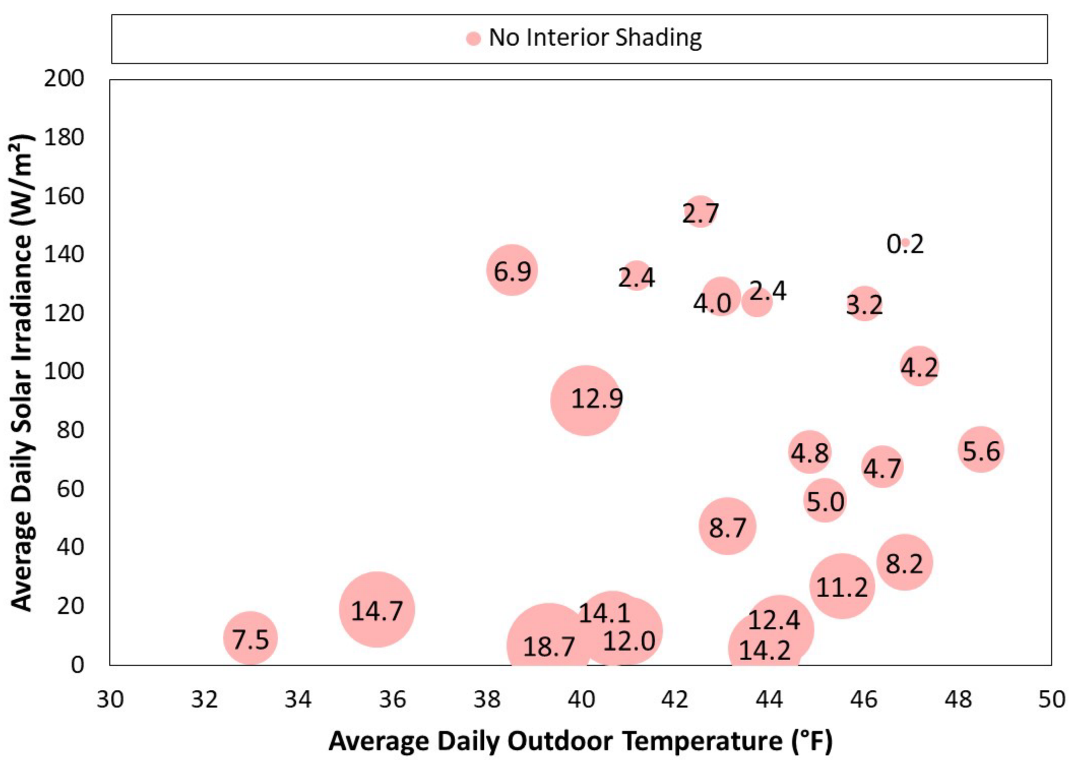


Figure 9. Daily HVAC Savings (kWh) for Thin Triple-Pane Windows during the Heating Season with No Interior Shading

Table 8 provides a summary of the HVAC savings for the cooling season for the thin triple-pane windows with and without interior shading. In addition, daily HVAC savings from an actual energy savings (kWh) and a percent savings perspective are presented in subsequent figures for the cooling season. Figure 10 provides daily percent energy savings with and without interior shading, while Figure 11 provides daily energy savings (kWh) with and without interior shading.

Table 8. HVAC Energy Savings for Cooling Season with Thin Triple-Pane Windows

No Interior Shading	**Range of Daily Average Outdoor Conditions**	Outdoor Temperature = 70.5 – 82.6 °F Outdoor Solar Irradiance = 107 – 324 W/m^2
	Range of Daily HVAC Savings	22.6% – 40.7% 2.5 kWh – 8.0 kWh
	Overall Averages for Test Period	HVAC Savings = 28% or 5.5 kWh Outdoor Temperature = 77.4 °F Outdoor Solar Irradiance = 258 W/m^2
Interior Blinds Closed	**Range of Daily Average Outdoor Conditions**	Outdoor Temperature = 76.8 – 84.0 °F Outdoor Solar Irradiance = 329 – 334 W/m^2
	Range of Daily HVAC Savings	24.4% – 24.8% 4.8 kWh – 6.8 kWh
	Overall Averages for Test Period	HVAC Savings = 24.5% or 5.9 kWh Outdoor Temperature = 80.6 °F Outdoor Solar Irradiance = 332 W/m^2

The daily HVAC savings associated with the thin triple-pane windows vary based on the outdoor temperature and outdoor solar irradiance. This variation is due to the windows affecting the temperature-driven heat transfer and the solar radiation-driven heat transfer. The average daily HVAC savings that are presented in Table 7 were determined based on the Lab Home data collection periods and associated weather conditions. For the cooling season, the daily HVAC savings varied from 2.5 to 8.0 kWh with no interior shading and from 4.8 to 6.8 kWh with interior blinds closed. For the cooling season, the daily solar irradiance was generally comparable 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 tripe-pane windows provided an energy-savings benefit. For the summer data collection period, the use of interior vinyl blinds had less of an impact on HVAC energy savings than during the winter data collection period.

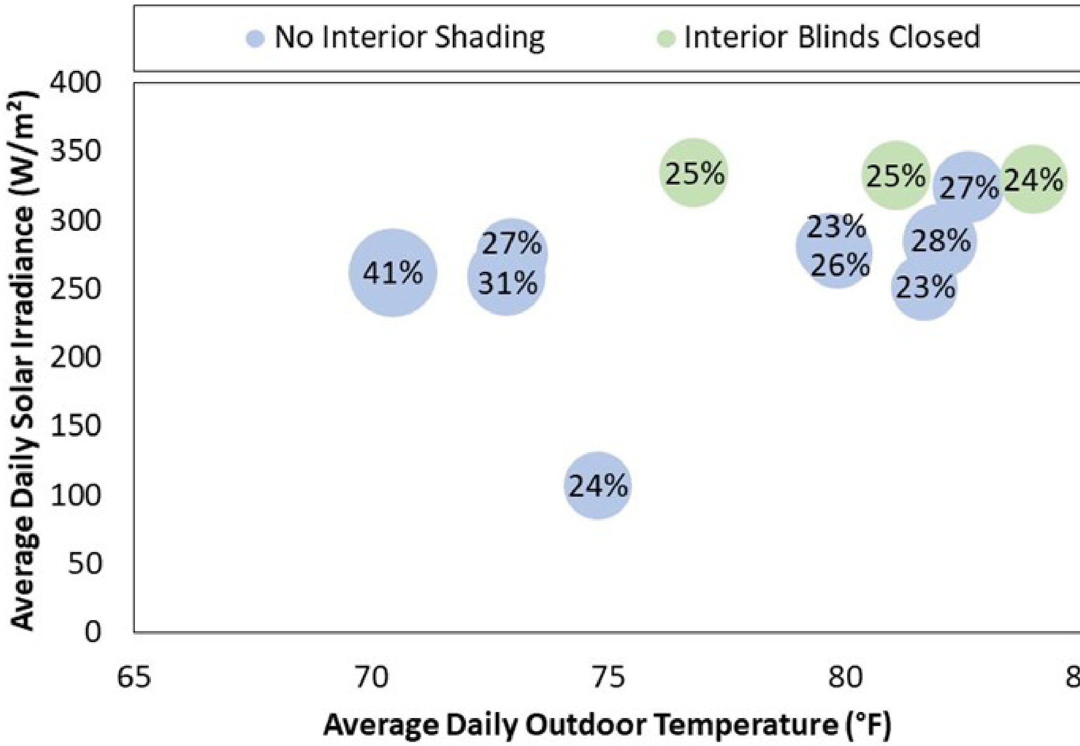


Figure 10. Daily HVAC Savings (%) for Thin Triple-Pane Windows during Cooling Season with and without Interior Blinds

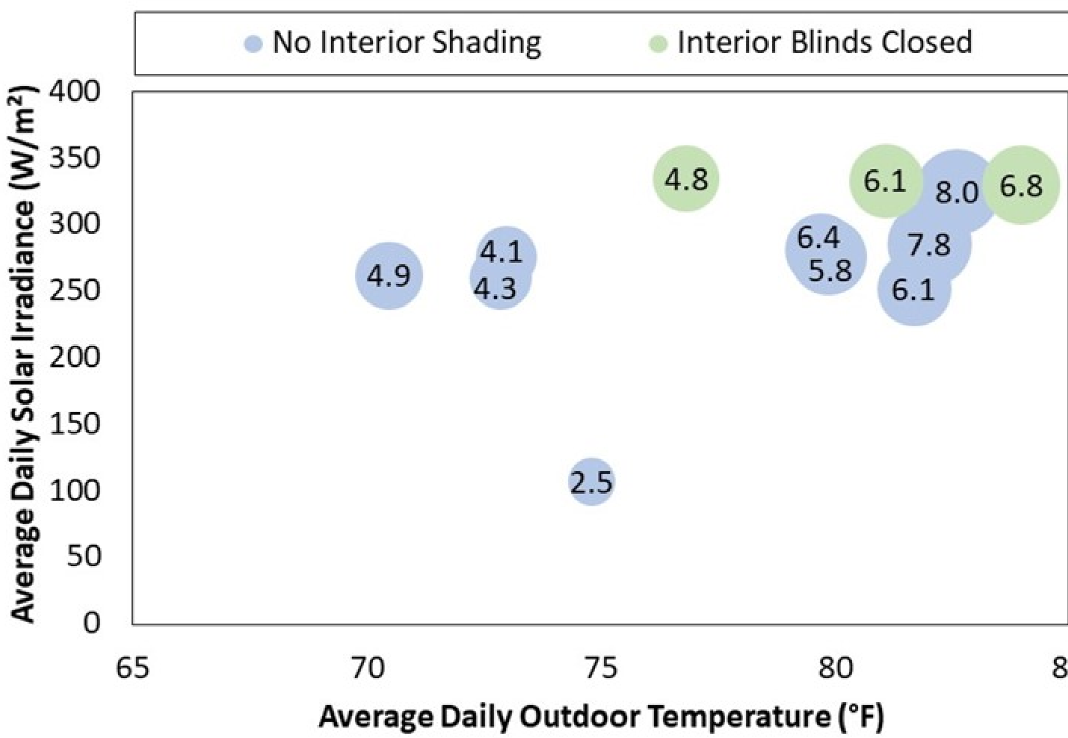


Figure 11. Daily HVAC Savings (kWh) for Thin Triple-Pane Windows during Cooling Season with and without Interior Blinds

4.2 HVAC Load Shapes

Electrical load shapes for the HVAC system in each Lab Home were developed for the entire data collection periods for the heating and cooling seasons. The developed load shapes are based on hourly averages for a 24-hour day and included test days with and without interior shading. The Lab Home's HVAC system consisted of a 15 kW, 1-stage electric central furnace during the heating season and a 3 ton, 1-stage, 13 SEER central air-conditioner during the cooling season. Figure 12 provides a comparison of the HVAC load shapes for the Baseline and Thin Triple-Pane Lab Homes for heating season data collection. The hourly peak HVAC power demand during the heating season occurred at the Lab Homes at ~6 AM. An average HVAC peak power reduction of approximately 17% (~650W) was observed for the Thin Triple-Pane Lab Home when compared to the Baseline Lab Home during heating season. During the morning hours of the heating season, the improved U-factor of the thin triple-pane windows offered improved thermal resistance for the Thin Triple-Pane Lab Home, resulting in a lower thermal load and HVAC demand. As shown in Figure 12, most of the HVAC savings from triple-pane windows are coincident with the regional peak loads at the beginning and end of the workdays during the heating season. This savings profile suggests that high-efficiency windows could passively benefit the grid by reducing peak period electricity demand and the sustained evening and early morning savings pairs well with variable renewable generation sources, such as solar photovoltaics (PV), where power generation drops as the sun sets.

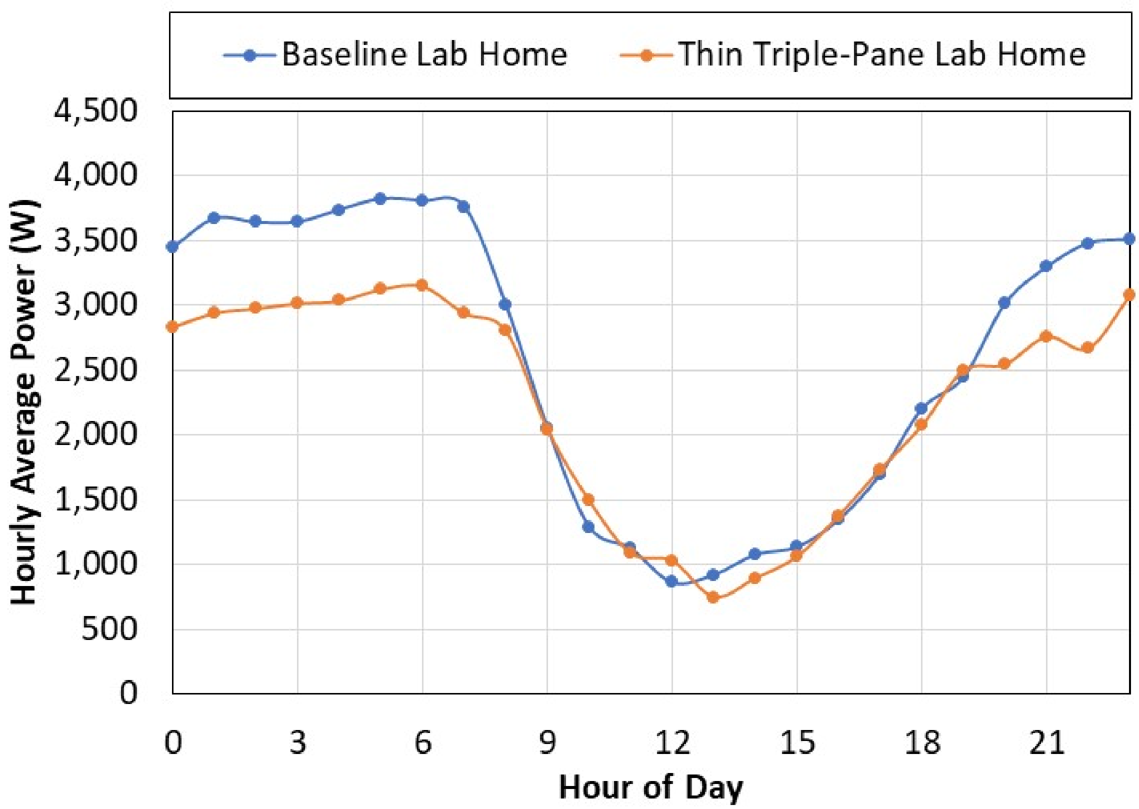


Figure 12. HVAC Load Shapes for the Baseline and Thin Triple-Pane Lab Homes for the Heating Season

For cooling season data collection, Figure 13 provides a comparison of the HVAC load shapes for the Baseline and Thin Triple-Pane Lab Homes. The hourly peak HVAC power demand during the cooling season occurred at the Lab Homes at ~5 PM. An average HVAC peak power reduction of approximately 33% (~1,200W) was observed for the Thin Triple-Pane Lab Home when compared to the Baseline Lab Home during cooling season. During the daytime hours of cooling season, the improved U-factor and SHGC of the thin triple-pane windows offered improved thermal performance for the Thin Triple-Pane Lab Home, resulting in a lower thermal load and HVAC demand. During the cooling season, the daily savings from the application of triple-pane windows are concentrated in the late afternoon and early evening hours, which coincides with peak electricity demand throughout the region. Figure 13 illustrates the peak flattening effect that triple-pane windows have on the HVAC load, which could provide substantial grid benefits if these measures were implemented across multiple residential buildings. For regions experiencing challenges with “duck curve”[1] power profiles, 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).

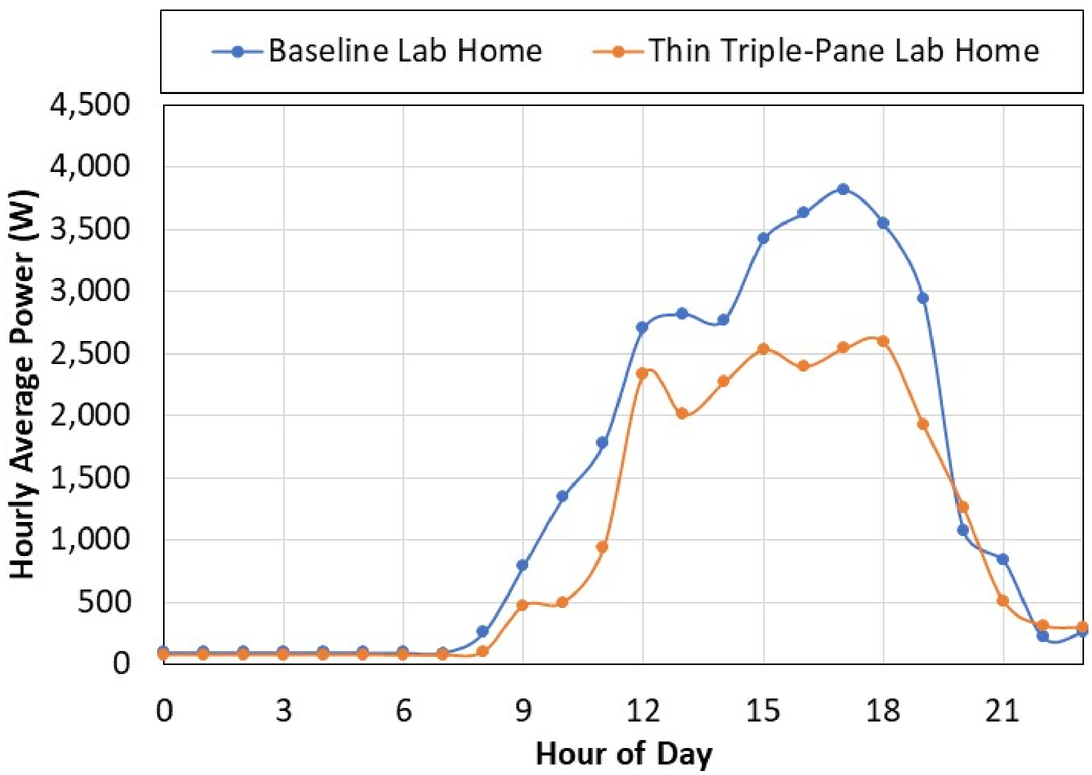


Figure 13. HVAC Load Shapes for the Baseline and Thin Triple-Pane Lab Homes for the Cooling Season

4.3 HVAC Operating Trends

During winter data collection, the central electric furnaces in each of the Lab Homes maintained the indoor temperature at approximately 70 °F, but on sunny, mild winter days the indoor

[1] The duck curve reflects the daily net power demand in areas with heavy concentrations of PV where the early evening demand spikes (as people return home from work) just as PV power generation drops.

temperature near the thermostat of the Baseline Lab Home could rise above the setpoint during the afternoon because of the higher SHGC of the baseline windows. Figure 14 provides an example of this wintertime scenario with measurements of indoor temperatures at the home's thermostat location, HVAC power consumption, and outdoor temperature. For the winter day shown, the indoor temperature of the Baseline Lab Home rose to approximately 77°F, while the Thin Triple-Pane Lab Home peaked at an indoor temperature of approximately 72°F. This effect at the Baseline Lab Home was an HVAC energy benefit during the day, but the thermal losses through the Baseline Home windows during the evening and morning hours resulted in net savings for the Thin Triple-Pane Lab Home with the more highly insulated triple-pane windows. The effect of the solar heat gain on mid-day indoor temperatures demonstrates the importance of specifying climate-appropriate U-factors and SHGCs. Although the thin triple-pane windows could have been specified to have a higher SHGC for south-facing windows to optimize these beneficial solar gains in the winter, the more common approach of selecting a balanced SHGC for all windows was employed, which is designed to have optimal heat balance through the window throughout the year.

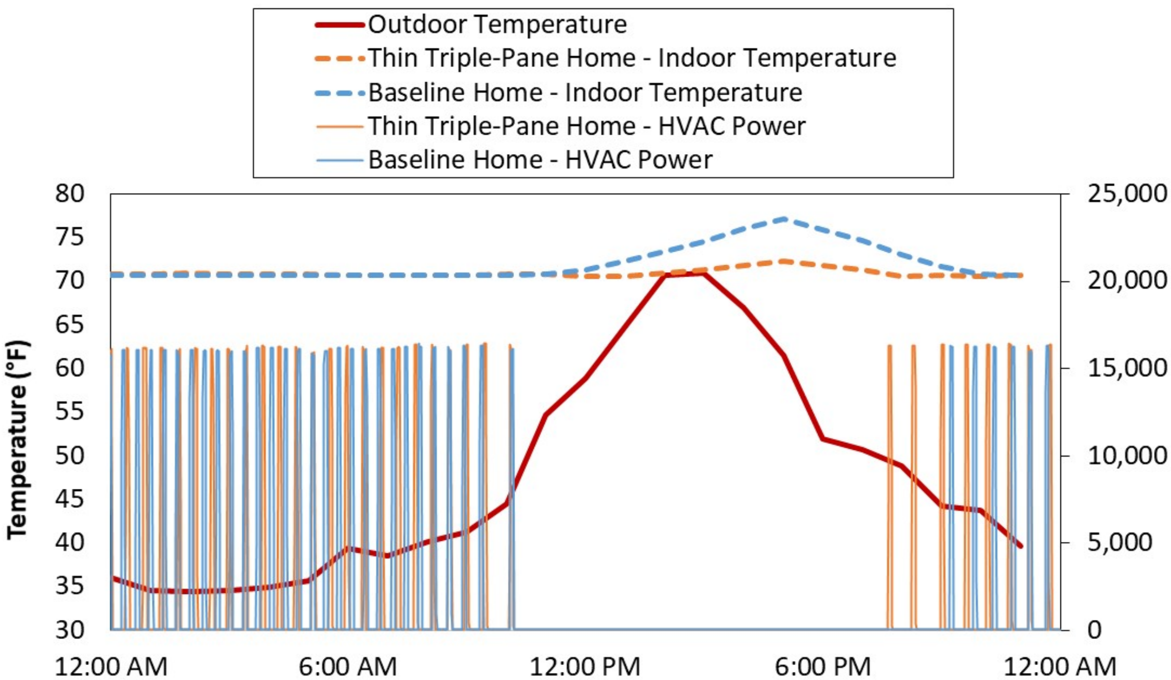


Figure 14. Indoor Temperature and HVAC Profiles for a Mild Winter Day with No Interior Shading

For the cooling season, indoor temperatures were generally maintained at the thermostat setpoint of 75 °F. Figure 15 provides an example summer day profile showing the measurements of the indoor temperature at the home's thermostat location, HVAC power consumption, and outdoor temperature. The indoor temperatures of the baseline and thin triple-pane homes were similar over the course of the day. The regional climate in which the Lab Homes are located generally consists of cooler outdoor temperatures (approaching 60 °F) in the late evening and early morning hours during the summer, while daytime outdoor temperature highs can approach 100 °F. This outdoor temperature profile and corresponding load profile of the Lab Homes resulted in minimal demand for space cooling until the mid-morning hours. In the late afternoon hours in the summer, the thermal load on the Lab Homes frequently resulted in the HVAC system operating continuously for an hour or longer based on the thermostat setpoint of 75 °F.

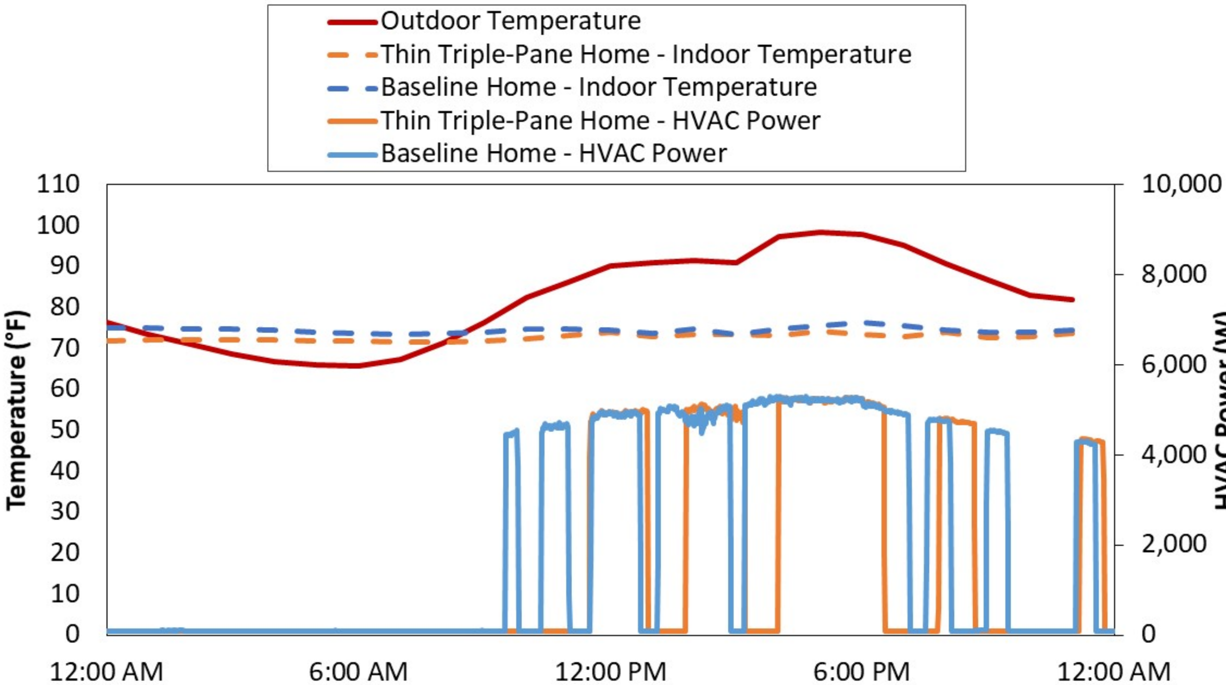


Figure 15. Indoor Temperature and HVAC Profiles for a Summer Day with No Interior Shading

4.4 Condensation Potential

Window condensation potential was examined by taking surface temperature measurements on the interior and exterior of the thin triple-pane and baseline double-pane windows. The west-facing dining room window of each Lab Home was selected to explore condensation potential. Surface-mount thermocouples were placed on the dining room windows approximately 2 inches from the bottom of the window frame and center of the glass. This location is generally one of the coldest areas on the interior surface of baseline windows during cold outdoor temperatures. During winter data collection, interior and exterior window surface temperatures varied based on the outdoor temperature and available solar irradiance. The coldest window surface temperatures were observed during the early morning and late evening hours, when the outdoor temperatures were coldest and no solar irradiance was present.

Figure 16 examines the condensation potential of the interior dining room window surface for the thin triple-pane and baseline Lab Homes. The figure provides the daily minimum temperature for the interior window surface for the winter data collection period. Also plotted in the figure is a theoretical indoor dewpoint temperature based on an indoor air dry-bulb temperature of 70 °F and a relative humidity of 50%. An interior window surface temperature below the indoor air dewpoint would result in condensation forming on the interior window surface. Using the theoretical dewpoint level, the baseline dining room window had the potential for condensation on approximately 40% of the days during the winter data collection period, while the thin triple-pane had zero instances below the established dewpoint threshold where condensation could form on the window surface. During winter data collection, the actual indoor air dewpoint at the Lab Homes never reached 50% relative humidity, because the Lab Homes are in a dry climate and no moisture was generated inside the Lab Homes during this study. During winter, an indoor condition of 70 °F and a relative humidity of 50% or higher is common in more humid climates or when considering moisture generation by occupants and occupant activities in the home.

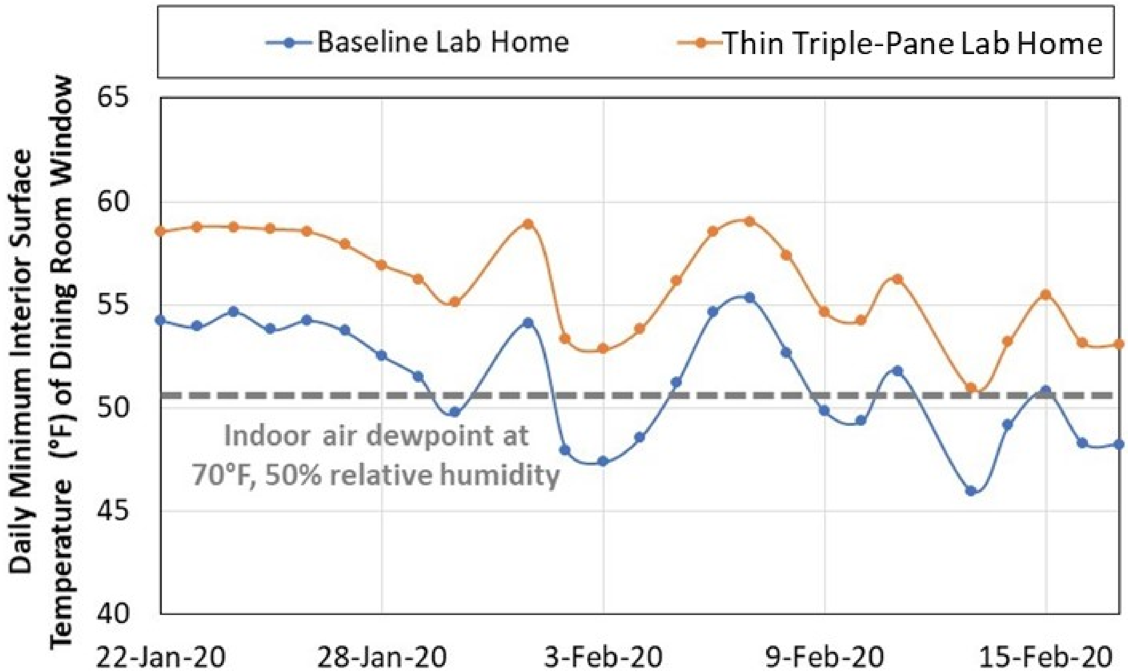


Figure 16. Condensation Potential of the Dining Room Window's Interior Surface during Winter

Figure 17 provides the interior and exterior window surface temperatures at the Baseline and Thin Triple-Pane Lab Homes for one of the coldest days of data collection during which the average outdoor temperature was 31 °F and solar irradiance was minimal. The figure provides daily average temperatures for the interior and exterior surface for the thin triple and baseline dining room windows. These window surface temperatures were taken approximately 2 inches from the bottom of the window frame and center of the glass. Each Lab Home was maintained at an indoor air temperature of 71 °F on this day. Because of the minimal solar irradiance on this day, heat transfer through the windows predominately occurred from the warm indoor air out to the exterior window surface. On the selected day, the baseline double-pane window (with lower insulation properties) demonstrated a colder interior window surface, while the thin triple-pane window (with higher insulation properties) exhibited a colder exterior window surface. For this day of data collection, the baseline double-pane window would have a greater condensation potential for the interior surface, while the thin triple-pane would have a greater condensation potential for the exterior surface. For condensation to form on either surface, the dewpoint of the indoor or outdoor air would have to be above the window surface temperature.

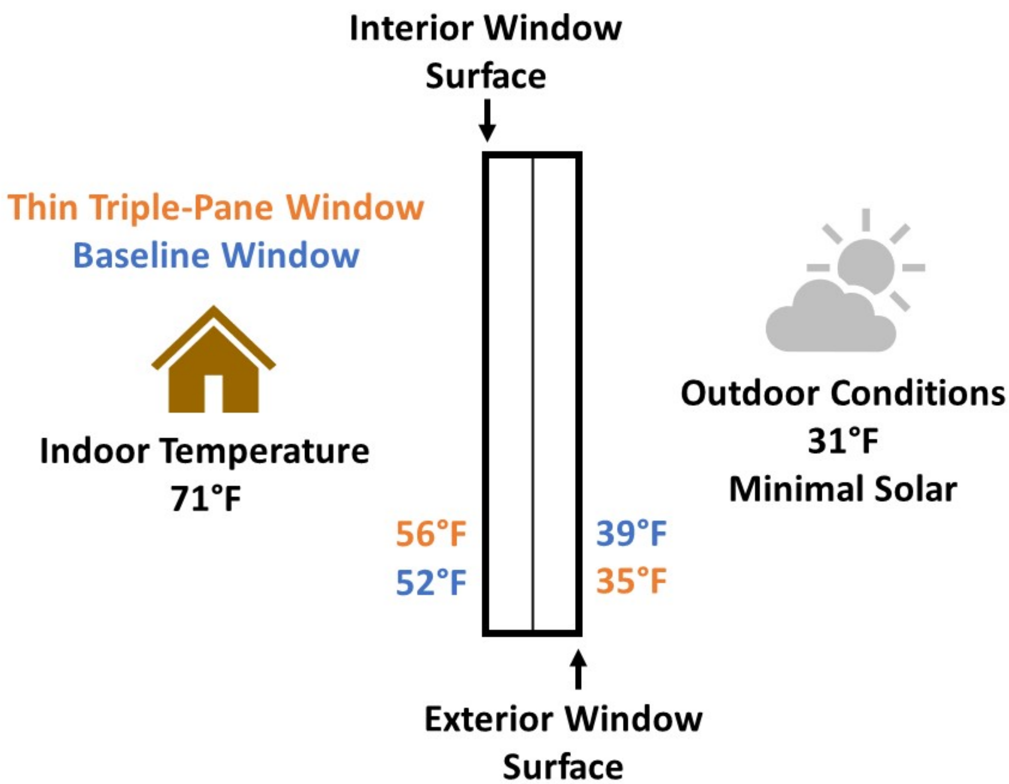


Figure 17. Dining Room Window's Interior and Exterior Condensation Potential on the Cold Day

Overall, the triple-pane windows exhibit a reduced condensation potential on the interior surface than the baseline, double-pane windows. This difference would be generally more pronounced in cold humid climates that feature limited winter solar irradiance. Condensation buildup on the interior surface is also influenced by the moisture-generating activities in the home. For example, higher occupancy homes and homes that include activities such as cooking, showers, and laundry could experience even more pronounced condensation buildup from this difference in thermal performance.

4.5 Occupant Comfort

Indoor space temperatures, indoor radiant temperature measurements, and interior window surface temperatures can be used to examine occupant comfort in the Lab Homes. To examine occupant comfort for the heating season, one of the coldest days of winter data collection was selected during which the average daily outdoor temperature was 31 °F and solar irradiance was minimal. For the selected cold day, Figure 18 provides the indoor space and interior window surface temperatures throughout the Lab Homes, while Figure 19 provides a radiant temperature measurement inside the Lab Homes. The data presented in the figures represent the hourly average and are shown over the 24-hour day of data collection. The interior space and interior window surface measurements were taken throughout each room of the Lab Home, while radiant temperature measurements were taken in the dining room and master bedroom. Interior window surface temperature measurements were taken from the center of the glass.

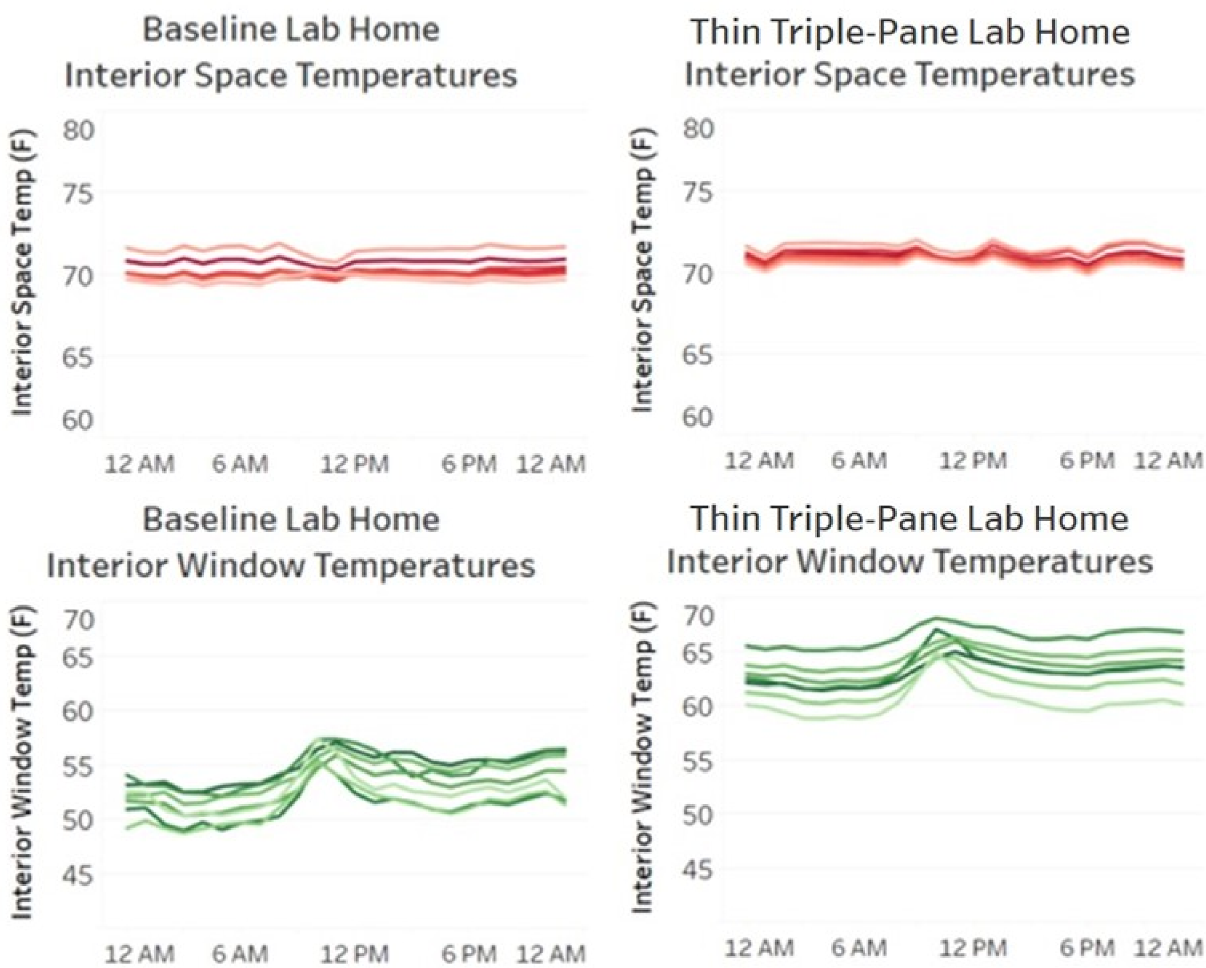


Figure 18. Space and Window Surface Temperatures throughout Lab Homes on Cold Day

For the selected cold day, both Lab Homes were maintained at approximately 70 °F throughout the day and throughout each room of the Lab Home. Considering the interior window surface temperatures and radiant temperature measurements, a clear difference is observed between the Thin Triple-Pane Lab Home and Baseline Lab Home. During the early morning and late evening hours, the interior window surfaces in the Baseline Lab Home were approximately 10 °F colder than their counterparts in the Thin Triple-Pane Lab Home. Similarly, the indoor radiant temperature measurement in the Baseline Lab Home was approximately 2 °F colder than Thin Triple-Pane Lab Home during the early morning and late evening hours. In the mid-morning hours on the selected cold day, solar irradiance caused a warming effect, which is observed in the interior window surface measurements and the radiant temperature measurements. This warming effect, which was relatively more pronounced through the clear glass windows of the Baseline Lab Home resulting in the radiant temperature being 2 °F warmer than that in the Thin Triple-Pane Lab Home. Although the interior space temperatures of the two homes were similar, an occupant would be expected to be more comfortable in the Thin Triple-Pane Lab Home on this cold day because of the warmer window surface temperatures, generally warmer radiant temperature measurements, and more even temperature distributions throughout the home. An occupant in the vicinity of a colder surface (e.g., window surface) would experience radiant heat loss to that surface, which can result in occupant discomfort.

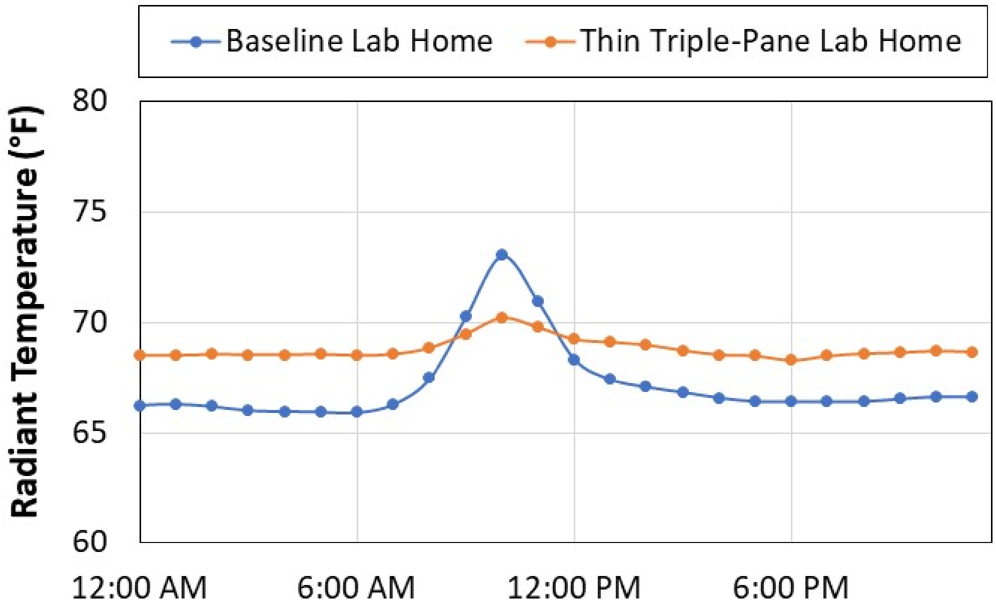


Figure 19. Indoor Radiant Temperatures on a Cold Day with No Interior Shading

To examine occupant comfort during the cooling season, a summer day was selected during which the interior vinyl blinds were closed and the daily outdoor temperature average was ~82 °F with significant solar irradiance. For the selected summer day, Figure 20 provides the indoor space temperatures throughout the Lab Homes, while Figure 21 provides a radiant temperature measurement inside the Lab Homes. The data presented in the figures are hourly averages and shown over the 24-hour day of data collection. The interior space temperatures are throughout each room of the Lab Home, while radiant temperature measurement occurred in the dining room.

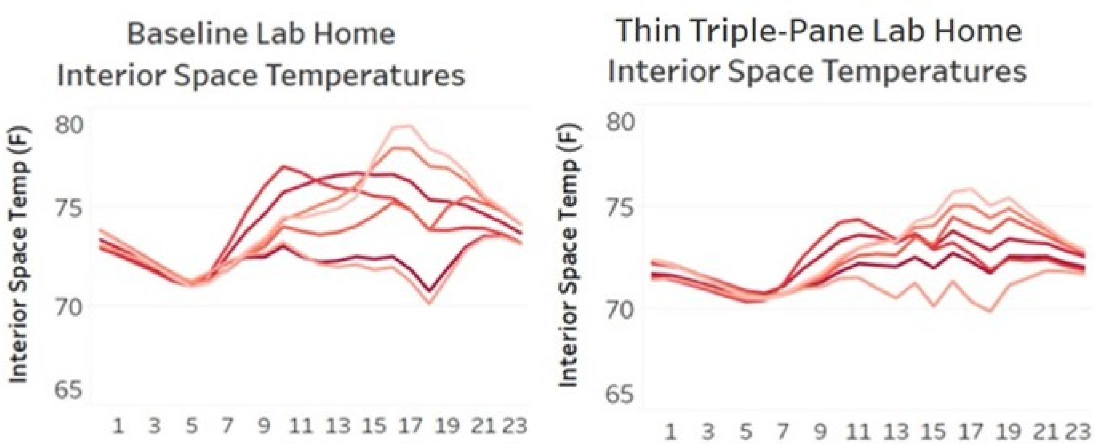


Figure 20. Space Temperatures throughout Lab Homes on a Summer Day with Blinds Closed

For the selected summer day, the interior space temperatures were distributed throughout the Lab Homes. South- and west-facing rooms (e.g., dining room) demonstrated warmer temperatures in the afternoon compared to the cooler temperatures in the north- and east-facing rooms (e.g., bedroom 2 and master bathroom). During the cooling season, the HVAC system was controlled based on a centrally located thermostat at 75 °F. In the Baseline Lab Home, temperatures throughout the home rose to as high as 78 °F for the selected summer day, while temperatures in the Thin Triple-Lab Home were maintained at or below 75 °F. In both Lab Homes, north- and east-facing rooms experienced indoor temperatures as low as 70°F. Considering radiant temperature measurements on the selected summer day in Figure 21, the Baseline Lab Home peaked at ~81 °F, while the Thin Triple-Pane Lab Home peaked at ~76 °F. Based on the interior space measurements throughout the Lab Homes and the radiant temperature measurements for the selected summer day, an occupant would have experienced improved comfort in the Thin Triple-Pane Lab Home during the late afternoon hours when solar irradiance was at peak.

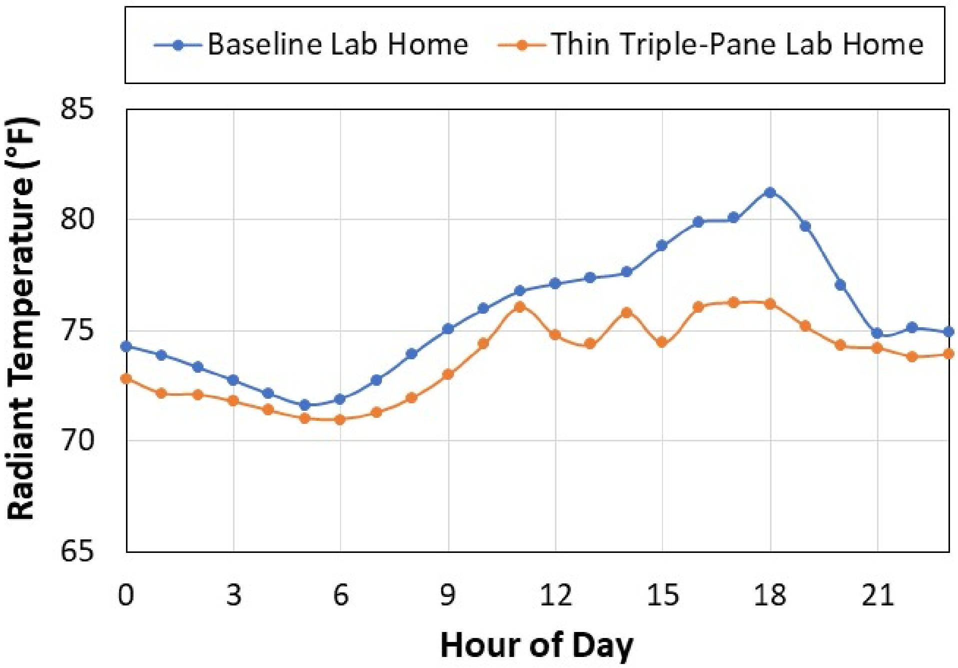


Figure 21. Indoor Radiant Temperatures on a Summer Day with Blinds Closed

4.6 Sound Infiltration

An evaluation of sound infiltration was conducted with the thin triple-pane windows at the PNNL Lab Homes as described in Section 3.0. The sound infiltration evaluation was conducted at the south-facing sliding glass door in the Lab Homes. Sound infiltration was examined using a set of sound meters and a sound generator at 90 dB and three frequency levels. The results of the sound infiltration evaluation are provided in Table 9. The thin triple-pane windows Lab Home demonstrated a reduced sound infiltration of 8 dB to 10 dB over the baseline double-pane windows Lab Home. It has been established that a 6 dB to 10 dB reduction in sound level generally reduces an individual’s perception of sound by half (Warren 1973; Stevens 1936).

Table 9. Sound Infiltration Results of Thin Triple-Pane Windows at the Lab Homes

	Measured Sound Level at Baseline Lab Home (Double-Pane)	Measured Sound Level at Thin Triple-Pane Lab Home	Sound Reduction with Thin Triple-Pane Windows
90 dB at 200 Hz Frequency	65 dB	55 dB	10 dB
90 dB at 1,000 Hz Frequency	61 dB	53 dB	8 dB
90 dB at 4,000 Hz Frequency	52 dB	43 dB	9 dB

4.7 Thermal Imaging

To examine the performance of thin triple-pane windows, thermal imaging was conducted in the late evening hours (i.e., no sunlight) when the outdoor temperature was approximately 30 °F and the interior of the Lab Homes was maintained at 70 °F. Figure 22 and Figure 23 provide a side-by-side thermal image comparison of the Thin Triple-Pane Lab Home and Baseline Lab Home (double-pane windows). Figure 22 provides a side-by-side comparison of the west side of the Lab Homes, while Figure 23 provides a comparison of the south side of the Lab Homes. For the thermal images in Figure 22 and Figure 23, a yellow/white color generally indicates a warmer surface temperature, while an orange/red temperature generally indicates a cooler surface temperature. A warmer surface temperature would generally be attributed to heat loss from inside the home out to the exterior building surfaces. In Figure 22, thermal images of the west-facing slider door demonstrate a significant difference in window performance. Heat loss related to the thin triple-pane slider is focused around the frame of the window, while heat loss of the baseline slider is more balanced between the frame and window surface. In Figure 23, thermal images of the south side of each Lab Home also demonstrate a significant difference in window performance. At the Thin Triple-Pane Lab Home, there is less defined heat loss between the windows and walls, while at the Baseline Lab Home there is distinctly greater heat loss around the three south-facing windows.

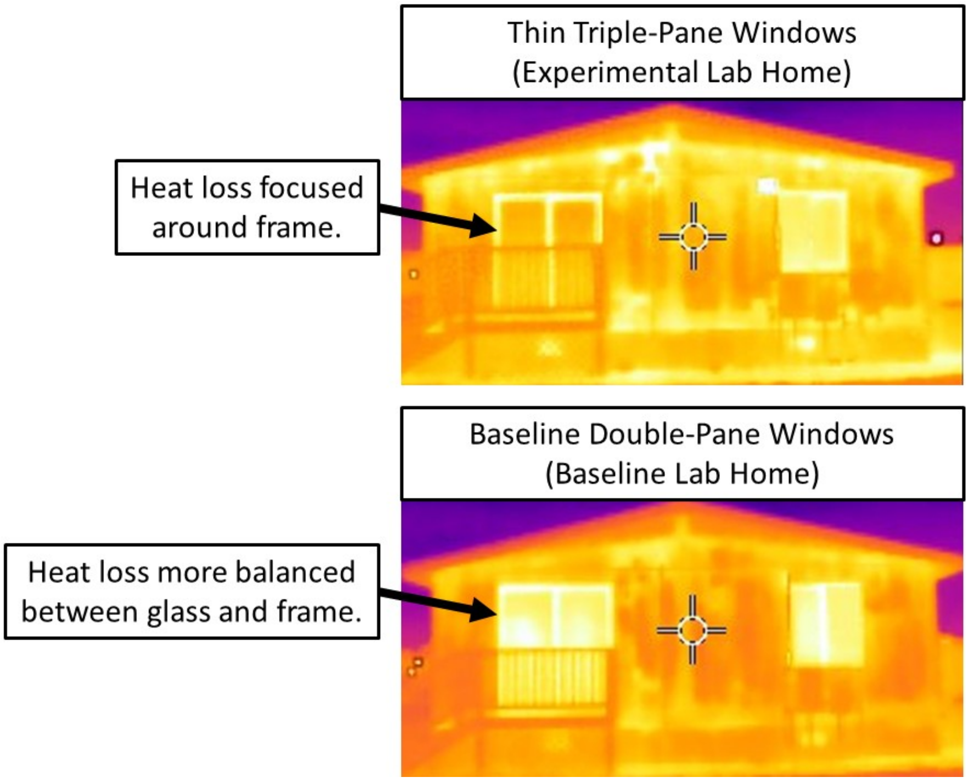


Figure 22. Thermal Imaging Comparison of the West Sides of the Lab Homes

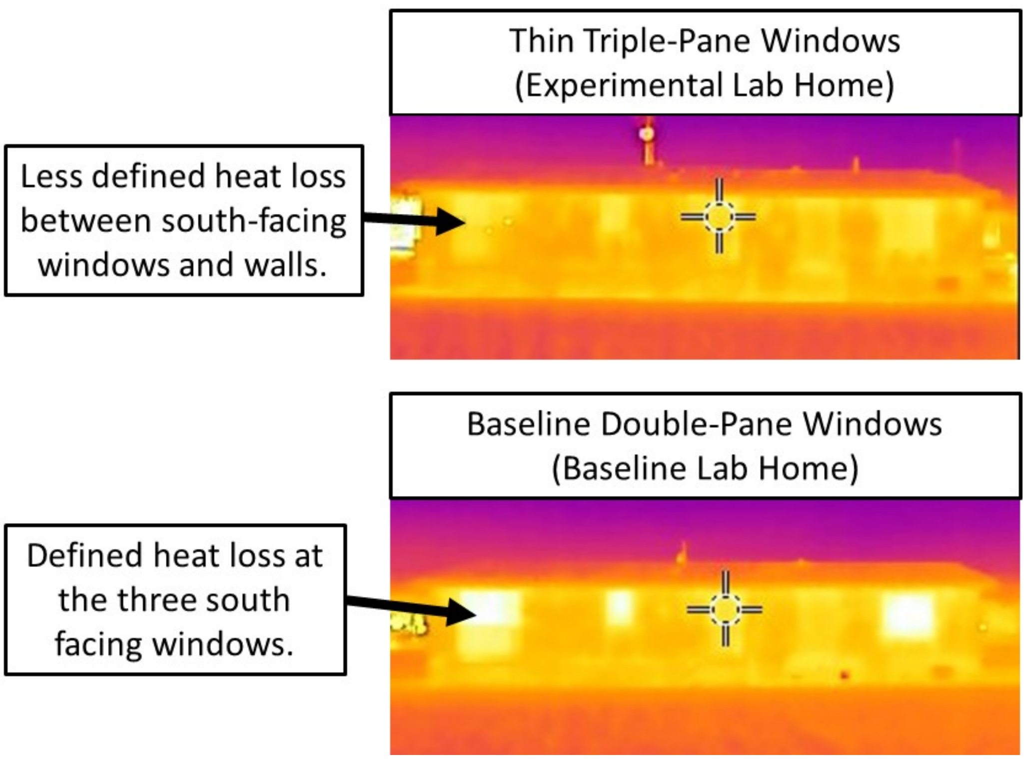


Figure 23. Thermal Imaging Comparison of the South Sides of the Lab Homes

4.8 Energy Modeling

An EnergyPlus model was created for the Lab Homes to estimate annual HVAC savings and compare modeled energy savings from the thin triple-pane windows to measured savings from the Lab Homes field testing. The modeled simulations demonstrated a heating season energy savings of 1,600 kWh, a cooling season savings of 1,100 kWh and a total HVAC energy savings of 2,700 kWh (Table 10). The modeled HVAC energy savings is comparable to the savings measured in the experimental study at the Lab Homes, which averaged 7.8 kWh/day during heating season data collection and 5.5 kWh/day during cooling season data collection.

Table 10. Annual HVAC Energy Savings from Lab Home EnergyPlus Model

	Lab Home Energy Model with Double-Pane Windows	Lab Home Energy Model with Thin Triple-Pane Windows	Energy Savings with Thin Triples based on Lab Home Energy Model
Annual Heating Energy Consumption (kWh)	12,300	10,700	1,600
Annual Cooling Energy Consumption (kWh)	2,200	1,100	1,100
Annual HVAC Energy Consumption (kWh)	14,500	11,800	2,700

Figure 24 provides selected HVAC energy consumption data from the EnergyPlus model and experimental data collection for the Thin Triple-Pane Lab Home. In the figure, the HVAC energy consumption is shown for both heating and cooling season as a function of outdoor temperature. The modeled energy results are comparable to the measured data; however, the energy model underpredicted the HVAC energy use at the Lab Homes, most noticeably during the cooling season. The HVAC energy savings between the Thin Triple-Pane and Baseline Lab Home was comparable between the EnergyPlus model and experimental data collection. Using a complex window object rather than a simplified window model object in EnergyPlus may provide improved agreement for the cooling season.

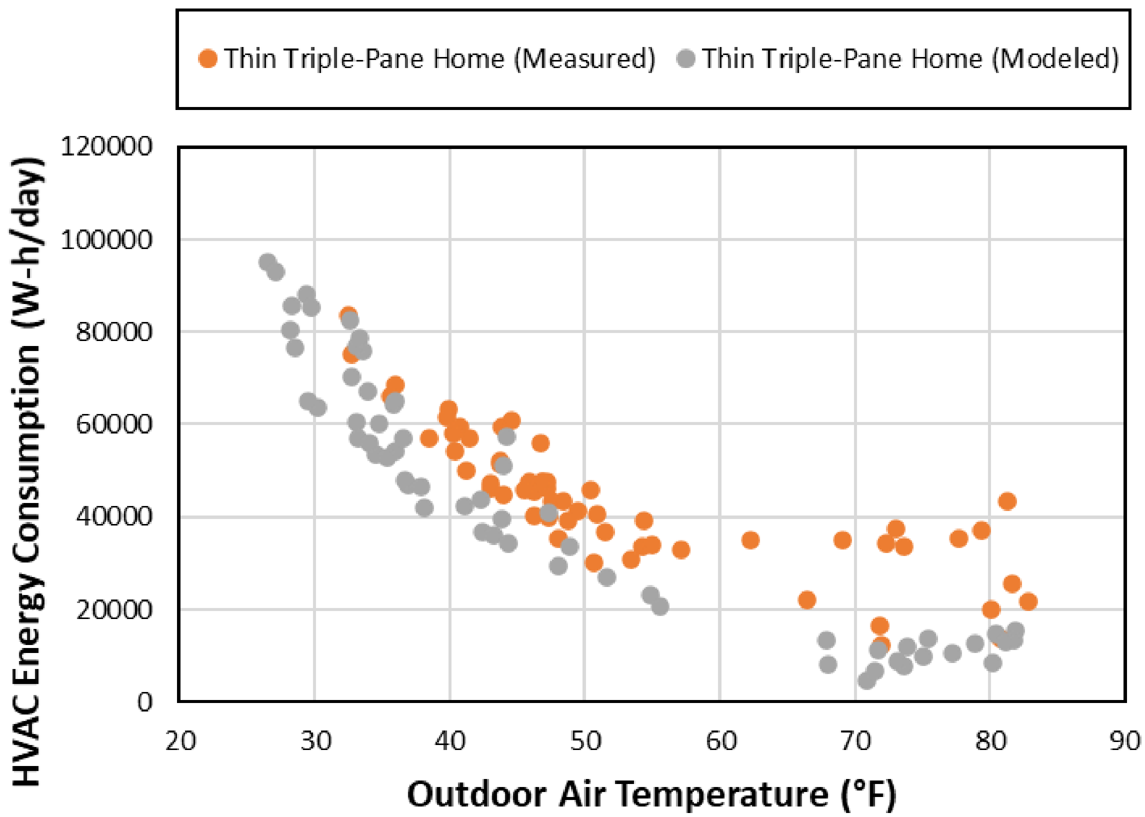


Figure 24. HVAC Energy Trends for Thin Triple-Pane Lab Home from Energy Model and Experimental Data Collection

5.0 Conclusions

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. The Lab Homes experiments 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.

5.1 HVAC Energy Savings

The experimental setup at the Lab Homes allowed for an HVAC energy comparison of the baseline double-pane windows and thin triple-pane windows using identical HVAC systems—each having a 13 SEER air-conditioner and a 15 kW electric furnace. HVAC energy savings with the thin triple-pane windows varied daily across the heating and cooling season based on the outdoor temperature and solar irradiance. Across the experimental test days, the daily HVAC savings ranged from 0.2 to 18.7 kWh (3%–18%) for the heating season experimental days and from 2.5 to 8.0 kWh (23%–41%) for cooling season data collection. When interior shading was used on winter days that featured higher outdoor solar irradiance, the HVAC savings with thin triple-pane windows increased, while the heating benefit from the sun decreased in the Baseline Lab Home. Building energy simulations estimated an average annual HVAC savings of 18.6% from the application of thin triple-pane windows.

5.2 Grid Benefits

An average HVAC peak power reduction of approximately 17% (~650 W) was observed for the Thin Triple-Pane Lab Home compared to the Baseline Lab Home during the heating season. 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. During both the heating and cooling seasons, most of the savings from the application of triple-pane windows are coincident with daily peak electricity demand in the Pacific Northwest (i.e., early morning/evening hours during the winter and late afternoon through early evening during summer months). In addition, the profile of savings observed from the application of triple-pane windows could help grid operators manage the power balance challenges associated with high amounts of variable renewable power generation, such as solar PV.

5.3 Condensation Potential

Using the dining room window of each Lab Home, condensation potential was examined based on a theoretical indoor relative humidity of 50°F and a 70°F dry-bulb temperature. For this application, the baseline dining room window had the potential for condensation on approximately 40% of the days during the winter data collection period, while the thin triple-pane had zero instances below the established dewpoint threshold where condensation could form on the window surface. Examining one of the coldest days of data collection, the baseline window exhibited greater condensation potential on the interior window surface, while the thin triple-pane window demonstrated greater condensation potential on the exterior window surface. Condensation forming on the interior or exterior window surfaces requires the surface temperature to be below the indoor or outdoor air dewpoint, respectively.

5.4 Occupant Comfort

When examining occupant comfort for a selected cold day, both Lab Homes were maintained at approximately 70°F throughout the day and throughout each room of the Lab Home; however, during the early morning and late evening hours, the interior window surfaces in the Baseline Lab Home were approximately 10°F colder than their counterparts in the Thin Triple-Pane Lab Home. Similarly, the indoor radiant temperature measurement in the Baseline Lab Home was approximately 2°F colder than Thin Triple-Pane Lab Home during the early morning and late evening hours. An occupant would be expected to be more comfortable in the Thin Triple-Pane Lab Home on the examined cold day because of the warmer window surface temperatures and generally warmer radiant temperature measurements. On hot days, the Thin Triple-Pane Lab Home experienced much more even temperatures throughout the home (aligned with the thermostat setting of 75°F) relative to the Baseline Home where mean radiant temperatures could exceed 80°F.

5.5 Sound Infiltration

Sound infiltration was examined 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.

6.0 References

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Appendix A

Photos Showing the Installation of Thin Triple-Pane Windows at the PNNL Lab Homes

This appendix contains additional photos of the installation process, as described in Section 2.7 of this report.

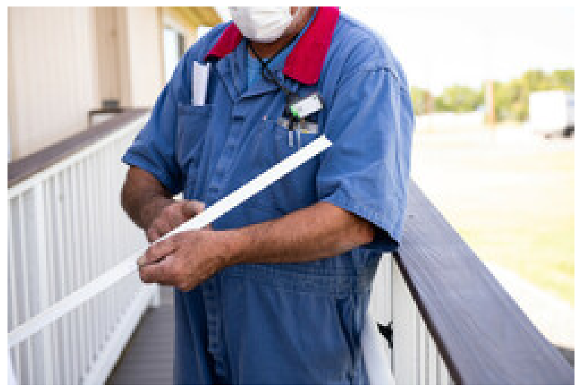

ALPEN

Appendix B

Replacement of Thin Triple IGU that Had a Cracked Interior Pane

This appendix provides a series of images that capture the high-level tasks necessary to replace the insulated glass unit (IGU) of a thin triple-pane window. The photos capture an actual thin triple-pane IGU replacement at the PNNL Lab Homes. Thin triple-pane IGUs may fit within existing double-pane framing, and therefore IGU-only replacements may be a consideration for retrofit applications.

Remove Horizontal and Vertical Framing Pieces

Loosen Glazing Bead around the Glass


Remove Old Glass from Frame

Scrap off Old Silicon Bead around Frame

Place New Silicon Bead and Setting Blocks into Frame and Place New Glass into Frame and Re-Install Framing Pieces

Appendix C

Impact Analysis of the Cracked Interior Pane of the Thin Triple-Pane Window in Bedroom 2

This appendix provides an impact analysis of the cracked interior pane of the thin triple-pane window in bedroom 2. As discussed in Section 2.7, the interior pane of the bedroom 2 thin triple was cracked during the installation process. The thin triple insulated glass unit (IGU) in bedroom 2 of the Lab Home was replaced prior to the completion of the field study, as highlighted in Appendix B. The bedroom 2 window in the Lab Homes is north-facing and does not receive direct solar irradiance. Table 8 provides a comparison of the average interior surface temperature of the bedroom 2 window two days before and after the IGU replacement along with the outdoor conditions. For the considered timeframes, the average and maximum outdoor temperatures were similar and the average interior surface temperatures were also similar. This interior surface temperature analysis along with consideration of thermal images of the bedroom 2 window and HVAC energy consumption were used to conclude that the cracked interior pane did not have a discernable impact on the overall assessment of the thin triple-pane windows.

Table C.1. Interior Surface Temperature Comparison of the Cracked Bedroom 2 Window

Data Collection Timeframe	2 Days before IGU Replacement	2 Days after IGU Replacement
Average Outdoor Temperature	74.2 °F	74.2 °F
Maximum Outdoor Temperature	92.2 °F	91.5 °F
Average Window Surface Temperature of Interior Pane	71.9 °F	71.9 °F

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