# Demonstration of the Performance of Highly Insulating (R-5) Windows in a Matched Pair of Homes

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## ABSTRACT

*Improving the insulation and solar heat gain characteristics of a home's windows has the potential to significantly improve the home's overall thermal performance by reducing heat loss (in the winter) and cooling loss and solar heat gain (in the summer) through the windows. A high-quality installation will also minimize or reduce air leakage through the building envelope, decreasing infiltration and thus reducing heat transmission through building envelope. These improvements all decrease overall annual home energy use. In addition to improvements in energy efficiency, highly insulating windows can have important impacts on occupant comfort by minimizing or eliminating the cold draft many homeowners experience near window surfaces that are noticeably cooler than the room temperature. Energy efficiency measures, such as highly insulating windows, also have the potential to decrease peak energy use in a home, which can lead to measurable peak load decreases for a utility service territory if implemented on a large scale.*

*High-performance windows now feature triple-pane glass, double low-e coatings, and vinyl insulated frames to achieve U-factors around 0.2 (the U-factor is the inverse of R-value, with units of Btu/h·ft$^2$·°F, it represents the rate of heat transfer through a material), as compared to double-pane clear glass windows with a U-factor of 0.67, which are common in existing homes across the United States. The highly insulating windows (as they will be referred to in this document) are now available from several manufacturers and have demonstrated the ability to yield considerable energy savings and thermal comfort improvements in homes.*

## INTRODUCTION

To examine the energy, air leakage, and thermal comfort performance of highly insulating (R-5) windows, a field evaluation was undertaken in a matched pair of "Lab Homes" located on the Pacific Northwest National Laboratory (PNNL) campus in Richland, Washington, during the winter heating and summer cooling seasons in 2011–2012.[1] In this field test, the energy savings from highly insulating windows in the experimental home (Lab Home B) were compared to those of the standard double-pane clear glass windows in the baseline home (Lab Home A).

In addition to the improved energy and thermal comfort performance, highly insulating windows must prove to be cost-effective compared to baseline, clear glass windows to enable significant market penetration. Based on measured and modeled energy savings, as well as installed cost data from window manufacturers, the cost-effectiveness of windows in new construction and retrofit scenarios was examined.

### The PNNL Lab Homes

The Lab Homes are factory-built,[2] all-electric, 1493 ft$^2$ (139 m$^2$) homes with 3 bedrooms/2 bathrooms and have

1. The final report for the heating and cooling season experiments can be downloaded at http://labhomes.pnnl.gov/resources.stm.

2. The homes were built at the Marlette Industries factory in Hermiston, Oregon.

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approximately 196 $ft^2$ (18.2 $m^2$) of window area. The matched pair of Lab Homes were constructed at a Marlette® Homes manufacturing plant in Hermiston, Oregon. The floor plan of the homes as constructed is shown in Figure 1.

Features of the PNNL Lab Homes that are relevant to the highly insulating windows evaluation include the following:

- all-electric
- window area: 196 $ft^2$ (18.2 $m^2$) or ~13% of the floor area
- frame: 2 in. × 6 in. (0.05 m × 0.15 m) walls; 2 in. × 10 in. (0.05 m × 0.25 m) floor and ceiling
- insulation: R-22 floors (with belly wrap), R-11 walls, R-22 vaulted ceiling, R-4.2 exterior ducts
- heating/cooling: non-setback central thermostat-controlled ducted 2.5 ton heat pump; 13 Seasonal Energy Efficiency Ratio (SEER)/8.0 Heating Seasonal Performance Factor (HSPF) with single-speed air handler; three 5 kilo-watt (kW) electrical elements, plus alternative heating provided by Cadet Model #RMC151W 120V fan wall heaters with individual thermostats[3]
- underfloor ducting (in belly of manufactured home)
- lighting: 100% incandescent
- 6 in. (0.15 m) overhang vented eaves all around
- bath fans, kitchen range hood, and whole-house exhaust fan
- wood panel siding
- carpet and vinyl flooring
- vented crawl space with Rapid Wall 2 in. (0.05 m) thick expanded polystyrene foam-backed aluminum (R-9 equivalent insulation value) with access panels
- foam-core exterior doors including an exterior access door to water heater

The homes were sited 90 ft (27 m) apart on the PNNL campus in a flat, open area with no buildings or trees near them that would create shade on the homes during any time of the year. The homes were oriented in an east/west direction with the main entry doors to the living room facing north. This orientation resulted in one sliding glass patio door facing west and the other sliding glass patio door facing south. The homes were sited such that neither house shaded the other or was affected by the other home's prevailing wind shadow.

The homes were fully instrumented to collect energy end-use and environmental data. One of the homes (Lab Home A—the baseline home) was retrofitted with standard double-pane

3. Note that the locations of the Cadet wall heaters are not shown in Figure 1. These heaters were not used/not activated during any part of the highly insulating windows winter evaluation.

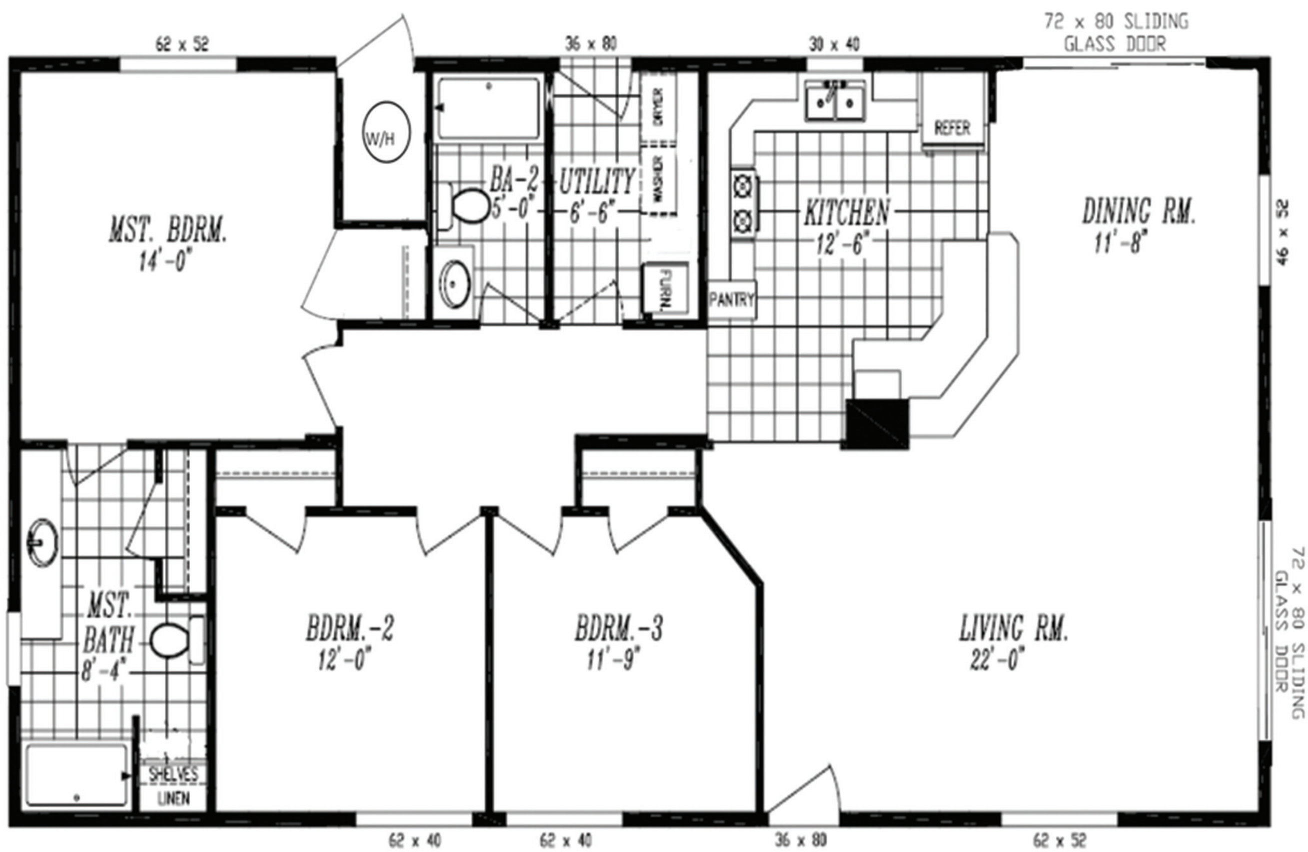


***Figure 1*** *Floor plan of the Lab Homes as constructed.*

clear aluminum-frame slider windows and patio doors typically found in many existing homes built in the decades of the 1960s through 1980s throughout the Pacific Northwest (PNW) region and across the country.[4] The other home (Lab Home B—the experimental home) was retrofit with Jeld-Wen® triple-pane vinyl-frame slider windows and patio doors. The retrofit windows' characteristics are given in Table 1. The homes are identical in every way except for the windows, including simulated occupancy and weather variations. Thus, all variations in energy use and temperature distributions are directly a result of the difference in window performance. This type of side-by-side experiment provides a degree of accuracy and precision in the results that pre-/post-assessments do not afford.

4. These double-pane clear windows are typical of many windows installed in homes across the country in the late 60s through the late 90s. They were also the 2006–2012 Federal Housing and Urban Development (HUD)-mandated nationwide minimum code for manufactured housing (see http://www.gpo.gov/fdsys/pkg/CFR-2003-title24-vol1/content-detail.html).

## Metering and Monitoring

The approach to the metering included metering and system-control activities taking place at both the electrical panel and at the end-use or point of use. Monitoring was broken into electrical (Table 2) and temperature/other (Table 3). Tables 2 and 3 highlight the performance metric (the equipment/system being monitored), the monitoring method and/or point, the monitored variables, and the data application

**Table 1. Window Performance Characteristics of the Windows in Lab Home A (Standard Retrofit Windows and Patio Doors) and Lab Home B (Highly Insulating Windows and Patio Doors) Retrofit in the Lab Homes**

| Value | Lab Home A Standard Retrofit Windows | | Lab Home B Highly Insulating Retrofit Windows | |
|---|---|---|---|---|
| | Windows | Patio Doors | Windows | Patio Doors |
| U-factor | 0.68 | 0.66 | 0.20 | 0.20 |
| SHGC[(a)] | 0.70 | 0.66 | 0.19 | 0.19 |
| VT[(b)] | 0.73 | 0.71 | 0.36 | 0.37 |

(a) Solar heat gain coefficient
(b) Visible transmittance

**Table 2. Electrical Points Monitored**

| Performance Metric | Monitoring Method/Points | Monitored Variables | Data Application |
|---|---|---|---|
| Whole Building Energy Use | Electrical panel mains | kW, amps, volts | Comparison and difference calculations between homes of: • power profiles • time-series energy use • differences and savings |
| Heating/ Cooling Energy Use (Heat Pump) | Panel metering compressor | kW, amps, volts | Comparison and difference calculations between systems of: • power profiles • time-series energy use • differences and savings |
| | Panel metering air handling unit | kW, amps, volts | |
| | End-use metering condensing unit (CU) fan/controls | kW, amps, volts | |
| Ventilation Energy Use (Ventilation) | Panel metering of 3 ventilation breakers (2 bathroom and whole-house fans) | kW, amps, volts | Comparison and difference calculations between systems of: • power profiles • time-series energy use • differences and savings |
| Water Heating | Panel metering of water heater breakers | kW, amps, volts | Comparison and difference calculations between systems of: • power profiles • time-series energy use • differences and savings |
| Appliances and Lighting | Panel metering of each individual appliance and lighting breakers | kW, amps, volts | Comparison and difference calculations. |

**Table 3. Temperature and Environmental Points Monitored**

| Performance Metric | Monitoring Method/Points | Monitored Variables | Data Application |
|---|---|---|---|
| Space Temperatures | 13 Ceiling-hung thermocouples/1–2 sensors per room/area, and 1 duct supply temperature per home | Temperature, °F (°C) | Comparison and difference calculations between homes of:<br>• temperature profiles<br>• time-series temperature changes |
| | 2 mean radiant sensors per home (main living area, master bedroom) | Temperature, °F (°C) | |
| Space Relative Humidity (RH) | 2 percent-relative-humidity sensors per home (main living area, hall outside of bathroom) | % rh | Comparison and difference calculations between homes of:<br>• RH profiles<br>• time-series RH changes |
| Glass Surface Temperatures | 22 thermocouples (2 sensors per window interior/exterior center of glass); west window with 6 sensors | Temperature, °F (°C) | Comparison and difference calculations between homes of:<br>• temperature profiles<br>• time-series temperature changes |
| Mean Radiant Temperature | 2 mean radiant temperature sensors (black body) per home (master bed-room and living room) | Temperature, °F (°C) | Comparison and difference calculations between homes of:<br>• temperature profiles<br>• time-series temperature changes |
| Through-Glass Solar Radiation | 1 pyranometer sensor per home trained on west-facing window | Watts/m$^2$ | Comparison and difference calculations between homes of profiles by window and location |
| Meteorological Station | Package station mounted on Lab Home B | Temperature, °F (°C)<br>Humidity, %<br>Wind speed, m/s (ft/s)<br>Wind direction<br>Barometric pressure, mm<br>Rainfall, in. (m) | Analytical application to quantify setting and develop routines for application to other climate zones |

for the electrical monitoring points and the temperature and environmental monitoring points, respectively.

All metering was done using Campbell® Scientific data loggers and matching sensors. Two Campbell data loggers were installed in each home, one allocated to electrical measurements and one to temperature and other data collection. Data from all sensors were collected via cellular modems that were individually connected to each of the loggers. The polling computer located in the metering lab on the PNNL campus connected to each logger using Campbell Scientific software.

In a parallel effort, occupancy in the homes was simulated via programmed access to a custom-designed 42-circuit breaker panel (one per home) using motorized breakers. These breakers were programmed to activate connected loads on schedules to simulate human occupancy.

## EXPERIMENT AND RESULTS

Building shell air leakage was measured prior to and after the windows retrofit to determine whether there was any difference in the air leakage of the windows or installation techniques. Prior to the windows retrofit and after the metering equipment and sensors were installed in the homes, the blower door test results show the air leakage of the two homes to be statistically the same, with 95% confidence. The homes are both fairly tight, which is typical of the manufactured housing industry in the PNW. Lab Home A has leakage of 657.6 ± 27.8 cubic feet/minute (CFM) at 50 Pascals depressurization (CFM50) and Lab Home B has an air leakage of 701.4 ± 26.7 CFM50, normalized for exterior weather conditions. These values correspond to 0.15 ± 0.01 natural air changes per hour ($ACH_n$) in Lab Home A and 0.16 ± 0.01 $ACH_n$ in Lab Home B.

The windows in Lab Home B were retrofitted by the general contractor (GC) with technical assistance and materials (foam sealant and window drain mat material) provided by Jeld-Wen, Inc. The Jeld-Wen, Inc. staff ensured installation was in accordance with the documented recommendations for these windows. The windows in Lab Home A were retrofitted by the same GC staff using standard caulking technique and no special flashing or additional materials.

In Lab Home B, air leakage, as characterized by the CFM50 depressurization with respect to the outside, decreased 46.4 ± 34.9 cfm50 or 6.9%. Conversely, air leakage in Lab Home A increased 50.3 ± 34.1 cfm50. While the total error is large in comparison to the magnitude of the change, the overall impact of these changes was statistically significant with 95% confidence.[5] This decrease in air leakage in Lab Home B is attributed primarily to the quality of the installation given that the air leakage (AL) rating of the highly insulating windows and patio doors (AL = 0.3 cfm/ft$^2$) is greater than the factory-supplied windows and patio doors (AL=0.1 cfm/ft$^2$).[6] This is, therefore, compelling evidence of the positive impact of the installation of the retrofit windows on home air leakage.

Prior to initiating the summer cooling season experiment, the air leakage in both homes was retested to determine the persistence of improved air leakage resulting from the windows installation. The measured air leakage was 660.1 ± 21.2 CFM50 in Lab Home A and 622.9 ± 21.9 CFM50 in Lab Home B after normalizing for outdoor weather conditions. These numbers show that the statistically significant difference in air leakage between Lab Home A and Lab Home B was maintained, with the leakage in Lab Home B being less than Lab Home A. However, the values have decreased slightly in both homes, as shown in Table 4.

## Winter Heating Season Results

During the heating season study period, the Lab Homes were operated in a number of configurations including with and without occupancy simulation, in heat pump (HP) and electric resistance (ER) heating modes, and at two different interior thermostat setpoints. Comparing the periods without occupancy simulation to comparable periods after occupancy simulation was introduced, the savings decrease approximately 2.5% when occupancy is introduced, as shown in Table 5. This decrease is logical, as one would expect increased energy use of equivalent magnitudes from the identical occupancy simulations in both homes and the resulting decrease in relative whole house energy savings because the magnitude of savings is diluted by increased internal electrical loads. However, this difference is not statistically significant due to the variation in savings based on other factors, such as outdoor air temperature and solar insolation.

When comparing savings from periods when the HP mode was providing heating versus ER mode, no statistically significant difference was observed. In HP mode, the ER elements were still enabled and cycled to provide heating during extremely cold periods.

## Combined Heating and Cooling Energy Savings

The measured energy savings in Lab Home B averaged 5821 watt-hours per day (Wh/day) during the heating season and 6518 Wh/day during the cooling season. The overall whole-house energy savings of Lab Home B compared to Lab Home A are 11.6% ± 1.53% for the heating season and 18.4% ± 2.06% for the cooling season. Extrapolating these energy savings numbers based on typical average annual heating degree days (HDD) and cooling degree days (CDD) for Pasco, Washington yields an estimated annual energy savings of 12.2%, or 1784 kWh/yr (see Table 6).

In addition to increasing the thermal performance of the windows, low-e coatings[7] also affect the solar heat gain through the windows. The highly insulating windows

5. Assuming a normal distribution of the data, the null hypothesis is rejected.

6. The AL rating of the retrofit windows in Lab Home A is unknown because this attribute was not included in the windows certification data the manufacturer provided to PNNL.

**Table 4. Building Shell Leakage in the Baseline and Experimental Homes Before Window Retrofits, After Window Retrofits, and Prior to Initiation of the Summer Experiment**

| | Baseline Home | ± Error | Experimental Home | ± Error |
|---|---|---|---|---|
| **Null Data** | | | | |
| CFM25 | 477.4 | 30.4 | 478.5 | 30.5 |
| CFM50 | 638.5 | 27.8 | 681.1 | 26.7 |
| ACH50 | 3.07 | 0.13 | 3.28 | 0.13 |
| $ACH_n$ | 0.14 | 0.01 | 0.15 | 0.01 |
| **Post-Windows Install** | | | | |
| CFM25 | 446.9 | 19.0 | 372.8 | 15.7 |
| CFM50 | 690.8 | 24.6 | 639.3 | 22.5 |
| ACH50 | 3.32 | 0.12 | 3.08 | 0.11 |
| $ACH_n$ | 0.15 | 0.01 | 0.14 | 0.01 |
| **Prior to Summer Experiment** | | | | |
| CFM25 | 432.8 | 17.7 | 401.8 | 26.3 |
| CFM50 | 660.1 | 21.2 | 622.9 | 21.9 |
| ACH50 | 3.18 | 0.10 | 3.00 | 0.11 |
| $ACH_n$ | 0.15 | 0.005 | 0.14 | 0.005 |

**Table 5. Average Heating Season Energy Savings and 95% Confidence Interval from Highly Insulating Windows in Different Operating Scenarios: With and Without Occupancy Simulation and in HP Versus ER Heating Modes**

| Operating Scenario | Average Savings, Wh* | 95% Confidence Interval, Wh | Average Savings, % | 95% Confidence Interval, % |
|---|---|---|---|---|
| Without Occupancy Simulation | 9392 | 4611 | 14.3 | 5.23 |
| With Occupancy Simulation | 4420 | 1025 | 11.7 | 2.08 |
| ER Mode (with occupancy simulation) | 7137 | 2348 | 10.4 | 2.96 |
| HP Mode (with occupancy simulation) | 4420 | 1023 | 11.7 | 2.08 |

* Watt-hours (Wh)

**Table 6. Average Daily Energy Use and Energy Savings in the Heating Season and Cooling Season**

| | | Average Daily Energy Use, (Wh) | Average Daily Energy Savings, (Wh) | Average Daily Energy Savings, (%) |
|---|---|---|---|---|
| Heating Season | Lab Home A (Baseline) | 47,599 | 5821 ± 1054 | 11.6 ± 1.53 |
| | Lab Home B (Experimental) | 41,896 | | |
| Cooling Season | Lab Home A (Baseline) | 35,572 | 6518 ± 842 | 18.4 ± 2.06 |
| | Lab Home B (Experimental) | 29,055 | | |

installed in Lab Home B have a very low SHGC compared to the clear glass windows in Lab Home A, as shown in Table 1, which was found to decrease the solar insolation measured on the inside of window by 83.2% in Lab Home B compared to Lab Home A. An analysis of the whole-house energy use in Wh versus solar insolation in watts per square meter (W/m$^2$) for Lab Home A and Lab Home B revealed that increased solar insolation decreased whole-house energy use in the winter and increased whole-house energy use in the summer. The difference in solar heat gain also affected the whole-house energy savings.

Data analysis of whole-house energy savings on overcast days during the heating season showed energy savings for Lab Home B compared to Lab Home A of 14.6% ± 1.86%, while the energy savings on clear days are 8.9% ± 1.42%. In the summer, days are much more consistently sunny in Richland, Washington, so the impact of solar insolation cannot be as clearly observed. However, the energy savings appear to be more correlated to outdoor air temperatures, with higher temperatures yielding higher savings. Also, the high savings observed in the cooling season (18.4% ± 2.06%) indicate that both the low U-factor and low SHGC are contributing to savings during the hot summer days.

## Energy Modeling

A representative EnergyPlus model was created for the Lab Homes to compare modeled savings from the highly insulating windows to measured results. The EnergyPlus analysis was run with typical weather data for the nearby Pasco, Washington, airport station to show average whole-building energy savings in Lab Home B from the highly insulating windows to be 13.9% during the heating and cooling season experimental periods (February 2012 to April 2012 and July to August 2012). These results agree fairly well with measured data, which indicated weighted average[8] savings of 14.4% ± 2.57% in Lab Home B versus Lab Home A for the combined heating and cooling test periods. The EnergyPlus model was also used to predict annual savings from the highly insulating windows using typical occupancy patterns and thermostat setpoints. The EnergyPlus model predicts 13.2% annual savings, or 1370 kWh/yr.

7. Low-emittance (low-e) coatings are microscopically thin, virtually invisible, metal or metallic oxide layers deposited on a window surface primarily to reduce the heat loss through the glass by suppressing radiative heat flow. The principal mechanism of heat transfer in multilayer glazing is thermal radiation from a warm pane of glass to a cooler pane. Coating a glass surface with a low-e material and facing that coating into the gap between the glass layers of multi-pane windows blocks a significant amount of this radiant heat transfer, thus lowering the total heat flow through the window.

8. Due to the fact that the heating season and cooling season test periods were different length, the average of the heating and cooling season is weighted based on the number of days in each test period.

### Peak Load Reduction

Another impact of reduced energy use that is important to mention from a utility and resource planning perspective is the ability to reduce peak load (kW). Figure 2 depicts peak load impacts due to installation of the highly insulating windows in the experimental home over a representative one-week time period in the summer. The impact on peak load is significantly more than the average daily energy savings, reducing the peak power consumed on an hourly basis in the home with highly insulating windows (Lab Home B) by 24.7% ± 0.1% over the entire cooling experiment study period. This is higher than the average observed daily savings because the peak load reduction represents a maximum real-time savings, rather than an average savings. Peak power savings occur, typically, between 10:00 a.m. and 6:00 p.m. when the overall grid demand is highest, as shown in Figure 2.

Peak load savings were also measured in the heating season. Average hourly peak savings for the heating season were 33.9% ± 0.6%. However, these savings occurred in the nighttime hours when outdoor air temperatures were coldest, which does not typically correspond with utility peak demand periods. The grey line shows the load curve, in megawatts (MW), for the Bonneville Power Administration service territory, for July 6 through July 13, 2011, since 2012 data was not available at the time of publication. While the load shape changes in the winter months, peaks still occur during the day, which juxtaposes the periods of peak demand in the Lab Homes during the winter heating season.

### Thermal Comfort

In addition to yielding energy savings, the highly insulating windows in Lab Home B exhibited much more consistent indoor temperatures than Lab Home A. For example, on a sunny day in February, the average indoor temperatures in the kitchen of Lab Home A reached a balmy 84°F (28.9°C), while Lab Home B reached only 78°F (25.6°C), within 3°F (1.67°C) of the 75°F (23.9°C) thermostat setpoint. The average outside temperature on this day was 39°F (3.9°C). This could cause a comfort problem for any occupants at home during this time, even during these cold winter months.

In the summer, comfort problems also were observed. Measured indoor temperatures reached 73°F (22.8°C), 3°F (1.67°C) above the 70°F (21.1°C) thermostat setpoint, on several days in Lab Home A, indicating that the heat pump is undersized for the load on this home with clear glass windows and no window coverings, while the heat pump in Lab Home B (also with no window coverings) was able to maintain an average interior temperature of 70°F (21.1°C) on most days, which was consistent with the 70°F (21.1°C) thermostat setpoint. Also, the temperature rise in Lab Home A caused increased overcooling in some rooms with the shortest duct runs, where temperatures as cool as 63°F (17.2°C) were observed. The outdoor temperature typically reached 90°F to 100°F (32.2°C to 37.8°C) during the cooling season experimental period.

The window surface temperatures also affect comfort in the home felt by occupants, particularly in the winter. A window with a colder surface temperature is noticeable to an

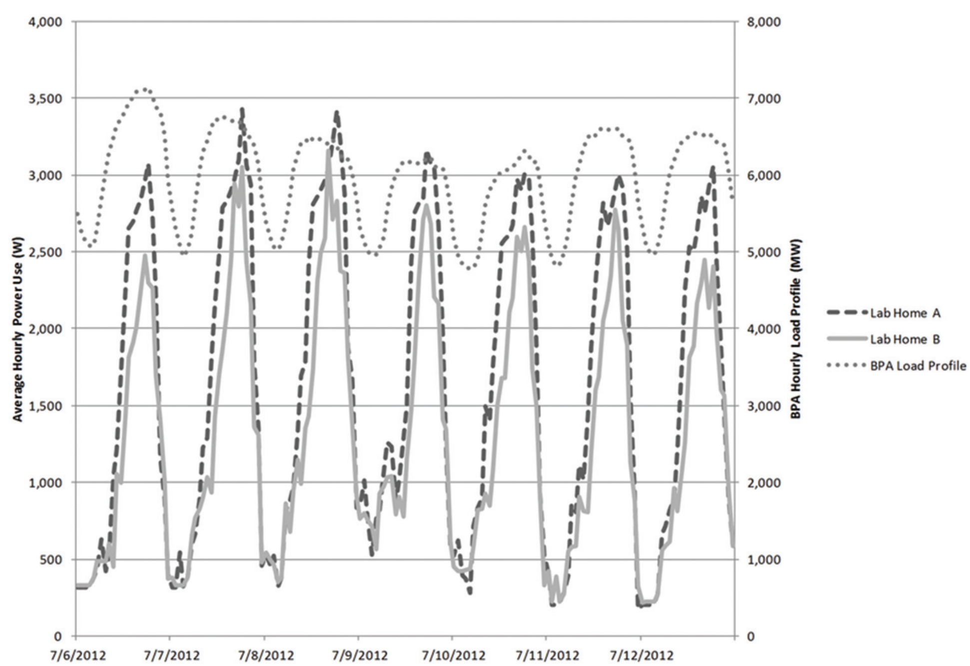


***Figure 2*** *Average hourly power use for Lab Home A (dashed), Lab Home B (solid), and the Bonneville Power Administration Load Curve (dotted) during a 1-week Period from July 6 to July 13, 2012 (Note: the Bonneville Power Administration data is for the same days in 2011 since 2012 data was not available at the time of publication).*

occupant (near the window area) even though the room dry bulb temperature may be at a comfortable level, due to convective and radiative heat transfer from the occupant to the cooler air near the window or cooler window surface temperatures. This effect is apparent in the Lab Homes, as illustrated by the dramatically cooler window surface temperatures observed in Lab Home A (baseline home); temperatures as low as 50°F (10°C) recorded on the west-facing living room window. In the Lab Home B (experimental home), the highly insulating window's surface temperature never dropped below 60°F (15.6°C)—the lowest temperature measured on the same window. When considering the average interior glass surface temperature measurement of all the windows over the heating season, a difference of 7°F (3.89°C) is observed, with an average interior glass surface temperature of 68.7°F ± 0.05°F (20.4°C ± 0.03°C) in the baseline home compared to 75.7°F ± 0.04°F (24.3°C ± 0.02°C)—almost exactly the interior thermostat setpoint—in the experimental home.

Mean radiant temperature (MRT) is also a measured proxy for thermal comfort/discomfort resulting from the radiant heat exchange between an occupant (a body) and surrounding surface temperatures such as the surface temperature of a window or a wall. Each Lab Home has two MRT sensors: one located in the master bedroom and one in the northwest corner of the living room. The average indoor MRT in Lab Home A and Lab Home B was determined after the windows retrofit over a 1-week time period when the radiant temperature loss was most extreme. During this week the outside temperature averaged 49°F (9.4°C), with a maximum of 65°F (18.3°C) and a minimum of 35°F (1.67°C), and the interior thermostat setpoint was 80°F (26.7°C).[9]

The average MRT in Lab Home A during the nighttime period during the week when radiant heat loss was most extreme was 79.0°F ± 0.02°F (26.1°C ± 0.01°C) in both the master bedroom and the living room compared to an average room temperature of 80.2°F ± 0.11°F (26.8°C ± 0.06°C). The average MRT of both the living room and master bedroom was 1.63°F ± 0.01°F (0.91°C ± 0.01°C) lower than the average interior room temperature in Lab Home A. The maximum MRT recorded in Lab Home A was 86.3°F (30.2°C) and the minimum MRT was 77.0°F (25.0°C).

In Lab Home B the average MRT in the living room and master bedroom was 1.64°F ± 0.01°F (0.91°C ± 0.01°C) lower than the average room temperature of 80.4°F ± 0.01°F (26.9°C ± 0.01°C) in the living room and master bedroom. The maximum MRT recorded in Lab Home B was 81.7°F (27.6°C) and the minimum MRT was 77.7°F (25.4°C). Overall, the average nighttime MRT in Lab Home B was slightly warmer than the average MRT in Lab Home A during the nighttime periods when radiant heat loss is most extreme, but the difference was small. However, the combined impact of decreased mean radiant temperature and surface glass temperatures can have a profound impact on occupant comfort. Also, the maximum MRT recorded in Lab Home B was much lower than Lab Home A during sunny afternoons, even when the outdoor temperatures where quite cool.

### Condensation/Moisture on Windows

Condensation on windows is of concern to homeowners and can be a health issue because moisture can lead to mold growth. A direct measurement was not made of condensation or moisture on windows in either Lab Home A or Lab Home B.[10] However, using the windows' inside surface temperature measurements allowed a calculation of the potential for condensation to form on the windows. An interior window temperature as low as 50°F (10°C) was recorded in Lab Home A, while the lowest interior window temperature was 60°F (16°C) in Lab Home B. With these temperatures and an average interior room temperature of 75°F (24°C), the relative humidity of the air in Lab Home B would have to exceed 70% to cause condensation on the highly insulating windows, while a relative humidity of 40% or more would cause condensation on the double-pane windows in Lab Home A. However, condensation was not a concern due to the dry climate in Richland. The average measured relative humidity in the heating season was 20.7%, with a maximum of 31.7%, in Lab Home A, and it was 21.7%, with a maximum of 28.1% in Lab Home B. During the cooling season, similarly low indoor relative humidities were observed. In addition, the warm interior glass temperatures do not cause concerns related to the potential for condensation in the cooling season.

### Windows Cost

While the highly insulating windows show significant energy savings compared to the baseline windows, the capital cost of windows must also be considered to determine the cost-effectiveness of highly insulating windows as an energy efficiency measure. The capital cost of highly insulating windows, as delivered, was used to determine the cost effectiveness of windows in a retrofit scenario. An incremental cost, compared to code minimum windows,[11] was also considered for new construction or if windows are being replaced for another reason (e.g., safety, functionality, aesthetics). In the incremental cost scenario, installation cost is not included and only the material cost difference between code minimum and highly insulating (triple-pane) windows is used.

The costs of purchasing the highly insulating windows was obtained from the window distributor as $6,243 or $32/ft$^2$.[12] However, window costs are highly variable and, thus, these

9. The thermostat setpoint was increased for some periods of the study to maintain a consistent temperature differential between the indoors and outdoors (approximately 70°F) throughout the heating season data collection period.

10. Humidity to represent occupants and occupant activity was not generated in the Lab Homes for this experiment.

11. Minimum code for the State of Washington Climate Zone 1 is 0.32 U-factor and 0.40 SHGC.

costs were compared with other manufacturers and other windows types, to ensure the costs were representative of the range of window costs observed in the retrofit market. A delivered (to the PNW) cost range for highly insulating slider windows and patio glass doors in small quantities for retrofit was obtained from the vendors participating in the US Department of Energy (DOE) Windows Volume Purchase Program who sell a product line of sliders and patio doors.[13] Observed window costs were highly variable and ranged from approximately $10/ft$^2$ to $100/ft$^2$ ($108/m$^2$ to $1,076/m$^2$). Although manufacturers were asked for data representing delivered costs (not including installation), it is assumed that higher costs represent window costs which include installation costs. Removing extreme values, average windows cost data for highly insulating windows and sliding glass doors in small quantities for retrofit from the Windows Volume Purchase Program ranged from $25/ft$^2$ to $46/ft$^2$, with an average cost of $34/ft$^2$.[14] Installation and materials costs were estimated at $3/ft$^2$ ($32/m$^2$) based on the demonstrated retrofit costs of installing the windows at the Lab Homes. However installation costs, similar to all contractor bids, can also be considerably variable. Using an installation cost of $3/ft$^2$ ($32/m$^2$), the total installed cost for the highly insulating windows and sliding glass doors in Lab Home B was estimated to be $4,900 to $9,000. This range is consistent with the cost for retrofitting (purchasing and installing) double-pane, clear glass, aluminum-frame windows with triple-pane, low-e, vinyl-framed windows listed in the National Residential Efficiency Measures Database, maintained by the National Renewable Energy Laboratory of $21/ft$^2$ to $55/ft$^2$ ($226/m$^2$ to $592/m$^2$), with an average of $33/ft$^2$ ($355/m$^2$).

Based on these costs and the modeled annual savings of 1370 kWh/yr, the payback period (PBP) for highly insulating windows ranges from 30 to 55 years, for the low to high cost estimates, respectively, as shown in Figure 3. Using the extrapolated measured data to estimate annual savings, a savings of 1784 kWh/yr, the PBP ranges from 23 to 42 years.

If the highly insulating windows were installed in a new home or windows are already being replaced for another reason (i.e., safety, operability, aesthetics), the incremental cost of the windows over a code minimum window should be considered and installation costs can be ignored. The incremental cost of highly insulating windows is estimated to be approximately $4/ft$^2$ ($42/m$^2$) and ranges from $2/ft$^2$ to $6/ft$^2$ ($17/m$^2$ to $63/m$^2$). Using the average value, the total incremental cost for highly insulating windows is estimated to be $1,372 for a home with the same window area as the Lab Homes (196 ft$^2$; 18.2 m$^2$). Based on the modeled incremental annual energy savings of highly insulating windows over code minimum windows of 363 kWh, the PBP is 32 years.

12. This price was obtained from the invoice from the local window supplier for the specified windows and sliding glass doors.

13. The window vendors selected for estimating costs from the qualified vendors in the Windows Volume Purchase Program were vendors who offered horizontal sliders and patio doors and who sold or delivered products in the Pacific Northwest. An average cost per square foot across the multiple sizes of windows in Lab Home B was determined.

14. To provide an average range for window costs, extreme outliers were removed from the cost data in the windows volume purchase program, and lower and higher averages (averages of lower 50% of data and of higher 50% of data, respectively) were taken to bound the average value.

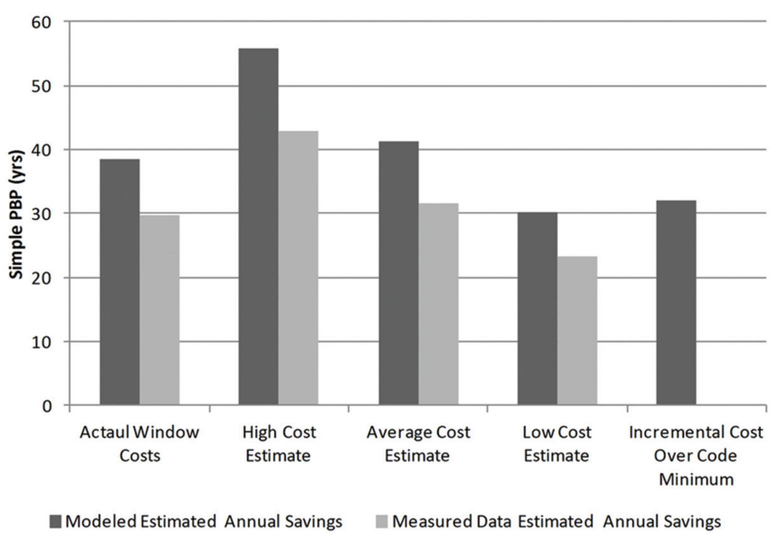


***Figure 3*** *Simple PBP for R-5 windows for a retrofit or in an incremental cost scenario. Costs considered are the actual windows costs as retrofit in the Lab Homes; a high, average, and low cost estimate based on data in the DOE Windows Volume Purchase Program; and incremental cost over code minimum windows. Modeled and an estimate of annual energy savings are calculated.*

## CONCLUSIONS

The side-by-side assessment in the PNNL Lab Homes demonstrates that highly insulating windows show considerable energy savings when compared to double-pane clear glass windows. These energy savings may also contribute to reduced peak energy load, especially in the cooling season, if implemented on a large scale. Highly insulating windows show more consistent interior temperature distributions and improved thermal comfort because interior glass surface temperatures are much closer to interior dry bulb temperatures. Increased glass surface temperatures in the winter could also decrease the risk of condensation and mold issues in regions where high humidity exists. Based on windows cost data available from manufacturers via the Windows Volume Purchase Program and a local cost of electricity, highly insulating windows have a simple PBP of 23 to 55 years. The range is primarily due to the large variability in primary window costs.

These data suggest that highly insulating windows are an effective energy-saving measure that should be considered for high-performance new homes and in existing retrofits. However, the cost effectiveness of the measure, as determined by the simple PBP, suggests that highly insulating window costs continue to make windows difficult to justify on a cost effectiveness basis alone. Additional reductions in costs via improvements in manufacturing and/or market penetration that continue to drive down the manufacturing cost of highly insulating windows will make this technology much more viable as a cost-effective energy efficiency measure.

This study also illustrates that highly insulating windows have important impacts on peak load, occupant comfort, and condensation potential, which are not captured in the energy savings calculation. In addition, more consistent and uniform interior temperature distributions suggest that highly insulated windows, as part of a high performance building envelope, may enable more centralized duct design and downsized heating, ventilation, and air-conditioning systems. Shorter, more centralized duct systems and smaller heating and cooling equipment could yield additional cost savings, making highly insulating windows more cost effective as part of a package of new construction or retrofit measures that achieve significant reductions in home energy use.

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## FOR FURTHER INFORMATION

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