U.S. DEPARTMENT OF ENERGY

PNNL-22855

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

Characterization of Energy Savings and Thermal Comfort Improvements Derived from Using Interior Storm Windows

JR Knox
SH Widder

September 2013

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Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

This report records the results of a field study conducted in a single historic home in Seattle, Washington, to document the performance of Indow® Windows' interior storm window inserts. The energy use and thermal performance of the house were monitored before and after the installation of the window inserts and changes in the two recorded metrics were examined. Using the defined analysis approach, it was determined that the interior storm windows produced a 22% reduction in heating, ventilation, and air-conditioning energy use and reduced building envelope leakage by 8.6%. While there were no measurable changes in the thermal comfort of the house, the occupant noted the house to be "warmer in the winter and cooler in the summer" and that the "temperatures are more even (throughout the house)."

Despite the significant energy savings that resulted from the installation of interior storm windows, the payback period for this investment was extensive (approximately 80 years) due in part to the upfront cost of the Indow Window inserts as well as relatively low baseline heating bills of the case study home. Prior to the installation of interior storm window inserts, the case study home had implemented a series of energy-saving retrofits, which included replacing the home's heating and cooling system with a high-efficiency heat pump, duct sealing, air sealing, and additional insulation. If the Indow Windows interior storm window inserts had been installed prior to these retrofits (e.g., house heated with an older, inefficient oil-fired furnace) and the same economic analysis was conducted, the interior storm window inserts would have resulted in a simple payback period of 9.0 years.

This field study has added to the body of knowledge about interior storm windows by presenting the measureable energy savings and evaluating the claims of increased thermal comfort. Additional studies are needed to fully document the performance of interior storm windows across a variety of building types and climate zones.

Acknowledgments

The authors acknowledge the guidance and support of Eric Werling and Sam Rashkin of the U.S. Department of Energy Building Technologies Program in sponsoring this work. The team is most appreciative of the homeowner who chose to invest in energy performance and comfort by purchasing the Indow Windows interior storm window inserts and who decided to participate in this study. This work would not be possible without this motivated individual who opened up her home to the research team, answered numerous questions, and showed incredible patience in participating in the research study. The PNNL research team was assisted by local building science professionals Dan Wildenhaus and Jeff Carter of Fluid, who assisted in assessing this home. The authors are also indebted to Katherine Cort of PNNL and Stuart Rosenfield of Indow® Windows, who provided excellent technical review and feedback on this work.

Acronyms and Abbreviations

B	basement
Btu/(h ft^2 °F)	British thermal units per hour per square foot per degree Fahrenheit
CDD	cooling degree day
CFM50	cubic feet per minute at 50 pascals of depressurization with respect to the outside
CT	current transformer
°F	degrees Fahrenheit
ft^2	square feet
gal	gallon(s)
HDD	heating degree day
HSPF	heating seasonal performance factor
HVAC	heating, ventilation, and air-conditioning
kWh	kilowatt-hours
low-E	low-emissivity
MB	master bedroom
OAT	outdoor air temperature
Off	office
RH	relative humidity
SEER	seasonal energy efficiency ratio
SR	sunroom
TMY	typical meteorological year
yr	year

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1.0 Introduction

Energy use in residential homes has increased over the past several decades and now accounts for 22% of total energy use in the United States (EIA 2012). Because the public's desire to decrease overall energy demand is growing (Akerlof et al. 2010), attention is focused on making the residential sector more energy efficient. During the current downswing in new residential construction (U.S. Census Bureau 2011), retrofitting existing homes to save energy has become the focus of new energy-efficiency programs. One focus of new energy efficiency programs is improving the efficiency of existing windows. Windows, while serving an important function in homes, are "holes" in a building's shell due to their low R-value[1]. However primary windows are very expensive to replace, which often means windows are overlooked or not addressed during home energy retrofits. New interior and exterior storm windows offer a low-cost alternative to primary window replacement. Preliminary field evaluations have demonstrated that exterior clear storm windows can save 13% on heating energy use and a similar product with low-emissivity (low-E) coating can reduce heating energy use by 21% (Drumheller, et al. 2009). Storm windows, as a mature technology, have the ability to dramatically and cost-effectively improve window performance in existing homes. However, storm windows currently have low market penetration because of the lack of information about the performance of current products.

Storm windows are available as exterior and interior installations. In fiscal year 2013 (FY13), Pacific Northwest National Laboratory (PNNL) is conducting research to document exterior low-E storm window performance in the PNNL Lab Homes,[2] develop models based on collected performance data to extrapolate storm window performance to climate zones across the nation, and further the market penetration of low-E storm windows across the nation.

In a related activity, PNNL is also exploring the performance of interior storm windows in terms of energy savings and comfort in a home in Seattle, Washington. The house was built near the turn of the century and has 27 original, single-pane wood-framed windows. The home underwent significant retrofits as part of the Building America Deep Energy Retrofit Research Project[3] in 2011 and 2012 and, as part of that project, has existing disaggregated energy metering and interior temperature and relative humidity measurements at several locations (Blanchard et al. 2012). One year after completion of the first phase of deep energy retrofits, the homeowner chose to install Indow® Windows interior storm window inserts[4] to address a condensation issue that had occurred since the completion of the first phase of retrofits and further improve the performance of the home. Leveraging this existing metering infrastructure PNNL initiated this research effort to evaluate the impact of Indow Windows interior storm window inserts on energy performance and thermal comfort in this Seattle home.

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[1] R-value is a measure of thermal resistance through a material and is determined as the ratio of the temperature difference across the material and the heat transfer per unit area of the material. It is the inverse of U-value, which is the overall heat transfer coefficient.

[2] Two custom factory-built double-wide homes set up, side by side, on the PNNL campus to conduct energy research. http://labhomes.pnnl.gov/

[3] http://deepenergyretrofits.pnnl.gov/

[4] http://www.indowwindows.com/

An Indow Windows interior storm window insert[1], like all storm windows, is designed to be an alternative to a replacement window, with similar performance, but at a fraction of the cost. A previous study of the Indow Windows interior storm window found that the insert reduces the U-value[1] of a single pane glass window from 1.005 to 0.5507 British thermal units per hour per square foot per degree Fahrenheit (Btu/[h ft^2 °F])[2], a reduction of 45% (Sailor 2013). In a field study, also completed by Sailor, that included four homes in the Portland, Oregon area, the Indow Windows inserts reduced infiltration by an average of 5.4% and lowered the heating bills by an average of 19% (2013).

Data collected in this field evaluation will add to the body of knowledge regarding the field performance of the Indow Windows interior storm window inserts. The data can then be compared to the similar data on low-E exterior storm windows that PNNL is collecting at the PNNL Lab Homes, as well as provide more information on the field performance of storm window products. Documentation of the benefits of storm windows, interior or exterior, can contribute to increased market penetration of these products and increased energy savings in existing homes.

The ensuing sections of this report describe the field results to date of an evaluation of Indow Windows' interior storm window inserts installed in a home in Seattle in March 2013. Specifically, Section 2.0 presents the materials and methods, Section 3.0 presents the results, and Section 4.0 presents the conclusions of the work and recommends future next steps.

[1] Interior storm window inserts are also sometimes referred to as interior storm panels. Both these terms refer to the same technology.
[2] U-value measured as center-of-glass U-value for 1/8-in. pane of glass.

2.0 Materials and Methods

The evaluation of Indow Windows occurred in a historic Seattle home from February 2012 until September 2013. This section describes the subject home, the design of Indow Windows interior storm window inserts, the experimental schedule, and the monitoring and analysis approach.

2.1 Seattle Study Home

The house evaluated in the study reported herein was a single-family, two-story home that was built in 1916 (Figure 2.1). It has three bedrooms and one and a-half baths; a total conditioned space of 2,141 ft^2, not including the semi-conditioned basement. The original building envelope is of wood-frame construction with about R-13 insulation in the walls and no insulation in the basement. The home has a half-basement, half-crawlspace, and the insulation in the crawlspace was rated at R-11. The attic is vented with R-30 blown-in cellulose insulation. The windows are single-pane clear glass with wood frames. In 2011 and 2012, this home took part in the Building America Residential Deep Energy Retrofit Research Project[1] and the owner completed several of the retrofits that were recommended by that project, reducing whole house energy use by 47% (Blanchard et al. 2013). The completed retrofits included replacing the oil-fired furnace with a heat pump (having a seasonal energy efficiency ratio [SEER] of 18 and a heating seasonal performance factor [HSPF] of 9), installing a new duct system, and insulating and air sealing the basement. These retrofits will be referred to in this report as the "phase I retrofits" and their impact on the home's energy-use characteristics are described in detail in previous work (Blanchard et al. 2012). An unintended consequence of the phase I retrofits was that the homeowner began to experience an accumulation of condensation on the interior side of some windows. The window condensation was likely a result of the air sealing that had occurred as part of the phase 1 retrofits. Because less air exchange with the outdoors was occurring, there was less opportunity for internally generated moisture sources (e.g. showering, cooking, plants, etc) to disperse out of the home, which may have caused the interior moisture levels to increase. Compounding this, the condensing unit of the heat pump was place directly below the windows in the sun room. When the heat pump was operating in heating mode, it blew cold air over the windows, which lowered the surface temperature of the windows and resulted in condensation. After a year of experiencing condensation issues, the homeowner chose to install the Indow Windows to help mitigate this problem by separating the moist inside air from the cold window pane with a tightly-sealed interior storm window insert. The homeowner was also interested in further improving her home's energy efficiency and, as such, chose to purchase interior storm windows for all the windows in her home, even though only a few windows were experiencing condensation problems. The home has 27 windows, with a total window area of 273 ft^2, all of which received Indow Windows interior storm window inserts in March 2013. The installation of Indow Windows interior storm window inserts will be referred to in this report as the "fenestration retrofit." With metering already in place and baseline data already collected, this was a perfect opportunity to explore the impacts of interior storm windows on a home in Seattle's marine climate.

[1] http://deepenergyretrofits.pnnl.gov/

Figure 2.1. The 2,141 ft^2 home in Seattle, Washington, where Indow Windows' interior storm window inserts were evaluated.

2.2 Indow Windows Interior Storm Window Inserts

The interior storm windows installed in the study home are Indow Windows—a single-pane, gasketed interior window insert. Indow Windows interior storm window inserts are made of sheets of acrylic glazing edged with a patented spring bulb made out of silicone and filled with urethane foam (Figure 2.2). The spring bulb holds the insert in place by expanding and pressing against the window frame. This mounting method makes a tight seal around the window, which reduces infiltration through the window opening, in addition to the increased insulating value from the additional window pane. Each acrylic panel is custom cut to give the best fit for the window frame for which it is designed.

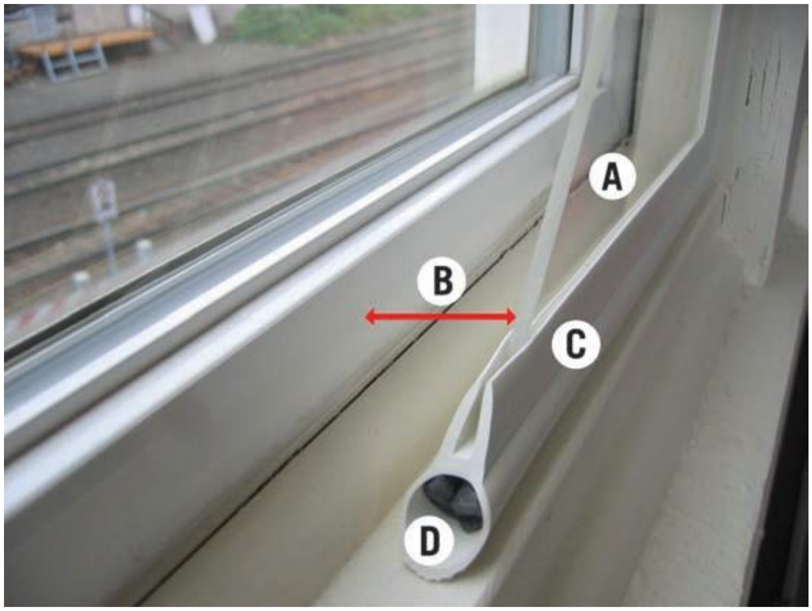

Figure 2.2. Indow Windows' interior storm window insert showing the (A) acrylic window; (B) air gap between window and insert; (C) silicone frame; and (D) urethane foam.

2.3 Experimental Schedule

Phase 1 heating, ventilation, and air-conditioning (HVAC) and building envelope retrofits were completed in February 2012. After completion of phase 1 retrofits, the Indow Windows interior storm window inserts were installed in this Seattle home in March 2013, according to the timeline shown in Table 2.1. Baseline data were collected from the date of completion of the phase 1 retrofits in February 2012 until the Indow Windows interior storm window inserts were installed in March 2013. Post-fenestration retrofit data were collected from April 2013 until September 2013. This report provides initial results from post-fenestration retrofit data collected during the 6-month period. Energy and temperature data will continue to be logged throughout the 2013-14 heating season.

Table 2.1. Schedule of experimental activities to evaluate interior storm windows.

Activity	Date
Pre-Experiment Activities(Phase I Retrofits)	
Retrofit completed	2/1/2012
Post-retrofit blower door test (measures infiltration)	7/23/2012
Baseline data collection	
Energy and temperature data collection	2/21/12-3/12/13
Post-fenestration retrofit data collection	
Installation of Indow Windows interior storm windows	3/1/13-3/10/13
Energy and temperature data collection	4/1/2013-9/6/2013
Blower door test	9/26/2013

2.4 Electrical Metering

An eGauge energy meter[1] was used to monitor and record the energy use in the home. Current transformers (CTs) were placed on several individual circuits to disaggregate the energy use in the study house, in addition to recording the whole house energy usage. The individual circuits monitored were the heat pump outdoor condensing unit, strip heat, the mini split head serving the master bedroom, and a subpanel, which contained all other circuits for appliances and outlets[2]. The sum of the heat pump, strip heat, and mini split circuits gives the total HVAC energy use of the home[3]. The eGauge metering system records integrated power readings at 1-second intervals and saves the data to a server, which can be accessed via the Internet. This metering approach is described more fully by Blanchard et al (2012).

Figure 2.3. Schematic and photograph of an eGauge energy metering system, consisting of a 1) main power meter unit, 2) current transformers, 3) voltage taps connected to a dual-pole breaker, 4) HomePlug communication adapter, and 5) an Internet router. Note that the HomePlug and Internet router are not shown in breaker panel photograph.

2.5 Temperature Metering

In addition to electricity metering, the home was equipped with four temperature and relative humidity (RH) meters to record thermal comfort information and to provide supporting data regarding thermostat set points, moisture concerns, etc. The temperature/RH sensors used were Madgetech RHTemp101A data loggers. The Madgetech data loggers typically can store 500,000 samples, which equates to a total of 347 days of collection for data recorded at 1-min intervals. Outdoor temperature data were obtained at hourly intervals from the University of Washington Department of Atmospheric Sciences.[4]

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[1] http://www.egauge.net/overview.php

[2] The heat pump was installed in a new panel to accommodate the additional load, which then fed a subpanel with all other existing circuits for the home.

[3] This home does not have dedicated mechanical ventilation.

[4] http://www.atmos.washington.edu/data/

2.6 Analysis Approach

To determine the impact of interior storm windows on the energy use and thermal comfort of the study home, the energy and temperature information collected prior to and after the installation of the Indow Windows interior storm window inserts were compared; these periods are referred to as the "baseline" and "post-fenestration retrofit" periods, respectively. However, the energy savings and increased thermal comfort data cannot be compared directly because the baseline and post-fenestration retrofit data were collected over different time periods that experienced different weather patterns, as well as differences in occupant behavior. Thus, a way to normalize the data is needed.

The energy data can be normalized to the heating and cooling loads experienced (in the form of heating degree days [HDDs] and cooling degree days [CDDs]) and can then be compared directly. A degree day is a measure of heating or cooling demand based on the deviation of outdoor air temperature from a certain "base temperature," which is typically representative of the balance point of the home. The HDD or CDD is calculated for one day by subtracting the average daily outdoor air temperature (OAT) in degrees Fahrenheit (ºF) from 65ºF if the average daily OAT is less than 65ºF (HDD) or subtracting 65ºF from the average daily OAT if the OAT is greater than 65ºF (CDD). The higher the value of the cooling (or heating) degree day, the greater the expected cooling (or heating) load is for that day.

Because the energy use in this home had disaggregated metering, the energy used by the HVAC system can be calculated by summing the readings from the CTs monitoring the heat pump, strip heat, and mini split. Then, by plotting the HVAC energy use to the number of degree days (see Figure 3.1) and fitting a best fit line to the data, the slope of the line gives an average energy use per degree day ($\frac{kWh}{°\text{F}\,Day}$). Multiplying the slope by the average number of degree days, which is the sum of HDD and CDD, experienced annually in Seattle based on a typical meteorological year (TMY) yields an expected annual energy usage, which can be compared for the baseline and post-fenestration retrofit periods of the Indow Windows interior storm window inserts to determine the expected energy savings.

The change in the thermal comfort of the house can be determined by taking the differences in temperature between different rooms and floors in the house, as well as comparing the absolute temperatures in each room on several time scales. The temperature in the house was monitored in four different rooms, the basement (B), the office (Off), the sun room (SR), and the master bedroom (MB). The office and sun room are both on the ground floor; the office is located in the southwest corner of the house and the sun room is in the southeast corner with more than half of the exterior wall area of the sun room consisting of windows. The master bedroom is on the second floor and the basement is below the southern portion of the home (the rest is crawlspace). The basement is not insulated, but air-sealing was performed as part of the retrofit package in February 2012. The new duct system has supply and return registers in the basement to allow for intentional conditioning, but these registers are typically closed.

Examination of the temperature differences involved comparison of the following pairs of rooms: MB-B, SR-Off, MB-Off, and Off-B. Comparing the differences in temperatures between rooms (pre- and post-fenestration retrofit) is a form of normalizing the data, which allows measurements taken under different conditions to be compared. Examining the difference in the temperature minimizes the impact of changes in absolute temperature caused by the occupant changing the thermometer set point (in winter and summer, or during thermostat setbacks). In addition, determining the difference in temperature between rooms can be more indicative of occupant comfort than absolute temperatures, because different

individuals perceive different temperatures to be comfortable and it is significant deviations from the desired temperature (e.g., rooms that are significantly hotter or colder than the rest of the house) that typically cause dissatisfaction with home comfort.

To determine whether a change in thermal comfort had occurred, the average and standard deviation of the average daily and hourly temperatures were compared for baseline and post-fenestration retrofit periods. In addition, the average daily temperature differences were examined. A reduction in the average daily temperature difference between rooms would suggest a more uniform temperature distribution throughout the house, and a reduction in the standard deviation would indicate that the temperatures in the house are maintained more consistently and are exhibiting smaller temperature swings. Both results would be indicative of an increase in thermal comfort.

3.0 Discussion and Results

The energy savings, reduction in infiltration, financial and thermal analyses, and additional benefits noted are described below.

3.1 Energy Savings

A comparison of daily average HVAC energy use per measured degree day in Seattle for the baseline and post-fenestration retrofit periods was conducted to determine the energy savings derived from installation of the Indow Windows interior storm window inserts. Normalized energy use was compared for the periods from April through September in 2012 (baseline period) and 2013 (post-fenestration period) by comparing the slopes of a linear least-squares regression through the normalized energy use data for each period, as shown in Figure 3.1, where positive values are HDDs and negative values are CDDs. This comparison yields a 21.1% savings in HVAC energy use derived from the Indow Windows interior storm window inserts when outdoor temperatures are cool and there is a call for heating. However, the Indow Windows interior storm window inserts show very little difference in performance during the cooling season. This could be because of the mild Seattle climate, which makes days with predominantly cooling loads difficult to differentiate from days with both heating and cooling loads or no space conditioning loads at all. Therefore, savings calculations are limited to only HDDs in this report.

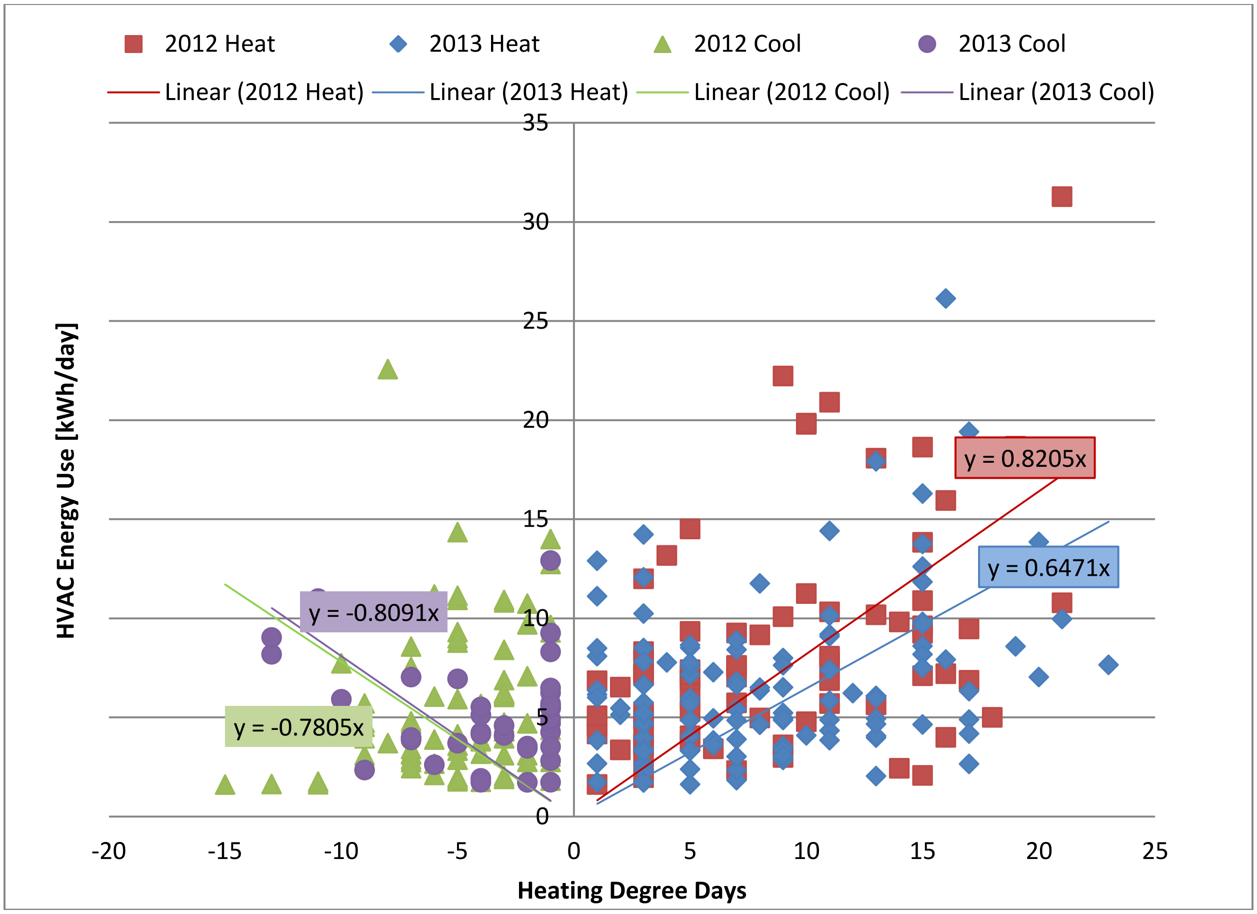

Figure 3.1. Daily HVAC energy use from April 1st through September 17th for the baseline period (2012; red and green) and post-fenestration retrofit (2013; blue and purple) normalized based on measured HDDs/CDDs for that period, where HDDs are positive numbers and CDDs are negative numbers.

To calculate the expected annual energy use in kilowatt-hours (kWh), one can multiply the slope of the regression by the typical annual degree days in Seattle (4,769 degree days). The calculated annual HVAC energy use for the baseline (2012), was 3,913 kWh. For the post-fenestration retrofit data, the calculated annual HVAC energy use was 3,086 kWh. Thus, the interior storm window inserts produced a savings of 827 kWh in annual HVAC energy usage.

However, the homeowner removed 6 of the 27 storm window inserts at the beginning of summer for ventilation and disclosed the fact that windows were often left open for increased airflow when the HVAC system was turned off. If the same analysis discussed above is conducted for the period when all of the storm window inserts are known to be installed (April and May) for HDDs only,[1] the percentage savings is similar—20.5%. The annual HVAC energy use based on data collected only during this period was calculated to be 3,812 kWh and 3,030 kWh for the baseline and post-fenestration retrofit periods, respectively. Table 3.1 compares the normalized and estimated annual HVAC energy use and HVAC energy savings for the two analysis periods. Data from the full analysis period (April through September) are used in subsequent calculations of cost-effectiveness.

[1] There was only 1 CDD in April and May in Seattle in 2013, and only 6 CDDs in 2012 during the same period.

Table 3.1. Normalized and estimated annual HVAC energy use and HVAC Energy savings for the full analysis period (April through September) and the shortened analysis period (April and May).

		Normalized HVAC Energy Use (kWh/°F)	Estimated Annual HVAC Energy Use (kWh/yr)	HVAC Energy Savings (%)
Full Analysis (4/1-9/17)	Baseline	0.8205	3,913	21.1%
	Post Retrofit	0.6471	3,086	
Shortened Analysis (4/1-5/31)	Baseline	0.7993	3,812	20.5%
	Post Retrofit	0.6353	3,030	

3.2 Infiltration Reduction

The reduction in HVAC energy use attributed to the Indow Windows interior storm window inserts is caused both by a reduction in infiltration and an increase in thermal resistance (decrease in U-value) through the window opening. To specifically determine the impact of the Indow Windows interior storm window inserts on building air leakage rates, the home was blower door tested before and after installation of the Indow Windows. The blower door reading for the baseline period was taken in July 2012. At that time, the building shell leakage was 2,450 cubic feet per minute at 50 pascals of depressurization with respect to the outside (CFM50). The home was blower door tested again in September 2013 after the installation of the Indow Windows interior storm window inserts, and the measured building shell leakage was 2,240 CFM50, a reduction of 8.6%.

3.3 Financial Analysis

While the estimated annual HVAC energy savings proved to be quite significant at 21.1%, or 827 kWh, the success of Indow Windows interior storm window inserts as an energy-saving retrofit measure is also based on the cost-effectiveness of the technology. With a current electric rate in Seattle of 8.41 ¢/kWh (Seattle City Light 2013), this savings equates to a reduction of $69 in the annual utility bill. The installed cost of Indow Windows interior storm window inserts for the 27 windows in this home is approximately $5,600. Installations costs are minimal and the inserts can be easily installed as a do-it-yourself project. For this case study, the Indow Windows interior storm windows have a simple payback period of 80.6 years. Indow Windows currently provides a warranty on its acrylic glazing for a period of 10 years; however, if properly maintained the lifetime of the product would be expected to be much longer than 10 years[1]. Not included in this calculation is the increased thermal comfort experienced by the occupant. Increased thermal comfort is impossible to quantify with a dollar value because it is valued differently by different individuals.

Because this home underwent significant retrofits as part of the Phase I retrofits (Blanchard et al. 2012), the heating system annual energy costs had already been reduced significantly, such that the 21% energy savings did not yield significant monetary savings. If we assume that the Indow Windows interior storm window inserts had been installed on the home prior to all of the Phase I retrofit measures (i.e. prior to installation of additional insulation, duct sealing, and a new heating system) and repeated the economic

[1] http://www.indowwindows.com/wp-content/uploads/2013/06/IndowWindows_Warranty.pdf

analysis above, the payback period for the investment of Indow Windows interior storm window inserts would be significantly reduced, as shown in Table 3.2. Prior to the retrofits, the annual distillate fuel oil consumption for heating was about 554 gal/yr with an additional 7,180 kWh used by electric space heaters (Blanchard et al. 2012). Assuming current prices for distillate fuel oil and electricity, $3.751/gal (American Petroleum Institute 2013) and 8.41¢/kWh respectively, the total annual heating (HVAC) cost would be $2,682. Assuming the Indow Windows interior storm window inserts would produce the same percent energy savings for the old heating system as for the current one, they would produce an annual savings of $566. This results in a simple payback period of 9.9 years.

Table 3.2. Calculation of simple payback period for Indow Windows interior storm window inserts based on an HVAC energy savings of 21.1% for the baseline and post-fenestration retrofit scenarios.

	Pre-Retrofit		Post-Retrofit	
	Fuel Oil	Electricity	Fuel Oil	Electricity
Amount	554 gal	7,180 kWh	0 gal	3812 kWh
Unit cost	$ 3.75/gal	$ 0.0841/kWh	$ 3.75/gal	$0.0841/kWh
Annual cost	$ 2,078.05	$ 603.84	$0	$ 329.08
Total annual cost	$ 2,681.89		$ 329.08	
Annual savings	$ 565.88		$ 69.44	
Simple payback (yr)	9.9		80.6	

It is not known if the percent HVAC energy savings produced by the interior storm windows is constant through all seasons or if the windows will be more or less effective in winter (for which data are not yet available). Energy data are needed for the fall and winter to accurately characterize the annual energy savings associated with interior storm windows and verify these preliminary results.

3.4 Thermal Analysis

The thermal analysis was performed for both the full analysis period (April through September) and the shortened analysis period (April and May) and similar results were observed in both cases. The data presented here are restricted to the time period when all of the interior storm windows were known to be installed, April 1st to May 31st.

Unlike the energy savings, there is no conclusive quantitative evidence that the Indow Windows interior storm window inserts increased thermal comfort. Two of the temperature differences had a decrease in standard deviation, SR-Off and Off-B, while the other two, MB-B and MB-Off, had an increase in the standard deviation of their temperature difference. The baseline and post-fenestration retrofit average temperature differences were similar, suggesting that the Indow Windows interior storm window inserts did not significantly affect that measure temperature distributions or fluctuations over the analysis period, as shown in Figure 3.2. The temperature differences suggest that there is little difference between the sunroom and office temperatures (on the ground floor) and little difference between the ground and second floor of the home (MB-Off). However, the basement appears to be about 7°F cooler than the other floors of the home, as might be expected; basements are often cooler than the main body of

a home. The second floor (MB) also appears to demonstrate the most significant fluctuations in temperature, probably due to its increased exposure and the influence of the stack effect.

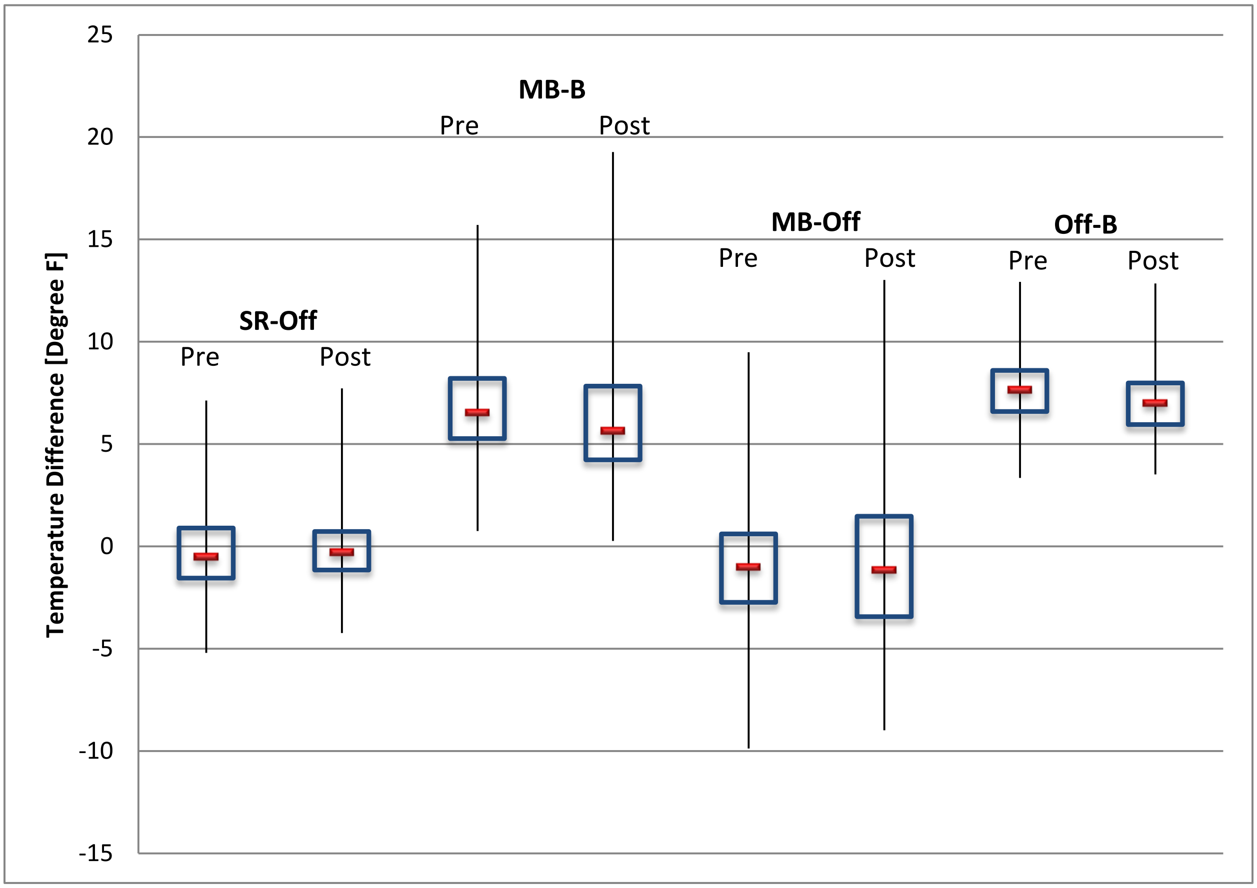

Figure 3.2. Average temperature difference between the sunroom and office (SR-Off), master bedroom and basement (MB-B), master bedroom and office (MB-Off), and office and basement (Off-B) during the baseline (pre) and post-fenestration retrofit (post) periods. The maximum and minimum temperature differences are represented by the solid black lines (whiskers) and the blue boxes mark the upper and lower quartile of the temperature differences.

Analysis of the hourly and daily average temperatures yielded similarly inconclusive results. Table 3.3 presents the average daily temperature and standard deviation recorded during the shortened measurement period (April 1st to May 31st)

Table 3.3. Average daily temperature and standard deviation (^oF) for the master bedroom, office, sunroom, and basement.

	Pre-Installation		Post-Installation	
	Average Daily Temperature	Standard Deviation	Average Temperature	Standard Deviation
Master Bedroom	65.4	2.9	65.3	3.9
Office	66.3	0.7	66.1	1.7
Sunroom	66.0	2.3	65.9	2.2
Basement	58.6	1.9	59.0	1.9

Despite the difficulty in quantifying conclusively an improvement in thermal comfort, the homeowner noted experiencing increased thermal comfort and is very pleased with the windows. The occupant found the house to be "warmer in the winter and cooler in the summer" and that the "temperatures are more even (throughout the house)." Because thermal comfort is very much a subjective metric, the homeowner's perception of increased thermal comfort is perhaps more significant than the measured data.

3.5 Additional Benefits

"it would have cost me tens of thousands to change out the windows and I didn't want to change the 'look' of the house…people can't even tell we have them!"

Installation of interior storm windows does not affect the exterior aesthetics of a home, which was considered a benefit for this homeowner, who wanted to preserve "the look" of the home. The installation of interior or exterior storm windows can also decrease the transmission of outdoor sounds into the home, making it seem quieter. While these attributes were not measured as part of this study, the homeowner was surveyed regarding her satisfaction with the windows and asked to describe the benefits. The homeowner commented that the home seemed much quieter since the installation of the windows and noted that the Indow Windows interior storm window inserts allowed the homeowner to cost-effectively improve the performance of the windows without altering their historic character. Also, interior storm windows can improve the durability of the window assembly (storm plus primary window) by reducing the risk of condensation. While not measured in this study, the homeowner stated that condensation issues previously experienced went away after the installation of the interior storm windows.

4.0 Conclusions and Recommendations

The decrease in infiltration and increased insulation produced by the Indow Windows interior storm window inserts led to a 21.1% reduction in HVAC energy use in this Seattle home during the full analysis period (April through September) and a similar 20.5% reduction during the analysis period when all 27 of the window inserts were installed (April 1st through May 31st). In addition, although the temperature data collected from the home did not suggest an improvement in thermal comfort, the homeowner is extremely satisfied with the windows' impact on perceived comfort. Although the interior storm windows did not yield a quick return on investment in this house based on energy savings alone, they yield a significant reduction in energy use and can be economical to install in older homes or climate zones with more extreme temperatures. Interior storm windows have many additional benefits beyond energy savings; they leave the exterior historic character of a house intact, significantly reduce outside noise, and can solve window condensation issues where they exist.

Table 4.1. Summary of impacts of Indow Windows interior storm window inserts on building shell leakage, HVAC energy use, and thermal comfort.

	Baseline	Interior Storm Windows	% Change
Building Shell Leakage (CFM50)	2,450	2,240	-8.6%
HVAC Energy Use (kWh/yr)	3,913	3,030	-21.1%
Thermal Comfort		Inconclusive	

To more accurately characterize the benefits of interior storm windows additional research should be undertaken. To further validate the preliminary energy savings of Indow Windows interior storm window inserts demonstrated in this study, PNNL will continue to monitor the energy use and temperature profiles in the home from this field study. With full heating season data, collected data could be used to create a calibrated building energy model and determine the percentage of the measured HVAC energy savings attributed to a decrease in infiltration versus the percentage attributed to increased thermal resistance through the window. Also, the energy model can be used to verify the "effective U-value" of the Indow Windows product alone and installed in conjunction with a primary window.

This experiment could also be expanded to more homes across a variety of climates to determine the applicability of these findings to different building types and climate zones and to generate recommendations regarding the installations in which interior storm windows will be most beneficial.

Also, Indow Windows is developing and testing a low-E interior storm window, which could be evaluated in a similar manner and the results compared to those presented here when released to determine the incremental benefit of a low-E coating on the window.

Supplementary testing of interior storm windows at the PNNL Lab Homes would yield the most accurate information about the impacts interior storm windows have on a house. This would be especially true for monitoring the change in the temperature profile of a house, because of the Lab Homes' controlled conditions and detailed data collection capabilities, which are not feasible in a field evaluation.

This field study has added to the body of knowledge about interior storm windows by presenting the measureable energy savings and evaluating the claims of increased thermal comfort. Additional studies are needed to fully document the performance of interior storm windows across a variety of building types and climate zones.

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