Mind the Gap: Summary of Window Residential Retrofit Solutions

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ABSTRACT

Improving the insulation, solar heat gain, and infiltration characteristics of windows in a home has the potential to significantly improve the overall thermal performance by reducing heat transfer through the window and also by decreasing air leakage into and out of the home. As approximately 43% of existing homes still have low-performing, single-pane clear windows (~50 million houses) and millions of other homes have only double-pane clear glass windows (Cort 2013), improving window performance also presents a significant opportunity for energy savings in the residential sector. Today, various energy-saving window retrofit opportunities are available to homeowners, ranging from window coverings and storm panels to highly-insulating triple-pane R-5 window replacements. Many of these technologies have been evaluated in the field, in the “Lab Homes” at Pacific Northwest National Laboratory, and through modeling to prove their cost-effectiveness and performance in different climate regions. Such information is necessary to increase market penetration of such efficient technologies. Recently, the Pacific Northwest’s Regional Technical Forum approved a utility measure for low- emissivity storm windows based on such data. This action represents a watershed moment for increasing the variety and prevalence of fenestration options in utility programs, especially for the low-income demographic. This paper will review various window retrofit options, the most recent field test and modeling data regarding their performance and cost-effectiveness, and discuss future rating efforts. This information is useful for utilities and energy-efficiency program managers to help effectively implement incentive measures for these technologies.

Introduction

Residential buildings in the United States currently consume approximately 8 quadrillion Btu/yr of energy for heating and cooling, which accounts for more than 40% of the primary energy consumed by homes (EIA 2015). Windows are a major source of heating losses and gains in residential buildings because of their heat transfer and infiltration properties, especially relative to other building shell components. For example, it has been estimated that windows account for approximately 25% of energy use in a typical residential building (Huang et al. 1999). Retrofitting and renovating existing homes to save energy has become an increasingly important component of U.S. energy strategy, and improving the performance of a home’s windows is an important part of any retrofit effort.

Improving the insulation and solar heat gain characteristics of a home’s windows has the potential to significantly improve the overall thermal performance by reducing heat loss (in the winter) and cooling loss and solar heat gain (in the summer) through windows. A high-quality window retrofit will also minimize or reduce air leakage through the building envelope, decreasing infiltration and thereby contributing to reduce heat loss in the winter and cooling loss in the summer. These improvements all contribute to decreasing overall annual home energy use.

Over the past 15 years, new window replacement and retrofit technologies have been developed that significantly increase the options available to homeowners and utilities when considering upgrading existing windows, including low emissivity (low-e) storm windows, insulating blinds, and other window attachments. Both window replacement and energy-efficient window attachments, such as high-efficiency shades, blinds, storm windows, or other window coverings, can significantly improve the thermal performance of a window. However, these technologies all have various performance levels in terms of U-factor reduction, solar heat gain and air infiltration impacts, and cost. This article reviews previous research conducted on window retrofit technologies, including experimental evaluation at the Lab Homes located at Pacific Northwest National Laboratory (PNNL), and discusses how these data are currently being used to support utility incentive and market transformation programs. The performance data are compared to performance data from baseline existing windows as well as highly-insulating replacement windows. While there are a number of window retrofit technologies, including low-e storm windows, insulating blinds, awnings, window films, and other innovative products, this article focuses on low-e storm windows and high-efficiency cellular shades, as most experimental data to date have been collected on these two technologies.

Review of Technologies

With a thermal conductance of approximately 1 Watt per meter Kelvin (W/mK), glass alone is a poor insulator. As a result, single pane windows often have an overall heat transfer coefficient (U-factor) around 5.5 W/m^{2}K or 1 Btu/hr ft^{2}F, which is only R-1 (m^{2}K/W). Clear glass also transmits between approximately 70 and 90 percent of light/heat at all wavelengths, including infrared (IR) radiation (LBNL 2016). Many window attachment technologies look to improve the thermal and optical properties of the window via coatings or coverings that, depending on the climate, decrease solar heat gain (by decreasing transmission of light through the window), decreasing light transmission in the IR wavelengths, and decrease the amount of thermal conduction or convection between indoor spaces and the outdoors.

Low-e Storm Windows

Traditional storm windows consisted of a single piece of clear glass (or plastic) mounted in a wood or aluminum frame, and were installed on the outside of an existing window. This window retrofit design focused on reducing thermal conduction and, to a limited extent, convection. However, modern storm windows feature new designs that can be operable or fixed in place and can significantly reduce air leakage through the window opening, much more than with previous storm window designs (CEE 2014). For example, as modern storm windows are intended to be permanently mounted, they typically feature tighter seals and gasketed or caulked window frames, further reducing conductive heat transfer as compared to older storm window designs.

In addition to conduction and convection, radiation is an important mechanism for heat gain and heat loss through windows. All materials radiate heat in the form of long-wave IR energy depending on the emissivity and temperature of their surfaces, which contributes to heat loss from buildings in addition to conductive and convective heat loss. Typical low-e storm windows include a low-e pyrolytic coating that lowers the emissivity of glass for certain wavelengths, effectively reducing heat transmission through the storm window (Culp et al. 2015). Specifically, low-e coatings are microscopic coatings consisting of very thin, electricallyconductive material that is transparent in the visible-light region and reflective in the IR region. Uncoated glass typically has an emissivity of around 0.84, while low-e coated glass can have an emissivity of 0.16 or lower. When the interior heat energy tries to escape to the colder outside during the winter, the low-e coating reflects the radiative heat back to the inside, reducing the overall heat loss through the glass. The reverse transfer of heat occurs during the summer (Culp et al. 2015).

For exterior low-e storm windows, the coating resides on the window pane side that faces the interior of the conditioned space. This placement removes any possibility of damage to the low-e coating by the elements throughout the life of the window. In contrast, the orientation of the low-e coating on the interior storm window does not alter the performance, and it can be effective in reducing heat loss when facing either direction, although it is most common to have the low-e coating face towards the existing primary window (Petersent et al 2015).

Insulating Cellular Shades

Other window fenestration products, such as window shades and blinds, have provided privacy for as long as windows have been in use. Over time attention has been focusing on the energy savings potential achieved by increasing the insulting values of window coverings, and reducing or optimizing the solar gains added to the space. The type and selection of differing attachment technology has greatly expanded in previous years; however, there is limited information on the differing energy-saving characteristics of these products, and currently, no comprehensive rating system exists to help distinguish the energy-saving features of one window covering from another (Curcija et al. 2013). High-efficiency shading devices, such as cellular shades (a.k.a., honeycomb shades), are one such window attachment technology that can provide significant energy savings and thermal comfort improvement. Cellular shades differ from other more conventional window covering technologies, such as blinds, in their construction materials, non-reflective fabric with mylar coating, and ability to insulate through the addition of air pockets.

Within the window-coverings category, honeycomb cellular shades are typically considered to have the highest R-values. Introduced in the 1980s, cellular shades are designed to trap air inside pockets that act as insulators, and this design can increase the R-value of the window covering and reduce the conduction of heat through the window that it covers (Ariosto and Memari 2013). Insulating shades can also impact solar heat gains if managed properly.

Along with the added insulating properties of the shades, many of these attachments have a built in automation feature to assist in optimizing management of solar gains throughout the year. This allows the blinds to open and close via predefined schedule. The automation process and scheduling can be optimized based on the solar calendar and geographical location and can be optimized to reduce the heating, ventilation, and air conditioning (HVAC) load while ensuring that adequate light and thermal comfort is achieved within the conditioned space. For example, during the heating season, the schedule can optimize visible light and solar heat gain to the space during the daylight hours. Of course, the automated controls also allow the blinds to be controlled based on home owner preferences.

Previous Research

As utility and government programs and regulations continue to drive reduced energy use in new and existing site-built and manufactured homes, new energy-efficient technologies and measures are needed to cost-effectively achieve energy-reduction goals. Lawrence Berkeley National Laboratory has identified highly-insulating windows with U-factors around 0.2 Btu/hr ft^{2}F as a key technology that could play an important role in the next phase of energy-efficiency improvements in the residential sector (Curcija etl al 2013). Improving the insulation and solar heat gain characteristics of windows in a home 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. In 2012, research conducted in the PNNL Lab Homes showed the added benefit in thermal and HVAC system performance by replacing the installed baseline window technology (i.e., double-pane, aluminum frame, clear glass windows) with R-5 windows.

Low-e storm windows and other window attachments have been evaluated via modeling and at the laboratory scale over the past 10 to 15 years. Beginning in 2007, DOE conducted a series of laboratory tests at the component level to validate the savings by applying a low-e coating to storm windows. The performance improvements were validated with field tests and case studies supported by DOE's Buildings Technology Emerging Technology team. The approaches and results of these field tests and case studies are described and summarized by Cort (2013). A high-level summary of these activities is provided in Table 1.

Table 1. Summarized case studies focused on low-e storm windows and cellular shades

Study	Sponsor	Baseline description	Findings
Chicago case study (2007)	DOE, HUD, NAHB Research Center, LBNL	Six low-income homes; single-pane wood-framed windows	Low-e storm windows showed: • 21% reduction in overall home heating load • 7% reduction in overall home air infiltration • Simple payback of 4 to 5 years
Atlanta case study (2-year study)	DOE, Quanta,[a] Larson,[b]	Ten occupied homes; single-pane wood-framed windows	High variability, but low-e storm windows showed approximately: • ~15% heating energy reduction • ~2 to 30% cooling reduction (highly variable) • 17% reduction in overall home air infiltration
Pennsylvania weatherization technical support (2010)	DOE, Birch Point Consulting	37 model homes with range of window types	Modeled window retrofit technology showing results for 7 climate zones: • 12%–33% overall HVAC savings
Energy savings from window shades (Zirnhelt et al. 2015)	Hunter Douglas and Rocky Mountain Institute	EnergyPlus modeling of DOE residential buildings	Modeling of cellular shades showed: Denver Max Cooling Savings – 25% Denver Max Heating Savings – 10% Peak electrical demand reduction of 9% for new homes

Calculations of energy savings and the cost-effectiveness of low-e storm windows have been conducted with two software platforms: 1) the National Energy Audit Tool, used by weatherization programs, and 2) RESFEN (RESidential FENestration), used to compare the annual energy performance of different windows in single-family homes (Culp and Cort 2015).

In 2013, DOE sponsored a comprehensive energy modeling study led by Lawrence Berkeley National Laboratory (LBNL) that focused on a range of window attachments, including products such as shades, blinds, storm window panels, and surface applied films simulated in four types of "typical" houses, located in 12 characteristic climate zones. The simulations captured the optical and thermal complexities of these products (Curcija et al. 2013) and also considered typical operation and usage patterns based on a separate study focusing on user behavior with respect to operable window coverings (Bickel et al. 2013). The study found that many of the window attachments examined can yield significant energy savings when installed over windows; however, the degree of savings depends on the attachment type, baseline window conditions, seasonal and climate factors, and how the attachment is operated, when applicable.

In addition to DOE's research focusing on window coverings, a number of research institutions, energy-efficiency programs, and utilities have completed characterization and meta-analyses (Ariosto and Memari 2013) and energy simulation analyses (CEE 2014; Zirnhelt et al. 2015) validating energy savings from cellular shades and other window attachments in multiple climate zones and prototype residential buildings.

Although field data and case studies provide valuable insights related to the savings potential of window attachments in specific applications or climate zones, the variability that occurs due to home type and occupancy behavior can make it difficult to isolate the savings from the window attachment and project these savings to alternative circumstances. Controlled side-by-side experiments, such as those conducted in the PNNL Lab Homes, provide a platform for more detailed and comprehensive data collection on HVAC system energy performance. The PNNL Lab Homes provide controlled experimental HVAC data, which can be used to appropriately tailor and calibrate building simulation models to account for relevant interactions, occupancy, climate zones, and baseline characterizations.

PNNL Lab Homes Experiments

The experiments described below were conducted in the PNNL side-by-side Lab Homes, which form a platform for precisely evaluating energy-saving and grid-responsive technologies in a controlled environment. The PNNL Lab Homes are two factory-built homes installed on the PNNL campus in Richland, Washington. Each Lab Home has seven windows and two sliding glass doors, for a window-to-floor area of 13.7%. To be representative of the Pacific Northwest climate, clear double-pane windows were installed as the baseline technology for both PNNL lab homes. For the primary experiments examined in this study, the "experimental home" was retrofitted with the fenestration technology under evaluation, while a matching "baseline home" remained unaltered. The floor plan of the Lab Homes as constructed is shown in Figure 1. The Lab Homes are meant to represent "typical" Pacific Northwest housing stock and include R-11 cavity insulation and R-22 floor and ceiling insulation. However, the building shell is relatively tight (~3.2 ACH_{50}) due to the capabilities of the manufactured housing fabrication process.[1]

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[1] More detail on construction characteristics and insulation levels can be found in Widder et al. 2012.

Figure 1. PNNL Lab Homes floor plan

The metering approach includes metering and HVAC system-control activities taking place at the electrical panel. Heat transfer through the primary glass and window fenestration produces will be aggregated by differing temperature sensors. For all experiments, metering was completed 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. All data were captured at 1-minute intervals by the data loggers. The 1-minute data were averaged over hourly and daily time intervals to afford different analyses. Occupancy in the homes was simulated via a programmable commercial lighting breaker panel (one panel per home) using motorized breakers. These breakers were programmed to activate connected loads on schedules to simulate human occupancy by introducing heat to the space. Widder et al. (2012) contains more details on the metering and data collection capabilities of the Lab Homes.

R-5 and Low-e Storm Windows

In March 2013 through 2014, PNNL evaluated commercially-available exterior and interior low-e storm windows in the PNNL Lab Homes for their thermal performance, including energy savings and impact on interior temperature distributions. The interior and exterior windows were testes separately over the experimental periods. The installation of each prduct was to the manufacture specification. To demonstrate and visual the thermal impact of the low-e storm windows, IR images were taken of both the baseline windows (in the baseline home) and baseline windows equipped with interior or exterior low-e storm windows (experimental home). These images, presented in Figures 2 and 3 for interior low-e storm windows, help visualize the temperature differential between the conditioned space and outdoor air and the interior photos help characterize the impact of the storm windows on the thermal comfort. The pictures in Figures 2 and 3, for example, were taken on February 2, 2015. During this day, the average outside temperature was 34ºF with a low of 17ºF and a high of 40ºF.

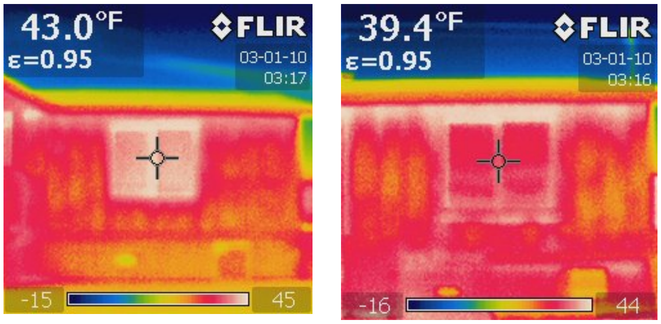

Figure 2. Baseline home master-bedroom exterior (left), experimental home master-bedroom exterior with interior storm windows (right)

Reviewing the exterior images (above) shows the effect of the storm windows on the envelope. The external surface temperature of the primary window within the baseline home was measured to be 43ºF as compared to the 39.4ºF of the experimental home. The change in temperature between the two surfaces is 3.6ºF, demonstrating the increased insulating quality of the window with the interior storm window, which reduces the amount of heat that is transferred though the window and thus keeps the exterior window temperature closer to that of the outdoors (Petersen et al. 2015b).

Similarly, on the same day measurements were taken of the the internal temperature of the master-bedroom glazing. In the baseline home the master bedroom window was 59.9ºF (see Figure 3), while the the internal temperature of the experimental home was 66.6ºF; a differential of 6.7ºF. This differential can also be attributed to the insulating properties of the interstitial space and low-e coating on the storm windows. The low-e surface was more effective at trapping and reflecting the internal heat back into the space, resulting in higher interior surface glass temperatures.

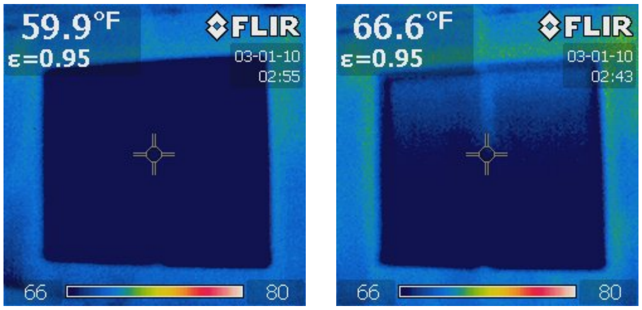

Figure 3. Baseline home master-bedroom interior (left), experimental home master-bedroom interior with interior storm windows(right)

Both interior and exterior storm windows were evaluated in the PNNL Lab Homes throughout differing heating and cooling seasons. During the heating season, the heat pump was disabled, and a forced-air electric resistance furnace supplied the required heating to the Lab Homes. In general, measured HVAC savings due to the exterior storm windows averaged 10.5% for the heating season and 8.0% for the cooling season for identical occupancy conditions (Knox and Widder 2014). Because of limitations on the manufactured size of interior storm windows, only an estimated 74% of the window area could be covered during the test. Testing was conducted during the winter heating and summer cooling seasons, and the collected data showed that interior low-e storm windows installed over 74% of the window area in experimental home resulted in an 8.1 ±1.9% and 4.2 ± 0.7% reductions in HVAC energy use during the heating and cooling seasons, respectively (Petersen et al. 2015b).

The average annual energy savings calculated from the measured PNNL Lab Homes data for the interior and exterior low-e storm window evaluations are summarized in Table 2, and are compared to the average annual energy savings estimated from primary window replacement with highly-insulating triple-pane windows (i.e., R-5). The animalization process of the individual heating and cooling savings data implemented a simple heating and cooling degree day calculations. The process can be found in detail within any of the case studies. Within a separate but similar test, data from the highly-insulating triple-pane windows was gathered using the same baseline window and represent window replacement within the lab homes. These can be another option that is often considered when retrofitting windows (Widder 2012).

Table 2. Annual estimated energy savings for each window replacement or attachment technology

Technology (experiment)	Baseline	Average Annual Energy Savings (%)
Highly-insulating window replacements (R-5) (Widder 2012)	Double-pane aluminum frame clear glass	12.2 ±1.3
Exterior low-e storm windows (Knox and Widder 2014)	Double-pane aluminum frame clear glass	10.1 ±1.4
Interior low-e storm windows (Petersen et al. 2015b)	Covering 74% of window area double-pane aluminum frame clear glass	7.8 ±1.5

High-Efficiency Cellular Shades

PNNL evaluated cellular shades in the PNNL Lab Homes during the 2015–2016 heating and cooling seasons. The specific technology examined as part of this study was the Hunter Douglas Duette® Architella® Trielle™ honeycomb fabric shades, which are made with six layers of fabric including two opaque layers and five insulating air pockets. The inclusion of insulating air pockets as well as the layer of metallized Mylar that lines the air pockets, minimizes conductive and radiant heat transfer and effectively increases the R-value of the fabric.

Figure 4. Hunter Douglas Duette Architella Trielle shades

These cellular shades were also equipped with the Hunter Douglas Green (HD Green) automated scheduling technology, which allowed researchers to evaluate both the thermal improvement of the shades and the impact of automated shading devices on optimal management of solar gains. To independently evaluate the functionality of the blinds and associated automation schedules, as well as their collective performance, PNNL tested the cellular shades compared to multiple baseline technologies ⁻ a residential building without window attachments and with standard vinyl blinds. The specific experiments and the results obtained are described in Table 3.

Table 3. Average HVAC savings of the cellular shades over the heating and cooling experimental periods

Experiment	Description	Season	Estimated Savings[a]
Optimum operation	Blinds operated per the HD Green schedule. Compared to no window attachments on the baseline home.	Cooling	Not Completed
		Heating	17.6 ±8.1%
Optimum operation comparison	Blinds operated per the HD Green schedule. Compared to standard vinyl blinds operated per the HD Green mode on the baseline home.	Cooling	10.4 ±6.5%
		Heating	16.6 ±5.3%
Static operation	Blinds remain closed for the duration of the experiment. Compared to standard vinyl blinds remaining closed for the full experiment.	Cooling	13.3 ±2.8%
		Heating	10.5 ±3.0%
[a] Note: Because these are preliminary results, the savings have not been annualized.			

Because data presented in Table 3 are preliminary results, each operational mode has not been annualized over both the heating and cooling seasons. Insulating values associated with cellular shades alone resulted in a reduction in total HVAC system load of 7.5 to 16.1% when compared to standard vinyl blinds, as shown in the static operation experiment. The savings realized though the implementation of the HD green mode schedule can be seen in the optimum operation experiment. The maximum achievable savings resulting from adding automated, insulating blinds to a home with no window attachments at all results in the highest savings of up to 17.6±8.1%.

Utility Acceptance for Window Attachments

Until recently, energy-efficient window attachments have received only modest support and recognition by utility energy-efficiency programs. Despite the demonstrated energy savings and cost-effectiveness, the Database of State Incentives for Renewables and Efficiency[2] indicates only 18 states have about 26 utility-sponsored incentive programs between them that explicitly identify storm windows as qualified measures (Cort 2013). Recently, however, there have been some major efforts by utility programs in Vermont and the Pacific Northwest focused on integrating storm windows into utility incentive programs. In the Pacific Northwest, the Regional Technical Forum (RTF)[3] conducted a modeling study based on its Simplified Energy Enthalpy

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[2] DSIRE database search available online at http://www.dsireusa.org/.

[3] The RTF is an advisory committee for the Northwest Power and Conservation Council established to develop standards to verify and evaluate energy savings from technologies, approaches, systems, and measures for the Bonneville Power Administration.

Model (SEEM)[4] and the RTF Operating Guidelines (RTF 2015) to evaluate the cost-effectiveness of low-e storm windows in the region. Supported by the existing field and experimental data discussed above, SEEM results demonstrated that low-e storm windows met the total resource cost (TRC) criteria to be considered a "proven" and cost-effective energy-saving measure for most applications in the Bonneville Power Administration region (includes Oregon, Washington, Idaho, and part of Montana), which led to approval by the RTF board for the measure in the Pacific Northwest.[5] In 2016, the RTF expanded the study to include manufactured and multi-family homes, and the board's approval followed.[6]

Additionally, in 2015, Efficiency Vermont launched a successful education and awareness campaign about low-e storm windows in conjunction local retailers. The pilot promotion resulted in a 37% increase in overall storm window sales, and a 337% increase in low-e storm window sales (Bonn et al. 2015). These cases demonstrate the feasibility of low-e storm windows as a utility incentive measure. In addition, RTF's conclusion regarding the "proven" status of the measure demonstrates the sufficiency and depth of the existing data on low-e storm windows.

Utility programs have not yet been established for other window attachment technologies, as measured field and/or laboratory performance data is just now becoming available. Based on the experience with low-e storm windows and the tested performance data from studies, like the PNNL Lab Homes evaluation, window attachments may also be considered for utility incentive programs. However, confirming the persistence of savings from window attachments and automated, optimized schedules will present additional hurdles for such technologies. However, just as programmable thermostats became incentivized, it is possible that programmable shade operation and highly-insulating shades could also be considered for incentive programs, provided there is sufficient evidence that supports consistent savings over time.

Window Attachment Energy Rating Council

One market barrier to achieving more widespread penetration of energy-efficient window attachment programs and utility incentives is the lack of standardized ratings for such products. Currently, there are not standardized metrics, test procedures, or performance criteria available for evaluating and describing the performance of window attachment technologies. Standards and ratings can help inform consumers and drive the market for energy-efficient products. Because no energy-related rating or standards existed for window attachments, in 2014 DOE helped establish a voluntary rating council for energy-efficient window attachments, which has become known as the Attachments Energy Rating Council (AERC).[7] The purpose of the council is to develop a comprehensive energy rating, labeling, and certification program for window attachments. The AERC is run as an independent, public interest, non-profit organization that serves the public interest by providing accurate and credible information about the energy performance of window attachments. AERC's goals include establishing a rating for storm window and cellular shade attachments by the end of 2016.

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[4] The SEEM program is designed to model small scale residential building energy use and consists of hourly thermal simulation and humidity simulation that interacts with duct specifications, equipment, and water parameters to calculate the annual heating and cooling energy requirements of the home.

[5] Meeting minutes and RTF staff presentations are available online at http://rtf.nwcouncil.org/meetings/2015/07/minutes20150721.pdf (accessed September 2015)

[6] See meeting agenda and minutes online: http://rtf.nwcouncil.org/meetings/2016/03/.

[7] http://aercnet.org/

Conclusion

For residential customers, the window attachment products, such as low-e storm windows or insulating shades, offer a reduction in HVAC system energy consumption without sacrificing utility or comfort. On a broader scale, high-efficiency window fenestration products have great potential for reducing energy consumption in the residential sector and offer a cost-effective incentive option for utilities.

Research, including studies conducted at the PNNL Lab Homes, have demonstrated the energy savings potential of window attachment products such as low-e storm windows and cellular blinds with automating scheduling. Additional studies have modeled the cost-effectiveness of such technologies, making them a compelling retrofit option for residential homes, including multi-family building. These data form the foundation for recent efforts by EfficiencyVT and the PNW's RTF to incentivize low-e storm windows. The addition of energy ratings and labels for window attachment programs should help consumers, designers, and home performance contractors make informed decisions about window retrofit options. Current data proves the energy-saving potential and cost-effectiveness of most window attachment technologies. Further utility incentives and market transformation efforts are the next step to saving some of vast amounts of energy we lose through the windows each year.

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