Affordable Window Retrofit Solutions for Multi-Family Buildings

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ABSTRACT

Multi-family buildings represent a pivotal opportunity to advance energy efficiency and decarbonization while reaching underserved communities such as low-income households and renters. In this aging and inefficient building stock, improving the building envelope can improve comfort, enable more efficient decarbonization, reduce energy burden, and provide a better overall experience for the occupant. With single-pane windows comprising 40% of existing windows in multi-family buildings, focusing on upgrading windows holds immense potential. Improving windows can have vast energy efficiency benefits, including air leakage reduction, HVAC load reduction and equipment downsizing, utility bill savings, and peak demand reduction; however, non-energy benefits such as improvements in indoor thermal comfort, acoustics, and passive resilience can be a game changer for tenants. Unfortunately, window replacement is often disregarded due to high first costs, lack of financing options, and concerns about tenant disruption. Consequently, tenants are left with high utility bills and an uncomfortable home – which can escalate into life-threatening scenarios during extreme weather events.

In this paper, we explore affordable window retrofit strategies, such as low-emissivity (low-e) storm windows, solar screens, cellular shades, and window inserts, which promise substantial improvements, lower costs, and less tenant disruption. We will share results of the Twin Cities (MN) Multi-Family Storm Windows Replacement Pilot along with other window attachment lab and field studies. Readers will learn about applications for various energy-efficient window attachments in multi-family buildings and understand how affordable window retrofit solutions can be used as a tool to enable equitable transition to a decarbonized multi-family sector.

Introduction

The majority of a building's heating, ventilation, and air conditioning (HVAC) loads are attributed to thermal transfer and air leakage through the building's envelope. Despite windows taking up only 7% of the building envelope, they are responsible for 48% of envelope heat transfer and 25% HVAC energy use (Harris 2022; Hart et al. 2019). Reducing heat transfer and decreasing air leakage by improving the insulation, solar heat gain, and infiltration characteristics of a window can significantly improve the building's overall thermal performance and energy efficiency. In the U.S., approximately 40% of all existing multi-family units still have poor-performing, single-pane clear windows, and approximately 80% of multi-family units have never replaced their original windows (EIA 2020). Seventy-five percent of multi-family units were prior to the year 2000, before higher-performing double-pane, low-emissivity (low-e) windows began to gain popularity (EIA 2020; Harris 2022), creating a huge opportunity to improve the old, inefficient windows of the multi-family building stock.

Looking to the future, the multi-family housing sector presents a unique potential for decarbonization. Multi-family buildings account for 60% of the U.S. rental market (JCHS 2022), and the sector has been particularly slow to implement energy efficiency upgrades compared to other building sectors, presenting the opportunity to leverage unrealized energy savings through deep energy retrofits. In addition to energy savings, efficiency upgrades help to improve affordability for residents, leading to reduced operating costs and ultimately the long-term preservation of affordable housing.

While full window replacement may be the standard for improving window performance, window attachments provide an effective alternative, improving energy efficiency at a fraction of the cost. Energy-efficient window attachments are products that can be installed on either the exterior or interior of the existing window to improve thermal performance, this product category includes storm windows, insulating panels, insulating cellular shades, roller shades, and solar screens. Window attachment products, particularly interior attachments, have traditionally been thought of as decorative features; however, these products offer a variety of benefits to building occupants, including energy savings, improved comfort, noise reduction, and improved aesthetics.

Standards and product energy ratings help to drive consumer awareness and market dynamics, increasing market adoption of energy-efficient technologies. In 2014, the U.S. Department of Energy (DOE) helped launch the Attachment Energy Rating Council (AERC), an independent, nonprofit rating council, to remedy the lack of energy ratings and standards for window attachment technologies. AERC offers a comprehensive program for energy-rating, certifying, and labeling window attachment technologies, providing the public with accurate and credible performance data. During the certification process, window attachments are simulated in both warm and cool climates to deliver independent ratings tailored to each climate type. A summary of commercially available window attachments is available on the AERC website, and as of 2024, AERC has energy ratings available for both interior and exterior storm windows (aka insulated window panels or secondary glazing), as well as cellular and roller shades, solar screens, blinds, Roman and pleated shades, and awnings. Figure 1. shows four AERC-rated window attachment retrofit solutions that can be applied to multi-family buildings.

Figure 1. Window attachment retrofits (from left to right) interior operable storm window, exterior low-e storm windows, insulating cellular shades, and exterior shades. *Source:* PNNL, AERC.

This paper explores affordable window retrofit technologies and strategies, which promise substantial improvements, lower costs, and less tenant disruption. It includes findings from multiple lab and field validation studies, including recent results of the Twin Cities (MN) Multi-Family Storm Windows Replacement Pilot. Readers will learn about applications for various energy-efficient window attachments in multi-family buildings and understand how affordable window retrofit solutions can be used as a tool to enable equitable transition to a decarbonized multi-family sector.

Technology Overview

With a thermal conductance of approximately 0.0243 BTU/(h ft °F), glass is a poor insulator. Clear glass also transmits between approximately 70 and 90 percent of light/heat at all wavelengths, including infrared (IR) radiation (LBNL 2023). In recent decades, new window replacement and retrofit technologies have been developed that significantly increase the availability of window upgrade options. Although replacing old existing windows with new high-performance windows (e.g., ENERGY STAR certified triple panes) is a time-tested retrofit that will provide energy savings as well as improving occupant comfort and increasing property values, window replacements are rarely completed in the multi-family sector due to the high upfront expense and tenant disruption. Window attachments are a less invasive and more affordable solution that can increase the frequency of window retrofits in multi-family buildings.

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), increase the reflectance of the window in the IR wavelengths, and decrease the amount of thermal conduction or convection between indoor spaces and the outdoors. The following provides a summary of window attachment technologies that are applicable to multi-family buildings.

Storm Windows and Insulating Panels

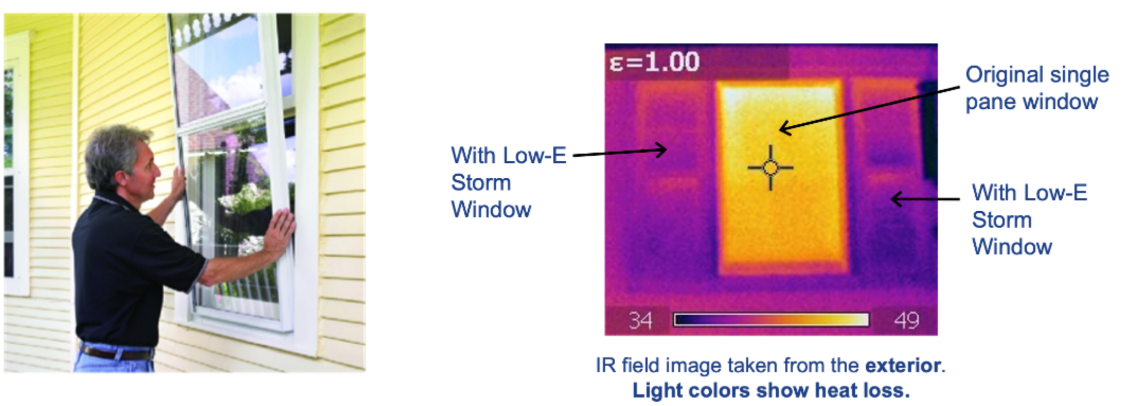

Figure 2. Exterior low-e storm window installation (left), and infrared image of a low-e storm window. *Source:* Larson, QuantaPanel.

Storm windows, sometimes referred to as window inserts or insulating panels, are typically made of a single pane of glass or plastic in a wood or aluminum frame and are installed on the interior or exterior of an existing primary window. This technology improves the thermal performance of the window by reducing air leakage and creating a dead air space to reduce both convective and conductive heat losses through the window. Storm windows can also include a durable low-emissivity (low-e) coating, which reduces the U-factor of the glass and acts as a heat mirror, reflecting heat inwards in the winter and outwards in the summer, as seen in Figure 2. (Culp et al. 2015). Low-e storm windows can provide 10-30% annual HVAC energy savings, as seen in Table 1. Unlike older versions, modern storm windows are permanently installed, aesthetically pleasing, and can maintain full window operability.

Insulating Cellular Shades

Also known as “honeycomb” shades, cellular shades are made of multiple layers of opaque fabric that create cellular pockets reminiscent of honeycombs when viewed from the side, as seen in Figure 3. They can be made with single, double, or triple layers of cells, and work to insulate the primary window and increase the R-value of the window assembly by creating a layer of trapped air between the cells to reduce heat transfer (Ariosto and Memari 2013). Insulating cellular shades can save 5-25% of annual HVAC energy, found in Table 1. Some models of cellular shades include a layer of metalized Mylar within the insulating air pockets, which serves to further minimize convective, radiant, and conductive heat transfer through the window (Petersen et al. 2016).

Figure 3. Side view of insulating cellular shades. *Source*: Hunter Douglas

Exterior Shades

Exterior shades are window attachments that are applied to the exterior of the existing window, such as solar screens or roller shades, as seen in Figure 4. They help to increase a window’s thermal performance by reducing solar heat gain during the cooling season, and also help to reduce glare and improve comfort in the home, saving 10-20% HVAC cooling energy, as seen in Table 1. Exterior shades regularly include a manual crank, motor, or rod that allows the resident to operate them from indoors, but many newer models utilize a remote-controlled motor to raise and lower the shade (Hunt and Cort 2020).

Figure 4. Example of exterior shade technology. *Source*: Hunt and Cort 2020.

Automation

Some operable window attachments have built-in automation features to assist in optimizing the management of solar gains throughout the year. This allows the blinds/shades to open and close via predefined schedules. The scheduling can be optimized based on the solar calendar and geographical location to reduce the 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 be operated to maximize the duration of visible light and solar heat gain to the space during the daylight hours. The automated controls also allow the shades to be controlled based on other homeowner preferences, such as privacy and security preferences (Cort et al. 2018).

Technology	**Application**	**Range of Validated Energy Savings**	**References**
High-R (triple-pane) Window Replacements	New and existing homes	7-16% (total energy savings)	(Hart et al. 2019; Hunt et al. 2021)
Low-e Storm Windows and Insulating Panels	Existing homes	10-30% (annual HVAC savings)	(Culp and Cort 2015; Knox and Widder 2014; Petersen et. al 2015)
Insulating Cellular Shades and Shade Automation	New and existing homes	5-25% (heating and cooling HVAC savings)	(Metzger et al. 2017; Cort et al. 2018; Kunwar et al. 2022)
Exterior shades	South- and west-facing homes	10-20% (cooling HVAC savings)	(Hunt and Cort 2020)

Table 1. Energy savings of window retrofit technologies

Field Validation

Field validation plays an essential role in ensuring that energy-efficient technologies perform as expected in real-world scenarios. By validating window attachments in the field, we can verify their energy performance, address potential challenges, and receive occupant feedback.

Philadelphia Multi-Family Low-e Storm Window Field Study

Figure 5. Philadelphia multi-family apartment building with installed low-e storm windows. *Source*: EERE 2013.

In 2013, DOE and Home Innovation Research Labs examined the effects of replacing old existing storm windows with modern, low-e storms in two large, three-story multi-family apartment buildings in Philadelphia, Pennsylvania, as seen in Figure 5. Constructed in 1962, the apartment buildings had 101 units and 4,720 ft^2 of single-pane, clear glass storm windows installed over the existing single-pane, metal-framed windows. The old storm windows were replaced with low-e storm windows, improving the overall performance of the window assemblies by lowering the estimated U-factor by 61% compared to the bare primary window and 24% compared to the single-pane window with the clear-glass storm window.

Improvements in energy performance were analyzed using a combination of blower door tests and utility bill analysis. A sample of 15% of units from any of the three floors and bedroom layouts were selected to undergo blower door tests, and air leakage was tested at 50Pa with the existing storm windows in both open and closed positions; this test was then repeated after the old storm windows were replaced with new, low-e versions. While the old storm windows did not show significant improvement in air infiltration when open or closed, the application of modern low-e storm windows achieved a 10% reduction in air leakage of the overall apartment unit and an average reduction of 3.2 CFM50 per ft^2 of glazing, demonstrating the potential for low-e storm windows to significantly improve energy efficiency through improved air tightness as well as reduced U-factor.

Whole building gas utility usage was examined to determine energy consumption and savings during the heating season, and individual unit electric utility usage was used to determine energy savings during the cooling season. As a result of replacing old storm windows with the new low-e storm windows, whole-building gas usage was found to be reduced by 18%

during the heating season, and electricity usage due to cooling was reduced by approximately 9% when normalized to the cooling degree days for the testing period (EERE 2013).

Twin Cities (MN) Multi-Family Storm Windows Replacement Pilot

In a 2023-2024 field study, Center for Energy and Environment (CEE) partnered with Xcel Energy and Pacific Northwest National Laboratory (PNNL) to evaluate exterior storm windows as an energy savings measure. The homes were selected through CEE's Home Energy Squad (single-family sites) and multi-family work (including Minneapolis' 4D program) as part of a pilot program for the Storm Window and Insulating Panel (SWIP) Campaign. New low-emissivity exterior storm windows, designed to block heat and ultraviolet radiation (UV rays), were installed in homes featuring old and leaky exterior storm windows. During the pilot, exterior storm windows were to be removed and replaced with new low-e storm windows. The pre-installation and post-installation measurements were collected for a thorough analysis of energy savings and cost-effectiveness by Xcel Energy, with the results to be included in a future report.

Pilot sites ranged in size from 1900 to 4300 sq. ft. and 25-55 windows per site. For the single-family interior storm window site, the old exterior storm windows were left in place (monolithic primary windows with both interior and exterior storm windows). For single-family and multi-family exterior storm window sites, the old storm windows were removed and replaced with new low-e storm windows.

In cold climates like Minnesota, storm windows are commonly installed outside of single- or double-pane primary windows. While they offer insulation benefits, their effectiveness diminishes over time due to quality of installation and the breakdown of seals and gaskets. For many old storm windows, the energy lost from air leakage surpasses the energy lost from conduction of heat through the window, significantly. The installation of new exterior storm windows improves window performance by adding air tightness using gaskets around the perimeter of the product.

To measure the change in performance of the house's windows, a blower door test was performed before and after installation of the new storm windows. In this test, the front doorway is filled with a membrane and a large fan. Air is blown out of the house to achieve a pressure of 50 pascals (Pa) and then the cubic feet per minute is measured to assess the air-leakage (CFM50).

Before installation, pilot houses were relatively leaky with higher CFM50 air leakage, ranging from 3,400-8,100 (for building square footage ranging from 1900-4300). Air leakage was tested at 50 Pa with the primary and storm windows in the closed position. Installation of the storm windows achieved whole-building air leakage reductions ranging from **[10-19 interim]**% and reductions of **1.2-2.8 CFM50 per ft2 of glazing**. For comparison, a house that has professionally retrofitted wall or attic insulation can expect a minimum leakage reduction of around 15%. This shows that using storm windows to address existing windows can provide as significant an improvement in overall building air tightness as other more common housing upgrades. Results for all buildings taking part in this pilot can be found in Table 2[1].

Table 2. Minneapolis storm window pilot results

[1] The final blower door test results will be available in the final version of this paper.

Home Type	Single-Family #1	Single-Family #2	Multi-Family #1 (4-plex)	Multi-Family #2 (duplex)	Multi-Family #3 (5-plex)
Storm Type	Interior	Exterior mfgr A	Exterior mfgr B	Exterior mfgr B	Exterior mfgr B
Home Sq. Ft.	3,800	3,200	4,300	1,900	3,000
Window Count	25	31	55	29	30
Glazed sq. ft.	341	268	602	259	525
Pre CFM50	5,162	3,356	7,857	4,405	8,118
Post CFM50	4,200	3,026	6,373	[TBD]	[TBD]
Difference	962	330	1484	[TBD]	[TBD]
Percentage Reduction	19%	10%	19%	[TBD]	[TBD]
cfm50/Window	38	11	27	[TBD]	[TBD]
cfm50/sq. ft. Glazed Area	2.8	1.2	2.5	[TBD]	[TBD]

After installation, homeowners were surveyed on the install experience. Homeowners & installers mentioned a measurement and installation time of 10-30 minutes per window. Additionally, residents noted equivalent or better aesthetics when viewed from either inside or outside, improved clarity through the windows, thermal comfort when near the windows, reduced condensation on the room-side surface of the windows, and significantly reduced external noise coming through the windows. At some sites, and with no major renovation required, the homeowners were able to keep the historic, stained-glass features to preserve the home's style while still maximizing comfort and efficiency.

The pilot study demonstrates that replacing old, leaky storm windows with new low-emissivity exterior storm windows is an effective window improvement measure for homeowners and utilities to consider. Modern storm windows with low-e coatings provide both improved insulating power and better air sealing compared to old, leaky storm windows. Xcel Energy will review the outcomes of the pilot closely to determine the viability of proposing an updated measure for storm windows.

Cellular Shades Lab Homes Field Study

Experiments were conducted at the PNNL side-by-side Lab Homes during the 2017-2018 heating and cooling seasons in order to study the thermal performance and effects of dynamic control methods applied to double-cell cellular shades. The PNNL Lab Homes are two identical, double-wide manufactured homes used to conduct energy research, where one home serves as the baseline home and the other as the experimental home. In this study, the cellular shades were installed in the experimental home and examined for dynamic and potentially automated operation, while the baseline home was outfitted with horizontal slatted vinyl blinds and observed a "typical" operation schedule (Bickel, Phan-Gruber, and Christie 2013). An example of the visual impact of cellular shades in a typical single-family home can be seen in Figure 6. The savings associated with cellular shades were found to range from 2-10% in the heating season and 5-25% in the cooling season, depending on baseline assumptions and operation schedules. Optimal operation of this technology can be achieved through automation or by manually keeping the shades shut during the day in the summer and raised during the day in winter (Cort et al. 2018). In 2022, Oak Ridge National Laboratory (ORNL) researchers tested the performance of cellular shades in a two-story residential home in the Southeast demonstrating significant energy savings during the winter heating season where the room with cellular shades achieved up to 24% heating energy savings. Additional energy simulations predicted how the shades would perform in different climate zones and it was estimated that a cellular shades market penetration rate of 20% in residential buildings could reduce carbon emissions by 3 million tons (Kunwar et al. 2022).

Figure 6. Experimental performance testing of cellular shades in ORNL Yarnell Station house (residential test home). *Source*: ORNL

Exterior Shades Lab Homes Field Study

Figure 7. PNNL Lab Homes shown with exterior shades rolled up (closed) and rolled down (open). *Source*: Hunt and Cort 2020.

During the cooling seasons of 2019 and 2020, PNNL conducted a series of field studies at both the PNNL Lab Homes and three occupied field sites in Richland, WA, to study the energy performance of exterior shades. As seen in Figure 7., exterior shades were installed in the experimental home on three larger west- and south-facing windows, while the baseline home's windows were covered with interior vinyl blinds. Compared to the baseline home, the home with exterior shades demonstrated HVAC energy savings ranging from 2.4 to 5.2kWh, which translates to approximately 20% cooling savings when including internal cooling loads. During a no-cooling test on a sunny day with outdoor mid-day temperature around 75°F, the home with exterior shades registered 9°F lower than the home with vinyl blinds, represented in Figure 8., suggesting that exterior shades have the potential to improve comfort and control solar heat gains in temperate climates without mechanical cooling.

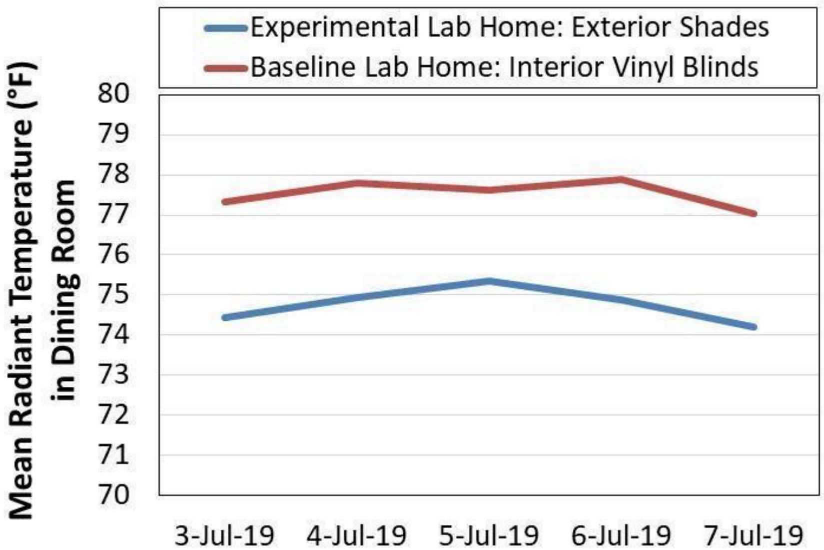

Figure 8. Indoor temperatures near covered windows. *Source:* Hunt and Cort 2020

Three occupied field sites in Richland, WA, were also outfitted with exterior shades, and the homeowners were surveyed in order to document their perspectives on and usage of the exterior shades. All of the homeowners were satisfied with the cellular shades, citing their reliability, ease of use, improved comfort, and ability to reduce glare while maintaining a view of the outside, as seen in Figure 9. Temperature data was collected during peak solar irradiance hours, demonstrating a reduction in indoor temperature ranging from 0.5°F to 4.0°F and substantiating the homeowners' statements of improved comfort (Hunt and Cort 2020).

Figure 9. View outside during sunlight with exterior shade closed at occupied field sites. *Source*: Hunt and Cort 2020

Energy Modeling

Partnering with Lawrence Berkeley National Lab (LBNL) and the Center for Energy and Environment, PNNL conducted a brief modeling study in 2024 to complement the findings of the Xcel Energy clear storm window replacement pilot in Minneapolis, Minnesota. The three multi-family apartment buildings participating in the pilot were characterized in [x modeling program], and the energy performance of low-e storm windows was modeled over a baseline model in which the existing windows were already equipped with clear glass storm windows, as outlined in Table 3. Results of this modeling study are listed in Table 4, and on average, the application of low-e storm windows conferred x% heating savings and x% cooling savings.[2].

Table 3. Modeling study baseline and assumptions

Building Characteristic	Multi-family #1	Multi-family #2	Multi-family #3
Number of units	4	2	5
Square footage	4,300	1,900	3,000
Number of windows	55	29	30
Glazed square footage	602	259	525
Heating system	Steam boiler	Forced air furnace	Steam boiler

[2] The results of this modeling study will be available in the final version of this paper.

Cooling system	Window AC	N/A	Window AC

Table 4. Modeled energy savings of low-e storm windows in multi-family buildings participating in the Xcel Energy Minneapolis pilot study

Building	Cooling Savings (kWh)	Heating Savings (kWh)	Heating Savings (Btu)
Multi-family #1	x	x	x
Multi-family #2	x	x	x
Multi-family #3	x	x	x

Window Attachments in Utility Programs

Technical Reference Manuals (TRM) serve as key resources for many utilities in identifying and assessing new energy-efficiency measures to include in their programs. Additionally, TRMs offer a standardized approach to calculating energy savings. Starting in 2019 AERC began submitting workpapers for residential low-e storm windows in several TRMs – hoping to raise awareness of the measure and open the door to broader inclusion in utility programs. Although several TRMs include window attachments measures for single-family buildings, only a subset of those measures also apply to multi-family buildings. However, there are ongoing efforts to expand eligibility of window attachments to multi-family buildings in these TRMs. Inclusion in a TRM does not guarantee that a utility will offer the measure, so some additional outreach and awareness building among program administrators may be necessary. A full list of TRMs that include window attachments are shown in Table 5. below.

Table 5. Technical Reference Manuals with window attachment measures[3]

Window Attachment Technology	Technical Reference Manuals
Storm Windows	**Arkansas**, Connecticut, **Illinois**, Iowa, Maine, **Louisiana, Michigan**, **Minnesota**, Missouri, New Orleans, **Texas**, **Vermont, Regional Technical Forum (Washington**, **Idaho**, **Oregon**, **Montana)**, **Tennessee Valley Authority (Tennessee**, **Alabama**, **Mississippi**, **Kentucky**, **Georgia**, **North Carolina**, **Virginia)**
Cellular Shades	**Illinois, Minnesota**

[3] In this table, for TRMs that are bolded, the corresponding window attachment measure is applicable to both single- and multi-family buildings, and un-bolded TRMs are only applicable to single-family.

Exterior Shades	**Texas,** New Mexico

Several utility programs offer incentives for installing window attachments. According to the Consortium of Energy Efficiency (CEE[4]) in 2022, a small minority of CEE member utilities provided incentives for window attachments, including 6 offering storm window rebates, 1 window insert rebate, 1 window film rebate, 1 cellular shade rebate, and 2 solar screen rebates. Most of these offerings only apply to single-family homes, presenting an opportunity for expansion to multi-family buildings. Historically, the multi-family segment has been underserved by utility energy-efficiency programs (Samarripas and York 2019). This is primarily due to split incentives, where tenants are responsible for paying their energy bills and directly benefit from the cost-savings of energy-efficiency improvements, but building owners who don't benefit from the improvements are responsible for paying for and approving the upgrades. This leaves renters with little power to apply energy-efficiency upgrades and thus little agency over decreasing their utility bills and increasing the comfort and resilience of their homes. Because of this multi-family utility programs are gaining more popularity.

Window attachments are a key technology for the multi-family sector, even though the current adoption of window attachments in multi-family buildings is virtually non-existent. Window attachments require less upfront capital investment from the building owner or manager compared to window replacements, but still offer similar energy efficiency and comfort improvements. Additionally, the installation of window attachments is much less disruptive to tenants than window replacement. For instance, storm windows can be installed on the exterior of the building and may only require a one-time entry into a tenant's space to take measurements. For multi-family buildings with multiple stories where exterior windows aren't easily accessible, interior storm windows could be used instead. Interior window inserts can also be used in this application and both measurement and installation are easy enough that they can be done by the tenant. A building owner may be attracted to these lower-cost, less-invasive options if they are receiving many tenant comfort complaints, or even tenant turnover due to comfort issues.

Building Performance Standards and Historic Building Applications

In addition to efficiency and utility programs, a new driver pushing upgrades in existing buildings are building performance standards (BPS). Building performance standards are established in city or state law to set maximum energy use or carbon emission limits on existing buildings. Building owners must pay financial penalties for exceeding those limits or not complying with reporting requirements, although the intent is not to punish building owners, but to encourage owners to invest in making energy efficient improvements to existing buildings rather than paying a fine to the city. The most famous example of a building performance standard is Local Law 97 in New York City, but these standards are expanding rapidly across the country in places like Boston, St. Louis, Washington D.C., Colorado, and Washington State. Figure 10. shows the locations that have either enacted a building performance standard or have committed to develop one as part of the National Buildings Performance Standards Coalition.

[4] CEE is a consortium of utility efficiency program administrators and other stakeholders from across the United States and Canada with membership representing 38 U.S. states and 4 Canadian provinces.

Most building performance standards are initially focused on commercial buildings, but many also apply to larger multi-family buildings over 50,000 ft^2. The building owner can only get so far with HVAC and lighting upgrades, so it is important to also address the building envelope. BPS limits are set conservatively to target the worst performing buildings in a jurisdiction, which usually means older buildings with inefficient windows, including single pane windows. This presents a prime opportunity for window attachments such as low-e storm windows, secondary glazing, and automated insulating shades.

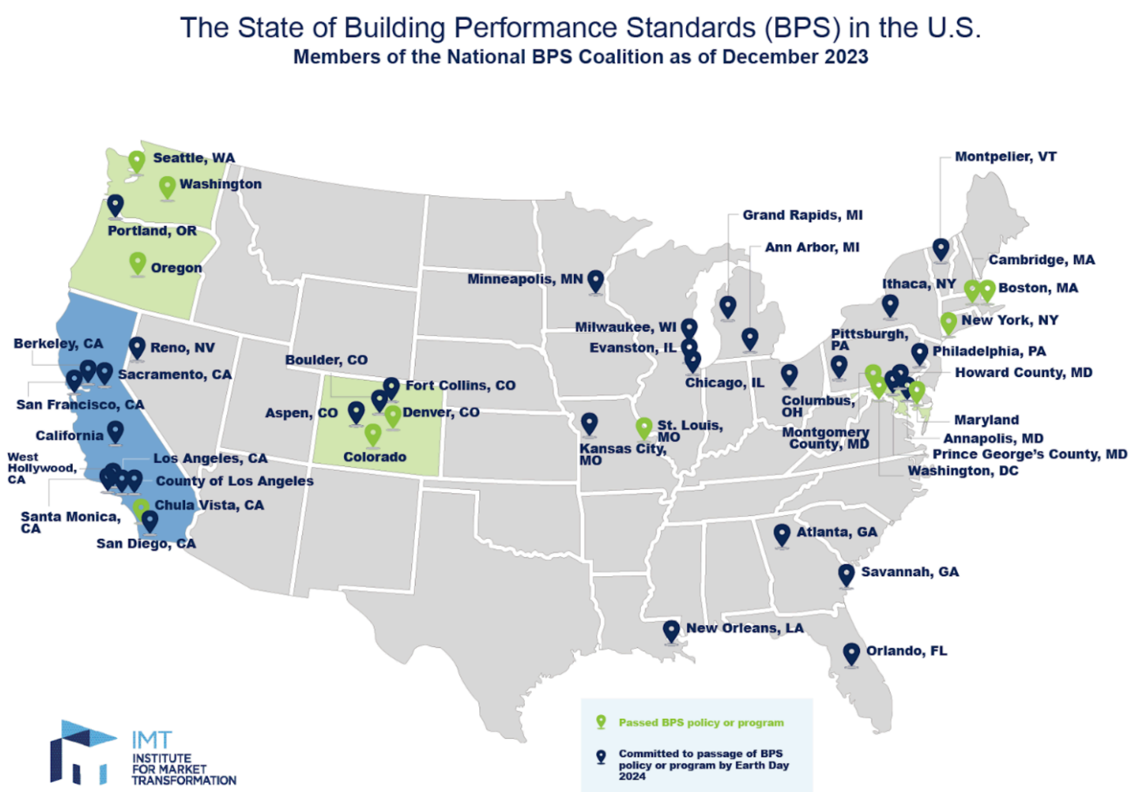

Figure 10: Passed or planned building performance standards in the U.S. as of Dec 2023. *Source*: https://www.imt.org/public-policy/building-performance-standards/

Older buildings may also fall under historic preservation requirements which often restrict window replacement. Low-e storm windows and insulating panels are ideal for upgrading existing windows while maintaining the historic attributes of the existing windows. These products can also be made with custom color framing to match the existing facade. Examples with both exterior and interior low-e storm windows are shown in Figure 11.

(a) (b) (c)

Figure 11. Examples of low-e storm windows on historic multi-family upgrades. (a) 1892 Umbrella Works, Lancaster PA - adaptive reuse to apartments, interior low-e panels. (b) Wissahickon Avenue Apartments, Chestnut Hill, PA - exterior low-e storm windows. (c) 1929 French Apartments, New York City, NY - interior operable low-e panels. Photos courtesy of QuantaPanel.

Conclusion

As existing inefficient residential buildings continue to age, improving the building envelope can improve comfort, enable more efficient decarbonization, and reduce utility bills for tenants or building owners. Multi-family housing in particular presents a unique opportunity for both meeting decarbonization goals and achieving energy equity in the building sector. The window attachments research and field validation studies described in this paper highlight the relative affordability, energy savings potential, and comfort improvements achievable with window attachments upgrades for residential buildings. Furthermore, these studies, have demonstrated that these benefits can be realized in the multi-family sector and that window attachments offer a scalable envelope retrofit solution for multifamily. As Building Performance Standards and other regulations and initiatives are adopted to drive existing building energy-efficiency improvements, multifamily building owners will need more affordable and scalable options to improve the thermal performance of the building envelope. The thermal comfort benefits to the occupant combined with the substantial energy savings provided by window attachment retrofits make these technologies an essential piece of the decarbonization equation. Utility and tax credit incentives that specify energy-rated window attachments (e.g., AERC ratings and ENERGY STAR specifications) could make these cost-effective solutions even more affordable.

References

Ariosto, T. and A. Memari. 2013. *Evaluation of Residential Window Retrofit Solutions for Energy Efficiency.* Pennsylvania Housing Research Center (PHRC). No. 111, December 2013, University Park, Pennsylvania.

Bickel S., E. Phan-Gruber, and S. Christie. 2013. *Residential Windows and Window Coverings: A Detailed View of the Installed Base and User Behavior.* Prepared for the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. September 2013. D&R International, Silver Spring, Maryland.

Cort, K.A., J.A. McIntosh, GP Sullivan, TA Ashley, CE Metzger, N Fernandez. 2018. *Testing the Performance and Dynamic Control of Energy-Efficient Cellular Shades in the PNNL Lab Homes*. PNNL‑27663, Pacific Northwest National Laboratory, Richland, WA.

Culp, T.D. and K.A. Cort. 2015. *Energy Savings of Low-e Storm Windows and Panels across US Climate Zones.* PNNL-24826, Pacific Northwest National Laboratory, Richland, WA.

Culp, T.D., S.H. Widder, and K.A. Cort. 2015. *Thermal and Optical Properties of Low-e Storm Windows and Panels.* PNNL-24444, Pacific Northwest National Laboratory, Richland, WA.

EERE (Energy Efficiency and Renewable Energy). 2013. "2012-13 Quarterly Reports" prepared by Quanta Technologies for U.S. Department of Energy under DOE EERE award #DE-EE0004015. United States: Philadelphia

EIA (Energy Information Administration). 2020. *2020 Residential Energy Consumption Survey*. U.S. Department of Energy/Energy Information Administration. United States: Washington, DC.

Harris, C. 2022. *Pathway to Zero Energy Windows: Advancing Technologies and Market Adoption*. United States: National Renewable Energy Laboratory

Hart, R., Selkowitz, S., and Curcija, C. (2019). Thermal performance and potential annual energy impact of retrofit thin-glass triple-pane glazing in US residential buildings. Building Simulation. 12. 10.1007/s12273-018-0491-3.

Hunt W.E., and K.A. Cort. 2020. *Evaluation of Exterior Shades at PNNL Lab Homes and Occupied Field Sites*. PNNL-30536. Richland, WA: Pacific Northwest National Laboratory.

JCHS (Joint Center for Housing Studies) 2022. *The State of the Nation's Housing 2022*. Harvard Graduate School of Design. Cambridge, Massachusetts: Harvard University.

Knox J.R. and S.H. Widder. 2014. *Evaluation of Low-e Storm Windows in the PNNL Lab Homes*. PNNL-23355, Pacific Northwest National Laboratory, Richland, WA.

Kunwar, N., M Bhandari, DC Curcija. "National energy savings potential of cellular shades: A measurement and simulation study." *Building and Environment.* Volume 225, November 2022, 109593.

Lawrence Berkeley National Laboratory (LBNL). 2023. *International Glazing Database.* Version 95.0. Accessed 3/6/2024 at https://windows.lbl.gov/igdb-downloads.

Metzger, C.E., J. Zhang, V.V. Mendon, and K.A. Cort. 2017. *Modeling Cellular Shades in Energy Plus*. PNNL-27187. Richland, WA: Pacific Northwest National Laboratory.

Petersen J.M., K.A. Cort, M.B. Merzouk, and G. Sullivan. 2016. *Evaluation of Cellular Shades in the PNNL Lab Homes.* PNNL-2485, Pacific Northwest National Laboratory, Richland, Washington.

Petersen J.M., G. Sullivan, K.A. Cort, M.B. Merzouk, V Srivastava, and JM Weber. 2015. *Evaluation of Interior Low-e Storm Windows in the PNNL Lab Homes.* PNNL-24827, Pacific Northwest National Laboratory, Richland, Washington.

Samarripas, S., and D. York. 2019. *Closing the Gap in Energy Efficiency Programs for Affordable Multifamily Housing*. Washington, DC: American Council for an Energy Efficient Economy.