Prepared for the U.S. General Services Administration and
the U.S. Department of Energy
By Pacific Northwest National Laboratory

February 2024

Window Retrofits: Ultralight Window Insulating Panels

Michael Myer
Edward Louie
Ammar Dehwah

Disclaimer

The work described in this report was funded by the Department of Energy under Contract No. DE-AC05-76RL01830.

Acknowledgements

The U.S. Federal Bankruptcy Court; U.S. Senator Tammy Baldwin's office; Internal Revenue Service offices located at the Federal Building and U.S. Courthouse, Eau Claire. The following local U.S. General Services Administration staff in Eau Claire, WI: Scott Jacobs, Daniel Carroll, James Feralin, and Becky Barnes; the following U.S. General Services Administration Green Proving Ground program staff: Erin Lannon and Joshua Banis; and the following Pacific Northwest National Laboratory staff: Allegra Steenson, Heather Culley, Linda Sandahl, and Margaret Axelson.

For more information contact:

Principal Investigator Name: Michael Myer
Lab: Pacific Northwest National Laboratory
Email: michael.myer@pnnl.gov

The U.S. General Services Administration Green Proving Ground program and the Department of Energy's Office of Energy Efficiency and Renewable Energy enable federal and commercial building owners and operators to make sound investment decisions in next-generation building technologies based on their real-world performance.

List of Figures

List of Tables

Introduction

Executive Summary

In October 2021, the Department of Energy (DOE) and the U.S. General Services Administration (GSA) released a joint request for information (RFI). The GSA/DOE RFI - Technologies for Net-Zero Carbon Buildings sought early commercial technologies that were high-performance and would result in low carbon use. WexEnergy submitted their PolarSkin window insulation panels in response to the RFI. WexEnergy has two types of panels, PolarSkin and SolarSkin, which have different properties for use depending on the climate zone: cooling-dominant climate zones (SolarSkin) and heating-dominant climate zones (PolarSkin). This project only evaluated the PolarSkin panel because of the location of the test site.

This report presents results from the evaluation of the PolarSkin window insulation panels at the GSA-operated Federal Building and U.S. Courthouse, Eau Claire in Eau Claire, WI (Eau Claire Courthouse). The principal occupants of the building include: U.S. Senator Tammy Baldwin's local office, the U.S. District Court for the Western District of Wisconsin, the U.S. Bankruptcy Court for the Western District of Wisconsin, the U.S. Probation and Pretrial Services office, and the U.S. Marshals Service. During this evaluation period, offices in the building were being renovated for new offices for the Internal Revenue Service (IRS).

This report also presents results from modeling of the window insulation in other climate zones and a generic medium-sized office building to allow for comparisons in other locations. Modeling was also used because the energy savings at the building level at Eau Claire were inconclusive for reasons discussed in the report.

Table 1 lists the quantitative metrics of this evaluation and the status of each metric. Table 2 lists the qualitative metrics.

Table 1. Quantitative Performance Objectives

Quantitative Objective	Metrics & Data Requirements	M&V Results
Reduce Energy Use	Heating appliance fuel usage rates. Heating appliance run times, before and after retrofit. Natural gas and oil delivery bills, before and after retrofits. Weather data and heating degree days.	Inconclusive from site measurements because of data oddities with the on-site heating, ventilation, and air conditioning (HVAC) system. Warm Climates: 5–6% whole-building modeled HVAC savings. Cold Climates: 3–4% whole-building modeled HVAC savings.
Cost Effectiveness	Material cost and labor/annual energy savings.	Longer than 15-year simple payback even using future prices for the models of buildings across the country using the same fuel prices for each location.
Increase Comfort	Thermocouples on interior window glass surfaces. Room temperature sensor data.	7°F average difference when outdoor temperatures are at 0°F. Improved room temperature variation and reduced rate of cooling in perimeter rooms by about 28%.
U-Value Improvement	Heat flux sensor on an untreated glass lite adjacent to a lite with the insulation panel installed.	Single-pane window performance observed for the double-pane primary windows because of seal failures not related to this study. Product reduced the U-value from 1.15 to 0.55—a 52% improvement.
Condensation Index	Existing window and insulating glass unit (IGU) configuration and dimensions to enter into the WINDOW and THERM window modeling software by Lawrence Berkeley National Laboratory (LBNL) and the Condensation Index (CI) Tool provided by the National Fenestration Rating Council. Modeled to ANSI/NFRC 500-2020. Interior and exterior temperatures, window surface temperatures, and interior relative humidity. Thermal images on cold days to check against models.	Unable to compute the CI or condensation resistance (CR) because of unsealed gaps. LBNL modeling research on unsealed gaps found that window attachments can make the CI/CR worse but that empirical observations may find the risk not as high as modeling predictions.

Table 2. Qualitative Performance Objectives

Qualitative Objective	Metrics and Data Requirements	M&V Results
Ease of Installation and Operation	Time of installation.	Installation time: 10 minutes per window panel.
Increase Occupant Satisfaction	Survey of occupants using a five-point scale for questions about noise, condensation, and view. Focus group with occupants. Focus group with building staff.	Occupants responded negatively to questions related to noise, condensation, and view. Building staff responded positively and differed from occupant responses.

Background

Per the DOE's Advanced Research Projects Agency-Energy, as of 2014, the United States had 43 × 10^9 ft^2 of windows (ARPA-E, 2014). This equates to ~125 ft^2 of window per person. It is estimated that windows are responsible for 39% of commercial heating energy use and 28% of commercial cooling energy use, or 34% of all commercial space conditioning energy use—equivalent to roughly 1.5% of the total U.S. energy consumption (Apte and Arasteh, 2006).

Table 3 lists the typical U-values and R-values for common window units. The U-value is the rate at which a window, door, or skylight transmits non-solar heat flow (Btu/ (ft^2 * hr * °F)). The lower the U-value, the less energy that is transmitted through the material. The R-value is the inverse of the U-value and is a rating of the thermal resistance of the ability to transfer heat from hot to cold through a material. The higher the R-value, the greater the thermal resistance.

As shown in Table 3, the window insulation panels part of this evaluation produce U-values less than and R-values greater than those of a single-pane window.

Table 3. Typical U-Values and R-Values for Common Window Units

Metric	Single Pane[1]	Double Pane[1]	High Performance Double Pane[2]	Triple Pane[1]	Quad Pane Thin Glass[2]	Window Insulation Panels Evaluated[3]
U-value	0.7–1.1	0.3–0.7	0.32	0.2–0.3	0.12/0.17	0.31
R-value	0.9–1.4	1.4–3.3	3.1	3.3–5.0	8.3/9.5	3.2

1. ARPA-E 2014 2. Kiatreungwattana and Simpson 2021 3. Taitem 2022

The envelope will last (or be in service) longer than other building technologies. Window lifespans can be 25–35 years. As an example of other government agencies and their decisions related to windows, the Minnesota (MN) Commerce Department allows for a long payback period for their window projects. The MN

Commerce Department accepts long recovery periods because it estimates a window's average life span at 35 years (MN Department of Commerce, 2023). In the later part of a double- or triple-pane window's life, the seals can start to fail, and the gas between the glass panes will likely escape, reducing the thermal properties of the window. Although windows may have a long life, the performance of windows will degrade before they need to be replaced. During this period of window seal failure, it could be cost effective to install a secondary glazing system, such as an insulation panel to improve the energy efficiency of a window.

Because of the potentially long cost recovery period, retrofit solutions that do not require replacement of the entire window unit are desired.

Technology Description

The vendor's transparent snap-on window insulation panels mount to the interior glass surface of an existing window via small translucent acrylic adhesive-backed snap-together connectors placed at the four corners of the glass surface. This is innovative because interior mounted products are easier to install in a multistory building. This product is clear, which can be an important factor for all buildings and particularly important for buildings listed in the historic building registry. Transparent window insulation panels snap onto a window by mating to the connectors installed at the four corners of the glass surface. The final installation step is to apply clear silicone sealant to each panel corner (vendor supplied) and remove the protective blue liner and labels. The addition of silicone to the standard installation process occurred after installation at the Eau Claire site. However, the use of clear silicone sealant would make it difficult to remove and reattach the fasteners post-installation if cleaning or other needs arise.

The insulation panel seals to the glass surface, creating a dead air space between the glass surface and the plastic panel that is spaced optimally to minimize the conductive and convective heat losses for an air-filled cavity. This is innovative because the air gap spacing can be consistently maintained for each glass unit or glass lite in a window by mounting to the window's glass surface as opposed to products that mount to the window frame.

This application also allows the existing window to remain as easily operable as before with the product installed. This contrasts with many secondary window products that render the window inoperable when installed or result in the need to open the secondary window product in addition to the primary window, increasing the difficulty of window operation. Maintaining the operability of operable windows can be important for climate control and egress.

For single-hung, double-hung, and slider windows and windows with muntins, the window insulation panels can be much smaller when installing to each glass unit or glass lite in a window instead of the window frame; thus, they are easier and lighter in weight to ship, handle, stage, and install than fitting one large panel that covers the whole window. The best window retrofit technology may not necessarily be the best one but rather the one that can be afforded and installed by the site. Thus, if a window in a building is too large to practically install an insulation panel that covers the whole window, this product could be the next best option.

The product is made from thin copolyester plastic (~0.5 mm thickness), which reduces the shipping weight compared to products made from glass or thicker acrylic and reduces its embodied carbon footprint. There are two profiles of window insulation panels—low and high. The high-profile version (0.6”) is the default; however, the vendor makes a low-profile version (0.33”) for applications where the high-profile version would interfere with window operation. Both use copolyester plastic with the same thickness. The high-profile panels bend the 0.5-mm-thick plastic over to create a taller edge. This evaluation considered only the high-profile window insulation panels.

Finally, the vendor mentioned (but it was not available for this evaluation) a mobile phone-based application to allow for measurements. Measuring the size of the window glass to order the product could be easier than measuring the size of a window frame because of the smaller lengths and greater chance that the glass is square compared to the window frame. However, some window lite measurements at Eau Claire, WI were complex because of the window locks on the existing windows. A small amount of additional time is needed for measurement if the window has locking hardware that an insulation panel needs to work around (e.g., Figure 1d). Figure 1 provides a visual depiction of the technology (1a and 1b) and shows how the window insulation panels attach to the windows (1c and 1d). Finally, Figure 1e and 1f show what the window looks like with the technology installed. The insulation panel can be worked around the window lock, and large panels can be stabilized at the mid-span. The production version is transparent, as seen in the middle panel in Figure 1f. However, these were new features that the vendor was implementing in their product; at the time of ordering the insulation panels for this demonstration project, the vendor could only 3D print these parts using translucent filament.

The technology is available in two varieties: a low/no-sun panel and a high-sun panel. The low-sun window insulation panel focuses on improving the U-value of the window without reducing its solar heat gain coefficient (SHGC) and the high-sun product is coated to reduce the SHGC, which is desirable for cooling-dominant climate zones.

(a) Corners of window insulation panels have attachment devices.

(b) Panel has metal edges and is a fraction of an inch in width.

(c) Window attachments in the corners of the window lite hold the panel in place.

(d) Installer presses the insulation against the window mounts.

(e) There is a small gap between the window panel and the overall frame.

(f) Panel mostly disappears when viewed at a reasonable (>5 ft) viewing distance from the window.

Figure 1. Overview of the window insulation panels.

Window Retrofit Weight

Windows are installed early in the construction process before the interior fit out is complete. This allows either large window units or large equipment to hoist the windows into place without the cumbersome aspects of the interior space limiting access to the facade. A challenge with a window retrofit is that it almost always needs to be completed from the exterior because the units and needed equipment cannot easily fit in elevators or around corners and because there are other challenges within the space. Installing window replacements or retrofits from outside the building requires special equipment that can hoist heavy window units multiple stories into place.

Table 4 lists the different window sizes found at the Eau Claire Courthouse. A ¼” (6 mm) thick piece of glass weighs roughly 3.2 lb/ft^2 (15.6 kg/m^2). The frame and related parts of the IGU add another 10–15% in mass. Table 5 lists the weights of the double- and triple-pane IGUs with standard glass for the window configurations at the Eau Claire Courthouse. (GPG evaluated Lightweight Quad-Pane Windows[1] made with thin glass that have the same thickness as and a comparable weight to those of double-pane windows.)

[1] https://www.gsa.gov/climate-action-and-sustainability/center-for-emerging-building-technologies/completed-assessments/building-envelope/quadpane-windows

Table 4. Window Unit Weights of the Configurations at the Eau Claire Courthouse

Floor	Configuration #	Area (ft^2)	Double Pane (lb)	Triple Pane (lb)
Basement	1	14.7	98.2	146.7
Basement	2	3.9	26.4	37.9
Basement	3	7.1	47.2	69.1
Basement	4	16.5	107.5	159.5
1st Floor	1	47.6	308.8	461.5
1st Floor	2	12.8	83.5	123.5
1st Floor	3	2.7	18.6	26.2
2nd Floor	1	33.1	214.8	320.4
2nd Floor	2	33.8	219.2	237.2
2nd Floor	3	79.7	515.7	771.9
2nd Floor	4	2.7	18.6	26.2
3rd Floor	1	2.7	18.6	26.2
3rd Floor	2	16.5	107.5	159.5
3rd Floor	3	29.8	193.3	288.3

As shown in Table 4, even the double-pane replacement could weigh multiple hundreds of pounds. Retrofit options that do not require large and heavy window units are needed to reduce the cost of installation.

The window insulation panels evaluated at Eau Claire were ultralight (0.17 lb/ft^2), a 95% weight saving compared to ¼” glass, and multiple panels, typically 10 panels per box, were shipped inside boxes that one or two people could move. Figure 2 shows the boxes used to ship the window insulation panels.


(a) Boxes of window insulation.


(b) Inside a box with multiple window insulation panels.

Figure 2. Shipping containers for window insulation panels.

Window Retrofit Installation

The window insulation panels are designed to be installed from within the building. The window insulation panels can be installed by occupants, building owners, facility managers, or contractors. The installation process involves few tools and no skilled labor. Figure 3 shows a window insulation panel being installed on the second floor of the Eau Claire Courthouse. Data from the Eau Claire, WI, installation indicated an installation time of 10 minute per window panel.


(a) Corner mounts are placed in the corner of each window lite.


(b) Window lites were premeasured, and the insulation panel was fabricated to size.

(c) Installer places a panel on the corner mount attachments.

(d) Installer presses the insulation against the window mounts.

Figure 3. Installation of a window insulation panel on the second floor of the Eau Claire Courthouse.

Window Retrofit Operation

Window retrofit options that do not involve replacement of the entire existing unit often limit the functions of the window. Storm windows are a retrofit option for increasing the energy performance of windows. However, they either prevent the window from being operable once installed, or window operation becomes a more difficult two-step process (e.g., open the interior window and open the secondary window). One reason for the selection of this technology is that the window insulation panels allow the windows to remain operable.

Low-Carbon Materials

During the evaluation of this technology, U.S. Congress enacted the Inflation Reduction Act. Section 60503 of the Inflation Reduction Act, Use of Low-Carbon Materials, provides funding to GSA for the procurement and installation of materials and products with substantially lower levels of embodied greenhouse gas emissions associated with all relevant states of production, use, and disposal as compared to the estimated industry averages of similar materials or products as determined by the U.S. Environmental Protection Agency.

The window insulation panels are made of plastic and low-carbon materials. The vendor is in the final process of an ISO 14040-compliant life-cycle accounting analysis of its technology.

Evaluation Plan

Demonstration Site

The desired test bed for this technology was a small commercial office building with no data centers (15,000 to 25,000 ft^2 or smaller); this was to constrain the number of windows that needed to be treated to a manageable, yet large enough, number to be a representative building for measuring whole building energy savings. The building needed to be in a cold climate (International Energy Conservation Code [IECC] climate zones 5–8) because heating energy savings was of greatest interest. The heating system needs to be one that is simple to instrument to measure the energy consumption, ideally through single-stage heating equipment. If the heating energy is gas, it is preferred that the heating equipment is on its own meter. If other gas-consuming appliances are co-metered, the gas consumption of the other appliances must be low. Historic heating energy data must be available at a monthly resolution or better for the past 12 months and throughout the study period. The building cannot have major envelope, mechanical, or space modifications that will impact energy usage during the winter of 2021–2022 when the baseline energy data are captured and in 2022–2023 when the experimental energy data are recorded. The building must have a window-to-wall ratio (WWR) of 30–70% and windows that are single-pane or double-pane clear with no low-e or noble gas fills.

The window glass pane(s) must be smaller than 4ft × 6ft, as this is the current manufacturing size limit of the product being tested. The windows must have rectangular glass (minimal to no curved, arched, or stained glass) for 95%+ of the windows.

Because the product being tested mounts to the interior glass surface, the windows cannot have aftermarket tint films applied; if an aftermarket film has been applied, the building manager/owner must be comfortable with a small corner of film being removed to allow small adhesive-backed snap-together connectors to be installed in each corner of the glass. The windows must have rectangular glass (minimal to no curved, arched, or stained glass) for 95%+ of the windows.

The test building had a small number of windows with aftermarket tint films applied. Unfortunately, the removal of a small section of the window film was extremely difficult. Removing a portion of the window film was only attempted on six lites. The insulation panel fasteners were adhered to the remaining 24 lites with film which turned out to not have adhesion problem, even with the weight of the insulating panel attached.

For evaluation purposes, the tenant base must be somewhat similar from 2021 to 2023 to the extent possible during the COVID-19 pandemic. Strong buy-in is necessary from facility management, GSA tenants (for surveys on comfort improvements), and custodial staff. The criteria for site selection are summarized in Table 5, along with the characteristics of the test bed building.

Based on the requirements in Table 5, the Eau Claire Courthouse[2], located at 500 South Barstow Street, Eau Claire, WI 54701, was selected as a good test bed for this technology. The town of Eau Claire, WI, is in IECC climate zone 6A, which is considered cold/moist.

Table 5. Site Criteria

System	Desired Site Requirements	Actual Site Characteristics
Facility Characteristics	Office building with no data centers.*	Office building with no data centers.
Fenestration	- WWR 30–70%. - No curtain walls. - Windows with glass pane(s) sized smaller than 4 ft × 6 ft. - Single-pane or single-pane with exterior storm windows. - Windows with no tint film or insulation film already applied. - Windows with rectangular glass (minimal to no curved, arched, or stained glass) for 95% of windows. - No major envelope, mechanical, or space modification building improvements that affect the energy used during the winters of 2021–2022 and 2022–2023. - If gas is the primary heating fuel, minimal gas usage for other end-uses.**	- WWR ≈ 30%; double-pane with clear glass with anodized aluminum frame. - Quantity: 75 windows, including frames, mullions, lites, etc. These 75 windows contain 287 individual lites (individual glaze pane; many lites may be within a window unit). These lites comprised 57 different sizes. This many different sizes are atypical for most buildings.
Location	Cold climate (IECC climate zones 5–8).*	Eau Claire, WI (IECC climate zone 6A, cold/humid).
Occupancy	Consistent occupancy for 2021–2023.**	2021–2022: ≈25 people 2022–2023: ≈75–100 people once 50-75 staff from the IRS are located in the building.
Site Engagement	Strong buy-in from facility management, GSA tenants (for surveys on comfort improvements), and custodial staff.*	Strong buy-in from facility management and GSA tenants (for surveys on comfort improvements).
Historical Heating Energy Data	12 months of historical heating energy data at a monthly resolution or better.*	12 months of historical heating energy data at a monthly resolution, though the historical data contained data abnormalities.

[2] https://www.gsa.gov/about-us/gsa-regions/region-5-great-lakes/buildings-and-facilities/wisconsin/federal-building-and-us-courthouse-eau-claire

System	Desired Site Requirements	Actual Site Characteristics
Documentation	Floorplans, furniture, and cubical arrangements in addition to as-built drawings, especially including equipment schedules.*	Floorplans and equipment specifications.
Control System	Ability to install sensors to monitor heating ignition circuit(s) if the building doesn't have run time data available.*	Single- or two-stage equipment allows sensors to monitor heating ignition circuits.
HVAC	Built-up HVAC systems are in good working condition and simple to instrument, such as single-stage equipment.**	Two dual-fuel (natural gas and heating oil) single-stage boilers and two natural gas rooftop units, which have two stages. All are 80% efficiency units, but not all units were working correctly. The rooftop units were repaired.
Building Size	15,000–25,000 ft^2. **	37,000 ft^2.

* Required, ** Strongly preferred

The exterior of the courthouse is shown in Figure 4. The construction of the three-story above-ground building with a basement was completed in 1909. The construction of a one-story addition with a raised basement and a flat roof located at the rear (southwest side) of the building was completed in 1935. The building's windows were replaced in 1981 with double-pane clear glass with anodized aluminum framed windows that replicated the original sash configuration. The building's 37,000 ft^2 of usable floor area was greater than the criterion outlined in Table 5.

Figure 4. Exterior of the Eau Claire Courthouse.

The building does have an aftermarket window tint applied to just the first-floor windows on the northeast side; a small section of the tint will be cut out to allow the acrylic adhesive-backed snap-together connectors to be placed at the four corners onto the glass surface.

The space is home to the U.S. Bankruptcy Court, the U.S. Probation Court, the U.S. Marshals Service, and court offices. Some interior renovations occurred near the end of the winter of 2021–2022 on the first floor to make space for the IRS offices. During the winter of 2022–2023, construction occurred to allow for 50–75 more staff from the IRS offices. Relative to the size of the building, this change in occupancy is expected to change the internal heat load minimally.

The site has support from facility management and the GSA tenants to study the energy savings of this insulating window panel product.

Historic Preservation

The Eau Claire Courthouse was built in 1909 in the neoclassical style of architecture. The building is listed in the National Register of Historic Places. A challenge with buildings listed in the historic registry is that envelope energy efficiency measures must not affect the exterior appearance of the building, and this restriction may limit options. One advantage of this technology is that it does not permanently alter the facade. Although the building is listed in the registry, the windows were replaced in the 1980s with double-pane windows. This project required approval by the State Historic Preservation Officer. An evaluation of this technology by the State Historic Preservation Office included the following statement:

> "It looks like a minimal impact, but the edging of the insert might read as a widened muntin or frame in some instances. Normally I would be concerned if the windows were original. They are not in the Eau Claire building. But the replacement windows that exist there now were designed in the profile of the original windows. So, to me, this building is a perfect test for this product for use at an historic property… In short, I think this looks like a promising product and endorse your moving forward. However, please include me in any discussion on product details as I note above."

Technology Demonstration

Table 6 lists the performance attributes of the technology evaluated.

Table 6. Technology Description

Attribute/Variable	Testing Protocol/Selected Instrument
Installation Time	**Tracking the amount of time** to install the insulation panels divided by the number of insulation panels to obtain the **average time to install an insulation panel**.
Cost Effectiveness (current and future)	**Material cost data from the vendor** to calculate the current and future simple payback periods. **Installation labor cost = (hourly rate × installation time).** **Simple payback period = (material + labor)/annual energy savings.**
U-Value Improvement	Two data loggers, four heat flux sensors, and two windows. 1. Window with a radiator underneath a. Stock window lite b. Window lite with an insulation panel 2. Window without a radiator underneath, as shown in Figure 5 a. Stock window lite b. Window lite with an insulation panel **Compare the U-value of the stock window lite vs. that of the lite with the insulation panel installed**.
Energy Savings	1. **Energy bill analysis**: Compare monthly gas and fuel energy usage from the baseline period (2021–2022) with that from the experimental period (2022–2023), correcting for heating degree days (HDDs). **Energy/(Day * HDD).** 2. **Heating appliance run time analysis**: Measure the heating appliance run time, convert the run time to fuel usage, compare the fuel usage from the baseline period (2021–2022) with that from the experimental period (2022–2023), correcting for HDDs. **Energy/(Day * HDD).** 3. **Modeled energy savings:** EnergyPlus using DOE's pre-1980 medium office building. **Percent savings** and **total site energy in millions of British thermal units.**
Condensation Reduction	1. **Reduction in the time/frequency when the window sweats** (condensation) because the glass has reached the dew point. **Interior surface temperature of the windows vs. interior dew point temperature.** **2. Model the change in the CRof the window.**
Comfort	**1. Interior surface temperature of the windows vs. outdoor temperature:** Attach thermocouples to the interior surface of the window, one in each orientation on each floor. Compare baseline period (2021–2022) vs. experimental period (2022–2023). 2. **Room temperature variation:** Attach a thermocouple next to the thermostat of each room/zone. Compare the temperature variation in the baseline period (2021–2022) vs. that in the experimental period (2022–2023).

Table 7 lists the monitoring points and instrumentation in this evaluation.

Table 7. Monitoring Points and Instrumentation

Monitoring Point	Logging Equipment Description	Location	Collection Period
Building Fuel for Heating System	Fuel oil meter, gas meter	Exterior of building and mechanical room	Nov. 1, 2022–March 31, 2023
Interior Glass Temperature	Thermocouples on windows	First floor north conference room and third floor north attic staircase	Nov. 1, 2022–March 31, 2023
Heat Flux of the Window	Heat flux sensors on windows	First floor north conference room and third floor north attic staircase	Nov 1, 2022–Feb. 23, 2023
Interior Room Temperature	Thermocouple next to the thermostat of each room/zone	Approx. 30 different spaces	Nov. 1, 2022–March 31, 2023
Door Openings	Door opening sensor	Five external doors	Nov. 1, 2022–March 31, 2023

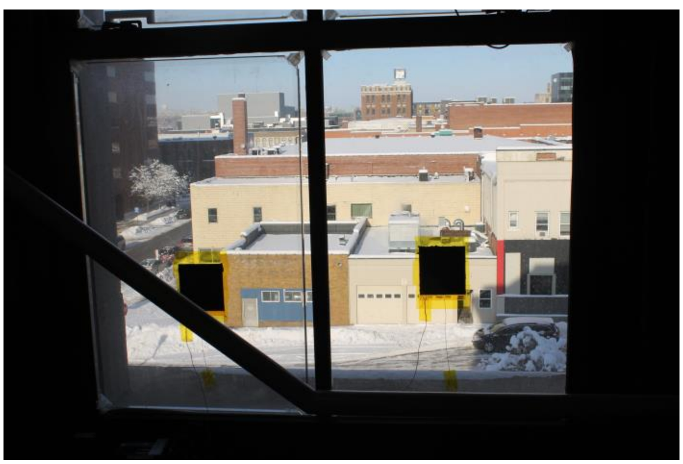


Figure 5. Window with heat flux sensors installed. The operable window sash had four glass lites. The insulation panel technology was installed on three of the four glass lites; both upper lites are outside the image frame, and the left lite is shown in this image. The insulation panel technology was not installed on the right lite so that a heat flux sensor could simultaneously measure the baseline IGU and the IGU that has the insulation panel technology installed.

Energy Savings Simulation Design

Energy modeling is an efficient way to understand how the energy savings of a technology applied to a building would change if the building was relocated to a different climate zone. Energy modeling also allows different energy saving technologies to be compared on a consistent basis by modeling the same prototypical model in the same climate zone locations. The prototypical building model that most closely matches this study's building is the pre-1980 DOE medium-sized office building. This is the same building model used by other GSA GPG studies. A rendering of the pre-1980 DOE medium-sized office building model is shown in Figure 6.

According to Im et al.'s research, the medium-sized office building model has three floors with a total conditioned space of 53,628 ft^2. Each floor has four perimeter zones and one core zone with a perimeter zone depth of 15 ft. The WWR is approximately 33%, and the ribbon windows are evenly distributed along four facades. The height of a window is 4.25 ft. The exterior walls are constructed of steel frames and the roof is a built-up roof composed of a roof membrane, roof insulation, and metal decking. The foundation type is unheated slab-on-grade with an 8" concrete slab poured directly onto the Earth. The building's HVAC system is a packaged direct-expansion cooling air-conditioning unit with a gas furnace and a variable air volume terminal box; an electric reheating coil provides conditioned air to each zone (Im et al., 2019).

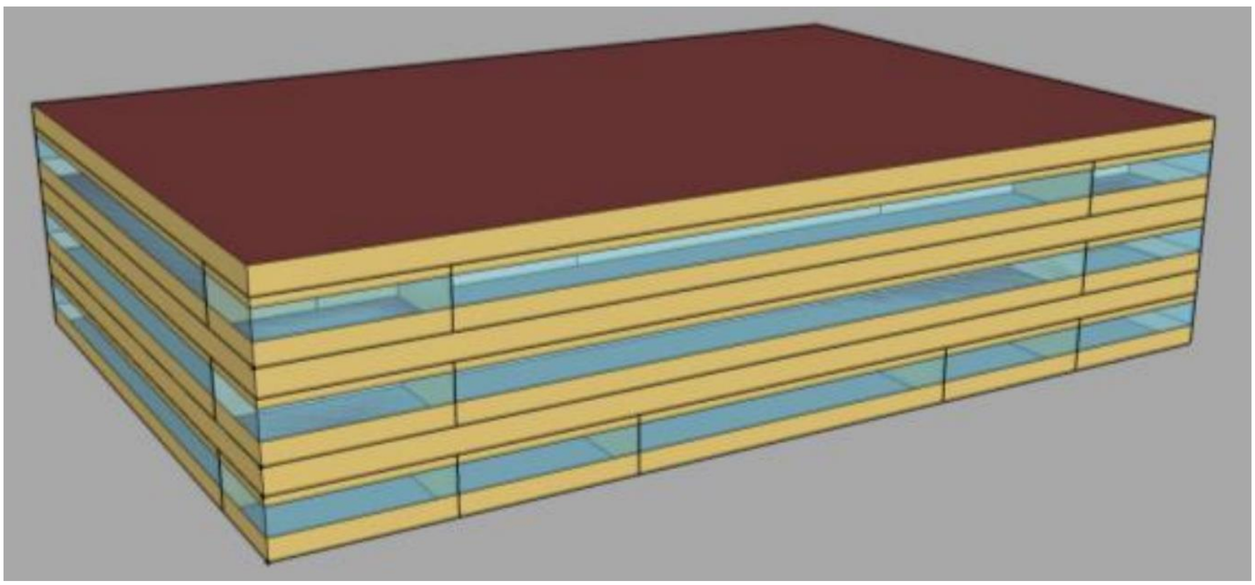


Figure 6. Department of Energy medium-sized office prototype.

The baseline model uses the typical frame, center of glass, and edge of glass U-values for single- and double-pane windows with metal and non-metal frames, as referenced in the *2021 ASHRAE Handbook – Fundamentals* (ASHRAE, 2021). The improvement in the U-value with the use of insulating window panels in place for double-pane windows with metal and nonmetal frames was determined using third-party test data supplied by the vendor. The improvement in the U-value with the use of an insulating window attachment in place for single-pane windows with metal frames was determined empirically via the heat flux data measured on-site at the Eau Claire Courthouse. The improvement in the U-value with the use of window insulation panels in place for single-pane windows with a nonmetal frame was interpolated using the value of the improvement in the U-value from the data obtained for the single-pane windows with metal frames multiplied by the percent difference between the metal- and nonmetal-framed double-pane window values. These changes in U-values were modeled in the context of the medium-sized office building model with the assumptions in Table 8.

Table 8. Modeling Assumptions

<table>
<tr><th>Modeling Attributes</th><th colspan="3">Characteristics</th></tr>
<tr><td>Building Size/Shape[3]</td><td colspan="3">Medium office, three floors (53,628 ft²)</td></tr>
<tr><td>Building Age</td><td colspan="3">Pre-1980</td></tr>
<tr><td>ASHRAE Climate Zones[4]</td><td>Warm Climate
1A (Miami, hot humid)
2A (Houston, hot humid)
2B (Phoenix, hot dry)
3A (Atlanta, mixed humid)
3B (Las Vegas, mixed dry)</td><td>Moderate Climate
3C (San Francisco, mixed marine)
4A (Baltimore, mixed humid)</td><td>Cool Climate
5A (Chicago, cold humid)
5B (Boulder, cold dry)
6A (Minneapolis, cold humid)</td></tr>
<tr><td>Baseline</td><td colspan="3">The baseline model uses the typical frame, center of glass, and edge of glass U-values for single- and double-pane windows with metal and nonmetal frames, as referenced in the 2021 ASHRAE Handbook - Fundamentals.</td></tr>
<tr><td>Window Frame</td><td colspan="3">Two different window frame materials were analyzed: nonmetal and metal. The window insulation only increases the thermal resistance of the window lite, not the entire window. The frame provides a vector for thermal transmission.</td></tr>
<tr><td>Frame Area</td><td colspan="3">Three different window frame areas were analyzed: 10%, 20%, and 30%. The overall WWR did not change, but the size of the frame in the window varied.</td></tr>
<tr><td>Glazing Configuration</td><td colspan="3">Two types of baseline glazing were analyzed:
1. Single-pane, clear glass and
2. Double-pane, clear glass with air-filled windows.
The energy models use the U-values of a double-pane IGU with intact seals.</td></tr>
</table>

[3] https://www.energy.gov/eere/buildings/commercial-reference-buildings
[4] http://www.iaqsource.com/article.php/ashrae-climate-zone-map/?id=194

Results

Quantitative Results

The following sections present the quantitative results.

Building Heating System

Meters were placed on the multiple heating systems in the Eau Claire Courthouse. GSA also provided monthly billing data from the gas meters. Table A1 in Appendix A lists the read dates, therm values, and numbers of HDDs.

This analysis deemed the winter of 2021–2022 as the baseline. There were 96 days in this baseline (11/3/2021–2/7/2022), and the building used 7,580 therms. There were 4,165 HDDs during this period, resulting in 0.0190 therms/(day·HDD). The window insulation panels were installed mid-October 2022. The evaluation period spanned the winter of 2022–2023. There were 97 days in this analysis period (11/3/2022–2/8/2023), and the building used 8,367 therms. There were 4,008 HDDs during this period, resulting in 0.0215 therms/(day·HDD). The building used more energy in the post-evaluation period than during the baseline period.

The window insulation panels are a passive technology. The panels do not use energy. The increased energy usage originates from the uncertainties in the data collection, the oddities of the building/mechanical system, construction activity, and the possible increase in building occupancy and uncontrolled occupant behavior that was not monitored. The building has a mechanical system with multiple components that are oversized compared to a building of this size. As a result, this complicates the energy usage of the building's heating system. During the evaluation period, the building was under construction, and this may have contributed to increased energy usage. In addition, the building occupancy increased between the baseline period and the evaluation period, which may partially have been related to the increased energy usage. The evaluation did not monitor building occupancy in the baseline and post-window insulation installation periods. Had the occupancy been tracked, the energy use of the building possibly could have been normalized by occupancy to determine how that affected the building's energy usage.

In addition, the "run time" of the data from the meters on the mechanical equipment was analyzed. This analysis also confirms that the building used more energy after the window insulation panels were installed than that used during the baseline period. As noted, the window panels do not use energy; it is a passive technology. The increased system "run time" is not a function of the installation of the window panels.

However, other measured data verified that the window insulation panels improved the performance of the windows at the Eau Claire Courthouse.

Interior Window Surface Temperature

The insulation panel improved the interior glazing surface temperature by 8.25°F versus the baseline glazing surface temperature during a particularly cold period in Eau Claire, WI, when the outdoor air temperature averaged -5.2°F (see Figure 7). When the outdoor air temperature was 0°F, the average improvement in the interior glazing surface temperature was 7°F.

The baseline window has a double-pane IGU with no low-e coatings and no noble gas fill. A measurement of the heat flux of the stock window's double-pane IGU found that it has a calculated U-value closer to that of a single-pane window than that of a double-pane IGU. This indicates that the IGU seals in the stock window have started to fail and that the air between the panes of glass is no longer dry desiccated air but rather air that contains humidity. Thus, for other sites, the improvement of 8.25°F when the outdoor air temperature averaged -5.2°F should be considered the improvement when applied to single-pane windows.

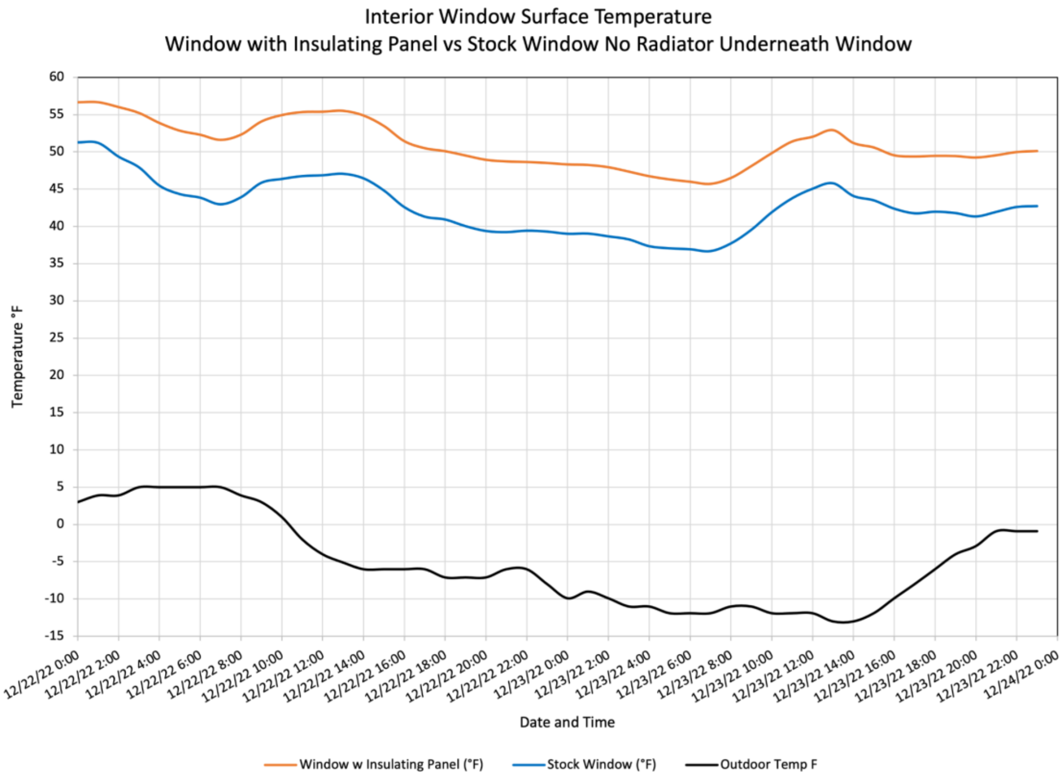


Figure 7. Interior glazed surface temperatures for a window lite with an insulation panel applied versus that of a lite with the stock IGU.

U-Value/Heat Flux Through the Windows

Figure 8 and Figure 9 show the calculated U-value (from measured data on site) for a bare window (baseline) and a window with the insulation panel. As shown in Figure 8 and Figure 9, the U-value for the bare double-pane window is 0.7–1.1 (top blue lines). U-values in this range match the performance of single-pane windows, as shown in Table 3. Therefore, the double-pane windows that were installed in the 1980s are now performing similar to single-pane windows. Figure 8 and Figure 9 show the U-values in the range of 0.4–0.7 for a window with the insulation panel (bottom red line). Although this field evaluation was not able to demonstrate building energy savings from the window insulation panel, Figure 8 and Figure 9 show that the window insulation panels do improve the performance of the windows.

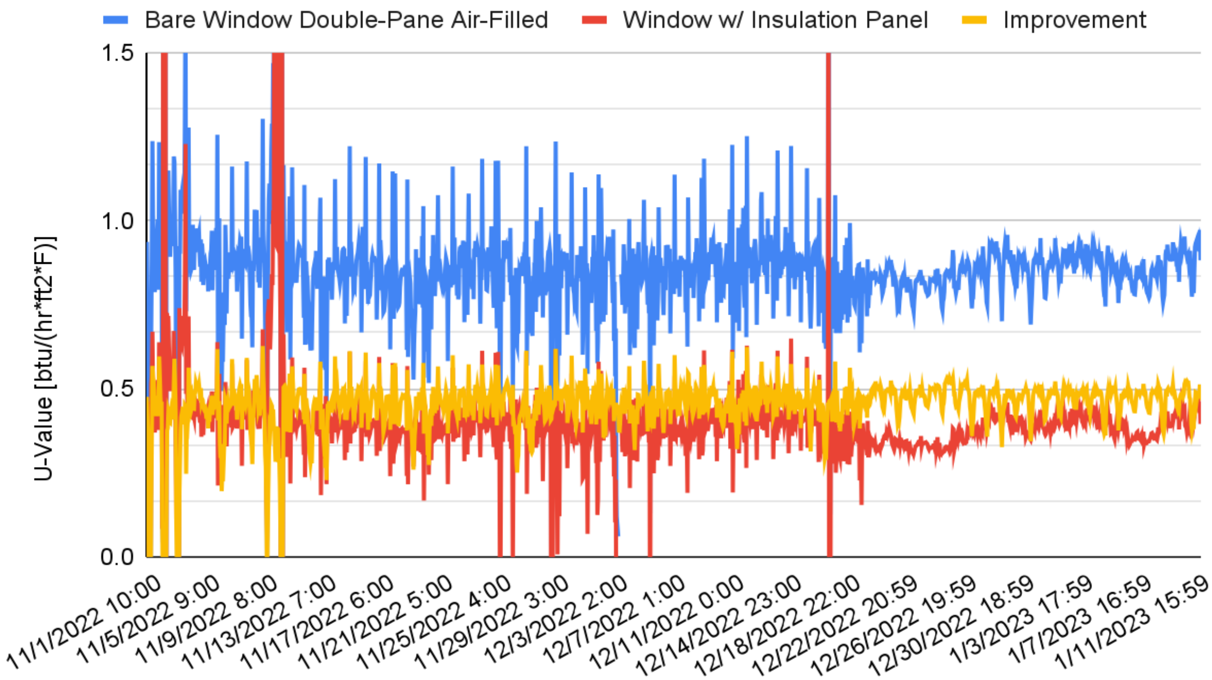


Figure 8. Comparison of the U-values of a bare window and a window with an insulation panel with a radiator below the windows.

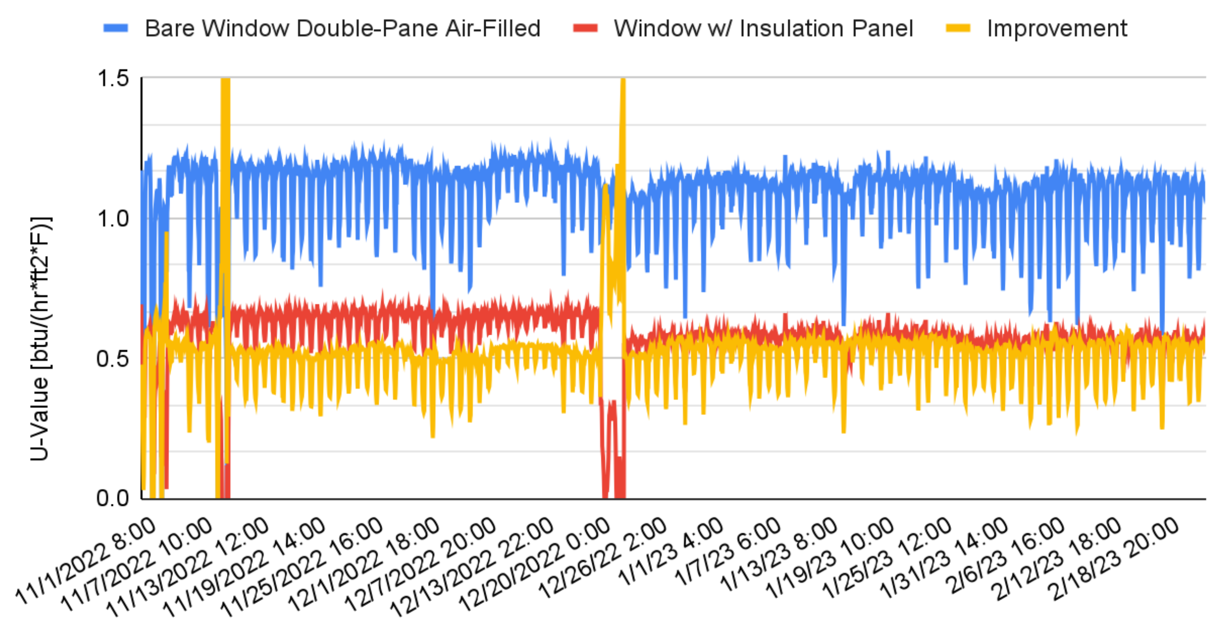


Figure 9. Comparison of the U-values of a bare window and a window with an insulation panel without a radiator below the windows.

The window insulation panels reduced the heat flux (movement of heat through the window) compared to that for the bare window. Figure 10 and Figure 11 show the heat fluxes of the windows compared to the outdoor temperature. For both the bare window (red dots) and the window with the insulation panel (blue dots), more heat moves through the window as the temperature decreases. However, as shown in Figure 10 and Figure 11, less heat moves through the window with the insulation panel. A linear trend line was added to each set of data to show this relationship.

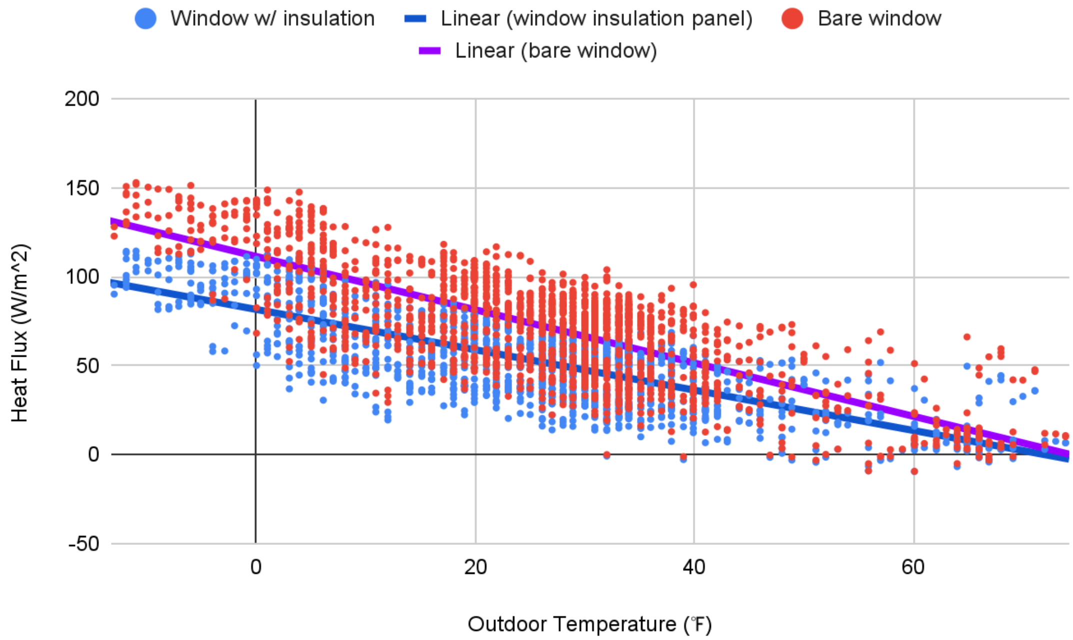


Figure 10. Comparison of the heat fluxes of windows in the first-floor conference room with a radiator under the windows.

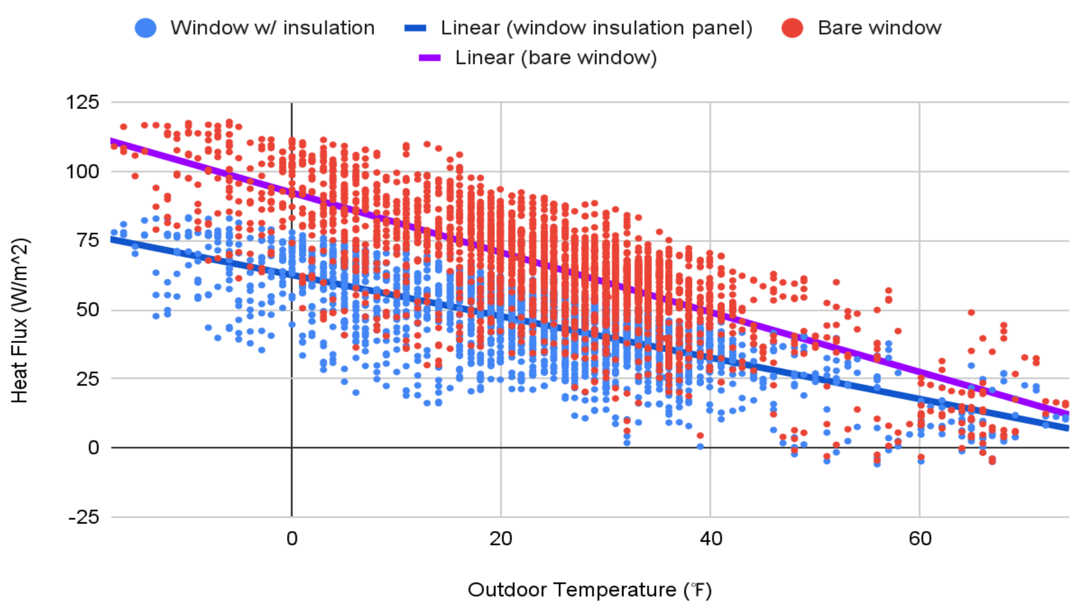


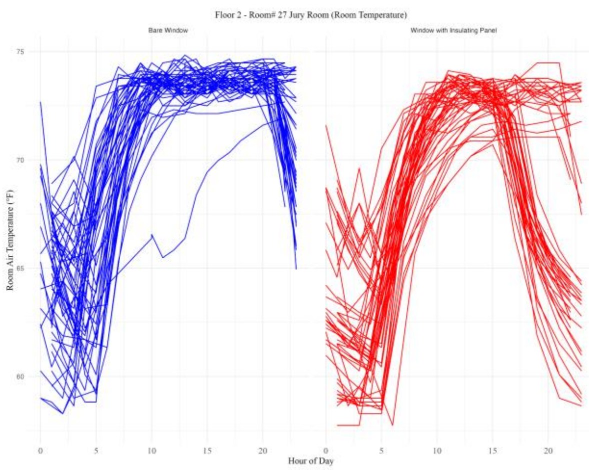
Figure 11. Comparison of the heat fluxes of windows in the third-floor attic stairwell with no radiator under the windows.

Room Temperature

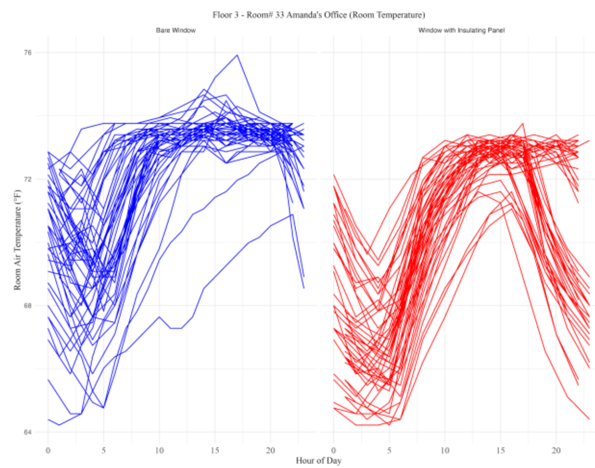
Temperatures of more than 30 different rooms in the Eau Claire Courthouse were monitored during the wintertime periods of 2021–2022 (baseline) and 2022–2023 (after installing window insulation) via wireless room temperature sensors in each room.

Some rooms showed a noticeable improvement in the stability of the room temperature after the window insulation panels were installed. A few rooms reported limited data. In some rooms, the use of the room changed from being unoccupied to occupied; therefore, the radiator zone for that room turned from “off” to occupied. A few of the rooms may have also changed purpose or function. Thus, there may be a notable change in temperature profile for a given sensor name when comparing the data before and after the installation of the window insulation panels.

Figure 12 shows the temperatures in two rooms. The x- and y-axes plot the time of day and the temperature measured in the room, respectively. Each day’s temperature is represented by a different line in each graph. A day starts on the left side of a graph and ends on the right side of a graph. The trends in the figures are more important than the actual values in the figures. Less drastic slopes and less drastic differences on the right and left sides of the graphs versus the middle indicate better temperature stability overnight. In both rooms, the temperature in the room was more consistent after the installation of the insulation panels (as evidenced by the temperature lines being closer together).



(a) 2nd Floor, Room 27 | Left side/blue lines are the baseline bare windows. Right side/red lines are after the installation of window insulation.



(b) 3rd Floor, Room 333 | Left side/blue lines are the baseline bare windows. Right side/red lines are after the installation of window insulation.

Figure 12. Room temperatures of two example perimeter rooms: baseline period versus the period after the window insulation panels were installed at the Eau Claire Courthouse.

Change in the Temperature Overnight

The change in the temperature (slope) overnight (~17th–21st hour to 4th hour) is another metric that was examined. The building controls set back the temperature to 55°F; the heating system enters that mode at 6:00 p.m. and returns to an occupied mode at 6:00 a.m. However, the hour at which the system enters the setback appears to have been adjusted between the baseline period and the period after the window insulation panels were installed. This is a longer temperature setback period than would be found in most other buildings.

The hot water boiler system at the Eau Claire Courthouse has ramp up and ramp down periods that take approximately 2 hours to cool once the heating of the radiators has stopped before the rate of natural heat loss affecting the room temperature can be detected. The slope of the natural rate of heat loss was calculated by visually observing when the temperature of the room starts to decline. For example, for

Room 27, these heat losses occur hour 21 through hour 4 during the baseline period and hour 17 through hour 4 during the period after the window insulation panels were installed.

In Figure 12, a comparison of the slopes of the temperature in the perimeter rooms for the overnight hours showed that the windows with insulation panels had a reduced slope of approximately 31% on average, from a decrease of 0.8°F/hr to 0.5°F/hr, as shown in Table 9.

Table 9. Rates of Cooling for the Perimeter Rooms (Decrease in Degrees Fahrenheit per Hour)

Perimeter Room	Baseline (2022)	With Insulation Panels (2023)	Change
Room #20 2nd Court Room	0.27	0.21	22%
Room #21B Judge's Chambers	0.49	0.36	27%
Room #27 Jury Room	1.7	0.90	47%
Room #32 Trac Office	0.9	0.60	33%
Room #33 Amanda's Office	0.72	0.55	24%
Average	0.82	0.52	31%

This means that the improved windows with insulation panels sufficiently reduced the heat loss of the room to slow the natural cooldown of the room due to heat loss. This observation is important because it relates to a concept called "hours of resilience" or "hours of safety" (Ayyagari et al., 2020). The concept evaluates how long a building can remain sufficiently warm to be a safe refuge for people if the building were to experience a power outage during the winter. Buildings with a better insulation envelope have more hours of safety.

Condensation Reduction

Condensation occurs when the temperature of a surface, such as a glass surface, is below the dew point of the air. Figure 13 shows the interior surface temperature of the baseline window (bottom blue line) and the surface temperature of the window insulation panel (top orange line) by date. The dashed line in Figure 13 is the dewpoint of air at 70°F and 50% relative humidity. There are many times when the baseline window's interior surface temperature drops below the dew point line, indicating that condensation was likely. In contrast, there are only a limited number of days when the surface temperature of the window with the insulation panel dips below the dew point line.

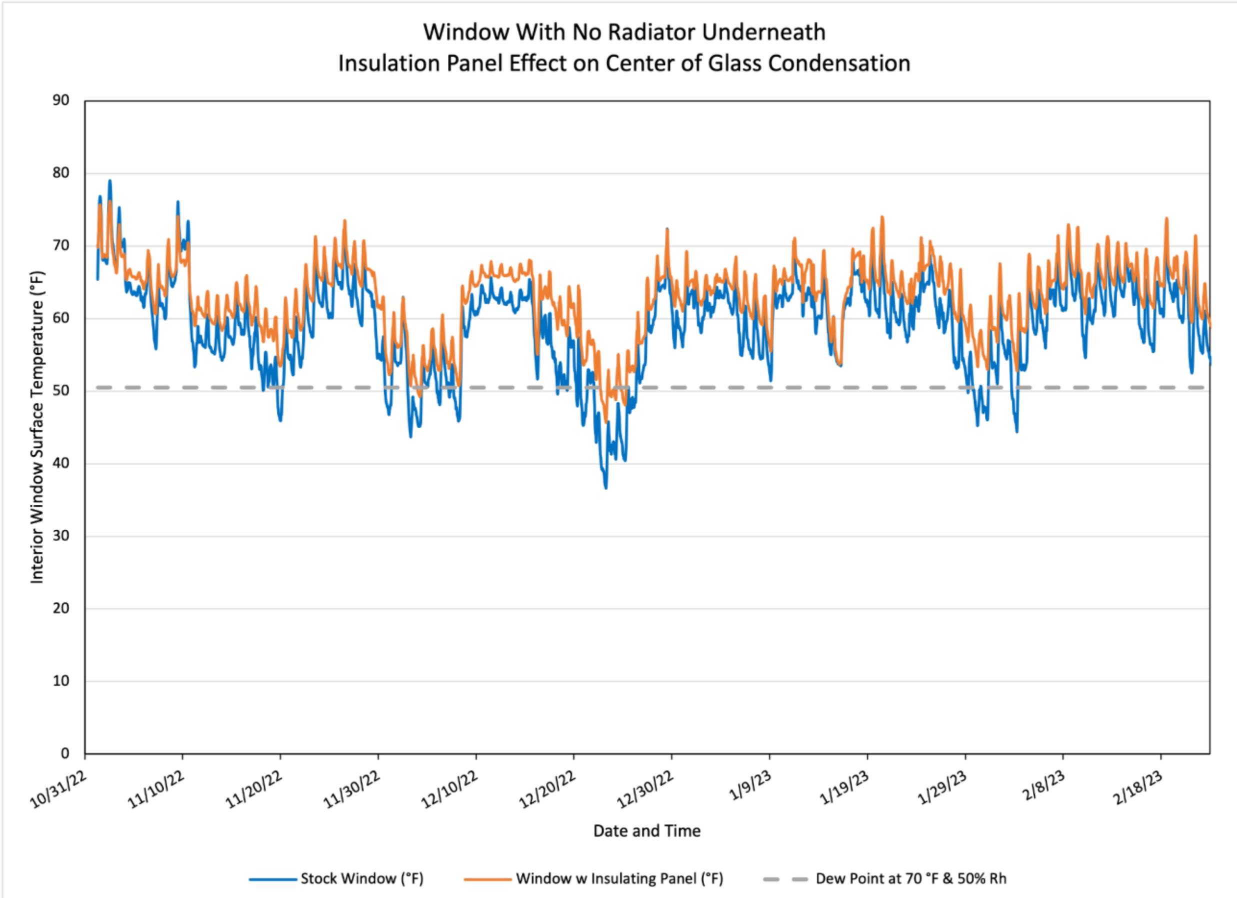


Figure 13. Window condensation at the Eau Claire Courthouse.

Figure 13 indicates that the window insulation panels reduce the number of hours when the surface temperature of the interior window glazing reaches the dew point.

While the data clearly show a reduction in the condensation potential for the interior glazed surface after the insulation panel has been installed, it does not necessarily mean a reduction in the condensation potential on other surfaces. How does the installation of an interior-mounted secondary window, such as an interior insulation panel, affect the risk of condensation on the interior surface of the primary window? Hart et al. studied the CRof unsealed gaps using computer modeling for secondary glazing systems mounted on window framing and found that the CRof the window is generally worse when an interior-mounted secondary window is installed (Hart et al., 2015). This is due to the reduced heat energy escaping through the window; as a result, the interior surface of the primary window becomes colder than that before the secondary window was installed.

The air gap between the primary window and the interior secondary window is not hermetically sealed and filled with desiccated air. Instead, it is air containing humidity. The moisture in the air in between the primary window and the interior secondary window can condense onto the interior surface of the primary window, especially since it is now colder than before because of the installation of the secondary window.

Hart et al. state that the chance of this occurring is affected by the infiltration and exfiltration rates of the air space between the primary and secondary windows (Hart et al., 2015). If the infiltration and exfiltration rates are high, then the chance of condensation is higher than if the rates are low. Since the insulation panel product tested in this project mounts to the interior glazing surface, the infiltration and exfiltration rates of the air between the product and the primary window are very low. Neither the researchers of this project nor the building's facility manager observed condensation between the insulation panel product and the primary window.

If the IGU seals have failed in the primary window, the IGU becomes another unsealed gap where air containing moisture has entered. The reduction in heat energy escaping through the window due to the installation of an interior secondary window can cause the IGU to cool to a temperature at which moisture that has entered the space between the panes of the primary IGU begins to condense. At the Eau Claire Courthouse, there were observations of some IGUs exhibiting this phenomenon prior to the installation of the insulation panels. Moreover, there were some instances of a small increase in the occurrence of fogging between the panes of glass in the primary window's IGU after the installation of the insulation panels. The fogging/condensation between the panes of glass in the primary window's IGU is from the failed seals of the IGU. However, mitigating the occurrence of fogging by foregoing the installation of an interior secondary window is not a good idea, as more heat will escape through the windows to achieve reduced fogging.

For the newly created interior window surface, it is clear from Figure 13 that the condensation risk is reduced because of the warmer interior surface. Although the project originally planned to assess quantitatively the reduction in condensation of the window insulation panels, for the reasons discussed, the CRwas not calculated.

Modeled Results

To evaluate the savings potential in other climates, the DOE medium-sized office prototype model[5] was modeled in 10 climate zones. Twelve model configurations were developed: nonmetal and metal window frames (configurations 1–6 and 7–12, respectively, in Figure 14), single- and double-pane baseline windows (configurations 1–3 and 7–9, and 4–6 and 10–12, respectively, in Figure 14), and window frame size increments of 10%, 20%, and 30%.

Figure 14 (Climate Zone 1A) and Figure 15 (Climate Zone 6A) represent the ends of the modeled range for this analysis. As expected, more energy is used with single-pane baseline windows, and greater potential energy savings are possible with single-pane baseline windows than double-pane baseline windows.

[5] https://www.energycodes.gov/prototype-building-models

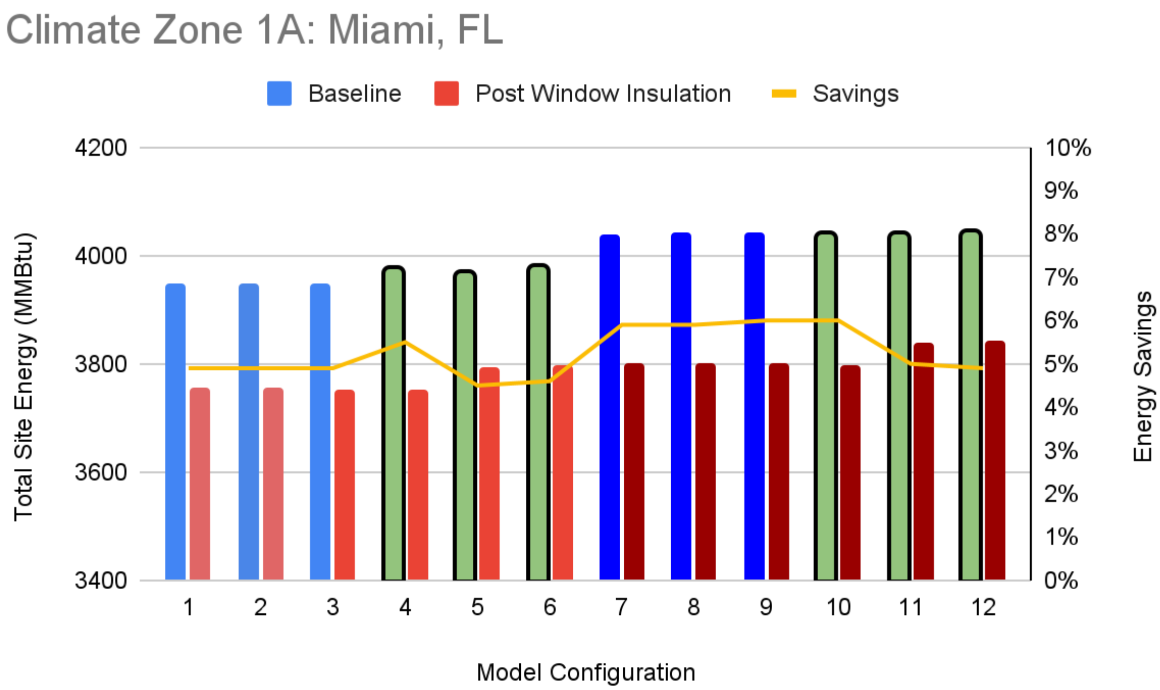


Figure 14. Climate Zone 1A: Miami, FL | Configurations 1–6 are double-pane glazing, and configurations 7–12 are single-pane glazing. Configurations 4–6 and 10–12 (shown in green with black borders) represent metal frames. For each configuration series (e.g., 1–3, 4–6, 7—9, and 10–12), an increase in the configuration number represents an increase in the frame area (e.g., configuration 4 = 10% area, 5 = 20%, and 6 = 30%).

Figure 15 (Climate Zone 6A) is a heating-dominant climate. The window insulation attaches to the window lite. The frame configuration is a vector for energy loss that is not affected by the window insulation, which is demonstrated in Figure 15.

When the increase in the frame area is small (e.g., 10% in configurations 4 and 10), the window insulation has a greater effect because the glazing area is the dominant source for thermal transfer. This is apparent for configuration 10 (single-pane), which has three times the energy savings of configuration 4 (double-pane).

In contrast, as the frame area increases (e.g., to 30% in configurations 6 and 12), the effects of the window insulation are lessened. This is because the frame plays a larger role in the thermal movement, and the frame area is not treated by this product. This is evident for configuration 12 (single-pane), which only has two times the energy savings of configuration 6 (double-pane).

As the window frame area increases, the frame material plays a more critical role. The metal frame transfers more heat; therefore, there is less energy savings in this window configuration.

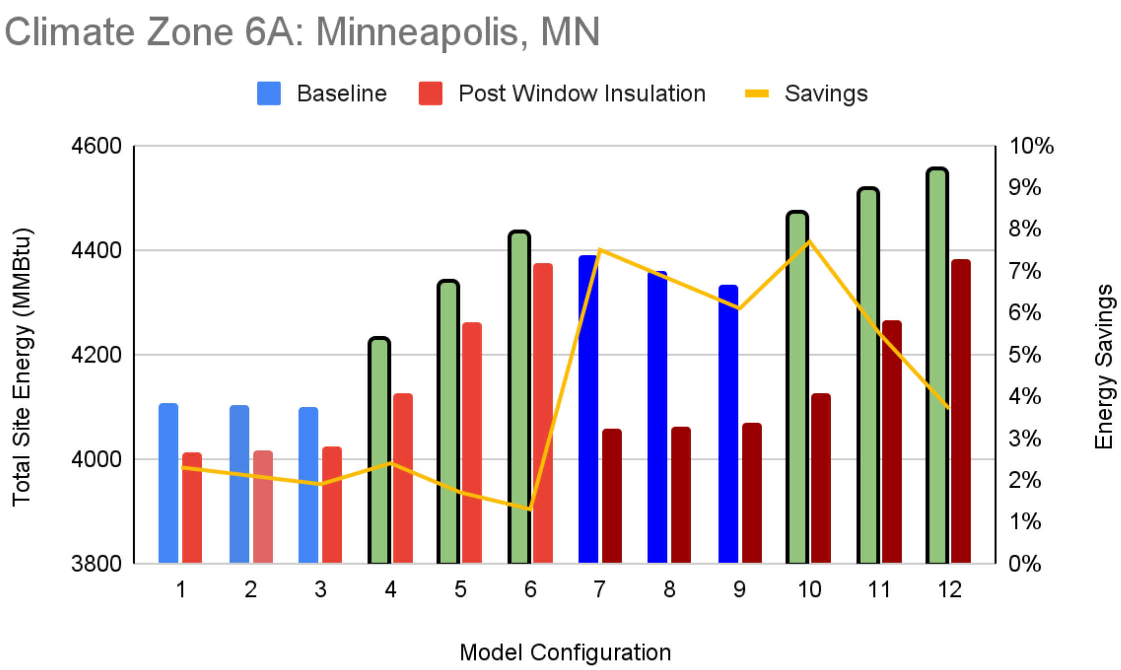


Figure 15. Climate Zone 6A: Minneapolis, MN | Configurations 1–6 are double-pane glazing, and configurations 7–12 are single-pane glazing. Configurations 4–6 and 10–12 (shown in green with black borders) represent metal frames. For each configuration series (e.g., 1–3, 4–6, 7–9, and 10–12), an increase in the configuration number represents an increase in the frame area (e.g., configuration 4 = 10% area, 5 = 20%, and 6 = 30%).

Table 10 presents the modeled energy savings by heating, cooling, and fan and the total building energy savings per climate zone/city. The energy savings ranged from 5% to 6% for warm climates; 2% - 3% for moderate climates; and 3% - 4% for cold climates.

Table 10. Modeled Energy Savings

Climate Zone	City	Window Insulation Type	Savings Heating kBtu/(ft^2·year)	Savings Cooling kBtu/(ft^2·year)	Savings Fan kBtu/(ft^2·year)	Savings Total
1A	Miami, FL	Warm-climate	0.04	0.11	0.13	5%
2A	Houston, TX	Warm-climate	(0.04)	0.12	0.13	5%
2B	Phoenix, AZ	Warm-climate	(0.04)	0.13	0.13	6%
3A	Atlanta, GA	Warm-climate	(0.03)	0.14	0.12	5%
3B	Las Vegas, NV	Warm-climate	(0.08)	0.13	0.14	5%
Average		Warm-climate	(0.03)	0.12	0.13	5%
3C	San Francisco, CA	Moderate-climate	0.14	0.06	0.06	2%

Climate Zone	City	Window Insulation Type	Savings Heating kBtu/(ft²·year)	Savings Cooling kBtu/(ft²·year)	Savings Fan kBtu/(ft²·year)	Savings Total
4A	Baltimore, MD	Moderate-climate	0.10	0.05	0.06	3%
Average		Moderate-Climate	0.12	0.05	0.06	2%
5A	Chicago, IL	Cold-climate	0.10	0.06	0.07	4%
5B	Boulder, CO	Cold-climate	0.11	0.06	0.06	3%
6A	Minneapolis, MN	Cold-climate	0.09	0.06	0.07	4%
Average		Cold-climate	0.10	0.06	0.07	4%

Note: Values are an average of ALL 12 configurations (two panes (single, double), two frame materials (metal, non-metal), three frame areas (10%, 20%, 30%)) evaluated.

Table 10 is the average of all 12 configurations. Tables C1 – C4 in the appendix show subsets of the values in Table 10. Tables C1 – C4 each show the average of 3 frame sizes (10%, 20%, 30%) for a window condition (i.e., single pane, double pane) and for frame material (i.e., metal, non-metal). The values in Table C1 – C4 will be different from Table 10 values because Table 10 is average of those four tables.

Qualitative Results

Occupants were surveyed to assess their opinion about the window insulation panels. The following sections present the qualitative results.

Survey Results and Focus Group

A survey (PNNL IRB #2022-23) was administered to building occupants in March 2023. Building occupants were asked for anonymous feedback on a series of five questions. A survey prior to the installation of the window insulation units was not practically possible because of remote work rules related to the COVID-19 pandemic and other reasons.

The site was under construction during the evaluation, which means that many of the window insulation panels still retained their blue protective film. Survey respondents include staff (*n=15)* that were relocated within the building during the evaluation and staff new to the building that were not there before the window insulation panels were installed. Therefore, the post-installation survey provides a limited qualitative assessment because of relocation and new staff.

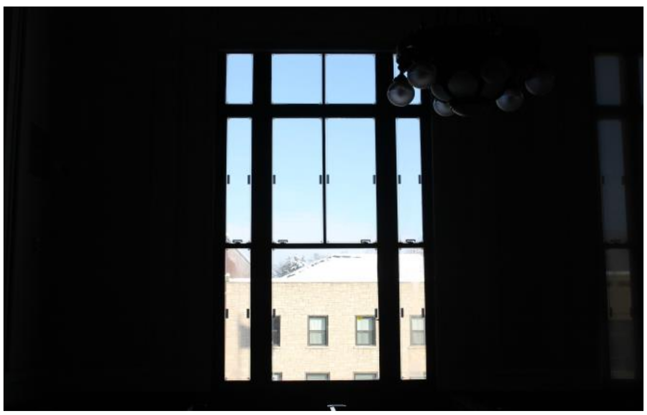
Following the anonymous survey process, there was an attempt to form a focus group (PNNL IRB #2022-23) of building occupants. The building occupants were not responsive to the request to participate in the focus group. However, members of the on-site operations and maintenance (O&M) staff participated in the focus group in June 2023.

Overall, the on-site O&M staff (*n=5)* found that the installation process was relatively quick and easy. The on-site O&M staff would also recommend this technology for other GSA facilities. The O&M staff were asked questions similar to those on the surveys, and their responses are interspersed into each topic addressed.

Window Insulation Panel Detection

Building occupants were asked how noticeable they found the window attachment. The majority of building occupants responded that they found the window insulation panel very noticeable. Occupants may have been aware of the window insulation panels for multiple reasons.

These windows are tall. At the time of production, the vendor could only provide 3D-printed spacers to support the panel in place. The 3D-printed spacers could not be produced with a transparent material; instead, the ones produced were a milky-white color. The white 3D spacers were the only available option from the vendor at the time of installation in October 2022. Figure 16(a) and (b) show the white spacers in the second floor courtroom.



(a) Spacers in the panels in the second-floor courtroom.

(b) Close-up photograph (3 ft from the window) of the spacers in the courtroom; window is adjacent to (a).

Figure 16. Window insulation panels, spacers, film, and stickers.

In March 2023, the vendor provided some panels with clear spacers for a handful of windows. In May 2023, one panel was installed with the clear spacers. Figure 17 is a photograph from inside the building with a window panel and a clear insulation panel.

Figure 17. Transparent spacers at the Eau Claire Courthouse. The left red circle is the clear spacer. The right red circle is the milky-white original spacers.

The June 2023 O&M focus group stated, “You can see the white piece on every window from the outside so clear would be better.”

Even though the Eau Claire Courthouse is a nonstandard installation, it passed historic preservation review. In the future, versions of the product will use transparent injection-molded spacers.

Besides the spacers, some panels were notched to fit around the window lock. This also created a visual element of an otherwise clear window system, as shown in Figure 18(b).

(a) White border was a 3D-printed portion of a panel that goes around the window lock (May 1, 2023).

(b) Window panels around the window lock in a first-floor office (May 1, 2023).

Figure 18. Window insulation panel locks.

Finally, the window insulation panels were installed in many spaces under construction. Each panel has a blue protective film and an information label, which is standard delivery for each panel. They are removed as part of the standard installation in the final step of installation. Because of construction activity, the blue film and information label were not removed in many cases. Therefore, occupants were often seeing the window panels before the blue film was removed during the final installation step. Figure 19 shows both the film and information label. This photograph was taken May 2023—two months after the survey was administered because the construction was still underway in the building.

(a) Interior photograph of a construction label still attached (May 15, 2023).

(b) Exterior photograph with a construction sticker visible (May 15, 2023).

Figure 19. Blue film with information labels on window insulation panels.

Each of these examples demonstrates reasons why the window insulation panels were obvious to the survey respondents.

Changes in View

Building occupants were asked about how their view had changed after the window insulation was installed. Most responded that the view was worse or slightly worse after installation during the survey. However, many of the occupants moved locations in the building or were reassigned to the building. Therefore, the occupants may not have a sufficient baseline view out the window. As mentioned in the previous section, many window insulation panels still retained the blue film and information label at the time of the occupant survey.

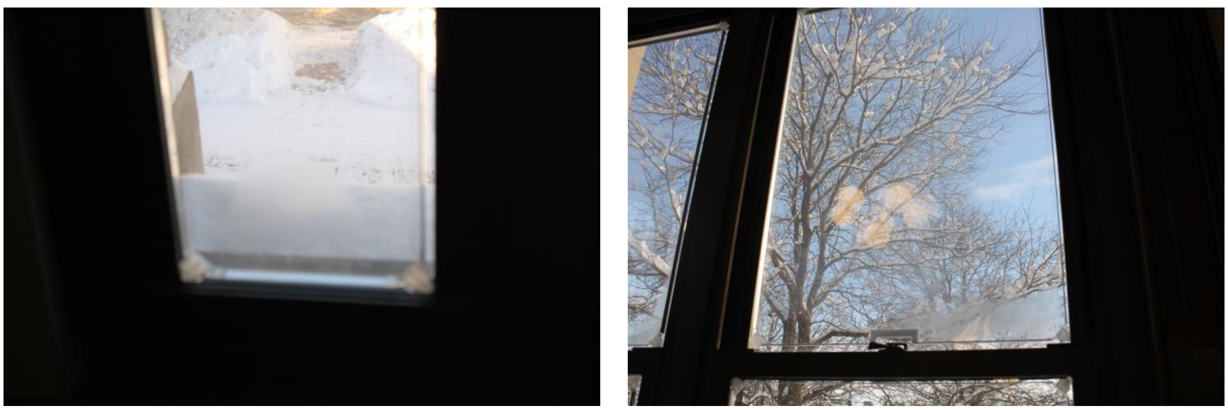
The June 2023 O&M focus group responses were diametrically opposed to the survey respondents in terms of views. The June 2023 O&M focus group emphatically stated that the window insulation panels did not change views.

The window panels are transparent, and the elements outside the windows did not really change. It is unknown if the survey responses of building occupants to changes in views originate from the construction and related relocation of staff during the process or something else.

Window Condensation

Building occupants were asked about condensation after the window insulation panels were added. The following question was asked: “have you noticed condensation on the windows?” The choices for answers were on a Likert scale of 1–5, with 1 being the most negative and 5 being the most positive. A majority responded with a 1 as their answer, suggesting that they think the condensation was worse—though there was no baseline survey of building occupants for reference. Additionally, the building O&M staff responses differed from the occupant responses.

Condensation was documented on windows in the second-floor courtroom and first-floor lobby in December 2022 (Figure 20).



(a) Condensation on the windows in the second-floor courtroom.

(b) Condensation on the first-floor windows.

Figure 20. Condensation on windows, not the panels.

The June 2023 focus group also differed from the survey respondents in terms of condensation. The focus group had not seen condensation between the window insulation panels and the glass panes of the windows. Instead, the focus group stated that there was condensation between the panes of glass on the double-pane windows in the spring.

The condensation question and responses may be misleading. All but four of the windows in the Eau Claire Courthouse had window insulation panels added. A baseline survey without the window insulation panels was not administered. Upon investigation, condensation occurred between the sheets of glass in the primary window. See the previous section on condensation reduction.

Window Draft

Building occupants were asked to characterize the air movement after the window insulation panels were installed. The majority found the spaces to be more drafty. However, there was no pre-installation survey, so it is unknown if the space just felt drafty to the occupants.

In contrast, the June 2023 O&M focus group was asked about how the window insulation panels improved thermal comfort. The focus group could not definitively state that comfort had improved. However, the focus group stated that there had not been calls to the O&M staff related to the space being cold. Before the window insulation panels, O&M staff had received complaints on the first floor. The focus group did caveat that there currently are no occupants on the first floor, so that may be why there were no complaints on that floor. The focus group also stated that there appeared to be fewer space heaters in the building after the window insulation panels were installed.

It is unknown why respondents indicated that the rooms were more drafty than before the installation of the insulation panels since heat flux measurements found the technology had improved the thermal characteristics of the window.

Sound

Building occupants were asked about sound level changes after the window insulation panels were installed. The majority responded that the sound levels/conditions were worse.

It is unknown why respondents indicated that the sound was worse post-panel installation. The changes in sound could be related to the season or construction activity or because of the relocation of staff within the building.

The June 2023 O&M focus group contradicted the survey respondents related to sound. When asked about the sound change from the panels, the focus group responded that the panels were very lightweight inserts. Therefore, they would not expect them to make a difference either way in terms of sound levels.

Other Comments from the Focus Group

Beyond the similar questions for the survey, the focus group was asked specific questions related to operations and potential use at other GSA properties.

The focus group found having to remove the top window panel to open the lower window a hindrance to the technology. The focus group elaborated that if there was not much difference in the savings for the thicker insert, the O&M staff would prefer to have the low-profile insert on the top window. The low-profile window insulation panels were considered for this project. However, the windows at the Eau Claire Courthouse were not typically opened, so the project team opted for high-profile window insulation panels for the top windows.

In general, the O&M staff found the installation process easy. Installation by GSA staff is not typical, but they installed the technology for this evaluation. Having the field measurements of the windows taken by the vendor was important. One staff member reiterated the concerns with GSA staff taking the measurements. He was concerned that if the window measurements were off, GSA might have a financial liability regarding the reordering of the window insulation panels. O&M staff stated that because the panels are lightweight, the installation was easier—particularly if a large panel had to be moved around furniture. Finally, GSA O&M staff reiterated that cleaning the windows before installation was imperative, and this should be factored into the process.

As noted in the next section, some of the fasteners failed during the evaluation. The O&M staff commented on these failures. A few fasteners disengaged. A few corner pieces on the skin detached. The vendor visited the site on January 23–24, 2023 to fix detachments with silicone. A tube of silicone was left behind in case the O&M staff saw other issues following the vendor visit. However, GSA O&M raised concerns over the longevity of the adhesive, fastener, and plastic itself.

The June 2023 O&M focus group pondered whether a temperature of 105°F would degrade the adhesive. The silicone is designed for high temperatures; therefore, this should not be an issue in hot environments. The June 2023 O&M focus group similarly wondered if a south- or west-facing facade in Arizona could experience more degradation of the plastic. The panels in Eau Claire were for cold climates. A site in Arizona would use warm-climate insulation panels. The vendor's warm-climate product is a slightly different design than the cold-climate product. The warm-climate product design protects the plastic from solar radiation degradation.

O&M also stated that tenants prefer to have operable windows. One commented, "People want to be able to open windows. Even if they don't do it very often, they like having the option."

When asked about use at other GSA properties, O&M staff were in agreement, "Yes, it was a great system and other GSA properties should consider it." However, a different staff member stated that he would like to see the results for energy savings with payback in <10 years. The cost of measurement and installation should be factored into payback calculations. Finally, another O&M staff member stated that the technology would work in Region 5, but this region has very few buildings with operable windows because of safety concerns and building automation system control of the building.

Failures During Evaluation

In mid-January 2023, one of the two secure digital (SD) cards recording the heat flux data failed. The SD card was not analyzed until late February 2023; as a result, roughly 6 weeks of data related to that thermocouple were lost.

Besides the SD card that failed, staff at the Eau Claire Courthouse reported to the team in early January 2023 that some of the window insulation panels had started to detach. The acrylic adhesive holding the corners of the panels failed, and part of the panel was hanging in mid-air.

In late January 2023, the vendor visited the Eau Claire Courthouse. A total of 27 of 287 (9%) of the window panels were affected. The vendor addressed the problem, reattached the window panels, and incorporated the solution into its manufacturing process. Figure 21 shows the detachment that occurred in early January 2023 before the vendor addressed the problem.

(a) Panel detachment. (b) Panel separating from window.

Figure 21. Window insulation panels separating from the windows (January 2023).

Window Operability

One of the features of the window insulation desired for evaluation was window operability after the insulation panels were installed. Window operability was not evaluated at the Eau Claire Courthouse. Although window operability was not assessed, the windows were not opened in the typical baseline conditions. The existing windows are heavy and require a great deal of effort to open.

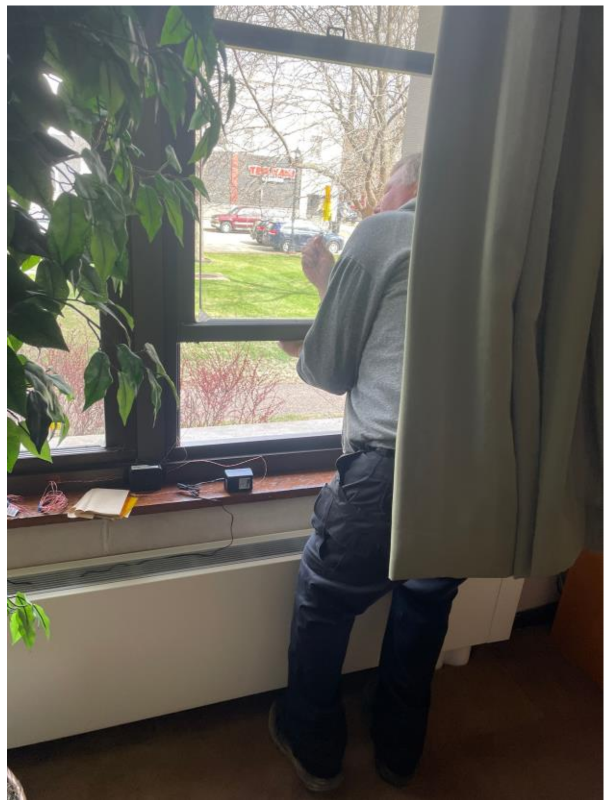
Most of the windows at the Eau Claire Courthouse are single-hung, vertical slider windows. Knowing that the baseline windows are not normally opened, GSA and the vendor selected a thicker panel to maximize the insulation value. As a result, a thicker panel would cause the upper insulation panel to strike the window frame, preventing the windows from being operated.

The locks on the existing windows at the Eau Claire Courthouse also physically conflicted with the window insulation panels. As a result, the vendor needed to make a cutout to work around the locks, as shown in Figure 22(a) and (b). The vendor currently sells a low-profile product with transparent cutouts. This transparent cutout product was not available at the time of installation for this project. Additionally, with the insulation panel installed, the locking mechanism on the lower window would strike the panel above when raised. Opening the window requires the upper insulation panel to be removed to operate the window, as shown in (Figure 22(c) and (d)).

(a) Window lock would strike the panel above if the window opened.

(b) Window panels are presented around the window lock in a first-floor office.

(c) Window insulation panel above the window is removed.



(d) Once the window insulation panel was removed, the lower window could be raised.

Figure 22. Window insulation panels had to be removed to operate the windows in the Eau Claire Courthouse.

Cost Effectiveness

This section analyzes the cost effectiveness of the window insulation panels. The energy savings could not be directly assessed at the Eau Claire Courthouse because of activities (e.g., construction and increased occupancy) at the building during the evaluation, the complex and oversized HVAC system for the building, and data reporting irregularities that prevented the determination of the energy savings at the Eau Claire

Courthouse. However, the energy models did reflect the energy savings, and the cost effectiveness will be assessed using these models.

GSA pays a national average of $0.13/kWh and $9.10/MMBtu. These energy rates will be used to determine the cost effectiveness for each of the models.

The Eau Claire Courthouse (building size: 37,000 ft^2) has 2,228 ft^2 of windows but only 1,651 ft^2 of glazed area where the insulation panels were installed (panels only attach to the window lites, which have a smaller combined area than the overall window area). This translates to a 74% frame factor, which is the area of glazing divided by the area of the window unit. In contrast, the models (building size: 53,000 ft^2) assume 7,026 ft^2 of window insulation panels.

This analysis assumes costs of $21/$ft^2$ (price at the time of installation at the Eau Claire Courthouse), $16/$ft^2$ (future price/volume-based price for warm-climate window insulation), and $9/$ft^2$ (future price/volume-based price for cold-climate window insulation). Although the specific product evaluated at the Eau Claire Courthouse was designed to be installed by building managers or others in the building, GSA would contract this work to an external party at other sites. The average labor rate for this type of work is $55/hr according to GSA. Based on the installation time data from the installation at the Eau Claire Courthouse and this rate, this analysis assumes $1.59/$ft^2$ for installation. This labor is based on 10 min/panel × 287 panels × $55/hr ÷ 1,650 ft^2 of window panels.

The window insulation panel is a retrofit application. This analysis assumes that the life of the panel is 15 years, partially based on the age of the overall system. As a retrofit, the existing windows will be 15–25 years old (or older) at the time of application of the retrofit. Once the window system is 30–40 years old (15 years without the insulation panel + 15 years with the retrofit panel), the entire assembly should be evaluated for a larger-scale replacement.

Table 11 shows the energy savings, the simple payback period (payback), and the savings-to-investment ratio (SIR) of the technology for different climate zones, averaging single-pane, double-pane, metal frame, and nonmetal frame windows. The energy savings range from lowest to highest for all 12 window configurations. Data for combinations of the number of panes and the frame material can be found in Appendix C.

Table 11. Envelope Baseline Defaults for a Medium-Sized Pre-1980 Office Building

Climate Zone	City	Window Insulation Type	Savings Electric Savings (kWh)	Savings Gas Savings (MMBtu)	Savings Total Savings*	Cost at Eau Claire (21/ft^2) Payback (Yrs)	Cost at Eau Claire (21/ft^2) SIR	Future Costs (16/ft^2 & 9/ft^2)	Future Costs (16/ft^2 & 9/ft^2)
1A	Miami, FL	Warm-climate	61,560	0.01	5%	19.9	0.8	15.4†	1.0
2A	Houston, TX	Warm-climate	54,551	(1.49)	5%	22.5	0.7	17.4†	0.9
2B	Phoenix, AZ	Warm-climate	77,618	(0.44)	6%	15.8	1.0	12.2†	1.2
3A	Atlanta, GA	Warm-climate	54,322	(2.80)	5%	22.6	0.7	17.5†	0.9

Climate Zone	City	Window Insulation Type	Savings Electric Savings (kWh)	Savings Gas Savings (MMBtu)	Savings Total Savings*	Cost at Eau Claire (21/ft^2) Payback (Yrs)	Cost at Eau Claire (21/ft^2) SIR	Future Costs (16/ft^2 & 9/ft^2)	Future Costs (16/ft^2 & 9/ft^2)
3B	Las Vegas, NV	Warm-climate	63,799	(4.38)	5%	19.3	0.8	14.9†	1.0
Average		Warm-climate	62,370	(1.82)	5%	20.0	0.8	15.5†	1.0
3C	San Francisco, CA	Moderate-climate	10,873	6.53	1%	107.9	0.1	87.4†	0.2
4A	Baltimore, MD	Moderate-climate	19,958	41.53	3%	53.5	0.3	47.6†	0.4
Average		Moderate-climate	15,416	24.03	2%	80.7	0.2	67.5	0.3
5A	Chicago, IL	Cold-climate	21,144	75.67	4%	46.3	0.3	27.1††	0.7
5B	Boulder, CO	Cold-climate	20,252	45.54	3%	52.2	0.3	28.3††	0.6
6A	Minneapolis, MN	Cold-climate	21,456	105.82	4%	42.4	0.4	26.7††	0.8
Average		Cold-climate	20,951	75.68	4%	46.9	0.3	27.3	0.7

Note: Range of savings represents the minimum and maximum savings from all 12 (two pane types (single, double) x two material (metal, non-metal) x three frame areas (10%, 20%, 30%) configurations evaluated.

† Future cost assumes a \$16 /ft^2 panel and †† future cost assumes a \$9 / ft^2 panel

Note that Table 11 shows negative gas savings in some climate zones. In cooling-dominant climates, it is not unusual for negative heating (gas) savings after a window treatment that reduces a portion of "free" heating from the solar heat gain that the windows provide. The windows became more efficient, reducing the amount of heat from the sun entering a building during the cooling season, but required slightly more heating energy as a result. Reducing the SHGC of the windows has cooling benefits but can yield negative heating savings. To save energy for both heating and cooling, the window treatment must improve the U-value and reduce the SHGC. Conversely, if a treatment reduces the SHGC without a substantial improvement in the U-value, it is possible for positive cooling savings but negative heating savings.

Sensitivity Analysis

A sensitivity analysis of the window insulation panels was conducted using similar inputs from the previous section. The sensitivity analysis determined either the maximum cost of the panels per unit or the cost of fuel to achieve an SIR of 1.0 (assuming a 15-year life for the window insulation panels). Two methods were used to construct Table 12. The maximum panel cost column was calculated using the energy savings listed in the table and fuel costs of \$0.13/kWh and \$9.10/MMBtu. The average panel costs for warm- and cold-climate panels need to be \$13.73/ft^2 and \$7.75/ft^2, respectively, to achieve an SIR of 1.0.

Conversely, to determine the minimum cost of fuel to achieve an SIR of 1.0, we modeled the fuel costs column in Table 12 using the energy savings listed in Table 12 and the future cost of panels from Table 11 (warm- and cold-climate panels at \$16.00/ft^2 and \$9.00/ft^2, respectively). To achieve an SIR of 1.0, warm-climate panels (at the future pricing rate) require the electricity rate to be \$0.18/kWh and gas to be \$12.6/MMBtu on average. Cold-climate panels (at the future pricing rate) require the electricity rate to be \$0.24/kWh and gas to be \$16.58/MMBtu to achieve an SIR of 1.0.

Table 12. Sensitivity Analysis

Climate Zone	City	Window Insulation Type	Savings Electric Savings (kWh)	Savings Gas Savings (MMBtu)	Savings Total Savings*	Max. Panel Cost	Fuel Costs Electricity (\$/kWh)	Fuel Costs Gas (\$/MMBtu)
1A	Miami, FL	Warm-climate	61,560	0.01	5%	\$17.09	\$0.13	\$12.35
2A	Houston, TX	Warm-climate	54,551	(1.49)	5%	\$15.10	\$0.15	\$13.94
2B	Phoenix, AZ	Warm-climate	77,618	(0.44)	6%	\$21.53	\$0.11	\$9.80
3A	Atlanta, GA	Warm-climate	54,322	(2.80)	5%	\$15.02	\$0.15	\$14.00
3B	Las Vegas, NV	Warm-climate	63,799	(4.38)	5%	\$17.62	\$0.13	\$11.92
	Average	Warm-climate	62,370	(1.82)	5%	\$17.27	\$0.13	\$9.41
3C	San Francisco, CA	Moderate-climate	10,873	6.53	1%	\$3.18	\$0.76	\$69.95
4A	Baltimore, MD	Moderate-climate	19,958	41.53	3%	\$6.60	\$0.41	\$38.11
	Average	Moderate-climate	15,416	24.03	2%	\$4.75	\$0.59	\$40.97
5A	Chicago, IL	Cold-climate	21,144	75.67	4%	\$7.34	\$0.23	\$21.66
5B	Boulder, CO	Cold-climate	20,252	45.54	3%	\$6.51	\$0.24	\$22.61
6A	Minneapolis, MN	Cold-climate	21,456	105.82	4%	\$8.01	\$0.23	\$21.34
	Average	Cold-climate	20,951	75.68	4%	\$7.28	\$0.24	\$16.58

Note: Range of savings represents the minimum and maximum savings from all 12 configurations evaluated.

Conclusion

Summary Findings

Window insulation panels are well suited for buildings with single-pane windows and double-pane windows with IGUs that have not displayed condensation problems between the glass panes (intact seals in windows prevent condensation). Because the window insulation panels evaluated do not treat the window frame and metal frames are a thermal bridge for heat loss, the window insulation panels evaluated are more suited for buildings with nonmetal window frames or thermally broken aluminum frames. The modeled results showed greater savings with nonmetal window frames versus metal window frames: 4.5% versus 3.7% whole-building energy savings in climate zone 6A (Minneapolis, MN scenario).

Substantial improvements in the U-value can be produced by the window insulation panels for single-pane windows and double-pane windows with failed or failing IGU seals. The failed IGU seals cause the double-pane windows to perform similar to single-pane windows. For example, a 44–54% improvement can be achieved for the center-of-glass U-value, from 0.85–1.2 Btu/(h·ft^2·°F) (double-pane with a failed IGU and no intervention) to 0.48–0.55 Btu/(h·ft^2·°F) (window with an insulation panel applied) from the results measured via heat flux sensors. The improvement in the U-value results in a detectable reduced rate of decrease in the temperature in perimeter rooms when the building switches to overnight/unoccupied temperature setback. The reduced rate of decrease because of overnight/unoccupied temperature setback means that the building has improved "hours of safety." Hours of safety is a resilience metric that measures the number of hours a building can stay sufficiently warm to be a safe refuge for people if the building were to experience a power outage during the winter (Ayyagari et al., 2020). Buildings with a better insulation envelope have more hours of safety.

The window insulation panels can work around locking mechanisms that intrude or protrude into the glazed area. However, the solution requires measuring the glazed area for where the lock intrudes/protrudes and adds measurement time, thereby increasing the product cost because of the higher cost to manufacture an insulation panel with a notch/cutout around the lock. At the time of this study, the vendor's experience in making insulation panels with a notch/cutout was limited; thus, the notch/cutout element was 3D printed using translucent white plastic filament. Additionally, a 3D printed mid-span support was added for long, skinny panels. In the months after ordering the insulation panels for this project, the vendor successfully transitioned these elements to be made of transparent injection-molded plastic.

The window insulation panels evaluated are well suited for windows where it is desired that operability be maintained, or fire egress is required. To service some HVAC equipment at the Eau Claire Courthouse, the on-site facilities staff had to open a window on the second floor and climb onto the roof. This is a good example of why window operability may be necessary in other buildings. As of the publication of this report, this is the only insulation panel product on the market that can be made (for most windows) such that it doesn't restrict window operability or make window operation a two-step process of operating the secondary window and then operating the primary window. At this demonstration site, the maintenance of window operability was not a high priority. Most staff never operate the windows because they are heavy and difficult to operate, and opening a window on the second floor to climb onto the roof for maintenance is an infrequent task. Thus, the occupant's thoughts on the maintenance of window operability wasn't an element that was surveyed. On some windows, it is possible to install the standard (high-profile) version of the product onto a single- or double-hung window without interference; however, at this field demonstration site, it is necessary to remove the insulation panels on the upper sash to open the window. The vendor makes a low-profile version for cases where a slimmer insulation panel is needed to avoid interference. However, since the windows at this field demonstration site are operated infrequently, the standard (high-profile) version was selected to maximize the improvements and benefits of window insulation.

The window insulation panels evaluated are well suited for large windows composed of multiple glazing lites assembled together with mullions and muntins. These large windows are often logistically challenging to retrofit using frame-mounted secondary window attachment products requiring one or more mullions located in a position that results in visual distraction. Glazing-mounted plastic products, such as the one tested in this study, are much lighter in weight to transport and handle during installation.

At present, the material cost of this product is quite high for the resulting final U-value. The product yields a 44–54% improvement in the center-of-glass U-value in a single-pane window. However, the overall whole window U-value improvement is quite modest when mated to windows with metal frames because the product does not improve the U-value of the frame area. As a result, the simple payback periods for heating-dominated climates are long—currently in the mid-50-year range and projected to be in the low-to-mid-40-year range when the production of the product is scaled up using current projected costs. Interestingly, the modeling found the combination of both solar heat gain reduction and U-value improvement in the product version designed for cooling-dominant climates to yield much better simple payback periods. These payback periods are currently in the high-10-to-low-20-year range and projected to be in the mid-10-year range when production is scaled up. This study did not empirically test the product version designed for cooling-dominant climates.

Another reason that the product does not yield more energy savings in heating-dominated climates is that it does not decrease the air leakage around windows with infiltration issues. A study by LBNL of infiltrative heat loss across 14 U.S. cities found that the energy loss due to infiltration was about 12.6% of the combined infiltration plus conduction heat loss of “leaky” double-glazed windows, on average (Klems, 1981). For windows with known, large infiltrative heat loss, additional window weatherization measures should be employed, such as adding or replacing worn weatherstripping. If window operation is not needed, consider removing the weights and filling the weight pockets with foam insulation, caulking the window shut to reduce air leakage, and installing a non-operable interior or exterior insulation panel product that significantly reduces air leakage at the window area while still being removable for cleaning.

Frame-mounted secondary window products can significantly reduce the air leakage in the window area. However, condensation or fogging can occur if there is significant air leakage from the primary window allowing moisture into the unsealed gap between the primary and secondary windows. This product is glazing mounted; the moisture transport resulting in condensation from air leakage is minimal because there is no pressure-induced air leakage occurring at the glazing. The condensation/fogging risk of unsealed gaps—a factor in all secondary window products—remains an area in need of greater empirical research.

In addition to significant air leakage reductions, frame-mounted secondary window products can be specified to have low-e coated glass. If the frame-mounted secondary window is installed exterior to the primary window, the low-e coating excels in reflecting infrared radiation from the sun, thus preventing it from penetrating the window and resulting in significant cooling energy savings. If the frame-mounted secondary window is installed interior to the primary window, the low-e coating excels in reflecting infrared radiation from within the room, preventing it from escaping through the window and thus resulting in heating energy savings. As of this writing, the vendor of the glazing mounted insulation panel product tested has not produced a product with a low-e coating. While the manufacturing technology and machinery to coat glass with low-e materials is mature with over five decades of development coating plastic with low-e materials presents new challenges and is an active area of research and development (LBNL, n.d.). The glazing mounted plastic-based insulation panel in this study is up to 95% lighter in weight than a frame-mounted secondary window. Thus, as of this writing, there is no product that satisfies all criteria perfectly; instead, there is a tradeoff between a heavy product with low-e coated glass and a lightweight plastic-based insulation panel without a low-e coating.

The most impactful ways to reduce noise transfer at window locations are reductions in air leakage and adding mass. The product tested in this study does not improve air leakage and is ultralight; thus, it does not significantly reduce noise transfer. In some applications, noise may not be a problem; therefore, noise reduction is not a priority.

In conclusion, the technology tested in this project is a good fit for certain applications—ideally, large, nonmetal-framed, single- or double-pane windows with IGUs not exhibiting internal condensation, where the window glass is subdivided by muntins and mullions, where the windows are not significantly leaky, and where the maintenance of window operability is desired or essential for fire egress. If the windows in a building are too large to practically install an insulation panel that covers the whole window, this product could be the next best option. The best window retrofit technology is not necessarily the best one thermally but rather the one that you can afford and install. Although not empirically tested, positive SIRs for cooling-dominated climates are observed from energy models of a DOE pre-1980 medium-sized office building when the vendor's product is designed for a cooling-dominated climate with reduced emissivity, solar heat gain reductions, and modest U-value improvements. A favorable (e.g., >1.0) SIR was not observed for the product version for heating-dominated climates given the present fuel costs and expected future scaled-up production costs provided by the vendor. It is possible for this product to become cost effective if fuel costs increase significantly, the future cost of the product is lower than projected, or both.

A significant next step for this product is the Attachments Energy Rating Council testing and certification process.

Lessons Learned and Best Practices

The decision on how to best retrofit a window in an existing building is a complex decision—no one solution will work for all sites.

The leakiness of an existing window should contribute to the selection of the retrofit product to best improve the window's efficiency. Windows that have significant air leakage occur through the weight pockets, meeting rail, and bottom rail to sill locations should consider the significant energy savings that comes from the reduced envelope air leakage. According to research done by Pacific Northwest National Laboratory, among the window types, single- and double-hung wood windows often have the most significant air leakage, with leakages ranging from 3 cfm/ft^2 for single-pane era windows and 1 cfm/ft^2 for double-pane era windows being considered conservative (Culp, 2015). However, it is necessary to measure a few representative windows to truly know the rate of air leakage of the windows in a building.

Secondary glazing products that mount to the interior framed opening of the window and exterior storm windows are the best products for reducing the air leakage of windows. However, interior or exterior secondary window products can render a window inoperable when installed or require twice the effort to operate the window by requiring one to operate the interior window attachment and then another to operate the primary window. For exterior secondary window products (i.e., storm windows), the effect on building aesthetics is another factor to consider, especially for historic buildings listed in historic registries. For buildings in which the windows are used for fire egress, products that increase the operating effort of the windows could be problematic.

As elucidated by Hart's research, the unsealed gap between the primary window and the secondary window results in an overall window assembly with poor CR (Hart et al., 2015). This could mean a tradeoff between aesthetics and possibly moisture-induced durability issues and energy savings. Moisture transport via air leakage through the primary window into the unsealed gap between the primary window and the secondary window can be more significant in frame mounted secondary glazing products than a glazing mounted product.

The cost of a window retrofit should include the labor cost of measuring the windows and installation. Measuring the width and height of the glazed portion of a window for a glazing mounted product is typically easier than measuring the finished (drywalled/plastered/trimmed) interior window opening because of the smaller dimensions and greater definition of where to measure. However, this pilot study led to the discovery of the need to measure these dimensions and the positions of the window locks because the product needed to work around the window locks. These additional measurements added time and labor to the procurement process.

One of the highlights of this product is its ability to be installed and neither inhibit window operability, nor increase its effort. However, doing so may require the use of a low-profile version of this product, which carries a small reduction in energy savings (a 25% versus 26% improvement in whole window U-value for a residential air-filled double-pane window with a thermally broken metal frame, and 23% versus 28% for a residential air-filled double-pane window with a vinyl frame according to vendor-provided third-party test data). In this pilot study, since the primary windows are almost never operated, the decision was made to install the standard high-profile version of the product to maximize the energy efficiency benefits. In the building studied, the upper panel needed to be removed to operate the window when installing the high-profile version. In these situations, it is desirable for the product to be easy to remove and reinstall when needed. The product in this study uses snap-together connectors on the four corners to make the panel easy to remove and reinstall. However, the cutouts that the vendor designed to work around the window locks featured double-sided acrylic adhesive tape to secure that area of the panel to the glass. The adhesive in that area significantly reduced the ease of removal and reinstallation. It is highly possible that the vendor will redesign the window-to-insulating-panel attachment method for panels that require a cutout to work around a window lock. Note that not all window locks require a cutout to work around; it depends on the shape, position, and clearance of the lock(s).

Ease of installation is an important factor to be considered in a retrofit because it often occurs when the building is occupied; if a product requires people and furnishings to be moved out of the way to be installed, those additional logistics can add significant expense to a project. Replacement of the primary window is often the most impactful retrofit pathway. Frame-mounted interior and exterior window attachments on large windows are also challenging to transport/ship and install. Glazing-mounted insulation panels are among the easiest to install product options.

Perhaps the most insightful element from this study is the need for a facility to consider the condition of its existing double-pane windows. A double-pane window with IGU seals that have failed will have performance much closer to that of single-pane windows. Visible moisture and fogging between the panes of glass are obvious indicators that the IGU seals have failed. However, when the IGU seals initially fail, it is possible for a window to not yet reach a state where there is visible moisture and fogging between the panes of glass or where the moisture and fogging between the panes of glass is only visible under specific outdoor temperature and humidity conditions. The cost of field deployable heat flux sensors is such that it is possible to empirically measure the U-value of a few representative double-pane windows to know whether the IGU seals have failed.

Lastly, pilot studies are invaluable for evaluating a new product prior to putting in the effort to enhance widespread adoption. Pilot studies help find flaws or needed improvements in a new product before it reaches widespread adoption. Additionally, pilot studies can greatly increase the understanding of the applications for which a product is a good fit and the applications for which another product would be a much better fit.

Deployment Recommendations

The top nine deployment priorities for the technology are listed as follows.

1. **Retrofit for existing buildings.** This technology is specifically designed as a retrofit option and should only be considered for existing buildings.
2. **Buildings with single-pane windows.** Any buildings with single-pane windows should consider this technology.
3. **Buildings with double-pane windows installed at least 15 years ago.** Over time, the performance of double-pane windows will degrade. The window seals will fail, and the interior gas will escape, reducing the performance of double-pane windows closer to that of single-pane windows.
4. **Reasonably sized windows.** Buildings with window lites no larger than 4 ft × 6 ft could be considered for this technology.
5. **Historic buildings.** Replacing windows in historic buildings may be a challenge. Temporary window insulation panels that do not permanently alter the appearance of the building may be an option for increasing the performance of the windows without affecting the historic status of the facade.
6. **Operable windows.** It is desirable that windows in buildings remain operable and functional after the efficiency is measured.
7. **Consistent/limited sizes of window lites.** Buildings with fewer quantities of differently sized window lites should be considered for this technology.
8. **Low embodied carbon.** Projects that are seeking low embodied carbon solutions should be considered for this technology.
9. **Buildings in locations with high energy costs.** Buildings in locations with high energy costs will see faster payback periods.

References

1 Apte, J. and D. Arasteh. 2006. *Window-Related Energy Consumption in the US Residential and Commercial Building Stock*. Lawrence Berkeley National Laboratory LBNL-60146. Berkeley, CA. https://facades.lbl.gov/sites/all/files/60146.pdf.

2 ARPA-E. 2014. *Single-Pane Window Efficiency.* ARPA-E Workshop, Philadelphia, PA, November 6–7, 2014. https://arpa-e.energy.gov/sites/default/files/02%20-%20Schiff%20-%20Single%20Pane%20Window%20Opportunity%20v2%20-%20FINAL.pdf.

3 ASHRAE. 2021. *2021 ASHRAE Handbook—Fundamentals*. ASHRAE. https://www.ashrae.org/technical-resources/ashrae-handbook/description-2021-ashrae-handbook-fundamentals.

4 Ayyagari S., M. Gartman, and J. Corvidae. 2020. *Hours of Safety in Cold Weather - A Framework for Considering Resilience in Building Envelope Design and Construction*. Rocky Mountain Institute. https://rmi.org/insight/hours-of-safety-in-cold-weather/.

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

6 Kiatreungwattana, K. and L. Simpson. 2021. *Demonstration and Evaluation of Lightweight High Performance Quad-Pane Windows*. General Services Administration. https://www.gsa.gov/system/files/NREL-79107-Lightweight%20Quad-Pane%20Windows.pdf.

7 Hart R., H. Goudey, R. Mitchell, M. Yazdanian, and C. Curcija. 2015. *Secondary Glazing System (SGS) Thermal, Moisture, and Solar Performance Analysis and Validation.* Lawrence Berkeley National Laboratory. Berkeley, CA. https://neea.org/resources/secondary-glazing-system-sgs-thermal-moisture-and-solar-performance-analysis-and-validation.

8 Im, P., J. R. New, and Y. Bae. 2019. *Updated OpenStudio Small and Medium Office Prototype Models*. 16th IBPSA International Conference & Exhibition on Building Simulation, Rome, September 2–4, 2019. https://www.osti.gov/servlets/purl/1607029.

9 Klems, Joseph. 1981. *Methods of Estimating Air Filtration through Windows*. LBL-12891. https://eta-publications.lbl.gov/publications/methods-estimating-air-infiltration.

10 LBNL n.d.. *Building Technology and Urban Systems⁄ Windows and Envelope Research: Low-e Windows.* Lawrence Berkeley National Laboratory, Berkeley, CA 2021. https://windows.lbl.gov/sites/default/files/low%20e%20windows.pdf.

11 Minnesota Department of Commerce. 2023. "Window Retrofit Technologies." Minnesota Department of Commerce. Accessed November 3, 2023. https://mn.gov/commerce/energy/industry-government/cip/card-grant-search/card-project-pages/.

12 Taitem. 2022. Correspondence from Taitem Engineering, P.C. to WexEnergy of NFRC testing results of insulation panels, performed by Intertek.

Appendices

A. Research Details

The energy use of the Eau Claire Federal Courthouse was tracked during the baseline period and the period after the window insulation was installed. The HDDs were calculated to help normalize the energy usage in both cases. Table A1 shows these energy readings and HDDs.

Table A1. Energy Readings and HDDs

Read Date Start	Read Date End	Days	Therms Gas Meter 1	Therms Gas Meter 2	HDDs
10/5/2021	11/3/2021	29	619	34	
11/3/2021	12/6/2021	33	1,543	182	996
12/6/2021	1/9/2022	34	2,035	616	1,589
1/9/2022	2/7/2022	29	256	628	1,581
2/7/2022	3/9/2022	30	2,618	500	
3/9/2022	4/7/2022	29	1,846	237	
4/7/2022	5/8/2022	31	1,344	157	
5/8/2022	6/7/2022	30	36	39	
6/7/2022	7/7/2022	30	0	24	
7/7/2022	8/7/2022	31	0	23	
8/7/2022	9/6/2022	30	0	24	
9/6/2022	10/5/2022	29	0	52	
10/5/2022	11/3/2022	29	1,000	60	
11/3/2022	12/6/2022	33	2,054	206	1,095
12/6/2022	1/9/2023	34	2,849	433	1,565
1/9/2023	2/8/2023	30	2,431	394	1,348

Rated and Measured Values

Table A1 shows the product specifications for the panels part of this evaluation. R-value is the inverse of U-factor (R-value = 1/U-factor). The table shows both the rated value and the measured value for the cold climate panels. When measured, the panes are in a controlled environment and do not include the frame or other elements. In contrast, the measured values come from field measurements in the report. The field measurements will involve the frame and other elements. Inclusion of the window frames on site reduces the U-factor for the window panels compared to the rated results.

Table A2. Performance Specifications

Metric	Metric	High Performance Panel for Cold Climates	High Performance Panel for Warm Climates
U-factor	rated	0.8	0.7
U-factor	measured	0.6	
R-Value	rated	1.2	1.4
R-Value	measured	1.7	
VT		0.9	0.4
Solar Heat Gain Reduction		10%	35-50%

B. Model Details

The reference medium-sized office building model has the characteristics shown in Table B1.

Table B1. Characteristics of the Reference Medium-Sized Office Building

Modeling Attributes	Characteristics
Number of Floors	3
Total Conditioned Floor Area	53,589 ft^2 (4978.6 m^2)
Structural Frame Material	Steel
Roof Composition	Built-up roof (i.e., roof membrane + roof insulation + metal decking)
Foundation	Unheated slab-on-grade with 0.2 m concrete slab poured directly onto the earth
HVAC	Packaged direct exchange air-conditioning unit with a gas furnace. A variable air volume terminal box with an electric reheating coil provides conditioned air to each zone.
Height of Window	4.27 ft (1.3 m)
Window-to-Wall Ratio	33% on all four facades
Window Frame	Two different window frame materials were analyzed: nonmetal and metal. The window insulation only increases the thermal resistance of the window lite, not the entire window. The frame provides a vector for thermal transmission.
Frame Area	Three different window frame areas were analyzed: 10%, 20%, and 30%. The WWR is the ratio of the overall window area compared to the opaque wall area. The frame area is the portion of a window that is frame (e.g., a 4 ft^2 window with 10% frame area would have 0.4 ft^2 of frame, and a 20% frame area would have 0.8 ft^2 of frame). The overall WWR did not change, but the size of the frame in the window was varied.

Modeling Attributes	Characteristics
Thermal Absorptance or Emittance	Modeled as 0.84 for both the front and back. The long-wave transmittance is 0.0.
Baseline	The baseline model utilizes the typical frame, center of glass, and edge of glass U-values for single- and double-pane windows with metal and nonmetal frames, as referenced in the 2021 *ASHRAE Fundamentals-Handbook* to build baseline windows with the U-values listed below.

Twelve configurations of the medium-sized office building were modeled per climate zone/location as shown in Table B1.

Table B2. Modeling Configurations of the Medium-Sized Office Building

Configuration	Frame Material	Glazing Configuration	Glazing Area	Frame Area	Baseline U Value [Btu/(hr ft2· F)]	Window Insulation [post] U Value [Btu/hr ft2· F)]
1	Nonmetal	Double	90%	10%	0.56	0.44
2	Nonmetal	Double	80%	20%	0.55	0.45
3	Nonmetal	Double	70%	30%	0.55	0.46
4	Metal	Double	90%	10%	0.74	0.60
5	Metal	Double	80%	20%	0.91	0.79
6	Metal	Double	70%	30%	1.08	0.97
7	Nonmetal	Single	90%	10%	0.99	0.50
8	Nonmetal	Single	80%	20%	0.94	0.50
9	Nonmetal	Single	70%	30%	0.89	0.51
10	Metal	Single	90%	10%	1.17	0.59

Configuration	Frame Material	Glazing Configuration	Glazing Area	Frame Area	Baseline U Value [Btu/(hr ft2· F)]	Window Insulation [post] U Value [Btu/hr ft2· F)]
11	Metal	Single	80%	20%	1.31	0.79
12	Metal	Single	70%	30%	1.44	0.99

The values are derived from a statistical average of a large sample size of medium-sized office buildings constructed before 1980 in the representative city of that climate zone. A high-level summary of the whole wall average and whole roof average insulation for a model of the medium-sized office building constructed before 1980 for different climate zones is shown in Table B3.

Table B3. Envelope Baseline Defaults for a Medium-Sized Pre-1980 Office Building

Climate Zone	City	Window Insulation Type	Wall U factor with film $W/(m^2 K)$	Wall R value $Btu/(ft^2 \cdot °F)$	Roof U factor with film $W/(m^2 K)$	Roof R value $Btu/(ft^2 \cdot °F)$
1A	Miami, FL	Warm-climate	1.306	4.3	0.569	10.0
2A	Houston, TX	Warm-climate	1.306	4.3	0.569	10.0
2B	Phoenix, AZ	Warm-climate	1.306	1.3	0.569	10.0
3A	Atlanta, GA	Warm-climate	1.278	4.4	0.569	10.0
3B	Las Vegas, NV	Warm-climate	1.306	4.3	0.569	10.0
3C	San Francisco, CA	Warm-climate	1.272	4.5	0.569	10.0
4A	Baltimore, MD	Warm-climate	1.011	5.6	0.489	11.6
5A	Chicago, IL	Cold-climate	0.886	6.4	0.400	14.2
5B	Boulder, CO	Cold-climate	0.914	6.2	0.422	13.5
6A	Minneapolis, MN	Cold-climate	0.823	6.9	0.335	16.9

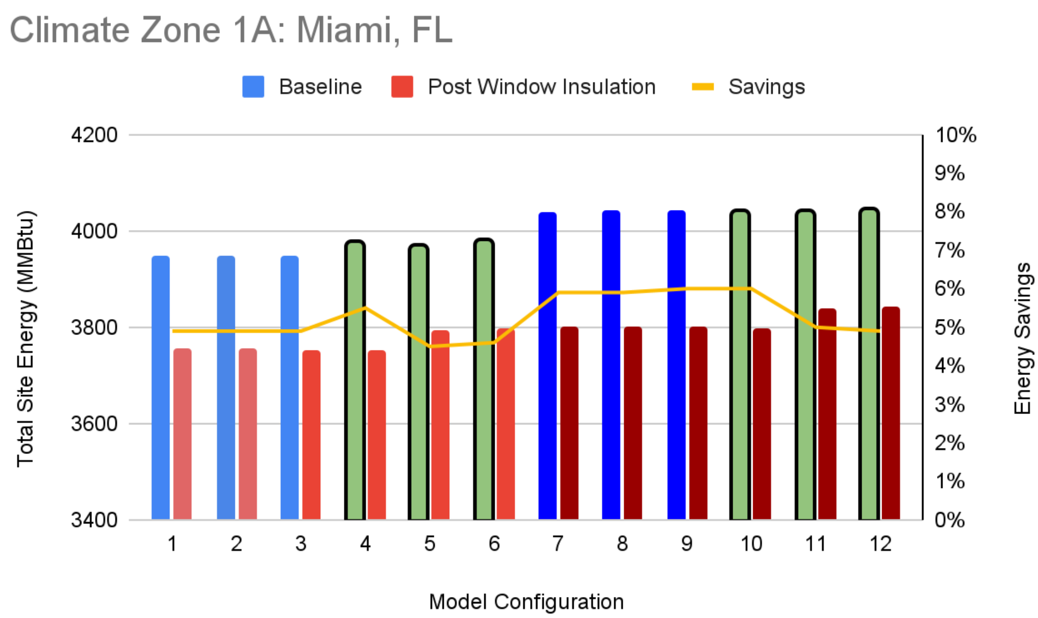


Figure B1. Climate Zone 1A: Miami, FL | Configurations 1–6 are double-pane glazing, and configurations 7–12 are single-pane glazing. Configurations 4–6 and 10–12 (shown in green with black borders) represent metal frames. For each configuration series (e.g., 1–3, 4–6, 7–9, and 10–12), an increase in the configuration number represents an increase in the frame area (e.g., configuration 4 = 10% area, 5 = 20%, and 6 = 30%).

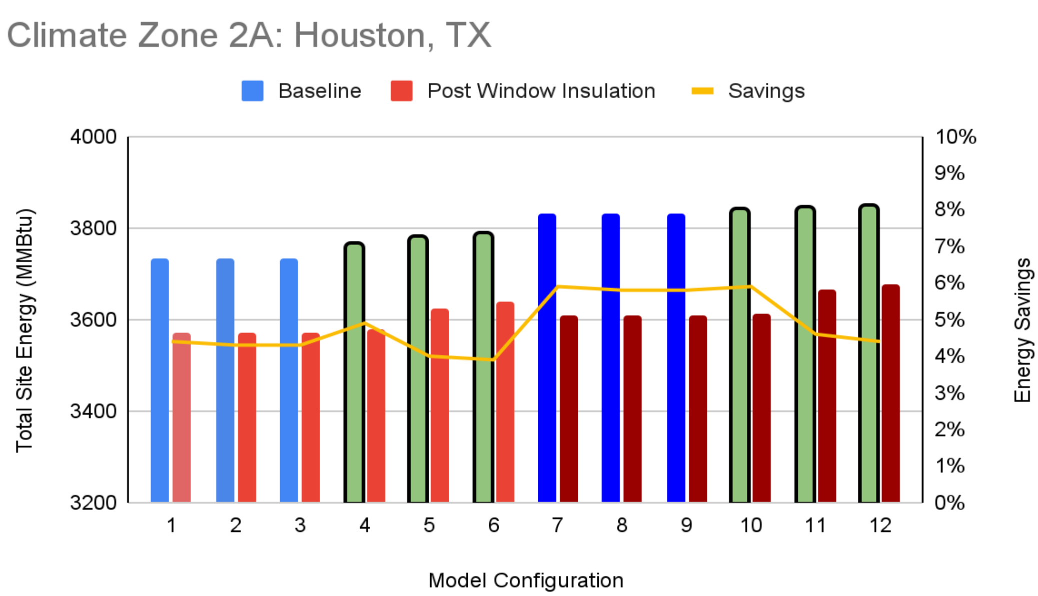


Figure B2. Climate Zone 2A: Houston, TX | Configurations 1–6 are double-pane glazing, and configurations 7–12 are single-pane glazing. Configurations 4–6 and 10–12 (shown in green with black borders) represent metal frames. For each configuration series (e.g., 1–3, 4–6, 7–9, and 10–12), an increase in the configuration number represents an increase in the frame area (e.g., configuration 4 = 10% area, 5 = 20%, and 6 = 30%).

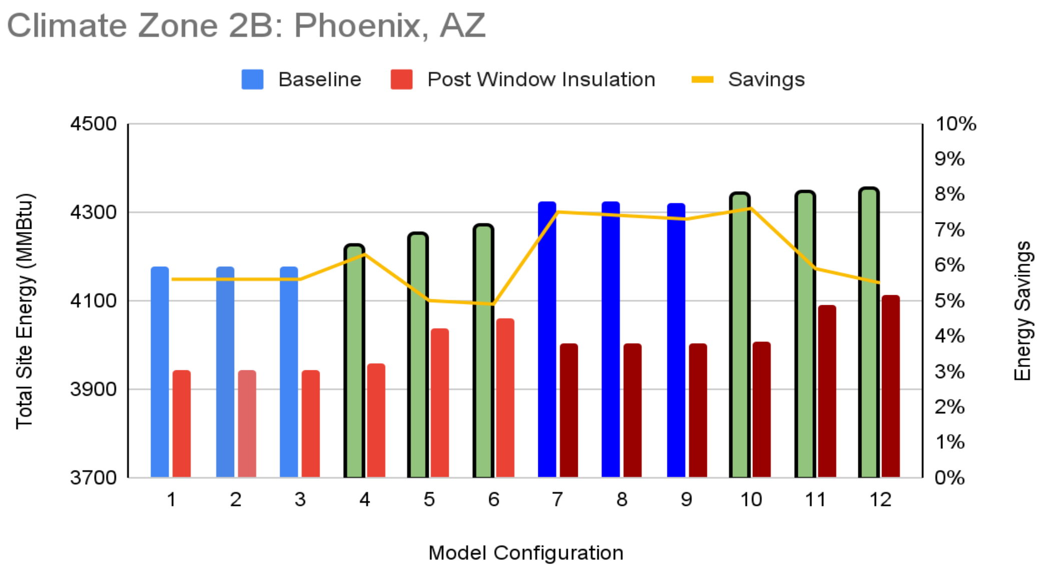


Figure B3. Climate Zone 2B: Phoenix, AZ | Configurations 1–6 are double-pane glazing, and configurations 7–12 are single-pane glazing. Configurations 4–6 and 10–12 (shown in green with black borders) represent metal frames. For each configuration series (e.g., 1–3, 4–6, 7–9, and 10–12), an increase in the configuration number represents an increase in the frame area (e.g., configuration 4 = 10% area, 5 = 20%, and 6 = 30%).

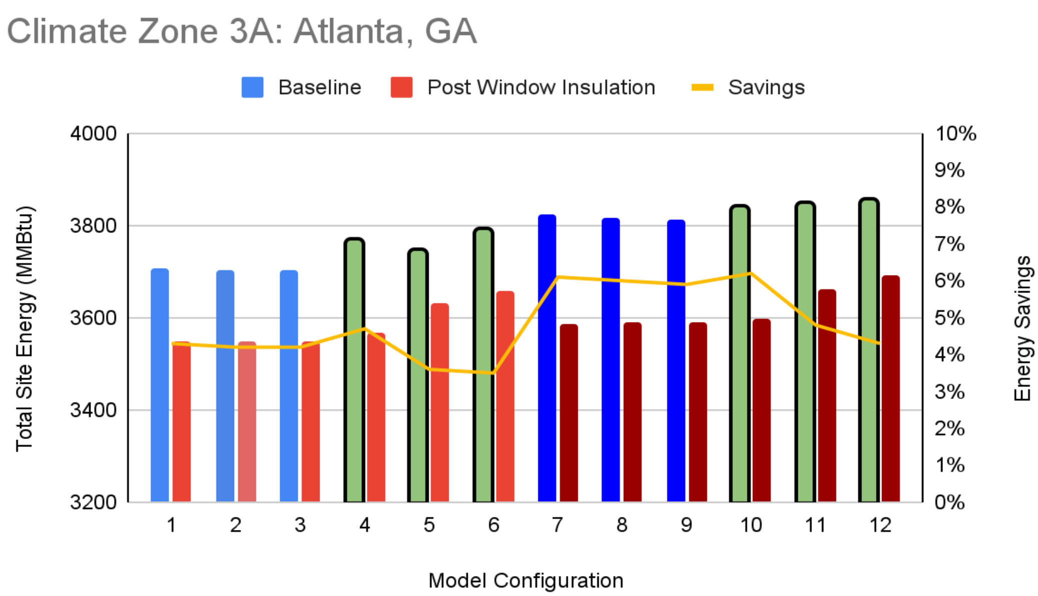


Figure B4. Climate Zone 3A: Atlanta, GA | Configurations 1–6 are double-pane glazing, and configurations 7–12 are single-pane glazing. Configurations 4–6 and 10–12 (shown in green with black borders) represent metal frames. For each configuration series (e.g., 1–3, 4–6, 7–9, and 10–12), an increase in the configuration number represents an increase in the frame area (e.g., configuration 4 = 10% area, 5 = 20%, and 6 = 30%).

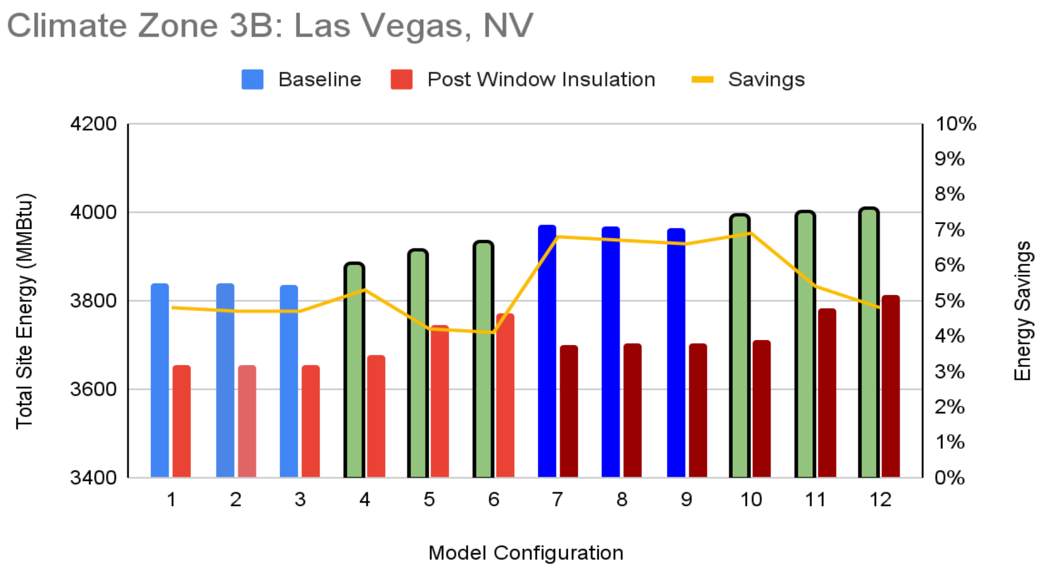


Figure B5. Climate Zone 3B: Las Vegas, NV | Configurations 1–6 are double-pane glazing, and configurations 7–12 are single-pane glazing. Configurations 4–6 and 10–12 (shown in green with black borders) represent metal frames. For each configuration series (e.g., 1–3, 4–6, 7–9, and 10–12), an increase in the configuration number represents an increase in the frame area (e.g., configuration 4 = 10% area, 5 = 20%, and 6 = 30%).

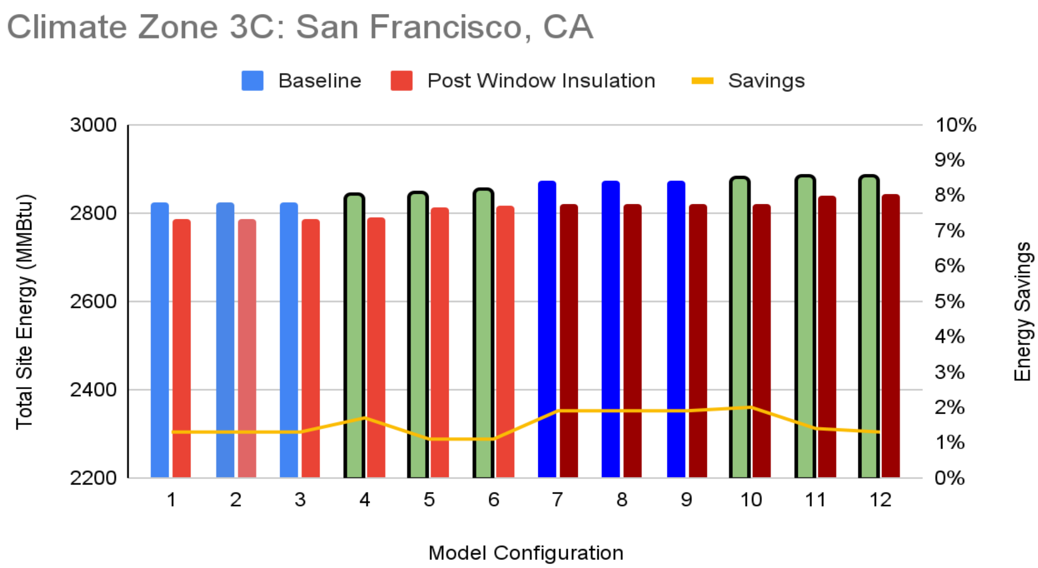


Figure B6. Climate Zone 3C: San Francisco, CA | Configurations 1–6 are double-pane glazing, and configurations 7–12 are single-pane glazing. Configurations 4–6 and 10–12 (shown in green with black borders) represent metal frames. For each configuration series (e.g., 1–3, 4–6, 7–9, and 10–12), an increase in the configuration number represents an increase in the frame area (e.g., configuration 4 = 10% area, 5 = 20%, and 6 = 30%).

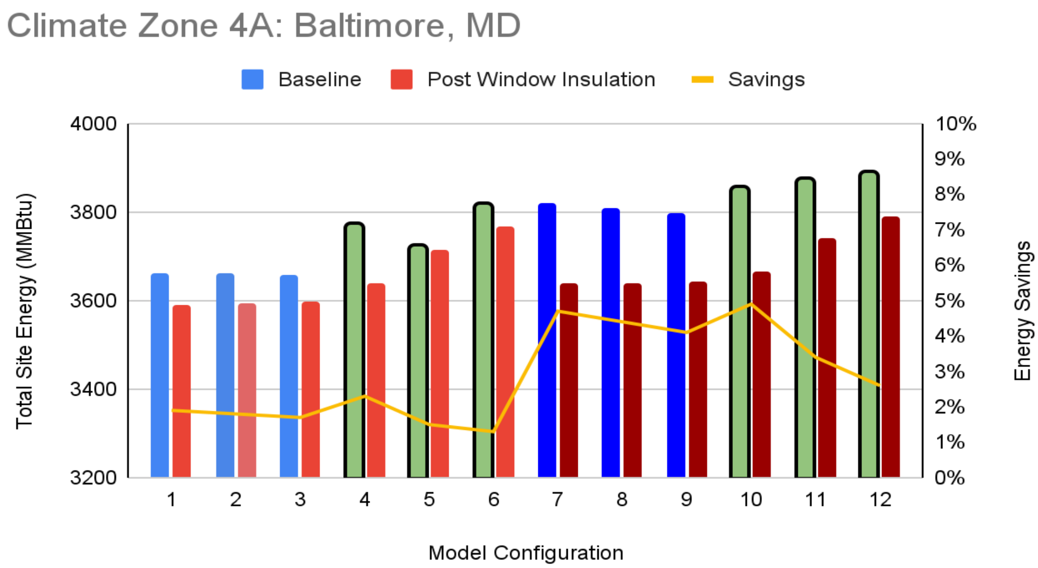


Figure B7. Climate Zone 4A: Baltimore, MD | Configurations 1–6 are double-pane glazing, and configurations 7–12 are single-pane glazing. Configurations 4–6 and 10–12 (shown in green with black borders) represent metal frames. For each configuration series (e.g., 1–3, 4–6, 7–9, and 10–12), an increase in the configuration number represents an increase in the frame area (e.g., configuration 4 = 10% area, 5 = 20%, and 6 = 30%).

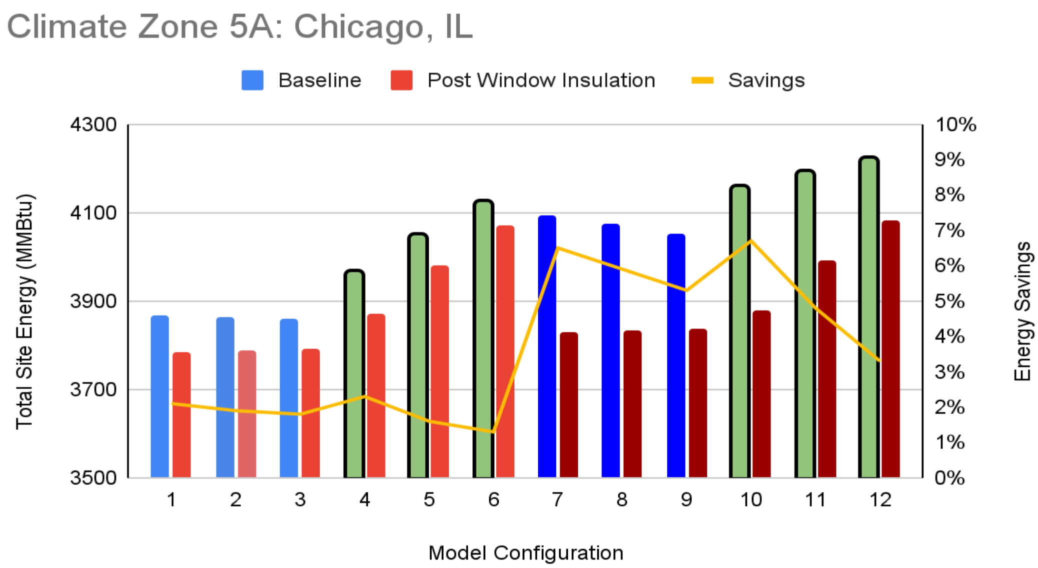


Figure B8. Climate Zone 5A: Chicago, IL | Configurations 1–6 are double-pane glazing, and configurations 7–12 are single-pane glazing. Configurations 4–6 and 10–12(shown in green with black borders) represent metal frames. For each configuration series (e.g., 1–3, 4–6, 7–9, and 10–12), an increase in the configuration number represents an increase in the frame area (e.g., configuration 4 = 10% area, 5 = 20%, and 6 = 30%.)

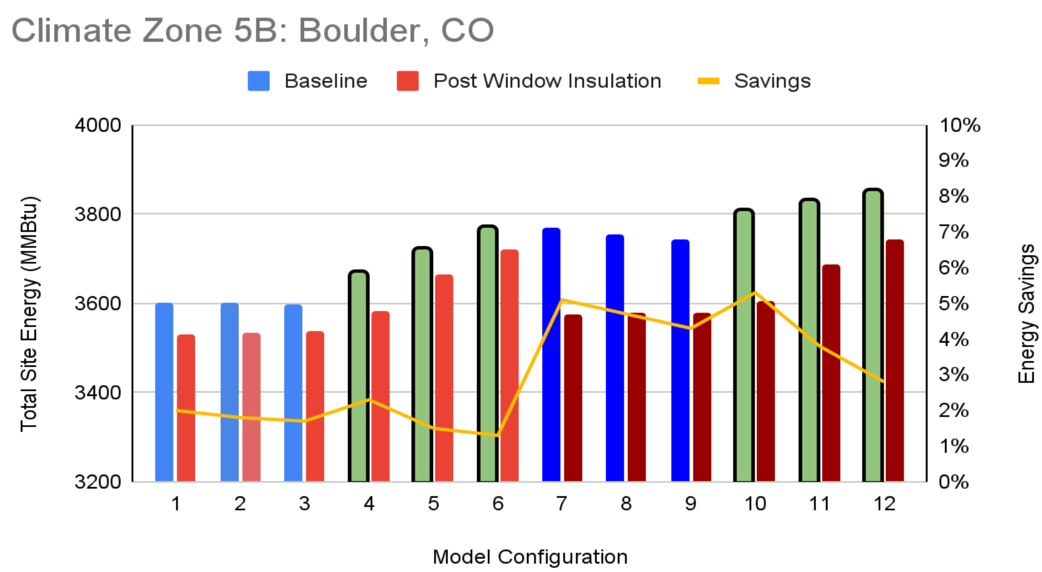


Figure B9. Climate Zone 5B: Boulder, CO | Configurations 1–6 are double-pane glazing, and configurations 7–12 are single-pane glazing. Configurations 4–6 and 10–12 (shown in green with black borders) represent metal frames. For each configuration series (e.g., 1–3, 4–6, 7–9, and 10–12), an increase in the configuration number represents an increase in the frame area (e.g., configuration 4 = 10% area, 5 = 20%, and 6 = 30%).

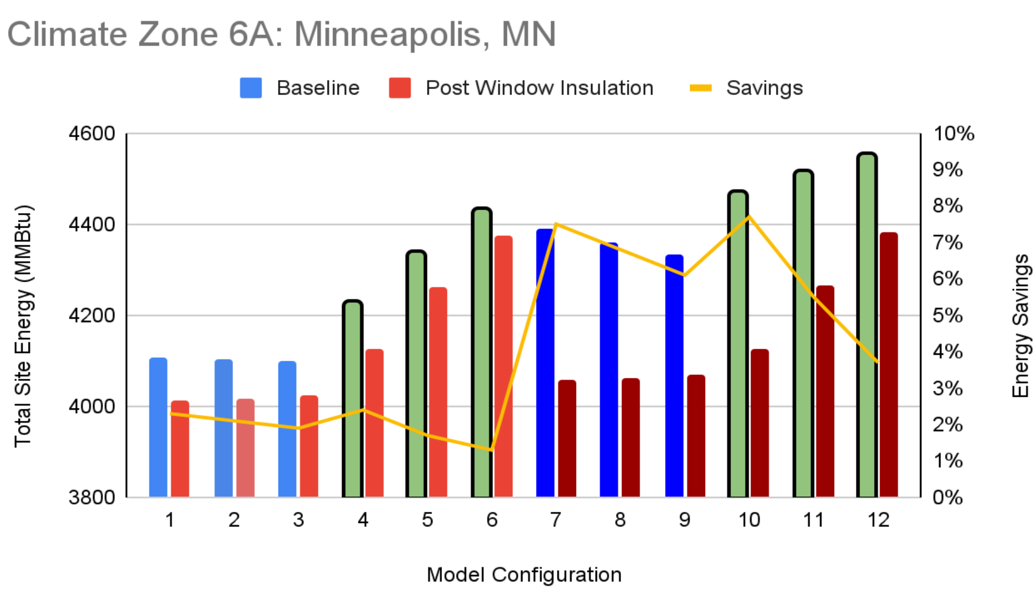


Figure B10. Climate Zone 6A: Minneapolis, MN | | Configurations 1–6 are double-pane glazing, and configurations 7–12 are single-pane glazing. Configurations 4–6 and 10–12 (shown in green with black borders) represent metal frames. For each configuration series (e.g., 1–3, 4–6, 7–9, and 10–12), an increase in the configuration number represents an increase in the frame area (e.g., configuration 4 = 10% area, 5 = 20%, and 6 = 30%).

C. Detailed Cost Effectiveness

Tables C1–C4 provide the detailed cost effectiveness for individual combinations of single- and double-pane windows with metal and non-metal frames.

Table C1 provides the average cost effectiveness for the three frame areas per climate zone for single-pane windows with nonmetal frames.

Table C1. Envelope Baseline Defaults for a Medium-Sized Pre-1980 Office Building: Single-Pane Windows with Nonmetal Frames

Climate Zone	City	Window Insulation Type	Savings Electric Savings (kWh)	Savings Gas Savings (MMBtu)	Savings Total Savings	Cost at Eau Claire (21/ft^2) Payback (Yrs)	Cost at Eau Claire (21/ft^2) SIR	Future Costs (16/ft^2 & 9/ft^2) Payback (Yrs)	Future Costs (16/ft^2 & 9/ft^2) SIR
1A	Miami, FL	Warm-climate	70,348	0.18	6%	17.4	0.9	13.5†	1.1
2A	Houston, TX	Warm-climate	63,787	5.50	6%	19.1	0.8	14.9†	1.0
2B	Phoenix, AZ	Warm-climate	93,074	2.93	7%	13.1	1.1	10.2†	1.5
3A	Atlanta, GA	Warm-climate	62,278	17.77	6%	19.3	0.8	15.3†	1.0
3B	Las Vegas, NV	Warm-climate	76,278	6.00	7%	15.9	0.9	12.5†	1.2
Average		Warm-climate	73,153	6.48	6%	17.0	0.9	13.3	1.2
3C	San Francisco, CA	Moderate-climate	12,130	14.37	2%	93.1	0.2	78.4†	0.2
4A	Baltimore, MD	Moderate-climate	25,109	86.87	4%	39.3	0.4	38.0†	0.5
Average		Moderate-climate	18,574	50.62	3%	66.2	0.3	58.2	0.3
5A	Chicago, IL	Cold-climate	27,935	153.60	6%	31.6	0.5	20.5††	1.0
5B	Boulder, CO	Cold-climate	25,898	94.17	5%	37.6	0.4	22.1††	0.9
6A	Minneapolis, MN	Cold-climate	28,046	212.67	7%	28.5	0.5	20.4††	1.1
Average		Cold-climate	27,293	153.48	6%	32.6	0.5	21.0	1.0

Note: Table shows average of three frame areas (10%, 20%, 30%) included in the analysis.

† Future cost assumes a $16 /ft2 panel and †† future cost assumes a $9 / ft2 panel

Table C2 provides the average cost effectiveness for the three frame areas per climate zone for single-pane windows with metal frames.

Table C2. Envelope Baseline Defaults for a Medium-Sized Pre-1980 Office Building: Single-Pane Windows with Metal Frames

Climate Zone	City	Window Insulation Type	Savings Electric Savings (kWh)	Savings Gas Savings (MMBtu)	Savings Total Savings	Cost at Eau Claire (21/ft^2) Payback (Yrs)	Cost at Eau Claire (21/ft^2) SIR	Future Costs (16/ft^2 & 9/ft^2) Payback (Yrs)	Future Costs (16/ft^2 & 9/ft^2) SIR
1A	Miami, FL	Warm-climate	62,605	0.17	5%	19.5	0.8	15.2†	1.0
2A	Houston, TX	Warm-climate	55,389	3.23	5%	22.0	0.7	17.2†	0.9
2B	Phoenix, AZ	Warm-climate	79,722	1.63	6%	15.3	1.0	11.9†	1.3
3A	Atlanta, GA	Warm-climate	54,213	11.83	5%	22.2	0.7	17.5†	0.9
3B	Las Vegas, NV	Warm-climate	66,389	1.77	6%	18.4	0.8	14.3†	1.0
Average		Warm-climate	63,664	3.73	5%	19.5	0.8	15.2	1.0
3C	San Francisco, CA	Moderate-climate	9,917	12.70	2%	113.2	0.1	95.9†	0.2
4A	Baltimore, MD	Moderate-climate	19,787	77.53	4%	48.5	0.3	48.0†	0.4
Average		Moderate-climate	14,852	45.12	3%	80.8	0.2	72.0	0.3
5A	Chicago, IL	Cold-climate	22,222	137.07	5%	38.4	0.4	25.8††	0.8
5B	Boulder, CO	Cold-climate	21,083	84.17	4%	45.3	0.3	27.1††	0.7
6A	Minneapolis, MN	Cold-climate	22,611	187.70	6%	34.2	0.4	25.3††	0.9
Average		Cold-climate	21,972	136.31	5%	39.3	0.4	26.1	0.8

Note: Table shows average of three frame areas (10%, 20%, 30%) included in the analysis. Only the “Total savings” column shows the possible range of values from the different frame areas.

† Future cost assumes a \$16 /ft^2 panel and †† future cost assumes a \$9 / ft^2 panel

Table C3 provides the average cost effectiveness for the three frame areas per climate zone for double-pane windows with nonmetal frames.

Table C3. Envelope Baseline Defaults for a Medium-Sized Pre-1980 Office Building: Double-Pane Windows with Nonmetal Frames

Climate Zone	City	Window Insulation Type	Savings Electric Savings (kWh)	Savings Gas Savings (mmBtu)	Savings Total Savings	Cost at Eau Claire (21/ft²) Payback (Yrs)	Cost at Eau Claire (21/ft²) SIR	Future Costs (16/ft²) Payback (Yrs)	Future Costs (16/ft²) SIR
1A	Miami, FL	Warm-climate	56,741	(0.11)	5%	21.6	0.7	16.8†	0.9
2A	Houston, TX	Warm-climate	49,324	(6.17)	4%	25.0	0.6	19.3†	0.8
2B	Phoenix, AZ	Warm-climate	69,315	(2.47)	6%	17.7	0.8	13.7†	1.1
3A	Atlanta, GA	Warm-climate	50,843	(17.63)	4%	24.7	0.6	18.7†	0.8
3B	Las Vegas, NV	Warm-climate	56,287	(10.67)	5%	22.0	0.7	16.9†	0.9
Average		Warm-climate	56,502	(7.41)	5%	22.2	0.7	17.1	0.9
3C	San Francisco, CA	Moderate-climate	10,407	1.00	1%	116.7	0.1	91.3†	0.2
4A	Baltimore, MD	Moderate-climate	17,037	8.37	2%	69.4	0.2	55.8†	0.3
Average		Moderate-climate	13,722	4.68	2%	93.1	0.2	73.6	0.2
5A	Chicago, IL	Cold-climate	16,852	18.30	2%	67.5	0.2	34.0††	0.5
5B	Boulder, CO	Cold-climate	16,444	10.50	2%	71.2	0.2	34.8††	0.5
6A	Minneapolis, MN	Cold-climate	17,176	28.40	2%	63.8	0.2	33.3††	0.5
Average		Cold-climate	16,824	19.07	2%	67.5	0.2	34.0	0.5

Note: Table shows average of three frame areas (10%, 20%, 30%) included in the analysis. Only the "Total savings" column shows the possible range of values from the different frame areas.

Value in ( ) indicates a negative value.

† Future cost assumes a \$16 /ft² panel and †† future cost assumes a \$9 / ft² panel

Table C4 provides the average cost effectiveness for the three frame areas per climate zone for double-pane windows with metal frames.

Table C4. Envelope Baseline Defaults for a Medium-Sized Pre-1980 Office Building: Double-Pane Windows with metal Frames

Climate Zone	City	Window Insulation Type	Savings Electric Savings (kWh)	Savings Gas Savings (MMBtu)	Savings Total Savings	Cost at Eau Claire (21/ft²) Payback (Yrs)	Cost at Eau Claire (21/ft²) SIR	Future Costs (16/ft²) Payback (Yrs)	Future Costs (16/ft²) SIR
1A	Miami, FL	Warm-climate	56,546	(0.19)	5%	21.6	0.7	16.8†	0.9
2A	Houston, TX	Warm-climate	49,704	(8.87)	4%	24.9	0.6	19.1†	0.8
2B	Phoenix, AZ	Warm-climate	68,361	(3.97)	5%	18.0	0.8	13.9†	1.1
3A	Atlanta, GA	Warm-climate	49,954	(23.80)	4%	25.3	0.6	19.0†	0.8
3B	Las Vegas, NV	Warm-climate	56,241	(15.60)	5%	22.2	0.7	16.9†	0.9
Average		Warm-climate	56,161	(10.48)	5%	22.40	0.7	17.2	0.9
3C	San Francisco, CA	Moderate-climate	11,037	(0.50)	1%	111.2	0.1	86.1†	0.2
4A	Baltimore, MD	Moderate-climate	17,991	2.50	2%	67.3	0.2	52.8†	0.3
Average		Moderate-climate	14,514	1.00	2%	89.3	0.2	69.5	0.2
5A	Chicago, IL	Cold-climate	17,565	10.37	2%	66.9	0.2	32.6††	0.5
5B	Boulder, CO	Cold-climate	17,583	3.37	2%	68.6	0.2	32.6††	0.5
6A	Minneapolis, MN	Cold-climate	17,991	17.80	2%	63.6	0.2	31.8††	0.5
Average		Cold-climate	17,713	10.51	2%	63.4	0.2	32.3	0.5

Note: Table shows average of three frame areas (10%, 20%, 30%) included in the analysis. Only the "Total savings" column shows the possible range of values from the different frame areas.

Value in ( ) indicates a negative value.

† Future cost assumes a \$16 /ft² panel and †† future cost assumes a \$9 / ft² panel

D. Vendor Cutsheets

The following images are the vendor's product specification sheets. This analysis applies "PolarSkin" to cold climates and "SolarSkin" to warm climates.

Polar*Skin*™ Product Spec Sheet

Product is part of the ***Wex****Window™ family of products*

Product Description

The ***Polar****Skin*™ is a snap-on window insulation panel that increases thermal resistance to reduce conductive heat transfer at the window. ***Polar****Skin's* controlled air gap optimizes the insulation gap between the existing window and ***Polar****Skin*, resulting in improved window energy performance. ***Polar****Skins* keep the heat inside in winter and outside in summer. ***Polar****Skins* are individually manufactured to fit each unique window and are part of the ***Wex****Window* family of products.

Product Classification

Polar*Skin* meets CLASS A criteria required for interior wall and ceiling finish materials under the International Building Code® (IBC), NFPA 1-1: Life Safety Code® (NFPA 1010), and NFPA 5000: Building Construction and Safety Code® (NFPA 5000). This determination is based on ASTM E84 test results performed by Intertek.[1]

Glazing Performance: Improvement to Thermal Insulation

Existing Prime Window:	Air-filled Double Pane + PolarSkin[2]	Single Pane with Storm + PolarSkin[3]	Single Pane + PolarSkin[3]
Polar*Skin* High-Profile[4,5]	38%	~40%	~56%
Polar*Skin* Low-Profile[4,5]	36%	~36%	~54%

Polar*Skin* Product Specs

	Visible Light Transmittance[6]	Emissivity[7]
Polar*Skin*	0.91	0.80

Window Operability

Polar*Skin* allows emergency egress through the window. Windows and window treatments will open and close, just as they did before ***Polar****Skins* were installed. ***Polar****Skin* installations allow buildings to remain in compliance with Building Code.

Custom Fit - Easy to Measure and Install

Polar*Skins* are individually manufactured to fit each window. ***Polar****Skins* are dimensioned and mounted to the inside glass pane. Available in 1/16" increments. Fits rectangular windows: double-hung, sliders, casement, awning and fixed. No tools. No construction. No disruption.

Minimum window-pane dimension (height or width): 15". Maximum window-pane dimension (height or width): 60". Modular arrangements available. Larger dimensions coming in Q3-2023. Contact WexEnergy for more information.

Materials

Polar*Skins* are made with polyester-based, GREENGUARD® Certified and Cradle-to-Cradle™ Certified materials. One of our key suppliers announced plans for advance recycling technology that will allow ***Polar****Skins* to be recycled into virgin material at end-of-cycle.

Effective Useful Life

For ***Polar****Skins* in IECC Climate Zones 4-8. South facing single-pane windows: 20 years. North facing single- and double-pane windows: 50+ years. ***Polar****Skin* is designed to be tamper resistant.

Footnotes

[1] Intertek Test Report No. M1880.01-121-24, issued 4/7/2021.
[2] NRFC 102-2020 results, Intertek. Intertek reports available upon request.
[3] Calculated based on ***Polar****Skin* R-value derived from NFRC 102-2020 results for air-filled double pane prime window. Intertek report available upon request.
[4] High-Profile ***Polar****Skin* requires at least 0.625 inch clearance for installation on operable sliding windows. Low-Profile ***Polar****Skin* requires at least 0.375 inch clearance for installation on operable sliding windows.
[5] ***Polar****Skin* R-Values for High Profile and Low Profile are 1.2 and 1.1, respectively based on independent testing by Intertek using NFRC 102-2020 protocols. Intertek reports are available upon request.
[6] Visible Light Transmittance (VLT) measures how much light comes through the center of the product when mounted on a window. A higher value, from 0 to 1.0, means the product transmits more daylight
[7] Estimated from https://www.sciencedirect.com/science/article/pii/S0378778818336004.

WexEnergy | Contact: Rachel Rosen, CEO & Co-Founder rachelrosen@wexenergy.com 585-213-5100

***Solar**Skin*™ Product Spec Sheet

*Product is part of the **Wex**Window™ family of products*

Product Description

SolarSkin is a snap-on window insulation panel that reduces solar heat gain (SHG) and increases thermal insulation at the window. ***SolarSkin*** provides thermal insulation by optimizing the insulation gap between the existing window and ***SolarSkin***. Its solar control properties reduce solar heat gain and glare to reduce A/C loads and improve building occupant comfort. ***SolarSkins*** keep the heat inside during the winter and outside during summer. ***SolarSkins*** are individually manufactured to fit each unique window.

SolarSkins are mounted to the inside windowpane. No tools. No construction. No disruption.

Product Classification

SolarSkin meets CLASS A criteria required for interior wall and ceiling finish materials under the International Building Code® (IBC), NFPA 1-1: Life Safety Code® (NFPA 1010), and NFPA 5000: Building Construction and Safety Code® (NFPA 5000). This determination is based on ASTM E84 test results performed by Intertek on ***PolarSkin***.[1]

SolarSkin Product Specs

	Visible Light Transmittance[2]	R-Value[3,4]	% SHG Reduction (Single Pane/Double Pane)[5]	Emissivity[6]
SK20 ***SolarSkin***	0.22	1.31	60% / 38%	0.84
SK50 ***SolarSkin***	0.45	1.35	48% / 35%	0.69
SK70 ***SolarSkin***	0.66	1.31	47% / 34%	0.77

SolarSkin + Existing Window Performance

	U-Factor[6] (Wood/Vinyl Frame)	U-Factor[6] (Aluminum Frame/Thermally Broken)	SHGC[7]
SK20 *SolarSkin*			
High-Profile ***SolarSkins*** + Existing Single-Pane[8] Window	0.45	0.62	0.32
High-Profile ***SolarSkins*** + Existing Double-Pane[9] Window	0.33	0.40	0.25
Low-Profile ***SolarSkins*** + Existing Double-Pane[9] Window	0.34	0.40	0.25
SK50 *SolarSkin*			
High-Profile ***SolarSkins*** + Existing Single-Pane[8] Window	0.45	0.62	0.42
High-Profile ***SolarSkins*** + Existing Double-Pane[9] Window	0.33	0.39	0.26
Low-Profile ***SolarSkins*** + Existing Double-Pane[9] Window	0.33	0.40	0.26
SK70 *SolarSkin*			
High-Profile ***SolarSkins*** + Existing Single-Pane[8] Window	0.45	0.62	0.42
High-Profile ***SolarSkins*** + Existing Double-Pane[9] Window	0.33	0.40	0.26
Low-Profile ***SolarSkins*** + Existing Double-Pane[9] Window	0.34	0.40	0.26
NYC Energy Code for Windows[10]	≤0.40		≤0.36

NYC Energy Code

Contact WexEnergy to learn if a ***SolarSkin*** retrofit can bring your building's existing, double-pane windows up to current NYC energy code.

Window Operability

SolarSkin maintains emergency egress through the window. Windows and window treatments will open and close, just as they did before ***SolarSkins*** were installed.

Contact: Rachel Rosen, CEO & Co-Founder rachelrosen@wexenergy.com 585-213-5100

SolarSkin™ Product Spec Sheet

Custom Fit - Easy to Measure and Install

SolarSkins are manufactured to fit each window size. ***SolarSkins*** are dimensioned and mounted to the glass pane. Available in 1/16" increments. Fits rectangular windows: double-hung, sliders, casement, awning and fixed.

Minimum window-pane dimension (height or width): 15"
Maximum window-pane dimensions: 48" x 60". Larger dimensions coming in 2023. Contact WexEnergy for more information.

Materials

SolarSkins are made with polyester-based, GREENGUARD® Certified and Cradle-to-Cradle™ Certified materials. One of our key suppliers announced plans for advance recycling technology that will allow polyester-based materials to be recycled into virgin material at end-of-cycle.

Effective Useful Life

SolarSkins will last 30+ years in IECC Climate Zones 1-9.

Footnotes

[1] Test Report No. M1880.01-121-24, issued April 7, 2021, ASTM E84 Test Report for PolarSkin issued by Intertek.

[2] Visible Light Transmittance (VLT) measures the amount of visible light which comes through the product. A higher value, from 0 to 100%, means the product allows more daylight through. SolarSkin SK50 results per Intertek testing (ASTM E972 E1084). SK50 VLT result was indistinguishable from the window film manufacturer's specification. SK20 and SK70 VLT values are based on the respective window film manufacturer product specification.

[3] R-Value measures the resistance to heat loss through the product in ft^2-°F-hr/BTU.

[4] The High-Profile SolarSkin provides a 5/8" air gap providing an R-Value of 1.35 as measured by NFRC 102-2020 test by Intertek. SK20 and SK70 are inferred based on window film specification Winter U-Factors relative to SK50 material. The Low-Profile SolarSkin provides a 3/8" air gap with 0.1 lower R-Value than the High-Profile SolarSkin R-Values shown in this table.

[5] % Solar Heat Gain Reduction is the percentage of solar radiation reduction at center of glass, including radiation directly transmitted and radiation absorbed and subsequently released into the building interior. Values in this table are for the SolarSkin product alone. NFRC 201-2020 test results for SK50 on a double pane clear window had "% Solar Heat Gain Reduction" that was indistinguishable from manufacturer product specification for the window film used in SK50. SK20 and SK70 "% Solar Heat Gain Reduction" values are based on the respective window film manufacturer product specification.

[6] U-Factor measures the heat loss through SolarSkin in BTU/ft^2-°F-hr. NFRC 102-2020 measurements for SolarSkin SK50 were performed by Intertek, a global certification laboratory. SK20 and SK70 values are based on the SK50 measurements, adjusted for differences in window film manufacturer Winter U-Factor specifications. Emissivity values are based on the respective window film manufacturer's product specification data.

[7] Solar Heat Gain Coefficient (SHGC) is calculated using respective % Solar Heat Gain Reduction for the SolarSkin and respective existing window SHGC.

[8] Existing single-pane window with 78% glazing area, 22% frame area used in the illustrations has a U-factor of 1.1 and SHGC of 0.8

[9] Existing double-pane window with 78% glazing area, 22% frame area used in the illustrations has a U-factor of 0.5 and SHGC of 0.4.

[10] New York City Energy Code, https://www.nyc.gov/assets/buildings/apps/pdf_viewer/viewer.html?file=2020ECC_CHC4.pdf&section=energy_code_2020, Table C402.4, for metal framing operable window.

Contact: Rachel Rosen, CEO & Co-Founder rachelrosen@wexenergy.com 585-213-5100