Field Demonstration of Non-Intrusive Secondary Window Systems for Energy Efficiency and Thermal Comfort Enhancement in Commercial Buildings

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ABSTRACT

Aging single-glazed windows in commercial buildings contribute significantly to heating and cooling loads due to high heat transfer through the building envelope. Conventional window retrofits rely on full window replacement with high-performance glazing, which can be costly, disruptive, and difficult to justify economically for many building owners. Secondary window systems (SWS) provide a low-intrusion retrofit alternative by attaching high-performance glazing units to existing windows, improving thermal performance while avoiding demolition and reducing installation costs.

This study evaluates the thermal and economic performance of two SWS technologies: a thin triple-pane insulated glazing unit and a vacuum insulated glass (VIG) unit. Laboratory testing using an infrared thermographic chamber measured whole-assembly U-factors for SWS installed on a single-glazed aluminum baseline window. Thermal modeling using WINDOW and THERM software was conducted to validate the experimental results. The measured results showed that both SWS technologies significantly reduced heat transfer through the window assembly, decreasing the U-factor from 4.67 W/(m²·K) [0.822 Btu/(h·ft^2·F)] for the baseline window to approximately 1.01–1.04 W/(m²·K) [0.178 – 0. 0.183 Btu/(h·ft^2·F)], representing about a 78% improvement. Modeling results showed strong agreement with experimental measurements when validated using calibration transfer standard (CTS) testing. A field demonstration in a commercial hotel in Indian Wells, California, is currently underway to evaluate real-world energy and comfort impacts.

INTRODUCTION

Commercial buildings consume substantial energy in the U.S., with aging single-glazed windows contributing significantly to heating and cooling loads. In 2025, commercial buildings account for approximately 17% of total U.S. energy consumption, equivalent to about 16.23 quadrillion Btu (quads) (EIA, 2025*Annual Energy Outlook 2025*). Windows are the weakest link in the building envelope and are responsible for ~5 quads, or approximately 10% of building energy use, due to heat transfer through building envelope (Hart et al., 2019). Therefore, improving window performance represents an important opportunity for enhancing building energy efficiency.

Traditional window retrofit method is full window replacement with high-performance windows, such as double-pane, triple-pane, or vacuum insulated glass (VIG) windows. But this method with code compliant windows to meet energy efficiency goals is disruptive, expensive, with difficult economics for building owners, often resulting in a “do nothing” approach.

Additionally, it may also introduce risk of new penetration and leakages. These high-performance windows are commercially available but represent less than 2% of the U.S. window market, limited by technical and cost challenges with full window replacement.

To address those challenges, this study investigated a cost-effective, high-performance window retrofit using a secondary window system (SWS) technology as a low-intrusion, cost-effective retrofit pathway to enhance building envelope performance. SWS provides an easier-to-install alternative to full window replacement by attaching a high-performance glazing unit to the interior or exterior of an existing window. This approach significantly reduces heat transfer through windows by introducing an additional high-performance layer while preserving the original window assembly. As a result, the technology reduces both retrofit cost and installation disruption by avoiding demolition (Petersen et al., 2015). However, the air cavity between the existing and added glazing may pose a condensation risk if moisture accumulates within the cavity (Hashemi & Gage, 2014; Park & Song, 2018). This risk can be mitigated either by sealing the cavity properly to limit humid air infiltration or by providing effective ventilation to prevent moisture buildup. Overall, SWS technology offers a practical and cost-effective retrofit strategy to improve energy efficiency by reducing the thermal loads, but its implementation requires careful consideration of potential condensation risks and thermal stress breakage risk in the air cavity.

The objectives of this study were to evaluate and demonstrate thermal and economic benefits of SWS with high-performance glazing technologies and demonstrate this technique in a commercial building. This study conducted laboratory testing and modeling for two types of glazing units – a thin triple-pane insulated glazing unit (IGU) with a pultruded fiberglass frame and a VIG unit with an aluminum frame – to evaluate whole assemblies' U-factor. Additional modeling was performed to propose improvement for SWS design for a better overall thermal performance in the field. What's more, the field demonstration, hosted at a large hotel in Indian Wells, CA, includes 138 windows (494 m^2 glazing area) using these two types of units. The measurement and verification (M&V) plan was developed to monitor window thermal performance, energy consumption, and indoor thermal comfort before and after the retrofit. Baseline monitoring is underway to capture pre-retrofit performance, with SWS installations planned for late-2026. Furthermore, the techno-economic assessment was also performed to evaluate the installation and total cost of SWS by using these two types of units. This assessment could help identify the most cost-effective retrofit pathway for building owners and justify incentives, policies, and retrofit programs for stakeholders.

METHOD

This study used laboratory testing, numerical modeling, and techno-economic analysis to evaluate secondary window systems (SWS). Whole-assembly U-factors were measured using an infrared thermographic chamber. WINDOW and THERM simulations were used to analyze thermal performance, while the techno-economic assessment compared the installed cost of SWS with Title 24–compliant replacement windows.

SWS PRODUCTS

As shown in Figure 1, two SWS products as test specimens tested in this study were: (1) a triple-pane unit with a pultruded fiberglass frame; the glazing had triple silver low-E coatings on the surface # 1, #3 and #4 of the unit from the outward side. (2) a VIG unit with an aluminum frame. Both had the same dimensions 762 x 1016 mm for the lab testing. To measure the whole assembly U-factor, each product was installed in the mask wall and then inserted into the infrared thermographic chamber, as shown in Figure 2(b).

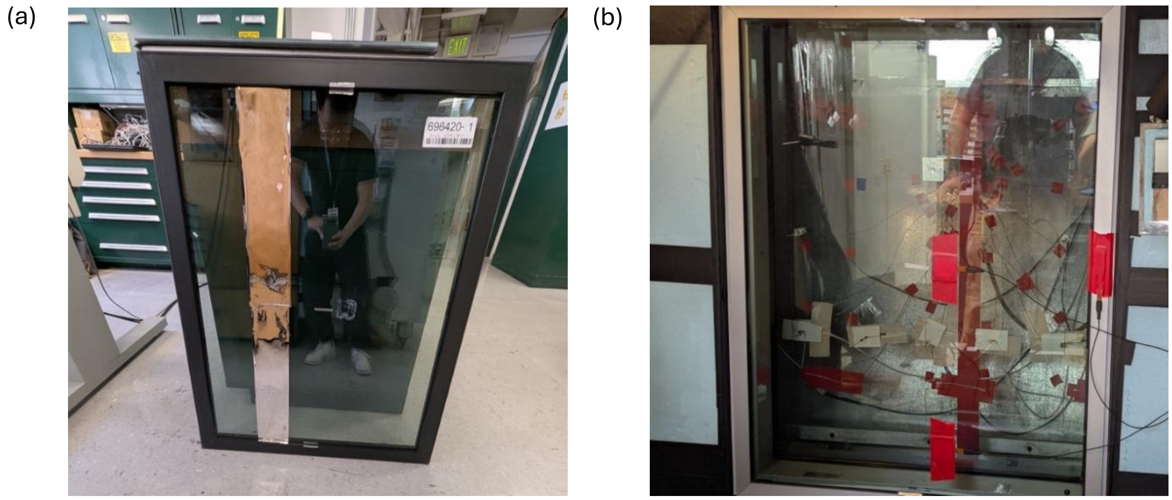

Figure 1. SWS products: (a) a triple-pane unit and (b) a VIG unit.

For the field demonstration, these two SWS products will be installed on four different sizes of existing single-pane windows in different hotel areas, as shown in Table 1.

Table 1. Selected windows for field demonstration

Hotel Area	Window Type	Width (mm)	Height (mm)	Area (m^2)	Total windows	Total Area (m^2)	SWS
Guest Room	D	3397.3	1816.1	6.2	35	215.9	Combination of triple-pane units and VIGs
Offices	F	1873.3	1816.1	3.4	12	60.6	
	G	1816.1	1816.1	3.3	6		
Conference Rooms	F	1873.3	1816.1	3.4	15	51.0	
Hallways	C	1549.4	1536.7	2.4	70	166.5	Triple-pane units
Total					138	494	

WHOLE ASSEMBLIES U-FACTOR MEASUREMENT

An IR thermographic chamber was used to evaluate whole assembly U-factor of the proposed SWS technologies. This chamber included a cold box, a hot box, two high thermal resolution IR cameras, and a test specimen with sensors inserted between two boxes. Both boxes included a cooling coil, a heater, and a fan to control chamber air temperatures and air flow rates. It could provide uniform enclosure temperature and air flow conditions, data collection of high-resolution quantitative surface temperature, detailed background radiation correction, and external referencing for the IR camera. These functions contributed to achieving a high accuracy surface temperature measurement with ± 0.5℃.

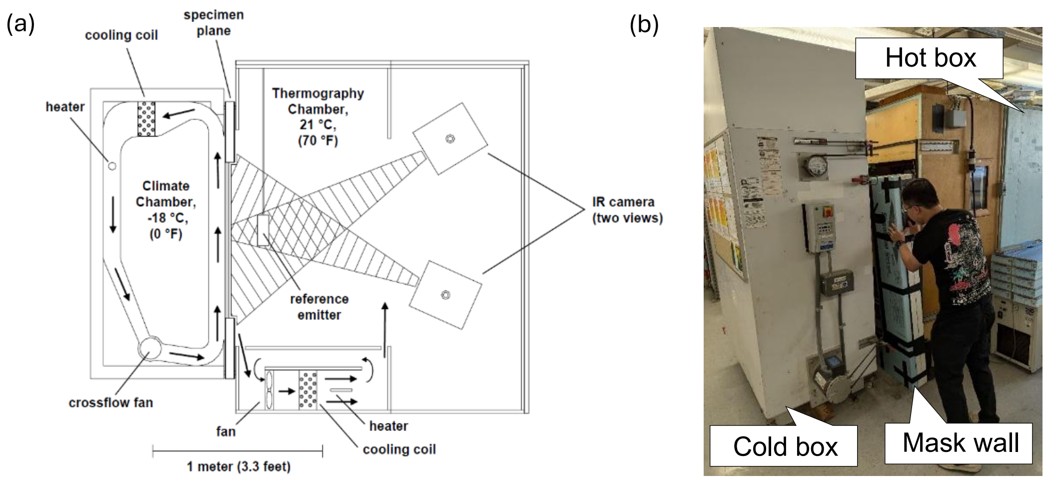

Figure 2. (a) Schematic diagram of IR thermographic chamber and (b) installation of the mask wall into the chamber.

To replicate the application of the SWS technology on typical single-glazed aluminum windows commonly used in older commercial buildings, the laboratory testing attached the SWS product to a baseline window consisting of a Kawneer 450 picture window with an aluminum alloy frame and a single glazing. The U-factor for the center of glazing is 4.671 W/(m^2·K) [0.823 Btu/(h·ft^2·F)]. In order to accommodate the baseline window and the SWS product, the mask wall included a 30 in. x 40 in. opening with a foam thickness of 6 in., allowing the assembly to be mounted between cold and hot boxes, as shown in Figure 3.

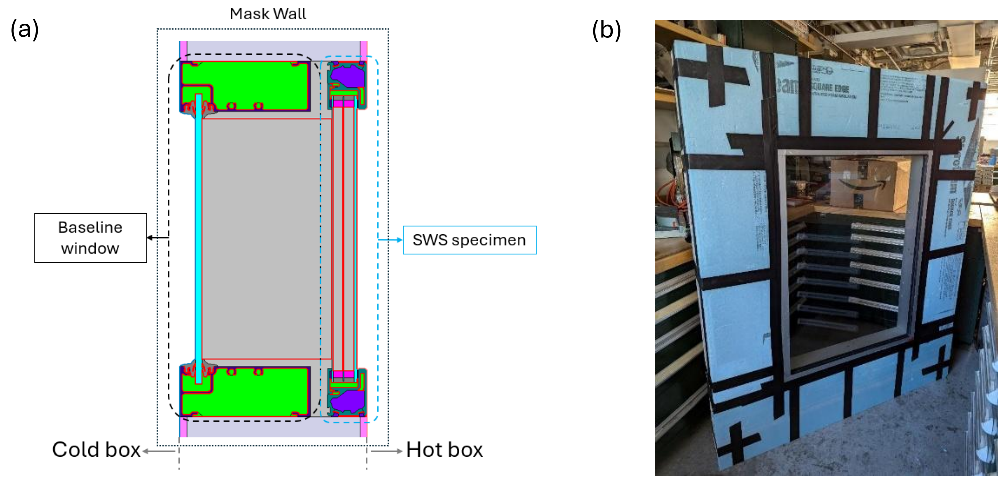

Figure 3. (a) Schematic diagram of mask wall with the baseline window and the SWS specimen, and (b) photo of the mask wall with the baseline window.

The test procedure included the following steps: (1) Installed the baseline window on the mask wall with the baseline window facing the cold side. (2) Installed the SWS product on the mask wall facing the warm side, as shown in Figure 3. (3) Mounted three thin-film heat flux sensors at the center, edge, and frame of the SWS product surface to measure the heat flux through the product under different temperature differences across the whole assembly. (4) Conducted the test under warm-side temperature of 21 ℃ (indoor condition) and cold-side temperatures of 0 ℃ and −18 ℃ (outdoor condition). The lower temperature condition −18 ℃ could provide a more comprehensive understanding of the SWS system performance in extreme cold climate. The test conditions are shown in Table 2. During each measurement, cold and warm side temperatures were maintained for more than three hours for thermal stabilization. The average values over the final 30 minutes to one hour of stabilized data were collected.

Table 2. Test conditions in the IR thermographic chamber

Test #	Window configuration	Cold-side temperature (°C)	Warm-side temperature (°C)
1	Baseline window	0	21
2	Baseline window + triple-pane unit	-18	21
3	Baseline window + VIG unit	-18	21

The area weighed heat flux ($\dot{q}_w$) could be calculated by:

$$\dot{q}_w = w_{cog} \cdot \dot{q}_{cog} + w_{eog} \cdot \dot{q}_{eog} + w_f \cdot \dot{q}_f.$$

where w_{cog}, w_{eog}, and w_f were the area weights of center of glass (cog), edge of glass (eog) and frame, respectively. The area weights varied based on window products. The sum of w_{cog}, w_{eog} and w_f was 1, i.e.

$$w_{cog} + w_{eog} + w_f = 1;$$
$$w_{cog} = \frac{A_{cog}}{A_w};\ w_{eog} = \frac{A_{eog}}{A_w};\ w_f = \frac{A_f}{A_w};$$
$$A_w = A_{cog} + A_{eog} + A_f.$$

where A_w, A_{cog}, A_{eog}, and A_f were the area of the entire window, center of glass, edge of glass, and frame, as shown in Figure 4.

The whole assembly's U-factor could be calculated using following equation:

$$U = \frac{q_w}{T_{air,warm} - T_{air,cold}}.$$

where $T_{air,warm}$ and $T_{air,cold}$ were air temperatures in warm- and cold- sides.

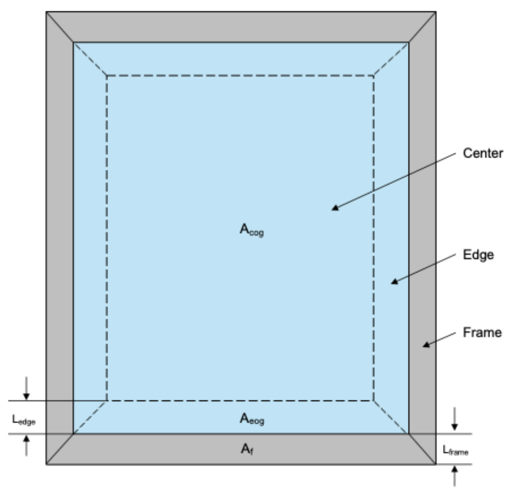

Figure 4. Illustration of the area of center, edge, and frame in a window

MODELING

Thermal performance modeling was conducted using the WINDOW and THERM software, according to ISO 15099 standard (Standardization, 2003). Modeling consisted of defining glazing assemblies in WINDOW, modeling frame and edge of glazing, calculating 2-D heat transfer in frame and edge of glazing, and evaluating the U-factor. Modelling was conducted on standalone products to generate National Fenestration Rating Council (NFRC) values for U-factor, Solar Heat Gain Coefficient (SHGC), and Visible Transmittance (VT). The geometry of the windows was based on the lab testing sample. The outdoor boundary used NFRC boundary conditions at the cold side to compare the U-factor, SHGC, and VT. The indoor boundary used the test data at the warm side to compare the IR thermography measurements. The convergence tolerance of THERM on heat flux was 10e-5. To ensure simulation accuracy, THERM also included error estimator to refine the meshes in the regions where error energy norm was more than 10%. Error energy norm of 10% roughly corresponds to 1% in the accuracy. Figure 5 shows the 2-D model configuration for two SWS products with the baseline window.

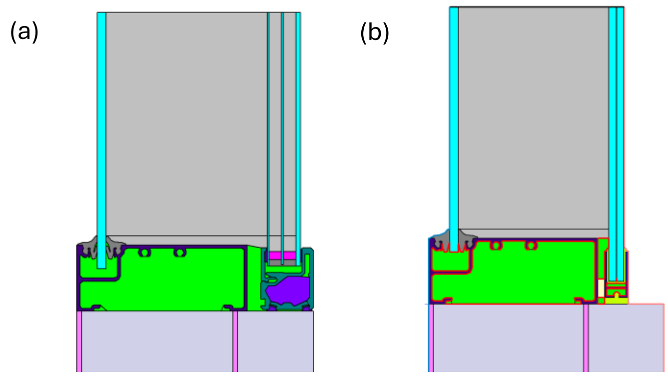

Figure 5. 2-D model configuration: (a) baseline window with a SWS with triple-pane unit and (b) baseline window with SWS with a VIG unit.

TECHNO-ECONOMIC ANALYSIS

The techno-economic assessment evaluates the installed cost of advanced secondary window systems (SWS) relative to a baseline Title 24–compliant replacement window. The analysis begins by establishing the installed cost of the baseline window using product cost data from the CalNEXT report (Birchfield et al., 2024) and installation and demolition costs from the RSMeans 2018 labor dataset. Because RSMeans reports costs per window opening, all labor activities were normalized to a per-square-foot basis using a representative 20 ft² commercial window module.

To ensure consistency with current construction pricing, the RSMeans labor and demolition costs were escalated from 2018 to 2025 dollars using a cost escalation factor of 1.35, derived from the RSMeans Construction Cost Index (CCI). After escalation, the labor and demolition costs were combined with the baseline product cost to determine the total installed cost of the Title 24 replacement window, which serves as the economic benchmark.

Installed cost data for the SWS technologies — including triple-pane insulated glass units and vacuum-insulated glass (VIG) systems — were obtained directly from technology manufacturers. These values were reported as fully installed costs per square foot, already incorporating materials, labor, and installation practices; therefore, no additional cost escalation or labor modeling was required. When manufacturers provided a cost range, low, mid, and high values were used to represent cost uncertainty.

Finally, the escalated installed cost of the Title 24 baseline window was compared with the manufacturer-provided installed costs of the advanced SWS technologies to establish a consistent framework for evaluating their relative cost competitiveness and economic feasibility.

FIELD M&V PLAN

The field M&V plan evaluated the performance of secondary window systems (SWS) through pre- and post-retrofit monitoring at a commercial demonstration site. The monitoring program included long-term baseline measurements and post-installation monitoring over at least nine months to quantify changes in window thermal performance, HVAC energy consumption, and occupant comfort. The summary of the M&V plan is shown in Table 3 including measured parameters and the related instrument used.

Table 3. Summary of M&V plan

Performance	Parameter measured	Sensor / Instrument
Weather Conditions	Outdoor temperature	Nearby weather station
	Relative humidity	
	Wind speed & direction	
	Solar radiation	
Window Thermal Performance	Interior surface temperature	Type-T thermocouples
	Exterior surface temperature	
	Heat flux through window	Heat flux sensor
	Air gap temperature (post-retrofit)	Temperature sensor
	Air gap relative humidity (post-retrofit)	RH sensor
	Window surface temperature distribution	Infrared (IR) thermal camera
Indoor Environmental Conditions	Indoor air temperature	Temp/RH data logger
	Indoor relative humidity	
	Occupancy patterns	Occupancy/light sensor
HVAC Energy Use – Guest Rooms	Electrical power of fan coil unit	Energy meter
	Heating element runtime	Current switch sensor
	Chilled water supply/return temperature	Thermocouples
	Chilled water flow rate	Ultrasonic flow meter
HVAC Energy Use – Offices / Conference Rooms	Chilled water supply/return temperature	Thermocouples
	Chilled water flow rate	Ultrasonic flow meter
	Hot water supply/return temperature	Thermocouples
	Hot water flow rate	Ultrasonic flow meter
Boiler System	Gas consumption	Gas flow meter
	Hot water supply/return temperature	Thermocouples
	Hot water flow rate	Ultrasonic flow meter

The demonstration is conducted at the Renaissance Esmeralda Resort in Indian Wells, California, where SWS technologies—including triple-pane inserts and VIG inserts—will be installed on the interior of the selected single-pane windows in guest rooms, office areas, conference rooms, and hallways. The selected windows have four different areas, 25.6 ft^2, 35.6 ft^2, 36.6ft^2, and 66.4 ft^2. These monitored zones represent different window orientations, occupancy patterns, and HVAC configurations to capture diverse operational conditions.

The M&V strategy combines several measurement approaches. Window thermal performance is assessed using heat-flux sensors and thermocouples to measure heat transfer and surface temperatures across the glazing. After retrofit installation, additional temperature and relative humidity sensors are installed in the air cavity between the existing window and the SWS to evaluate potential condensation risk.

HVAC energy impacts are quantified by monitoring electrical and thermal energy delivered to the conditioned zones. For hydronic systems, ultrasonic flow meters and temperature sensors measure supply and return water temperatures and flow rates, enabling calculation of heating and cooling energy delivered. In guest rooms, electrical meters and runtime sensors track fan coil unit operation and electric resistance heating loads.

Environmental conditions and occupant behavior are also monitored. Indoor temperature, relative humidity, and occupancy sensors are installed in selected spaces, while thermostat data and occupant surveys provide additional information on thermal comfort, HVAC operation, and window usage. Weather data from nearby meteorological stations are used to account for outdoor conditions influencing building energy performance.

All sensors are connected to a data acquisition system that logs measurements at one-second intervals and aggregates them into 15-minute averages for analysis. The collected data are used to calculate window heat transfer, zone-level heating and cooling loads, and HVAC energy consumption before and after the retrofit. These results support evaluation of the energy and comfort benefits of SWS technologies and provide calibration data for building energy modeling and code-compliance analysis.

RESULTS

MEASURED WHOLE ASSEMBLIES U-FACTOR

The whole-assembly thermal performance of the SWS was measured using the IR thermographic chamber. Table 4 summarizes the measured air temperatures, surface temperatures, heat flux values, and the calculated whole-assembly U-factors for the baseline window and the two SWS units.

The measured U-factor of the baseline window was 4.67 W/(m^2·K) [0.822 Btu/(h·ft^2·F)], indicating relatively high heat transfer due to the single-pane glazing and thermally conductive aluminum frame. When the triple-pane SWS unit was installed on the interior side of the baseline window, the whole-assembly U-factor decreased to 1.01 W/(m^2·K) [0.178 Btu/(h·ft^2·F)], corresponding to a 78.3% reduction in heat transfer compared with the baseline configuration. This improvement demonstrates the effectiveness of the triple-pane secondary glazing increasing the thermal resistance of the window assembly.

Similarly, installing the VIG unit substantially reduced the heat transfer through the window system. The measured U-factor for the baseline window with this VIG insert was 1.04 W/(m^2·K), representing a 77.8% improvement relative to the baseline window. Despite the high thermal resistance associated with VIG glazing, the measured improvement was slightly lower – approximately 0.5% less than that achieved with the triple-pane unit. Further investigation through the modeling indicated that this unexpected result was caused by the frame design of the VIG unit. The VIG frame lacked an effective thermal break, which increased heat loss through the frame region. As a result, the overall thermal performance of the VIG unit was limited by the frame rather than the glazing itself.

Table 4. Measured U-factor

#	Window configuration	Air temperature (°C)		Surface temperature (°C)	Heat flux (W/m²)			Window area (m²)	Area weighted heat flux (W/m²)	U-factor (W/m²·K)	U-factor improvement
		Cold side	Warm side	COG	COG	EOG	Frame				
1	Baseline window	0.16	20.95	2.86	11.168	95.7	88.15	0.774	97.13	4.67 [0.822 Btu/(h·ft^2·F)]	-
2	Baseline + triple-pane unit	-17.3	21	16.67	26.95	43.1	37.74	0.774	38.81	1.01 [0.178 Btu/(h·ft^2·F)]	-78.3%
3	Baseline + VIG unit	-17.2	20.93	18.78	10.64	29.15	93.02	0.774	39.59	1.04 [0.183 Btu/(h·ft^2·F)]	-77.8%

MODELING RESUTLS

Table 5 compares the modeled U-factors with the measured values obtained from laboratory testing. For the triple-pane SWS configuration, the modeled U-factor was 0.99 W/(m^2·K), which is in close agreement with the measured value of 1.013 W/(m^2·K) [0.178 Btu/(h·ft^2·F)], with a difference of only 2.3%. This strong agreement indicates that the modeling approach accurately captured the thermal behavior of the triple-pane SWS system. For the VIG configuration, the modeled U-factor was 1.291 W/(m^2·K) [0.227 Btu/(h·ft^2·F)], compared with the measured value of 1.039 W/(m^2·K) [0.183 Btu/(h·ft^2·F)], resulting in a difference of approximately 24.3 %. This discrepancy may be partly attributed to the laboratory measurement method.

To improve the accuracy, additional tests were conducted using the calibration transfer standard (CTS) – a large format heat flow meter, consisting of layer of foam with known conductivity sandwiched between two sheets of glass. The CTS measurements showed better agreement with the expected thermal performance. For the CTS + triple-pane configuration, the modeled U-factor was 0.815 W/(m^2·K) [0.144 Btu/(h·ft^2·F)], closely matching the measured value of 0.826 W/(m^2·K) [0.145 Btu/(h·ft^2·F)], with a difference of only 1.3%. Similarly, for the CTS + VIG configuration, the modeled U-factor was 0.977 W/(m^2·K) [0.175 Btu/(h·ft^2·F)], compared with the measured value of 0.948 W/(m^2·K) [0.167 Btu/(h·ft^2·F)], resulting in a difference of 3.0%.

These results demonstrate that the thermal modeling approach provides reliable predictions of window thermal performance when validated against the CTS measurements. The improved agreement between modeled and measured results using CTS confirms that the remaining discrepancies observed in the baseline window configurations are primarily related to measurement uncertainties and frame thermal effects rather than limitations of the modeling methodology.

Table 5. Modeling results and comparison to the measurements

Window configuration	Width (mm)	Height (mm)	SHGC	Visible transmittance	$U_{modeled}$ (W/m²·K)	$U_{measured}$ (W/m²·K)	Δ
Baseline window + triple-pane unit	762	1016	0.328	0.43	0.99	1.013	-2.3%
Baseline window + VIG unit	762	1016	0.177	0.38	1.291	1.039	24.3%
CTS + triple-pane unit	762	1016	0.053	0	0.815	0.826	-1.3%
CTS + VIG unit	762	1016	0.028	0	0.976	0.948	3.0%

FIELD MEASUREMENT

Field monitoring is currently underway at the demonstration site to establish baseline building performance prior to the installation of the secondary window systems (SWS). The ongoing monitoring collects data on window thermal behavior, indoor environmental conditions, and HVAC energy consumption to characterize pre-retrofit conditions.

Once the SWS installations are completed, the monitoring system will continue to collect data under the same measurement framework. The retrofit impact will be evaluated by comparing the monitoring results before and after the installation of SWS technologies. This analysis will quantify improvements in window thermal performance, reductions in heat transfer, and potential changes in HVAC energy consumption. The results will provide real-world validation of the laboratory and modeling findings and support further assessment of the energy and comfort benefits of SWS technologies in commercial buildings.

FURTHER RESEARCH

While this study demonstrated the thermal and economic performance of commercially available secondary window systems (SWSs), several opportunities remain for future investigation.

First, future studies should evaluate advanced frame designs for both triple-pane and vacuum insulated glazing (VIG) systems. The results of this study indicate that whole-assembly thermal performance is strongly influenced by frame and edge-of-glass heat transfer. Therefore, integrating VIG technologies with thermally broken frame systems may further improve overall thermal performance.

Second, field demonstrations are needed to validate the long-term thermal performance, durability, condensation resistance, and occupant impacts of SWS technologies under real operating conditions. The project team is currently planning a field deployment to quantify thermal performance improvements across both heating and cooling seasons.

Third, whole-building energy simulations using DOE Commercial Building Prototype models could be conducted to translate window-level performance improvements into annual building energy savings, peak load reductions, and greenhouse gas emission reductions. Such analyses would provide greater insight into the building-scale implications of SWS retrofits.

Finally, future work could compare advanced SWS technologies against other retrofit options, including conventional storm windows and alternative high-performance fenestration systems, to better understand the tradeoffs between cost, energy performance, and retrofit feasibility across different building types and climates.

CONCLUSIONS

This study evaluated the thermal and economic performance of commercially available secondary window systems incorporating thin triple-pane insulated glazing units and vacuum insulated glazing (VIG) technologies for commercial building retrofits. Laboratory testing and thermal modeling demonstrated that both technologies substantially improved thermal performance compared with the baseline single-pane window.

Among the evaluated products, the triple-pane SWS achieved the lowest whole-assembly U-factor and provided the most cost-effective thermal performance improvement. Although VIG technology offers exceptionally high center-of-glass thermal resistance, the measured performance of the evaluated VIG assembly was influenced by its frame design, resulting in whole-assembly performance comparable to that of the triple-pane SWS.

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