Quantifying Retrofit Value: Energy Modeling and Field Validation of Commercial Secondary Windows in Schools

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ABSTRACT

Windows are major sources of energy loss in buildings and can be expensive to replace due to both high upgrade costs and potential hazardous material removal. This study presents an ongoing California Energy Commission (CEC) funded lab testing, modeling and field demonstration effort of an innovative, easy-to-install secondary window retrofit approach at two school sites in the hot, dry Central Valley region of California. The secondary window product tested as part of this project is an interior-mounted window retrofit product that adheres onto each corner of a windowpane or frame if the framed version is used. It provides insulation by sealing and creating an airgap between the panel and the existing windowpane thereby reducing solar heat gain and glare. Field deployment and monitoring, lab testing and energy modeling offer key insights into affordability and scalability potential of this technology to improve existing building thermal performance and reduce heating and cooling demand.

Field deployment and lab testing revealed advantages in practicality and performance of the proposed technology compared to traditional window replacement. Modeling through California Building Energy Code Compliance 2022 (CBECC 2022) and EnergyPlus, the project team predicted the energy savings and peak demand reduction potential of this technology. Ongoing site monitoring provides pre- and post-installation quantitative data in a real-world context. The team further modeled the potential of this technology in different California climate zones and commercial building types and consulted commercial energy efficiency program implementers on product positioning and go-to-market strategies. These insights are critical to understanding commercial secondary window market opportunities, appropriate modeling tactics and go-to market strategies within the commercial building retrofit market to maximize return on investment.

Introduction

Windows are the most thermally porous component of the building envelope. Single-pane models are the worst offenders, and aging windows of all kinds can contribute to poor building thermal performance. According to a 2013 Pacific Northwest National Laboratory (PNNL) report, *Low-E Storm Windows: Market Assessment and Pathways to Market Transformation*, approximately 40% of windows in the US are single pane windows (PNNL, 2013). However, windows can be expensive to upgrade or replace relative to other building envelope improvements due to their high upfront cost and high labor cost of installation, removal and disruption to building occupants. Consequently, poorly performing windows are often left unaddressed, especially in low-income or disadvantaged households and communities.

The Attachments Energy Rating Council defines commercial secondary windows (CSW) as retrofit window attachment products that are installed on the interior or exterior of existing windows to create an additional insulating barrier, reducing heat transfer and air leakage (AERC, 2023). Importantly, they offer a cost-effective alternative to full window replacement in commercial buildings for improving thermal performance.

Advanced Cost Effective Window Retrofits for Schools (CEC PIR 23-001) is a project funded by the California Energy Commission (CEC), which aims to demonstrate the effectiveness of CSW in public schools and commercial buildings. The project deployed interior-mounted secondary window retrofits across over 5,800 square feet of existing glazing at two school sites in the California Central Valley, an inland region with high heat index and disproportionately high levels of air pollution. This paper reviews the current progress of the project, lessons learned from field deployments, modeling, and insights from commercial and institutional energy efficiency program implementers to understand the performance, economic viability and market scalability of CSW technology for commercial buildings across California. The scope of this project includes field deployment and monitoring, lab testing, energy modeling, and a market deployment plan.

Technology Background

EPRI tested and deployed an interior-mounted CSW retrofit product designed for warm climates, that creates an insulation air gap when applied to the existing window along with solar heat gain and glare reduction properties. The combined solar heat gain reduction and optimized insulation can double the energy savings when compared to traditional window film alone. In addition to the frameless window panel insert, the participating manufacturer now also has both a framed unit and frame insulation and air-sealing kit. All of the above are deployed and tested as part of the field demonstration and lab testing. Figure 1 shows the CSW product types tested as part of CEC PIR 23-001 with their assembly method.

Table 1: Assembly and CSW Product Types

	**Frameless CSW**: Fasteners are adhered directly to the windowpane corners; panels snap into place and are sealed with silicone at the corners.

	**Framed CSW**: Panels are pressed into the window frame and secured with adhesive clips; installation requires alignment and pressure to ensure seal contact.
	**Frame Insulation and Air Sealing Kit:** Custom insulation units are dry-fit, trimmed if needed, adhered to mullions, sills, and headers, and sealed with silicone at all interfaces

Host Sites

The host sites are located on two school campuses associated with a Central Valley elementary school district with 45 elementary schools and 30,000 students. Both campuses that participated had been passed over for window replacements multiple times during previous modernization efforts due to high costs for replacements, exacerbated by asbestos issues and permitting costs. Figures 2 and 3 include photos of the school sites.

Figure 2. Site 1: Junior High School. *EPRI*. 2024.

Figure 3. Site 2: Elementary School. *EPRI*. 2024.

Table 2 provides details of the existing conditions at both schools prior to the CSW retrofits. At both campuses, the existing windows are single pane. At Site 1, the Junior High, the windows are original to the 1940s vintage school with steel frames with many of the original panes having been replaced with a mixture of single-pane glass or plexiglass. Many of the windows had also been previously treated with dark window film, whose properties were unknown, had degraded and was in poor condition. These windows were also suspected to have asbestos caulking. At Site 2: the Elementary, classroom windows are estimated to be ten-to-twenty-year-old retail-style single pane glass mounted in thermally unbroken aluminum frames.

Table 2. Pre-Installation Window Conditions at School Sites

	Site 1: Junior High	Site 2: Elementary
Existing Window Type	Single-pane, steel frame fixed and operable awning style windows	Single-pane, aluminum frame fixed window
Age	original to building, circa 1940s	10 - 20 years old
Façade Orientation	North	North & South at classrooms West at multipurpose
# of Window Pane Units	532	144
Typical Glazing Dimension	4.1 ft2 41.0" x H 14.5"	17.9 ft2 W 80.0" x H 32.1"
Glazing Area ft2, est.	2,273	2,570
Window Area ft2, est.	2,580	2,783
Overhang	Large overhang covering full glazing area	Large overhang covering full glazing area

Site Energy Modeling

To evaluate and estimate the energy performance of the CSW product, the schools were modeled based on existing conditions and the presumed conditions post CSW installation using CBECC 2022. The modeling approach relies on California Building Energy Code Compliance (CBECC), a software tool developed by the CEC for the Title 24 (California's Energy Code) non-residential building compliance fulfillment purposes. CBECC is powered by EnergyPlus, a building energy simulation tool developed by the US Department of Energy. The baseline modeling assumptions and inputs for the existing building conditions are collected through site visits and documents review, as listed below in Table 3.

Table 3. Modeling Inputs Based on Existing Conditions at School Sites

	Site 1: Junior High – Classrooms	Site 2: Elementary – Classrooms	Site 2: Elementary – Multipurpose
Exterior Wall	R-19 insulation	R-19 insulation	R-19 insulation
Interior Wall	R-11 insulation	R-11 insulation	R-11 insulation
Floor	Slab on grade + Carpet	Slab on grade + Carpet	Slab on grade + Carpet
Roof	R-30 insulation	R-30 insulation	R-18 insulation
Windows	U=1.28 (T24 default value for single-pane operable windows), SHGC=0.3~0.5 (depends on each classroom's measurement), VT=0.53	Fixed single-pane window with metal frame: U=1.19, SHGC=0.68, VT=0.77	U=1.28, SHGC=0.67, VT=0.53
Doors	U=0.5	U=0.5	U=0.5
HVAC	Single-zone air conditioner for each classroom: DX Cooling: 60k Btu/h, EER 11, SEER 14 Gas Heating: 150k Btu/h, AFUE 0.8 Fan: 1,950 cfm, nameplate 1.06 hp, motor efficiency 0.855	Single-zone air conditioner for each classroom: DX Cooling: 60k Btu/h, EER 11, SEER 14 Gas Heating: 150k Btu/h, AFUE 0.8 Fan: 1,950 cfm, nameplate 1.06 hp, motor efficiency 0.855	Single-zone air conditioner: DX Cooling: 34k Btu/h, EER 12, SEER 15 Gas Heating: 53k Btu/h, AFUE 0.8 Fan: 800 cfm, nameplate 0.44hp, motor efficiency 0.855

Tables 4 and 5 present the results of modeling the application of the CSW to the existing school sites for the selected buildings. The incremental performance gain expected for the post-retrofit glazing assembly with framed CSW is an approximate U-Factor of 0.4 Btu/hr-ft2-F and an approximate 20% reduction in SHGC based on lab testing results. Note that Building C and D and Building E and F at Owens Site 2: Elementary are two sets of identical buildings.

For both schools, according to CBECC modeling results, the existing glazing would fail California energy code (Title 24) compliance by today's standards. **Importantly, both the framed and frameless CSW enable both campus's classroom buildings to reach Title 24 (2022) compliance levels post-retrofit**. 2022 Title 24 is appropriate as the project was kicked off before the latest version of Title 24 was released. Except for the multipurpose at Site 2: Elementary, all the buildings are estimated to achieve over 6% HVAC energy savings, mostly due to savings from heating. Cooling savings was very limited due to 1) most windows (all windows at Site 1: Junior High and half of the windows at Site 2: Elementary) are being north-facing, which is the orientation with the least solar heat gain, 2) all targeted buildings having large overhangs over the glazing areas, and 3) the schools are unoccupied during the summer and left with high setpoints, which represent a significant portion of the cooling season. Therefore, although U-Factor and SHGC are both significantly improved, impacts on cooling energy savings is minimal as the existing conditions already limit cooling energy consumption.

Table 4. Modeled HVAC Energy Savings at Site 1: Junior High

	Baseline			CSW Retrofit			
	U=1.28, SHGC=0.3~0.5, vary by classroom			U=0.4, SHGC 20% off			
Building	Heating (MBtu)	Cooling (MWh)	Fan (MWh)	Heating (MBtu)	Cooling (MWh)	Fan (MWh)	Total HVAC Savings %
B	130.9	12	20	115.7	11.7	19.9	6.90
C	131.7	12	20	116.5	11.7	19.9	6.88
D	114.5	10	16	101.5	9.8	16	6.73
	T24 Compliance Failed			T24 Compliance Passed			

Table 5. Modeled HVAC Energy Savings at Site 2: Elementary

	Baseline			CSW Retrofit			
	U=1.19, SHGC=0.68			U=0.4, SHGC=0.5			
Building	Heating (MBtu)	Cooling (MWh)	Fan (MWh)	Heating (MBtu)	Cooling (MWh)	Fan (MWh)	Total Saving %
C/D	127.5	12.1	20	113.8	11.6	19.9	6.64
E/F	102.6	9.7	16	91.7	9.3	15.9	6.62
Staff Room	11.63	2.26	N/A	10.51	2.26	N/A	5.79
	T24 Compliance Failed			T24 Compliance Passed			

Peak demand reduction potential was also investigated for all scenarios. Peak demand occurs during summer at the sites. Except for the Elementary's Multipurpose Building, where the glazing area is too small to be significantly effective at reducing peak demand, all other buildings achieve a peak demand savings over 2% (Table 6). Peak demand savings is also limited due minimal cooling energy saving due to overhangs and building orientations.

Table 6. Modeled Peak Energy Demand Savings

Building	Baseline (kW)	CSW (kW)	Peak Demand Saving %
Site 1: Junior High_B	24.9	24.3	2.6%
Site 1: Junior High_C	24.9	24.3	2.6%
Site 1: Junior High_D	20.9	20.3	2.5%
Site 2: Elementary_C/D	19.4	18.7	3.7%
Site 2: Elementary_E/F	15.8	15.1	3.7%
Site 2: Elementary_Staff Room	0.38	0.4	0.0%

Field Deployment

Since the site energy modeling showed modest HVAC energy savings, the project team decided to build on initial plans to apply the frameless CSW units and install frame insulation and air sealing as well as framed units for a portion of the buildings, tailoring the retrofit strategy based on each window pane's existing conditions to optimize retrofit impact. The CSW products were successfully installed at the two target schools in November and December 2025. At Site 1: Junior High, 554 *frameless* units were installed at three classroom buildings, covering 2,866 ft^2 of glazing over three and half days. At Site 2: Elementary, 152 *framed* units were installed at four classroom buildings and 12 *frameless* units were installed in the Multipurpose Building with additional frame insulation and air sealing kits in staff breakroom areas, covering a total for the site of 2,986 ft^2 in only two days. The frame insulation kits are designed specifically for metal framed windows, as unbroken metal frames can be significant contributors to the overall window assembly U-Factor. The products were efficiently installed, utilizing regular after-school hours. District feedback on the installation was generally positive. The vendor identified additional training materials and on-the-job process improvement and cost savings opportunities through the project through the efficient storage, product staging and segmentation of labor across crew members. Figure 4 shows the installation in progress at Site 1: Junior High.

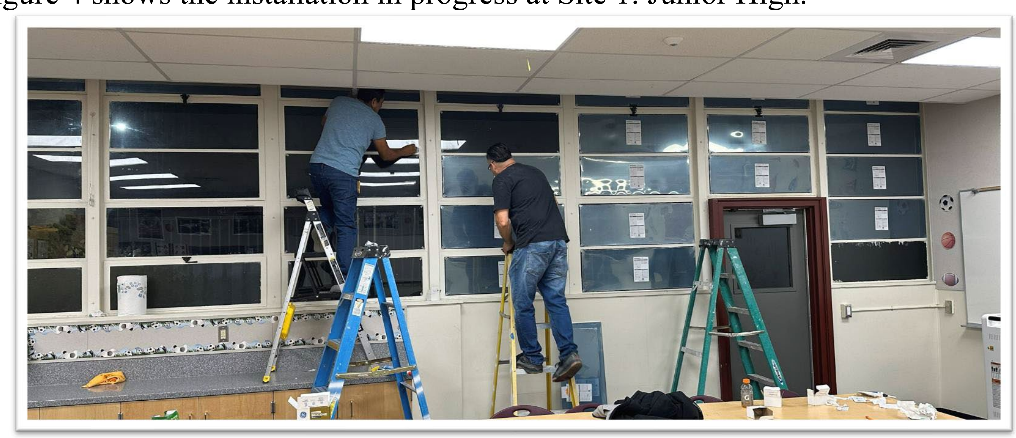

Figure 4. CSW Retrofit at Site 1: Junior High. Photos provided by vendor. 2025.

Lab Testing

Lab testing was conducted by an accredited national testing laboratory in accordance with National Fenestration Rating Council (NFRC) and American Society for Testing and Materials (ASTM E972/E1084, NFRC 102, and NFRC 201) standards. As required by the funder's solicitation requirements, the baseline window for testing was a Title 24 compliant window of aluminum frame, double-pane with argon fill. The U-factor of the baseline window is 0.31. Two framed CSW products were tested. The CSW80 is considered an upgrade to the base product, CSW50, designed to have higher visible light transmittance and less reflectance. Table 7 summarizes the preliminary lab testing U-factor, solar heat gain coefficient and visible light transmittance results.

CSW retrofits alone show moderate improvement (U-value increase of 0.4) with the greatest gains achieved when combined with frame insulation and air sealing (U-value incremental increase of 0.5-0.6). The laboratory results also demonstrate improvements toward reduced solar heat gain with retained daylight transmission, informing future optimization, modeling, and climate- and site-specific deployment pathways.

Table 7. Summary of Lab Testing Results

	U-Factor (Btu/hr-ft2-F)	SHGC	VLT
Baseline: Title 24 Window	0.31	0.36	0.73
Baseline + CSW50	0.27	0.26	0.38
Baseline + CSW50 + Frame Insulation	0.24		
Baseline + CSW50 + Frame Insulation + Air Sealant	0.22		
Baseline + CSW80	0.28	0.28	0.57
Baseline + CSW80 + Frame Insulation	0.23		
Baseline + CSW80 + Frame Insulation + Air Sealant	0.22		

Field Measurement and Verification

Indoor and outdoor window surface temperatures and solar irradiance were trended over a one-year period prior to the CSW retrofit. Figure 5 provides an early indication of thermal improvement, illustrating the daily average temperature difference between the inside and outside surface temperature sensors located on a south-facing window at Building C at Site 2: Elementary. The temperature difference is greater between the inside and outside of the window - increasing from the pre-installation +0.7 °F to the post-installation +3.2 °F, meaning the window panel lowers the heat transfer through the window, and keeps the heat better contained during heating season. There was a mild increase in temperature difference observable during the installation window starting November 19th, which was due to the school district replacing the damaged glazing units in preparation for the retrofit.

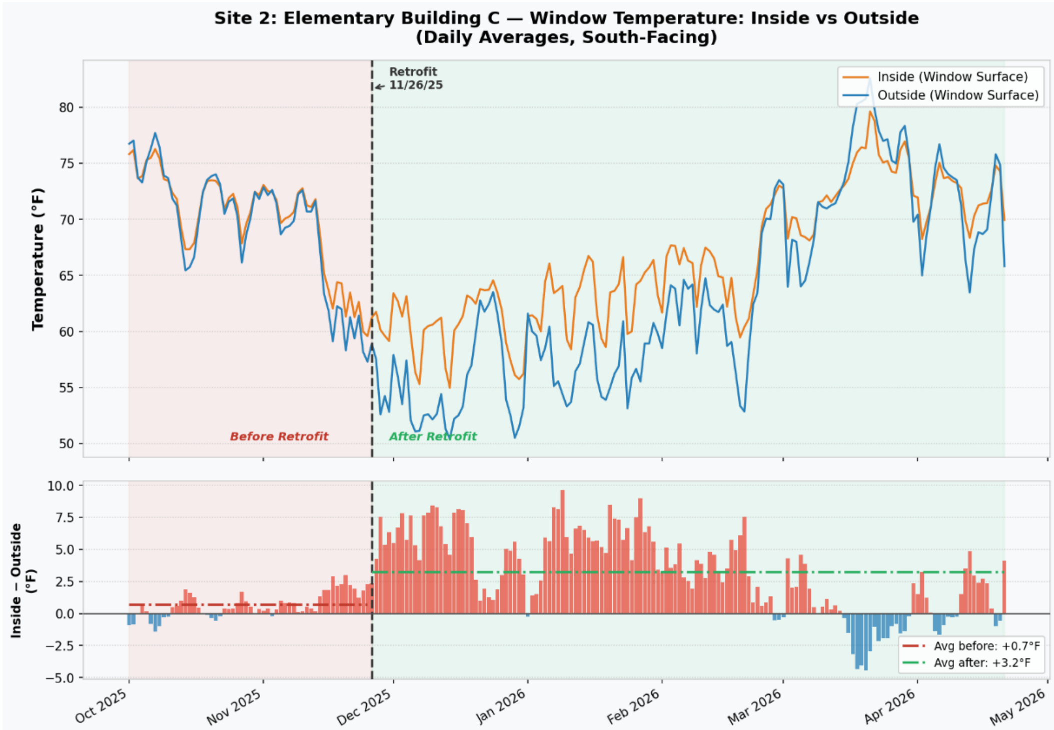

Figure 5. Temperature Difference (Inside vs. Outside) at Building C, Site 2: Elementary

Market Deployment Plan

To assess the economic viability of the proposed CSW across a larger population of California's commercial building stock, a cost effectiveness analysis was conducted by modeling multiple California commercial building types using EnergyPlus across all 16 California climate zones, including small office, medium office, large office, small school, small hotel, and small restaurant. Referencing CBECC standard models as the starting point, existing windows were characterized using DOE's pre-1980 commercial reference properties, reflecting the significant share of California's building stock pre-dating modern low-E code requirements, where this measure is highly applicable.

Two retrofit approaches were modeled in comparison: the traditional outright window replacement with a new Title 24 compliant window and the framed CSW product. Table 8 lists the window properties modeled for the pre-1980 baseline window and the two approaches: Title 24 window replacement and CSW retrofit. The upfront costs are estimated to be $200/ft^2 for Title 24 window replacement and $35/ft^2 for the CSW retrofit. The former is based on commercial Title 24 window replacement industry benchmark costs from the project's California Energy Commission (CEC) solicitation, while the latter reflects industry data from federal demonstrations and market studies. In CalNext's 2024 Commercial Secondary Window study, total cost of CSW, including labor and material, is estimated to be $35/ft^2 (CalNext, 2024). Other sources also support this cost to be a representative planning value (GSA/NREL/LBNL, AERC, and NEEA). These sources support using ~$35/ft² as a representative planning value, reflecting high volume, standardized CSW deployments and contrasting with higher per unit costs observed in smaller pilot projects such as CEC PIR 23-001 ($88/ft²). Energy cost savings are estimated based on the application of time-of-use (TOU) rates provided by the respective utilities in each climate zone.

Table 8. Window properties modeled for cost effectiveness analysis

	Pre-1980 Baseline Window	T24 Compliant Window Replacement	CSW Retrofit
U-Factor (Btu/hr-ft2-F)	1.22	0.34	0.4
SHGC	0.54	0.22	0.26

Figure 6 and 7 illustrate the simple payback periods for each building type in each climate zone for adopting Title 24 window replacement and CSW retrofit respectively. Title 24 window replacements (Figure 6) show payback periods for most building types over 100 years with the exception of large offices in all but one climate zone. On the other hand, CSW retrofits (Figure 7) show much stronger financial viability, with most payback periods concentrated between 20 to 70 years with large offices again achieving the shortest payback. Large offices consistently achieve the shortest payback (<20 years with CSW in all climate zones except CZ16), due to high window-to-wall ratios (WWR) and exposure to large-commercial TOU rates.Building types that tend to have relatively longer payback periods (small office, small restaurant and small hotel) are those with a WWR less than 20%. A comparison (Figure 8) shows that CSW retrofits yield consistently shorter paybacks across all modeled scenarios compared to Title 24 window replacements.

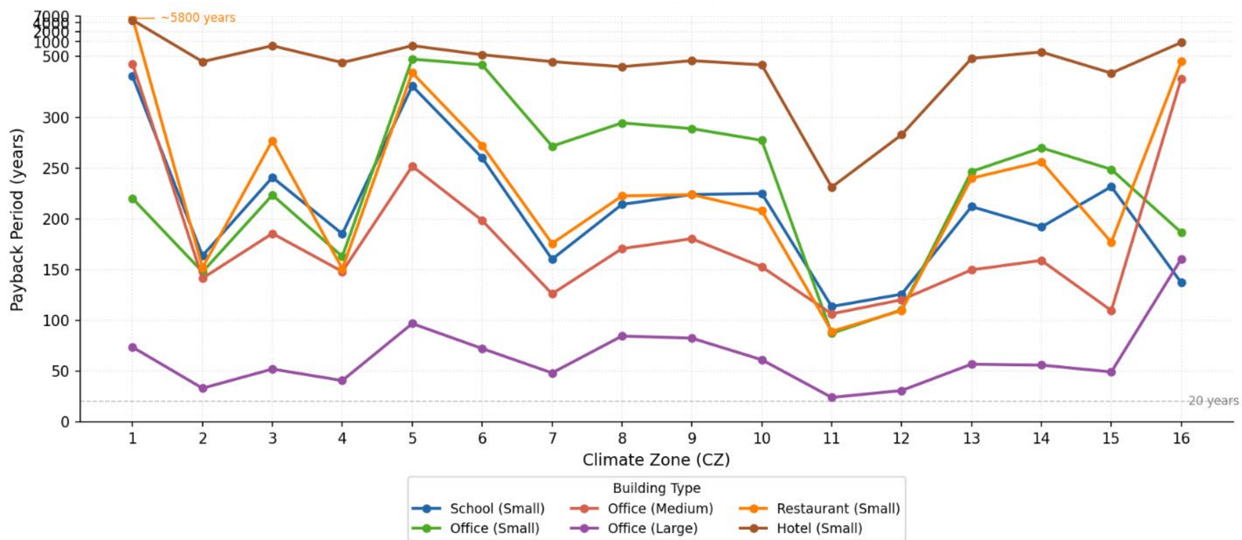

Figure 6. Payback of Title 24 window Replacement by Commercial Building Type and by Climate Zone

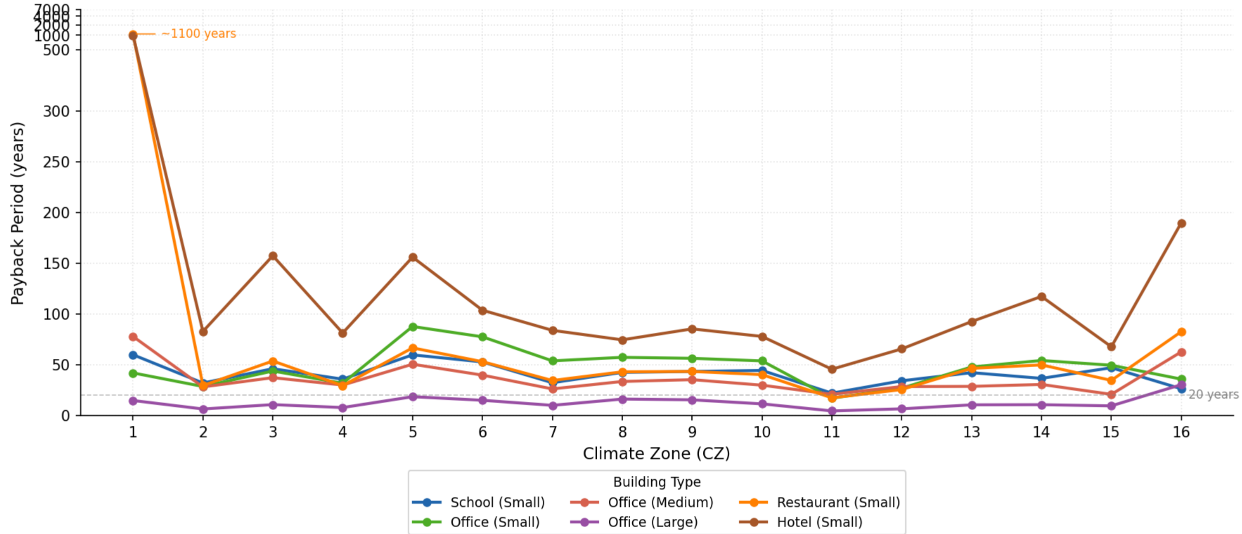

Figure 7. Payback of CSW Retrofit by Commercial Building Type and by Climate Zone

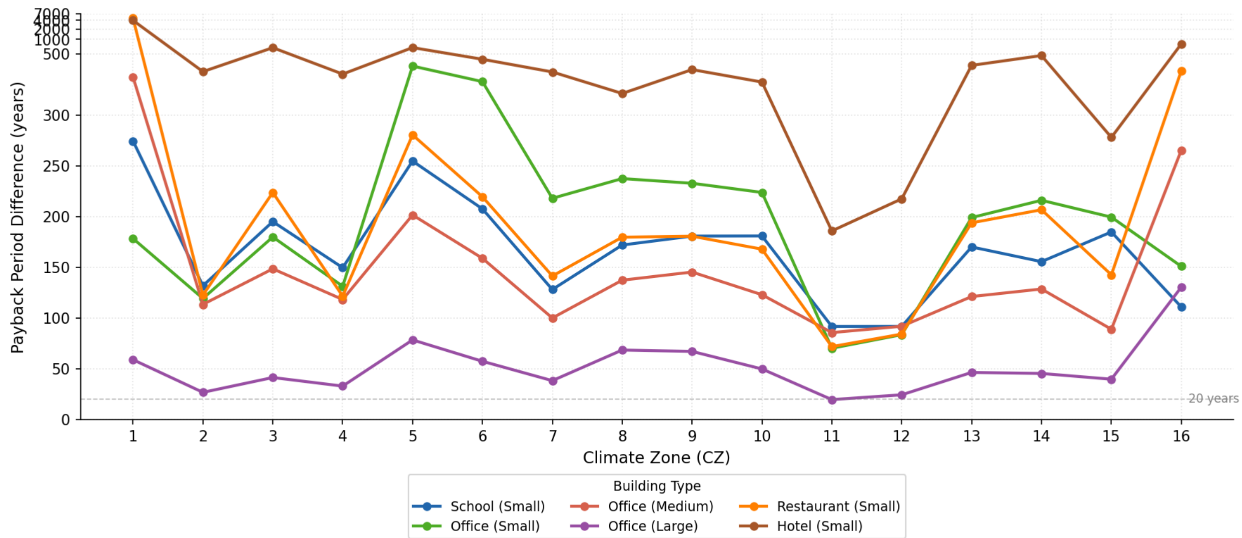

Figure 8. Difference in Payback between T24 Window Replacement and CSW Retrofit

This payback analysis helps to clarify a few factors that support favorable economics for CSW retrofits:

- Vintaged buildings with single-pane, non-low-E windows
- High Window-to-Wall Ratio (WWR) (≥50%)
- Minimal north-facing glazing
- Building subject to more expensive rate structures and operating/occupancy profiles with HVAC usage during peak pricing periods

The U.S. market with the highest potential for secondary window retrofits is older commercial buildings: 46% of the national commercial building stock was built before 1980

(EIA, 2021), containing 46–53% single-pane windows and minimal (<1%) triple-pane glazing (LBNL, 2025). In California specifically, 42% of commercial buildings fall in this pre-1980 category, and many still lack low-E coatings (NEEA, 2020). California's commercial sector contains over 590 million ft² of existing window area, concentrated in (CalNext, 2024):

- Assembly buildings: 137 million ft²
- Large offices: 100 million ft²
- Medium offices: 84 million ft²
- Schools (small and large): 105 million ft² combined

These building categories represent the highest deployment potential, especially where preservation concerns or high disruption costs make full-window replacement impractical.

Stakeholder Feedback

Accelerating the deployment of CSW retrofits requires coordinated actions across manufacturing, supply chain development, stakeholder engagement, and incentive alignment. EPRI conducted interviews with third party institutional and commercial energy efficiency program implementers to capture field-based perspectives, grounding the recommendations below in real-world decision-making processes, customer barriers, and program constraints.

Manufacturing and supply chain scalability emerged as a core requirement for market expansion. Interviewees noted that traditional glazing distribution channels are not well-suited for CSW due to limited established pathways for product awareness and procurement. Instead, direct manufacturer-to-customer models can streamline purchasing, reduce transaction friction, and shorten timelines—an observation consistent with broader market findings. Because CSW do not require specialized glazing labor, installation can be expanded through training general contractors, school facilities teams, and local trades, reducing labor constraints, lowering costs, and improving scheduling flexibility. Stakeholders also emphasized the importance of standardized terminology and consistent performance specifications to reduce confusion, particularly in distinguishing high-performance CSW from low-e storm windows and other attachments.

Cost and incentive alignment are also critical to adoption. Interviewees confirmed that budget constraints frequently delay or prevent window upgrades in both public-sector and commercial buildings. The significant cost advantage of CSW relative to full window replacement creates a strong economic case, which can be further strengthened by layering available incentives, including utility rebates, federal tax deductions, historic preservation funding, and disadvantaged community (DAC) or hard-to-reach (HTR) programs. Interior-mounted CSW, such as those deployed in CEC PIR 23-001, were also noted to reduce or eliminate the need for scaffolding and specialized access equipment, significantly lowering installation costs—particularly for multi-story buildings.

Market positioning must align with how decisions are made within target sectors. In school districts, for example, maintenance and facilities staff typically identify comfort or performance issues, while funding decisions are made by chief business officials and executive leadership. Effective messaging should therefore connect operational benefits—such as improved comfort, glare reduction, and reduced HVAC strain—with broader priorities, including safety, resilience, and deferred maintenance. Stakeholders stressed that non-energy benefits often play a decisive role in public-sector adoption, and that CSWs should be framed not only as an efficiency measure but as improving occupant comfort, health, and learning environments. Case studies from early adopters were identified as particularly influential, given the importance of peer-to-peer validation in the K-12 sector.

Finally, stakeholders emphasized that long-term market growth depends on establishing validated technical performance and formal inclusion in incentive programs. Furthermore, uncertainty around code compliance and technical specifications can limit consideration of CSW during early design phases, especially among architects and engineers unfamiliar with the technology (NEEA, 2020). This can include expanding performance documentation across climates, aligning with certification frameworks such as those from the Attachments Energy Rating Council (AERC), which is an independent certifier of window attachment energy performance, and developing standardized utility measure packages for inclusion in California's Electronic Technical Reference Manual (eTRM). Integration into these frameworks signals credibility and enables CSWs to be bundled with broader decarbonization or energy efficiency retrofit efforts, including heat pumps, lighting and, or other building envelope upgrades, and capital planning cycles. Positioning CSWs within these larger upgrade pathways allows them to be deployed alongside scheduled maintenance, improving cost-effectiveness and supporting comprehensive building performance improvements.

Conclusion

This study demonstrates that CSWs provide a practical and scalable retrofit solution for improving the performance of existing school buildings, particularly where full window replacements are cost-prohibitive and the solution can be bundled as part of large-scale retrofits. Across lab testing, modeling, and field deployment, the results consistently show that CSWs—especially when combined with frame insulation and air sealing—can significantly improve thermal performance (U-factor and SHGC) while enabling Title 24 level of achievement, using a lower-cost, minimally disruptive approach.

Initial modeling suggests modest HVAC energy savings (~6–7%) and peak demand reductions (~2–4%) under the CEC PIR 23-001 site specific demonstration conditions, which were constrained by north-facing orientations and large overhangs that inherently limit solar gains. These findings reinforce that CSW value is highly site-dependent, with greater savings expected in buildings with higher solar exposure to glazing, larger window-to-wall ratios, and higher internal loads—conditions common in many commercial and mixed-use buildings beyond the demonstration sites.

Importantly, installation outcomes and stakeholder feedback highlight CSWs as a feasible, repeatable retrofit solution with lower labor complexity and disruption compared to traditional replacements. Combined with favorable cost assumptions relative to full window replacement, this positions CSWs as a strong candidate for broader programmatic deployment—particularly in older facilities where envelope upgrades are often deferred.

While this study provides early indications of expected performance outcomes and implementation pathways, additional work is needed to expand field verification and address diverse building types and cooling-season opportunities, and to support standardization for code compliance, utility program integration and broader market adoption. Continued progress in these areas, along with manufacturing scale-up, will be critical to unlocking the full market potential of CSWs as a cost-effective envelope decarbonization strategy.

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Acknowledgement

This paper utilizes AI tool to generate figures based on modeled and collected data. All figures have been verified its accuracy manually. All data used for figure generation are modeled or collected by human.