# Commercial Replacement and Attachment Window Solutions (CRAWS) Market Transformation Initiative

## Appendix C: Product Assessment Report

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## List of abbreviations

| Abbreviation | Definition |
|---|---|
| AERC | Attachments Energy Rating Council |
| BMA | Baseline Market Adoption |
| BOMA | Building Owners and Managers Association |
| BPS | Building Performance Standards |
| CalMTA | California Market Transformation Administrator |
| CBO | Community-based Organization |
| CE | Cost-Effectiveness |
| CEDARS | California Energy Data and Reporting System |
| CET | Cost-Effectiveness Tool |
| CPUC | California Public Utilities Commission |
| CSW | Commercial Secondary Window |
| CRAWS | Commercial Replacement and Attachment Window Solutions |
| DOE | U.S. Department of Energy |
| DR | Demand Response |
| ESCO | Energy Service Company |
| ESJ | Environmental and Social Justice |
| EUL | Effective Useful Life |
| GHG | Greenhouse Gas |
| HVAC | Heating, Ventilation, and Air Conditioning |
| IMC | Incremental Measure Cost |
| IOU | Investor-Owned Utility |
| LBNL | Lawrence Berkeley National Laboratory |
| Low-e | Low Emissivity |
| MR | Market Research |
| MT | Market Transformation |
| MTAB | Market Transformation Advisory Board |
| MTI | Market Transformation Initiative |
| MUSH | Municipal, University, School, and Hospital |
| NEB | Non-energy Benefit |
| NLR | National Laboratory of the Rockies |
| PAC | Program Administrator Cost |
| PAWS | Partnership for Advanced Window Solutions |
| PG&E | Pacific Gas & Electric |
| PNNL | Pacific Northwest National Laboratory |
| REN | Regional Energy Network |
| ROI | Return on Investment |
| RFI | Request for Ideas |
| RPR | Repeat Purchase Rate |
| SCE | Southern California Edison |
| SDG&E | San Diego Gas & Electric |
| SME | Subject Matter Expert |
| TA | Technology Assessment |
| TSB | Total System Benefit |
| TMA | Total Market Adoption |

| Abbreviation | Definition |
|---|---|
| TRC | Total Resource Cost |
| UEI | Unit Energy Impacts |
| VIG | Vacuum Insulated Glass |
| WE&T | Workforce Education and Training |

# 1 Executive summary

Windows are significant contributors to energy consumption in buildings, which constitute a substantial portion of the United States' energy usage. They influence consumers' utility bills and California's energy demands. Many of California's buildings were constructed before double-pane glass and low-e coatings became common. Despite having inefficient windows, older buildings can realize energy savings and other benefits through advancement of window-retrofit technology. Commercial Replacement and Attachment Window Solutions (CRAWS) offer affordable and convenient solutions for building owners to capitalize on these technological advancements and avoid the high cost of complete window replacement.

The CRAWS market transformation initiative (MTI) currently covers two technologies: vacuum insulated glass (VIG) for single-pane replacement (SPR) and commercial secondary windows (CSWs). VIG are high-performance glazing units with a vacuum between the glass, intended to be installed within a building's existing window frames. Recent technological advances have improved the durability of vacuum-sealed glass and reduced the thickness of the glass used in VIG units. This has resulted in a reduction of the overall VIG glazing unit thickness, which allows thin-profile VIG units to fit within window frames built for single panes. CSWs are intended to be installed inside or outside existing commercial window systems, similar to how residential storm windows are installed; they are easy to install and low-cost.

Both technologies meeting CalMTA's product definition include low-emissivity (low-e) coatings, which reduce solar heat gain and cooling loads and provide a significant advantage in California's climate. VIG products meeting the CRAWS product definition must have a maximum solar heat gain coefficient (SHGC) of 0.25. CSWs meeting the CRAWS product definition must have a maximum U-factor of 0.35 and a maximum solar heat gain coefficient (SHGC) of 0.25.

## 1.1 Key deficiencies/barriers

### 1.1.1 Commercial secondary windows

Secondary windows face few technological barriers. Currently available CSWs perform well, and third-party certifications are available to inform consumer choice and utility incentive programs. However, the supply chain for distributing, selling, and installing CSWs in California is immature. Consumers may encounter a small number of CSW vendors and installers operating in their area; conversely, the low level of specialized skill required to install CSWs and scarcity of CSW vendors presents an opportunity for workforce development. Additional performance data and field installations are needed to assess the risk of condensation within the unventilated cavity created by CSWs.

### 1.1.2 Vacuum insulated glass

VIG has been manufactured in the United States for over 20 years but is still not deployed at scale with reasonable lead times and competitive prices. As an emerging technology, VIG for SPR is still more costly than other window upgrades, with few VIG manufacturers and products available in the market.

VIG units can be installed into existing window frames that previously housed single-pane glass. The thermal properties of existing frames vary widely, and there is currently no method for rating the window assembly U-factor of VIG for SPR. Without a certified rating, consumers must use default performance values for window assemblies that have not been rated by the National Fenestration Rating Council (NFRC). These default values assume low performance of the existing frames, and therefore VIG for SPR consumers may not be able to take full credit for VIG performance when applying for building permits and incentives. Further, utility programs cannot easily quantify savings and incentivize the products.

Additional data is needed on VIG for SPR to quantify the risk of condensation occurring on existing window frames. Additionally, the long-term degradation of VIG performance has not been quantified through field installations, preventing the development of an aged performance value for VIG units. Fabrication of VIG units requires high temperatures for the vacuum evacuation process, driving up the costs and embodied energy and greenhouse gas (GHG) emissions of VIG units.

## 1.2 Key recommendations for product plan

### 1.2.1 Collaboration with industry stakeholders

The California Market Transformation Administrator (CalMTA) will collaborate with industry stakeholders including the United States Department of Energy (DOE), national laboratories, and manufacturers to share the latest data on CRAWS technology performance to inform industry standards as they are developed for VIG and CSW products. We will collaborate with the Attachments Energy Rating Council (AERC) or a similar organization to develop a method for rating the performance of VIG for SPR. We will share data with heating, ventilation, and air conditioning (HVAC) designers[1] so that they make it standard practice to recommend CSWs and VIG for SPR prior to designing HVAC upgrades and replacements, as an opportunity to downsize equipment.

[1] CalMTA's strategy for CRAWS distinguishes between the roles of HVAC designer and HVAC installer. See the CRAWS MTI Plan section 2, Market transformation theory and opportunity, for more discussion.

### 1.2.2 Field demonstrations

CalMTA is conducting a field demonstration at Madison Elementary School, located in an ESJ community in Madera, California, to monitor energy consumption and non-energy benefits (NEB) of CRAWS. CalMTA will expand its field demonstration to include more sites and more building types. We will collaborate with field studies conducted by other market transformation initiatives (MTIs) such as Commercial Rooftop Units (CRTUs) and Commercial Building Efficiency Accelerator (CBEA) to boost efficiency and demonstrate synergies between CRAWS and the other MTIs. By collecting and sharing data on energy performance and NEBs from field demonstrations, we can build awareness among energy service companies (ESCOs) and equip them with data so that they increasingly include CSWs and VIG for SPR in their portfolios. We will collect data to close data gaps on condensation and VIG performance degradation.

By sharing data from analysis and field installations, the CRAWS MTI aims to enhance activity in the supply chain by encouraging HVAC designers to routinely consider the potential of CRAWS technologies in reducing HVAC system sizing during system upgrades.

## 1.3 Energy savings impacts

CalMTA has found that CSWs and VIG offer significant energy savings potential across all California climate zones and utility service areas. The energy savings attributable to the two CRAWS technologies are very similar. The average annual whole-building electric savings are around 8% statewide and average annual whole-building gas savings are roughly 17% to 22%, varying by investor-owned utility (IOU) service territory. Because CRAWS technologies reduce space conditioning loads, and because commercial buildings in California generally consume more energy for space cooling than space heating, most of the energy savings benefit from CRAWS technologies comes  from reduced cooling energy use.

### 1.3.1 Peak demand impacts

CalMTA analysis found that CRAWS technologies reduce peak cooling demands in California commercial buildings by about 5%-20%, depending on building type and location. For buildings with electric resistance heat, CRAWS reduce peak heating loads by about 10% on average.

### 1.3.2 Utility bill impacts

CRAWS technologies reduce commercial customer utility bills by around 9% annually.

# 2 Purpose and context

The purpose of the Product Assessment Report is to describe the methods used to refine and evaluate the target technology. This report also aims to share key findings and recommendations that directly inform development of market transformation (MT) strategy and interventions, which are described in the Market Transformation Initiative Plan (MTI Plan).

This report is not intended to provide an exhaustive examination of CRAWS products and technology. Instead, this report focuses on the key technical barriers, opportunities, and potential impacts from broader adoption of CRAWS technologies in California, which are all key components for the development of effective MT strategies to achieve that objective. This report focuses on technical aspects of the products and generally avoids discussion of the CRAWS market, which is covered in Appendix D: Market Characterization Report, although some overlap is necessary.

# 3 Product overview and definition

This section summarizes the status of products considered in this MTI Plan, including the definition of CRAWS products, their features, and limitations that are barriers to market adoption.

## 3.1 General product overview

Commercial buildings account for a substantial portion of primary energy consumption in the United States, comprising 17.9% of the total in 2021.[2] Among the various building components, windows play a pivotal role, contributing 12% of all energy usage within buildings.[3] This highlights the significant influence of window performance on consumers' overall energy consumption and utility bills.

Building owners and tenants have numerous options available to enhance the performance of their windows, ranging from affordable to more expensive choices. Higher-cost options include replacing window glazing and either maintaining existing window frames or replacing the window frames. Lower-cost options include:

- Installing fixed and operable attachments, which include frame-mounted stretched film panels and frameless acrylic and copolyester attachment panels
- Applying window films
- Installing internal window shading devices

This MTI focuses on two mid-cost solutions that offer substantial energy and operational cost savings potential: vacuum insulated glass (VIG) as a replacement for single-pane clear[4] (SPC) glass

[2] Chioke Harris, Pathway to Zero Energy Windows: Advancing Technologies and Market Adoption (Golden, CO: National Renewable Energy Laboratory, 2022), https://docs.nrel.gov/docs/fy22osti/80171.pdf.
[3] Stephen Selkowitz, Robert Hart, and Charlie Curcija, "Breaking the 20 Year Logjam to Better Insulating Windows," in 2018 ACEEE Summer Study on Energy Efficiency in Buildings (Lawrence Berkeley National Laboratory, August 2018), https://windows.lbl.gov/publications/breaking-20-year-logjam-better.
[4] Clear glass refers to glass without a low-e, reflective, or tinted coating intended to reduce solar heat gains.

and commercial secondary windows (CSW) for windows with SPC and double-pane clear (DPC) glass.

## 3.2 Product definition

**VIG for SPR:** Commercial VIG units replace existing SPC glass while retaining use of the existing frame. VIG units are comprised of two glass panes, separated by spacers, and hermetically sealed around the edges. A vacuum is drawn in the void space between the glass panes resulting in a center-of-glass R-value of R-10 to R-15. The R-value does not include frame effects, which can reduce the whole-window R-value.[5] The VIG unit may also include low emissivity (low-e) coatings that reduce solar heat gain and further improve energy performance.

**CSW:** Commercial secondary windows are retrofit products comprised of one or more panes of glass, polymer, or acrylic, which are mounted in a fixed or operable frame that is attached either on the interior or exterior of existing windows without replacing the primary glass or frame. CSWs meeting CalMTA's product definition include low-e coatings, insulating gases, thermal films, and/or VIG units in their construction. They may be permanently installed or removable. Because CSWs are installed over the existing window and because lightweight options are available, installation can be substantially easier, faster, and less expensive than glazing or full window replacement, making CSWs an attractive solution for any building that needs to address envelope performance and may not be undergoing a deep retrofit.

The CRAWS MTI will include products with the following attributes:

- For all products, a maximum solar heat gain coefficient (SHGC) of 0.25
- For CSW products, a maximum U-factor of 0.35

VIG can achieve higher center-of-glass insulation values than CSW but can also have higher product and installation costs. Given the cost, VIG is likely more attractive for buildings undergoing deep retrofits. In some cases, CSW can achieve better assembly U-factors than VIG for SPR, depending on the window frame properties.

No federal or state codes govern CSW attachment products, though local building codes may be triggered for VIG for SPR depending on the magnitude of the retrofit. See Section 6 for more information on codes, standards, and policies.

[5] R-value is a measure of a material's ability to restrict heat flow; the higher the R-value, the greater the insulating power.

## 3.3 Energy efficiency landscape

This section describes the activities of other market actors across the U.S. who are actively investigating CSW and/or VIG for SPR (Table 1). The section also discusses major findings from research activities.

**Table 1. Programs and organizations active in CRAWS**

| Program/Organization | Description |
|---|---|
| Northwest Energy Efficiency Alliance (NEEA) | • NEEA promoted CSWs as part of its Window Attachments Initiative until 2023, when it paused the program.<br>• Published a study characterizing the market potential for CSWs.[6] Conducted a multiple-site field study to validate energy savings in their region and identified market barriers of high cost and low product awareness, but found installation was easy and quantified NEBs.[7] |
| CalNEXT | • Assessed the market potential in California for CSWs.<br>• Released a report in May 2024 characterizing the market for window replacements and inserts, including CSWs. This report was an initial step toward understanding the market potential for deemed savings measure packages for high-efficiency window projects in California. It found that cost, education, a lack of incentive programs, and flexible and inconsistent building energy codes are major barriers to window measures.[8] |
| DOE | • Announced in 2023 that LuxWall, a manufacturer of VIG, was awarded a grant intended to "strengthen clean energy supply chains and accelerate domestic clean energy manufacturing," to manufacture VIG units.[9] In October 2025, DOE cancelled LuxWall's |

[6] Ingo Bensch, Ross Donaldson, Lyndsey Shimazu. Commercial Window Attachments: Secondary Window Market Characterization, April 9, 2020. https://neea.org/wp-content/uploads/2025/03/Commercial-Window-Attachments-Secondary-Window-Market-Characterization.pdf.

[7] Jordan Pratt, Sean Wynne. Commercial Secondary Windows Field Test, December 18, 2023. https://neea.org/wp-content/uploads/2025/03/Commercial-Secondary-Windows-Field-Study.pdf.

[8] Julie Birchfield, Kyle Booth, Jesse Zucker, Simpson Tanner, Scott Honegger, Nancy Metayer Bowen. May 28, 2024, Commercial Windows Market Study and Measure Package Development. https://calnext.com/wp-content/uploads/2024/05/ET23SWE0018_Commercial-Windows-Market-Study_Final-Report.pdf.

[9] Biden-Harris Administration Announces Actions to Strengthen Clean Energy Supply Chains and Accelerate Manufacturing in Energy and Industrial Communities, November 27, 2023. https://www.energy.gov/articles/biden-harris-administration-announces-actions-strengthen-clean-energy-supply-chains-and?utm_medium=email

| Program/Organization | Description |
|---|---|
| | grant, along with other grants targeting battery and green manufacturing projects.[10]<br>• In 2024, DOE's Building Technologies Office (BTO) initiated the Building Envelope Innovation Prize awarding up to $2 million for secondary glazing systems.[11] Seven winners were announced in November 2024 for Phase 1, the Design Concept phase. At the time of writing, scheduled milestones have passed for entering Phases 2 and 3 and announcing Phase 2 winners.[12] |
| General Services Administration (GSA) | • Promoted CSWs in its buildings, many of which are historic.<br>• In 2023, initiated a Green Proving Ground (GPG) collaboration with DOE to evaluate the performance of secondary windows, including secondary windows with VIG.[13]<br>• In 2021, the National Laboratory of the Rockies[14] (NLR) released a report commissioned by the GSA that assessed the applicability of CSWs on GSA buildings with existing, SPC glass.[15] It assessed thermal performance, HVAC energy reduction, thermal load reduction, and comfort improvement. |
| California Energy Commission (CEC) | • Commissioned a series of reports, concluding in 2021, on the current and future states of the technology, market barriers and opportunities, and recommended initiatives to promote advanced window and building envelope systems, including VIG.[16] |

[10] Dylan Berman, "American Battery Technology Company Stock is Moving Lower on Wednesday: What's Going On?" *Benzinga*, October 22, 2025. https://www.benzinga.com/trading-ideas/movers/25/10/48366595/american-battery-technology-company-stock-is-moving-lower-wednesday-whats-going-on

[11] DOE Launches $2 Million Prize to Advance Cost-Effective, Energy-Efficient Commercial Windows, February 21, 2024. https://aercenergyrating.org/doe-launches-2-million-prize-to-advance-cost-effective-energy-efficient-commercial-windows/.

[12] Building Envelope Innovation Prize - Secondary Glazing Systems. https://www.herox.com/envelopeprize/updates

[13] Secondary Interior Window Framing with Advanced Glazing. November 2023. https://www.gsa.gov/system/files/2023-Secondary-Interior-Window-Framing-With-Advanced-Glazing.pdf.

[14] The National Laboratory of the Rockies was formerly known as the National Renewable Energy Laboratory (NREL). The U.S. DOE changed its name in December 2025.

[15] Kosol Kiatreungwattana, Lin Simpson. November 2021. Demonstration and Evaluation of Lightweight High Performance Secondary Windows. https://docs.nrel.gov/docs/fy22osti/79112.pdf.

[16] William Goetzler, Kristin Landry, Micah Turner, Palak Thakur. March 2021. Next Generation Window and Building Envelope Systems. https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2021-018.pdf.

| Program/Organization | Description |
|---|---|
| Partnership for Advanced Window Solutions (PAWS) | • Collaborative organization that was funded by the DOE from 2021-2023 consisting of multiple industry stakeholders including manufacturers, government and non-government organizations, and national laboratories, to promote high-performance window solutions for new and existing buildings.[17]<br>• Aims to provide a consumer window selection tool, assist utility campaigns and incentive programs, and perform some residential-focused tasks.<br>• In May 2025, PAWS published a savings calculator for secondary windows for commercial and multifamily buildings.[18] |
| Utilities | • Consolidated Edison (ConED) has promoted CSWs in its service area of New York City and some surrounding areas. It ran a pilot in 2020 and an incentive program in 2023 that offered a $200 per MMBtu ($20 per therm) incentive for energy savings achieved through CSWs.[19,20]<br>• In Washington state, Puget Sound Energy (PSE) awards $15 per annual therm saved in CSW incentives.[21] |



[17] Partnership for Advanced Window Solutions (PAWS). July 24, 2023. https://www.energy.gov/eere/buildings/articles/partnership-advanced-window-solutions-paws.

[18] Secondary windows savings calculator. May 9, 2025. https://betterbricks.com/resources/secondary-windows-savings-calculator.

[19] Danielle Meyer. AERC Launches Commercial Secondary Window Program, Moves into New Sector of Window Attachment Market. October 22, 2020. https://aercenergyrating.org/aerc-launches-commercial-secondary-window-program.

[20] DOE Recognizes 10 Storm Window and Window Attachment Programs for Their Impact and Innovation. February 8, 2024. https://www.energy.gov/eere/buildings/articles/doe-recognizes-10-storm-window-and-window-attachment-programs-their-impact.

[21] Commercial Secondary Windows. https://www.pse.com/en/business-incentives/commercial-secondary-windows.

# 4 Research objectives and methodology

## 4.1 Research objectives

The following describes the key research objectives and questions investigated by the CalMTA team while conducting the Product Assessment:[22]

1) Quantify energy and non-energy impacts specific to California climates through energy modeling and determine the impact of demand response events.
2) Quantify energy benefits by assessing the impact of CSWs and VIG on HVAC run times including evaluating air leakage, assessing the potential for the elimination of baseboard heating located under windows to counteract cold drafts, determining the additional energy savings associated with reducing HVAC sizing, and comparing these results to the potential of competing solutions such as blinds, film, and full-window replacements.
3) Identify the NEBs and document the dollar equivalent, when available.
4) Quantify peak electrical load impacts for most common HVAC types.
5) Investigate resiliency and grid flexibility benefits from increased CSW and VIG installation.
6) Evaluate product performance and durability
7) Review product ratings and test procedures to determine the relevant barriers and requirements to create a ratings standard for VIG.

## 4.2 Research methods

### 4.2.1 Field study/demonstration

CalMTA is conducting a field demonstration in four classrooms at Madison Elementary School in Madera, California.[23] The purpose of the demonstration is to monitor the impacts of CSWs on indoor air quality (IAQ), temperature, light quality, energy consumption, and other NEBs such as thermal comfort, visual comfort, and sound reduction. Four additional classrooms with no upgrades are being monitored to serve as a baseline. The team performed blower door testing to determine air infiltration levels before and after installation. The team also installed metering equipment to collect data on indoor environmental conditions and HVAC power consumption for

[22] The CRAWS Advancement Plan included an additional technology assessment activity: *investigate financial & cost factors*. Financial and cost factors are addressed in the CRAWS Market Characterization Report.

[23] The CRAWS Advancement Plan included laboratory testing of CRAWS products in its research plan to address product performance and durability, and product ratings and test procedures. These objectives were already being addressed by industry partners, so CalMTA reassigned costs allocated for lab testing to the field demonstration.

12 months, starting in September 2025. The census tract containing Madison Elementary School is classified as a disadvantaged community (DAC) by CalEnviroScreen, with a high pollution burden of 93 out of 100.

### 4.2.2 Manufacturer and expert engagement

The CalMTA team met with representatives from CSW manufacturers including Alpen and Indow, and Lawerence Berkeley National Lab (LBNL) to better understand the current state of the market for VIG and CSW products. The team discussed the number and locations of projects utilizing these technologies in California and beyond, business models for funding CRAWS installations, factors influencing consumer choices regarding CRAWS products, new products in development, and industry partnerships and collaborations.

### 4.2.3 Literature review

The CalMTA team compiled and reviewed reports, publications, and industry white papers that considered all aspects of CSWs and VIG for SPR. Studies were obtained from existing resource repositories, the CEC, DOE, national laboratories, the American Council for an Energy-Efficient Economy (ACEEE) website, NEEA, and sources found through internet queries. The studies formed a basis of knowledge to inform our product definition and recommendations.

### 4.2.4 Energy modeling

Energy modeling was conducted to assess statewide impacts and support the development of total system benefit (TSB) and bill impact calculations. Energy modeling tasks were performed using EnergyPlus, an open-source, whole-building energy simulation program developed by the DOE. CalMTA used prototype building energy models from the California Database for Energy Efficient Resources (DEER) for 18 commercial building types. The DEER models were run as-is, with only window properties changed to reflect CRAWS performance specifications. Each prototype building was run with three window installation cases – SPC, DPC, and CSW – in all 16 California climate zones. These model runs produced electric and natural gas consumption profiles at 15-minute intervals, which were used in avoided-cost and bill-impact analyses. A detailed description of the energy modeling can be found in Appendix B of the CRAWS MTI Plan in Attachment 2.

# 5 Technical barriers and opportunities to broader adoption

This section reviews the barriers and opportunities for adoption of currently available CRAWS products.

## 5.1 Energy benefits

### 5.1.1 Reduces HVAC equipment sizing

CSWs indirectly contribute to capital cost savings by reducing peak building thermal loads. This can lead to a reduction in the capacity of equipment installed during HVAC retrofits. For instance, an NLR study using ResStock data found that upgrading the envelope resulted in an average heat pump size reduction of 1.4 tons, saving $2,500 in installation costs for high-efficiency air source heat pumps and 2.1 tons and $4,000 for medium-efficiency air source heat pumps.[24] The study found that envelope upgrades in older buildings have a more substantial impact on heat pump size compared to newer buildings. Moreover, envelope upgrades could eliminate the need for ductwork, electrical panel, or service wire upgrades, further reducing upfront costs.

### 5.1.2 CRAWS technologies provide an unintrusive compliance pathway for building performance standards

At the time of writing, over 40 states, cities, and jurisdictions nationwide have either passed or are considering some form of building performance standards (BPS). BPS are performance-based standards used to reduce energy consumption and operational costs in existing buildings.[25] Given the simplicity of installation and the substantial savings they provide, CSWs and VIG for SPR could offer a one-measure solution for compliance with whole-building energy and emissions reduction targets set by BPS. For instance, the city of Chula Vista, California, implemented local BPS that includes window upgrades as one of nine possible compliance measures for multi-family buildings built before 2006.[26]

BPS requirements potentially improve the economics of envelope retrofits such as CSW and VIG for owners who are out of compliance with BPS requirements by raising the cost of taking no action. Further, CRAWS technologies improve the business cases for other retrofit projects that comprise key strategies for BPS compliance, such as reducing the cost of upgrading HVAC systems to heat pumps, by reducing peak space conditioning loads and allowing consumers to downsize replacement HVAC systems.

### 5.1.3 Increased impacts in older buildings

Installing CSWs and VIG for SPR in older buildings can save large amounts of energy because these buildings typically have poor insulation and older windows with high U-factors and no low-e coating. Using NLR's ComStock to estimate the window market, CalMTA found that 85% of

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[24] Prateek Munankarmi, Eric Wilson, Janet Reyna, Stacey Rothgeb. Size up or size down? National analysis of heat pump sizing and impacts. https://docs.nrel.gov/docs/fy24osti/85347.pdf.

[25] Building Performance Standards. https://www.energycodes.gov/BPS.

[26] City of Chula Vista Building Energy Saving Ordinance (BESO) Policy Summary. January 2024. https://www.chulavistaca.gov/home/showpublisheddocument/27410/638409963775670000.

windows in California are over 30 years old. Over 40% of commercial buildings in California have windows with U-factors exceeding 1.0, which is far less efficient than current energy code requirements.[27,28]

## 5.2 Significant non-energy benefits

### 5.2.1 Increased thermal comfort

In a 2021 study, NREL found that CSWs can significantly reduce vertical surface radiant asymmetry (the temperature difference experienced on opposite sides of a person), which is a contributor to occupant discomfort in buildings.[29] Another study found that VIG retrofits can improve thermal satisfaction by 9.2%.[30]

Work performance can serve as a proxy for the relationship between comfort and indoor thermal conditions in office buildings. LBNL conducted a meta-analysis of nine studies on the effects of temperature on productivity and established that temperature has no effect on productivity within the range of 21°C to 25°C (69.8°F to 77°F), but that there is a 2% decrease in productivity per degree when temperatures exceed 25°C (77°F) and a 4.7% decrease in productivity per degree when temperatures dropped below 21°C (69.8°F).[31] New York State Energy Research and Development Authority (NYSERDA) found that respondents from their Commercial/Industrial Performance Program (CIPP) would be willing to pay an additional $0.42/ft$^2$ for additional thermal comfort and HVAC effectiveness.[32]

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[27] Existing Buildings Study Building Characteristics Report. March 4, 2025. https://www.bayren.org/sites/default/files/documents/2025/BayREN%20Detailed%20Building%20Characteristics%20Report_Final.pdf.

[28] Title 24-2025 requires a maximum area-weighted average U-factor of 0.47 or less for vertical fenestration products for new construction in California. California Energy Commission. Building Energy Efficiency Standards for Residential
and Nonresidential Buildings, July, 2025. https://www.energy.ca.gov/sites/default/files/2025-07/CEC-400-2025-010-F_0.pdf.

[29] Kosol Kiatreungwattana, Lin Simpson. Demonstration and Evaluation of Lightweight High Performance Secondary Windows. https://docs.nrel.gov/docs/fy22osti/79112.pdf.

[30] Changyu Qiu, Hongxing Yang, Kaijun Dong. Energy and Thermal Comfort Performance of Vacuum Glazing-Based Building Envelope Retrofit in Subtropical Climate: A Case Study. https://www.mdpi.com/2075-5309/15/12/2038.

[31] Olli Seppänen, William J. Fisk, David Faulkner. Cost benefit analysis of the night-time ventilative cooling in office building. https://escholarship.org/uc/item/3j82f642#page-3.

[32] Brent Barkett, Nicole Wobus, Rachel Freeman, Daniel Violette. Non-Energy Impacts (NEI) Evaluation. https://www.aceee.org/files/pdf/conferences/workshop/valuation/MCAC_NEI_Report_06.pdf.

### 5.2.2 Reduced noise

NEEA field tests found that CSWs achieve a 6.9 decibel (dB) (12%) reduction in sound transmission under ambient conditions with an additional 5.7 dB (11%) reduction on average at a 90 dB exterior testing condition.[33] Measurements conducted by Pacific Northwest National Laboratory (PNNL) at a CRAWS field installation site in Madera, California, demonstrated a 7 dB reduction in sound transmission levels attributable to CSWs (see Section 8.1.4 for more information on the CRAWS field installation.)

Reducing ambient noise levels below an average of 55 a-weighted decibels (dBA), the maximum 24-hour limit for exposure to environmental noise recommended by the EPA, results in several positive health outcomes and improvements in quality of life.[34] A 2013 study cites an estimate that over 100 million Americans are exposed to unhealthy levels of noise annually.[35] A National Center for Biotechnology Information (NCBI) study found that reducing noise exposure for these people by 5 dB would reduce the prevalence of hypertension by 1.4%, or almost 1.2 million cases. Furthermore, it would reduce coronary heart disease by 1.8%. The associated cost savings that would be gained from this reduction in noise exposure were estimated as $2.4 billion in annual health care costs and $1.5 billion annually in productivity gains.[36]

### 5.2.3 Improved resiliency

Extreme weather events are becoming more frequent and severe, leading to significant losses of property and lives. The National Safety Council reported a 20% increase in weather-related deaths and a 120% rise in injuries since 2019.[37] CRAWS technologies can enhance the resiliency of buildings by providing thermal comfort and maintaining indoor air quality (IAQ) during extreme weather events.

CSWs can also reduce air infiltration. In addition to energy benefits, increasing airtightness reduces the amount of dust and pollutants that enter a building. A meta-analysis of 20 research studies investigating the impact of increasing airtightness on IAQ found a positive correlation

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[33] Commercial Secondary Windows: Better Comfort, More Savings, Easier Compliance, February 21, 2025. https://betterbricks.com/news/commercial-secondary-windows-better-comfort-more-savings-easier-compliance.

[34] Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety, March 1974. https://books.google.com/books?hl=en&lr=&id=sB1SAAAAMAAJ&oi=fnd&pg=PA1&ots=rK9Rw22aLv&sig=npzSiQkM4XEc69Ra5P7RcLXklkY#v=onepage&q&f=false.

[35] Monica S Hammer, et. al. December 2013. Environmental Noise Pollution in the United States: Developing an Effective Public Health Response. https://pmc.ncbi.nlm.nih.gov/articles/PMC3915267/.

[36] Valuing Quiet: An economic assessment of US environmental noise as a cardiovascular health hazard. https://pmc.ncbi.nlm.nih.gov/articles/PMC4819987/#R9.

[37] Weather-Related Deaths and Injuries. https://injuryfacts.nsc.org/home-and-community/safety-topics/weather-related-deaths-and-injuries/#:~:text=Over%20the%20last%20five%20years,the%20most%20deaths%20during%202023/.

between reduced infiltration and decreased $PM_{2.5}$ and $NO_2$ concentrations in areas where there are high outdoor contaminant levels.[38,39] This study suggests that CSWs are particularly advantageous in locations with degraded air quality or those that are prone to wildfire smoke. Reducing envelope infiltration can increase levels of indoor air contaminants like $CO_2$ and formaldehyde, so building owners should ensure that ventilation systems are adequate.

### 5.2.4 Fast installation and workforce training opportunity for CSWs

Full window replacement can be time consuming and disruptive, ranging between 30 minutes and several hours per window to perform a full replacement, depending on the type of window and complexity. In most cases, full window replacement requires an experienced window installer.

By contrast, installing CSWs is fast, which results in low installation costs and minimal disruption to occupants, even when they are present in the building during installation. An NLR survey found that installation of secondary windows required one person and took approximately 7-10 minutes per window and can often be fully completed from the building interior.[40] Furthermore, installation of CSWs does not require specialized window replacement skills or opening the building envelope. This positions CSW installation as an accessible workforce education and training (WE&T) opportunity that bridges general multi-craft construction skills and more specialized window trades. Easy installation offers scalable job pathways without the training burden associated with full window replacement. This characteristic is particularly relevant for expanding local workforce participation in ESJ communities. See Section 2.4, Workforce Development, of the MTI Plan for additional detail on WE&T strategy and implementation.

### 5.2.5 Choices for operable windows

Since VIG for SPR retains existing window frames, VIG does not pose challenges where operability is required; windows that are operable before being retrofitted with VIG remain operable.

Operable CSWs are available, but at least one CSW manufacturer engaged by CalMTA has expressed that their products typically are not operable, so requirements for operability may limit choice for CSW consumers. On the other hand, all participants in a recent NEEA study on three sites that installed secondary windows had requirements for their original windows to remain

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[38] Leela Kempton, et. al., October 2022. A rapid review of the impact of increasing airtightness on indoor air quality. https://www.sciencedirect.com/science/article/abs/pii/S2352710222008117.

[39] $PM_{2.5}$ stands for particulate matter that is are generally 2.5 micrometers and smaller. $NO_2$ is stands for nitrogen dioxide and primarily gets into the air from fuel combustion.

[40] Kosol Kiatreungwattana, et. al. November 2021. Demonstration and Evaluation of Lightweight High Performance Secondary Windows. https://docs.nrel.gov/docs/fy22osti/79112.pdf.

operable. The fact that all participants were all able to proceed with CSW retrofits suggests that operability is not a barrier to choosing CSWs.[41]

## 5.3 Product performance and durability: data gaps

### 5.3.1 Little information on real-world performance to determine condensation risk

While several studies have attempted to simulate and quantify the condensation risk of CSWs, little data has been collected from field installations. LBNL reported that simulations of secondary windows indicate increased condensation risk over single pane base windows but notes that real-world performance might not reflect this condition.[42] It notes that future work should include installing and monitoring CSWs in real buildings to validate the simulation results.

A NEEA report found that most respondents surveyed experienced no issues with condensation when they installed CSWs.[43] A United Kingdom field study found that secondary windows enhance insulation and reduce condensation on the interior glazing surface, without observing condensation forming in the cavity between the original glazing and the secondary window.[44]

CSWs have been shown to significantly reduce the risk of condensation on interior window surfaces. An NLR study found that the condensation resistance of a single pane window increased from a baseline of 12 to 44 by installing single-pane secondary windows or to 46 by installing double-pane secondary windows.[45,46] While the rating increase in both cases still did not meet the minimum recommended rating of 50, the authors considered the improvement to be substantial.

### 5.3.2 Little information on VIG performance degradation

Little data is available on the long-term thermal performance of VIG units, and how that performance degrades over time. Although this issue applies to all VIG applications (not only VIG for SPR) it creates uncertainty for energy code officials and energy efficiency program administrators regarding the durability of savings attributable to VIG for SPR.

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[41] Commercial Window Attachments: Secondary Window Market Characterization
[42] Robert Hart, et. al. February 2015. Secondary Glazing System (SGS) Thermal, Moisture, and Solar Performance Analysis and Validation. https://www.rbbwindow.com/wp-content/uploads/LBNL_report_secondary_glazing1.pdf.
[43] Commercial Windows Attachment (SGS) Initiative. https://neea.org/wp-content/uploads/2025/03/commercial-window-attachments-sgs-phase-1-research.pdf.
[44] John Kaiser Calautit, et. al. Keeping it simple: Field testing and techno-economic assessment of a low-cost secondary quad glazing for enhanced energy efficiency in buildings. https://www.sciencedirect.com/science/article/pii/S2666123325000273.
[45] Condensation resistance is a rating on a scale of zero to 100 that measures a window's ability to resist condensation on the interior surface.
[46] Kosol Kiatreungwattana, et. al. November 2021. Demonstration and Evaluation of Lightweight High Performance Secondary Windows. https://docs.nrel.gov/docs/fy22osti/79112.pdf.

## 5.4 Financial & cost factors

### 5.4.1 Lower-cost window upgrade options for historic buildings

Many historic buildings and preservation sites have requirements to maintain the appearance of a building, which adds to the cost of window replacements with custom specifications. Conversely, CSWs can be installed inside or outside the existing window, allowing window performance to be upgraded while leaving historic windows intact. NEEA interviews have found preservation to be a main driver in secondary window installations in the Pacific Northwest.[47]

### 5.4.2 High manufacturing costs of VIG

To retain the vacuum and efficiency of the window, VIG must be hermetically sealed. While multiple research studies explore different methods of edge sealing at lower temperatures, current manufacturing processes typically require high temperatures for the vacuum evacuation process. This process consumes significant amounts of energy, which increases costs and raises embodied GHG emissions. Newer, lower-temperature seals are being tested, but durability remains a design challenge. VIG for CSW also requires ultra-thin glass panes with precise thickness tolerances that are currently produced by less than ten global suppliers.[48]

Despite the higher cost of VIG units, VIG for SPR is a more economical solution compared to full window replacement for buildings with single-pane windows. CalMTA's discussions with suppliers have indicated that the cost of VIG for SPR is approximately half that of full replacement. Suppliers also indicated that the cost of CSW is even lower, at approximately 15% to 25%.

### 5.4.3 Limited VIG product availability

At the time of writing, only three VIG products are commercially available. However, manufacturers may accelerate their rate of production. For example, Luxwall will open a new factory in Michigan in late 2026 and recently announced a partnership with Viracon to increase fabrication capacity.[49,50]

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[47] Ingo Bensch, Ross Donaldson, Lyndsey Shimazu. Commercial Window Attachments: Secondary Window Market Characterization, April 9, 2020. https://neea.org/wp-content/uploads/2025/03/Commercial-Window-Attachments-Secondary-Window-Market-Characterization.pdf.

[48] Vacuum Insulating Glass (VIG) Market. https://pmarketresearch.com/chemi/vacuum-insulating-glass-vig-market/.

[49] LuxWall™ Showcases Preview of Detroit Factory as a Catalyst for Manufacturing Innovation and Community Growth. https://www.luxwall.com/luxwall-showcases-preview-of-detroit-factory-as-a-catalyst-for-manufacturing-innovation-and-community-growth/.

[50] Viracon® and LuxWall™ Partner to Set New Benchmark for High-Performance Commercial Facades. https://viracon.com/viracon-and-luxwall-partner-to-set-new-benchmark-for-high-performance-commercial-facades/.

# 6 Codes, standards, and policies

## 6.1 California codes

Part 6, the Building Energy Efficiency Standards, of Title 24, the California Code of Regulations — often referred to simply as Title 24 — applies to buildings for which a building permit is required (those undergoing new construction and additions or alterations to existing buildings). Title 24 defines an alteration as any change to a building's water heating, space-conditioning, lighting, or envelope systems that is not an addition. It specifies that the Energy Code applies to the altered components of a system (i.e., the glazing units in VIG for SPR) and that alterations must comply with mandatory and prescriptive requirements for those components.[51] VIG glazing units meeting the CRAWS product definition exceed the prescriptive energy code requirements for glazing units.

Since the installation of CSW attachment products leaves the existing building envelope in place, the definition of alteration does not apply. Therefore, no state codes govern CSW attachment products.

CalMTA has set performance specifications for CRAWS that are in line with standards for new construction and alterations in Title 24-2025 to ensure that our MTI is technically feasible with readily available materials and will align with building owners' expectations for contemporary glazing systems.

Title 24 contains mandatory requirements for all projects that fall within its scope. It also contains prescriptive requirements, which are generally more stringent than mandatory requirements. A permit applicant can document compliance with Title 24 by following all prescriptive requirements, or they can use the performance method that allows an applicant to "trade off" systems or components that perform below the prescriptive standards with other higher-performing systems elsewhere within the project, as long as the overall performance is equivalent to that of a building in which all prescriptive requirements are met. When using the performance method, all systems or components must meet or exceed mandatory requirements.

Title 24-2025 adds new mandatory maximum area-weighted U-factor requirements for fenestration (Table 2). Previously, window performance could be traded off without limit with other building systems like HVAC, allowing builders to install less-efficient glazing. To ensure that long life-cycle systems like fenestration are not traded off for less durable equipment, Title 24-2025 introduced a mandatory maximum U-factor of 0.47 for new construction and 0.58 for

[51] Section 100.0. California Energy Commission, 2022 Nonresidential and Multifamily Compliance Manual (First Quarter Errata), TN #250098 (Sacramento: California Energy Commission, May 11, 2023).

alterations. Prescriptive requirements for nonresidential window U-factor in Title 24-2025 range from 0.34 to 0.46 for new construction, depending on building type and climate zone, and between 0.47 to 0.58 for alterations. Prescriptive requirements for SHGC range from 0.22 to 0.26 for new construction and from 0.31 to 0.45 for alterations.[52] CalMTA's specifications for CRAWS fall within these ranges.

**Table 2. Title 24-2025 fenestration requirements for nonresidential buildings**

| Building Permit Type | U-factor, Mandatory | U-factor, Prescriptive | SHGC, Prescriptive |
|---|---|---|---|
| New Construction | 0.47 | 0.34 - 0.46 | 0.22 - 0.26 |
| Alterations | 0.58 | 0.47 - 0.58 | 0.31 - 0.41 |

A proposed update to the 2028 Building Energy Code would improve U-factors for nonresidential windows in climate zones 1 and 16; however, current and proposed fenestration performance in Title 24 can be met by standard glazing products without the use of VIG.[53]

## 6.2 Federal standards

Fenestration is not covered by federal energy performance standards.

## 6.3 Product ratings: barriers and limitations

Several barriers related to national performance ratings limit the broader adoption of VIG and CSW:

### 6.3.1 VIG for SPR

- To demonstrate compliance with Title 24, window assemblies must have assembly U-factors and SHGC ratings issued by the NFRC. Glazing units that have not been rated by the NFRC as an assembly must use default values that generally fall short of actual performance. The 2023 version of the NFRC-100 standard adopted U-factor calculations for VIG products. The NFRC-100 standard also added a simulation of VIG into the THERM certification software, which allowed for the standard certification of new VIG fenestration products.[54] However, there is no NFRC rating method for VIG for SPR, since the glazing unit is installed directly into existing frames. An approach similar to the "site built" calculation for fenestration that is assembled at

[52] Sections 120.7(d), 140.3(a), and 141.0(b). 2025 Building Energy Efficiency Standards for Residential and Nonresidential Buildings. Nonresidential and Multifamily Compliance Manual. Sacramento: California Energy Commission, July 2025.

[53] 2028 Cycle Fenestration Improvements. Title 24. https://title24stakeholders.com/measures/2028-cycle/fenestration-improvements/.

the building site may be needed for VIG for SPR. Without one, the default rating for VIG for SPR will limit the amount utilities can pay out in incentives and the compliance credit builders get in their energy modeling simulations.

- Measures like VIG that degrade in performance over time are assigned performance values in energy codes and modeling software that account for degradation (an analogous example is the aged solar reflectance value for cool roofs). The lack of long-term VIG performance data has prevented development of an aged performance value. VIG will need this value before the technology will be widely adopted.

### 6.3.2 CSWs

- While AERC provides ratings for CSW products, the industry lacks a program like ENERGY STAR® that guides consumers by certifying only high-performing products.

### 6.3.3 VIG for SPR and CSWs

- Most utility incentive programs compare performance to new code-minimum equipment. However, CRAWS will motivate and enable retrofit projects that would not have otherwise happened. To accurately capture the higher energy savings (and thus the full benefit of the technology), it may be necessary for utility programs to compare the performance of CRAWS technologies to the actual window baseline of SPC glass rather than to code-minimum new glazing equipment.

## 6.4 Product ratings: opportunities and leverage points

### 6.4.1 American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)

The 2025 version of ASHRAE Standard 90.1, the Energy Standard for Buildings Except Low-Rise Residential Buildings, proposed new fenestration requirements. While California does not directly reference ASHRAE standards in its building energy codes, more stringent U-factor requirements for commercial new construction nationwide could accelerate the market adoption of VIG. The changes for 2025 are incremental improvements in U-factor; only climate zone 8, which is relatively small, requires advanced glazing (e.g., triple-pane windows or VIG).

### 6.4.2 Attachments Energy Rating Council (AERC)

NFRC ratings for window assemblies consider the performance of glazing units within their frames. CalMTA and AERC have begun work to develop a rating method for VIG for SPR. Default NFRC values for VIG for SPR applications assume low thermal performance of the existing frames; therefore, building designers and owners may not receive full credit for the performance of VIG for SPR when using default values to demonstrate compliance with energy codes or energy incentive programs.

### 6.4.3 The American National Standards Institute (ANSI)

ANSI NRFC 100 VIG Ballot outlines procedures for determining the U-factors of fenestration products and includes VIG as a covered product. The 2023 version of NFRC 100 incorporates additional language related to VIG.

### 6.4.4 ASTM International

In September 2022, ASTM established two working groups, WK83379 and WK83445, to develop VIG specifications, durability, and strength standards. In the meantime, several VIG products have already passed the existing E2190 standard for insulated glazing certification.

The draft standard WK83445, Load Resistance and Deflection, covers VIG load structural calculations.[55] This standard could lead to improved confidence in the accuracy of VIG load calculations by providing engineers with consistent and accurate data, thereby increasing VIG market share.

### 6.4.5 International Organization for Standardization (ISO)

ISO-19916 Part 1, published in 2018, provided a specification for VIG. Part 3, which followed in 2021, introduced a test method for evaluating VIG's performance under temperature differences.

### 6.4.6 National Foundation for Refrigeration and Air Conditioning (NFRC)

NFRC will update the VIG simulation module that assesses thermal performance for ENERGY STAR certification through the upcoming LBNL Window 8 program.

# 7 Competitive landscape

Consumers with existing SPC or DPC glass might choose between replacing single-pane glazing with VIG, installing CSWs, installing a variety of other competing products described in this section – or they might choose to do nothing.

To understand the competitive landscape for CRAWS, two factors must be considered: building owners' tendency to retain existing windows and the varied factors that motivate those who choose to upgrade. First, the typical response to window-related problems is inaction; inefficient, single-pane windows often remain in place for decades. Therefore, for a window solution to be selected, it must not only outperform less-efficient alternatives considered during routine or early replacement but also overcome the "do-nothing" option and motivate action to improve the building envelope. Second, energy efficiency is not the primary driver of window upgrades, and the optimal solution may not deliver the greatest energy savings. As documented in various

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[55] ASTM WL83445k: New Practice for Standard Practice for Determining Load Resistance of Vacuum Insulating Glass in Buildings, https://www.astm.org/workitem-wk83445.

market characterization studies, a common primary driver for building owners to invest in window solutions is to address thermal comfort and noise-related problems, with energy and HVAC savings being a secondary benefit.[56,57] While NEBs are frequent drivers of adoption in other MTIs, NEBs are commonly the primary driver for the CRAWS MTI. Therefore, no one window technology solution can be definitively identified as superior based simply on energy performance alone; it must deliver a compelling value proposition to the building owner that, in part, is often based on NEBs.

The optimal solution for a given application is the one that overcomes the do-nothing response, most effectively addresses the non-energy problem being addressed, and provides the greatest energy savings. For example, the optimal technology solution for a building with inefficient SPC glass and well-performing window frames will be different than the optimal solution for a building with more efficient glass but with leaky window frames. The former may have a smaller impact than the latter on overall energy savings but still delivers significant improvements over taking no action.

This competitive analysis will compare the energy and non-energy performance characteristics of competing technologies and identify the strengths and weaknesses of each for defined use cases.

## 7.1 CSWs

CSWs can be installed quickly, with minimal disruption to occupants, and are the lower-cost option of the two considered for this MTI. There are several categories of window attachment products that consumers might consider as alternatives to CSWs:

1) **Frame-mounted stretched film panel with weatherstripping seals around the perimeter.** Like CSWs, these products include a frame. Unlike CSWs that use rigid glass, polymer, or acrylic panel, they use a pliable, stretched film.
2) **Glazing-mounted (frameless) acrylic and copolyester panels.** These products do not include a frame. Instead, the acrylic or copolyester panel attaches directly to the glazing of the original window using a variety of attachment techniques, creating an unsealed dead-air space between the panel and the original glazing. Panels are sized to be slightly smaller than original glazing, leaving a small portion of the original glazing exposed.



[56] Ingo Bensch, Ross Donaldson, Lyndsey Shimazu. Commercial Window Attachments: Secondary Window Market Characterization, April 9, 2020. https://neea.org/wp-content/uploads/2025/03/Commercial-Window-Attachments-Secondary-Window-Market-Characterization.pdf.
[57] Sarah Zahid, et. Al. February 2026. https://calmta.org/wp-content/uploads/2026/02/CRAWS_Market_Characterization_DRAFT.pdf.

3) **Window film.** Thin laminate film is permanently applied directly to the original window's glass surface. There is a wide range of window films for commercial applications that provide energy benefits and NEBs. These films are also used in the construction of CSWs.

4) **Window shades.** Also commonly referred to as window coverings or window attachments, this product category includes cellular shades, roller shades, and solar screens that are installed on the interior or exterior of the existing window. Most commonly they are operable and can be controlled automatically or at the discretion of the user. Some products are installed like residential window screens. They are not operable but can be removed and reinstalled as needed.

Table 3 presents a competitive analysis of the strengths and weaknesses of CSWs and competing products that consumers might consider for buildings that are not undergoing a significant retrofit.

**Table 3. Competitive landscape for CSWs**

| Product | Strengths | Weaknesses |
| --- | --- | --- |
| **MTI Product – CSW** | • Equal or better energy performance and up to 90% less expensive than full window replacement<br>• Comparable performance with VIG for SPR for lower cost<br>• Strong thermal comfort and noise-reduction benefits<br>• Mitigates all forms of unwanted heat transfer – conductive, radiant, and air leakage<br>• Excellent clarity and light transmittance<br>• Larger and more flexible sizing than most competing technologies<br>• Can be installed quickly and easily without envelope or occupant disruption<br>• Options available for AERC-rated product | • Risk of condensation between primary and secondary window if primary window is not in good physical condition<br>• Few options for operability. Some manufacturers may not offer operable CSWs or may not offer operable CSWs for all window configurations (e.g., hung windows, sliders)<br>• More expensive than other attachment products<br>• Heavier than other attachment products<br>• Installer network is in development |

| Product | Strengths | Weaknesses |
|---|---|---|
| | • Can be removed/replaced easily<br>• Mature supply chain | |
| **Competing Product – Frame-mounted stretched film panel with weatherstripping seals around the perimeter** | • Strong thermal comfort benefits<br>• Mitigates all forms of unwanted heat transfer – conductive, radiant, and air leakage<br>• U-factor and SHGC improvement can be on par with CSWs<br>• Lightweight<br>• Can be installed quickly and easily without envelope or occupant disruption<br>• Can be removed/replaced easily<br>• Lower cost than CSWs | • No noise-reduction benefits<br>• No options for operability<br>• Poor aesthetics due to uneven surface and strong coloration<br>• Poor clarity<br>• Limited sizes due to maximum film width of approximately 48 inches<br>• No AERC-rated options<br>• Emerging technology lacking robust supply chain<br>• Competing technologies at higher price points (e.g., CSWs) and at lower price points (e.g., film) offer better performance, value, and more professional-looking solution |
| **Competing Product – Glazing-mounted acrylic and copolyester panels** | • Can install on many window types including sliders and hung windows while maintaining operability of the original window<br>• Mitigates conductive and radiant energy losses, but to a lesser degree than CSWs and film panels<br>• Lightweight – approximately 1/3 the weight of other attachment products<br>• Can be installed quickly and easily without envelope or occupant disruption | • No noise-reduction benefits<br>• No air-leakage benefits<br>• U-factor and SHGC benefits lesser than competing products<br>• Poor aesthetics due to panel having to be slightly smaller than original glazing, making edges visible and potentially reflecting light<br>• For larger windows, panels must be tiled to cover entire area, creating gaps and visible edge lines<br>• No AERC-rated options<br>• While panels can be removed/replaced, the adhesive |

| Product | Strengths | Weaknesses |
| --- | --- | --- |
| | • Lower cost than CSWs and frame-mounted stretched-film panels | mounting tabs are applied permanently to the window<br>• Limited manufacturers lacking robust supply chain |
| **Competing Product – Window film** | • Diverse options for delivering a wide range of energy benefits and NEBs including safety and security films that contain shattered glass<br>• Can be applied directly to the original window or applied to CSWs to enhance CSW performance<br>• Mitigates conductive and radiant energy losses<br>• SHGC improvement on par with CSWs<br>• Weight is insignificant<br>• Can be installed quickly and easily without envelope or occupant disruption<br>• Cost varies widely based on product but in general is lower cost than other attachment products<br>• Mature products from multiple international suppliers, robust supply chain and installer network. | • No air-leakage benefits<br>• No noise-reduction benefits<br>• U-factor improvement is less than CSWs or full replacement due to lack of insulating gap<br>• No AERC-rated options<br>• Permanent installation |
| **Competing Product – Window coverings (e.g., cellular shades, roller shades, blinds, shutters, and screens)** | • Diverse options (blinds, shades, screens) for delivering a wide range of energy benefits and NEBs<br>• Mitigate conductive and radiant energy losses<br>• AERC-rated products | • No air leakage benefits<br>• No noise-reduction benefits<br>• U-factor and SHGC benefits lesser than framed attachment products due to leakage around the window covering |

| Product | Strengths | Weaknesses |
|---|---|---|
| | • Highly customizable with diverse designer options<br>• Most flexibility and effectiveness in addressing glare, visual comfort, and visual privacy issues<br>• Diverse operability options; can be automated and connected to smart devices to optimize energy savings under changing environmental conditions<br>• Lightweight<br>• Easy to install, including DIY options<br>• Can be removed/replaced<br>• Mature and robust supply chain | • Energy savings is a function of user-behavior; difficult to predict, model, and guarantee<br>• May reduce daylighting if not operated properly |



## 7.2 VIG for SPR

VIG for SPR is a more costly and labor-intensive intervention than CSWs that results in high performance and a discreet aesthetic. Consumers considering VIG for SPR might also consider alternatives such as:

1) **Full window replacement**. Existing window and frame are replaced with framed double- or triple- pane windows, though full replacement rarely occurs due to cost and the disruptive nature of installation.
2) **Other competing technologies**. CSWs and the products identified in Section 7.1 are also a competing solution for VIG for SPR.

## 7.3 Summary of benefits for window retrofit solutions

Table 4 presents a subjective ranking of the energy benefits and NEBs of VIG, CSW, and competing products. It underscores that the optimal choice for window solutions hinges on the specific challenge the building owner is attempting to resolve. Many retrofits are driven by a confluence of factors.

### Table 4. VIG, CSW, and attachment products feature comparison

| | VIG | CSW | Frame-Mounted Stretched Film | Frameless Non-glass panels | Window Film | Shades, blinds, screens |
|---|---|---|---|---|---|---|
| Low Installed Cost (Mat'l + Labor) | ◔ | ◑ | ◑ | ◑ | ◕ | ● |
| Energy Savings | ● | ● | ◕ | ◑ | ◑ | ◑ |
| U Value | ● | ◕ | ◕ | ◑ | ◑ | ◑ |
| SHGC | ● | ● | ● | ◕ | ● | ◑ |
| Air Leakage | ◑ | ● | ◕ | ○ | ○ | ○ |
| Savings Certainty | ● | ● | ● | ● | ● | ◔ |
| Non-energy Benefits | | | | | | |
| Thermal Comfort | ● | ● | ● | ◕ | ● | ◑ |
| Noise Reduction | ● | ● | ◔ | ○ | ○ | ○ |
| Safety | ◕ | ◕ | ◔ | ○ | ◕ | ○ |
| Aesthetics | ● | ◕ | ○ | ◔ | ◕ | ◕ |
| Daylighting | ● | ● | ◑ | ● | ● | ◑ |
| Operability | ● | ◑ | ○ | ● | ● | ● |
| Large Sizes | ◑ | ◕ | ◔ | ◕ | ◕ | ◕ |
| Weight | ◑ | ◑ | ◕ | ◕ | ● | ◕ |
| Supply Chain | ◔ | ◕ | ◔ | ◑ | ● | ● |

*Circles represent subjective rankings of various characteristics for each window product. A filled circle indicates the greatest relative benefit in a given category, while an empty circle indicates the least benefit.*

# 8 Product performance

## 8.1 Energy consumption/UEI/peak electrical

The energy consumption and peak electric load reduction benefits for this MTI were assessed using whole-building energy models run in EnergyPlus. DEER prototype models for 18 building types were used as shown in Table 5. DEER models were run as-is, with only window parameters modified to reflect CRAWS installation cases.

**Table 5. Prototype building names and abbreviations**

| Abbreviation | Full name |
|---|---|
| Asm | Assembly |
| ECC | Education – community college |
| EPr | Education – primary school |
| ERC | Education – relocatable classrooms |
| ESe | Education – secondary school |
| EUn | Education - university |
| Hsp | Health/medical - hospital |
| Htl | Lodging – hotel |
| Mtl | Lodging – motel |
| Nrs | Health/medical – nursing home |
| OfL | Office - large |
| OfS | Office - small |
| RFF | Restaurant – fast food |
| RSD | Restaurant – sit down |
| Rt3 | Retail – multistory large |
| RtL | Retail – single story large |
| RtS | Retail – small |
| SCn | Storage - conditioned |

A full description of the building characteristics, modeling assumptions, and weighting factors can be found in Attachment 2 to Appendix B.

### 8.1.1 Energy consumption

CalMTA found that CSWs and VIG for SPR can offer significant energy consumption savings across all California climate zones and utility service territories. Energy savings from CSWs and VIG for SPR are very similar to each other (within 1%) on average[58]. Most of the savings are driven

[58] Because CalMTA found the energy performance of CSWs and VIG for SPR to be similar, and since the MTI assumes the market adoption of VIG for SPR will be low, figures in this section report the energy performance of CSWs to represent all CRAWS technologies.

by reduction in SHGC, rather than improvements in U-factor or infiltration. Results in Table 6 indicate a 7% to 8% reduction in annual electric consumption and a 17% to 22% reduction in annual gas consumption in the proposed cases, compared to the baseline. Utility consumption varies slightly by IOU because service territories cover different climate zones.

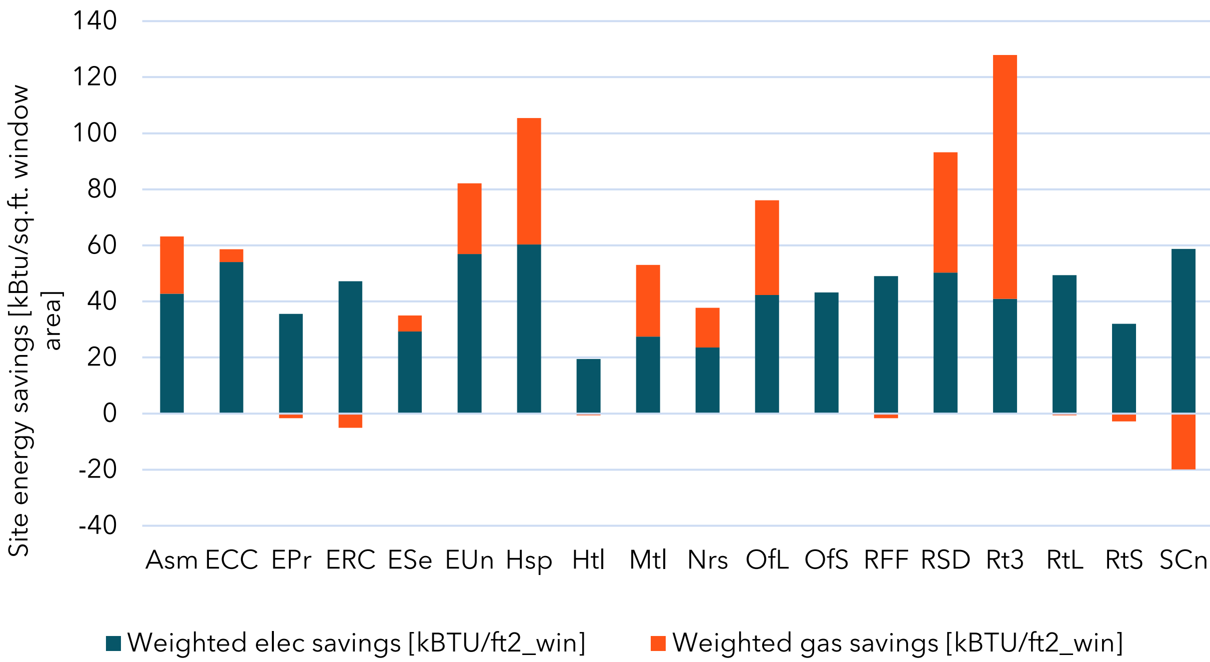
**Table 6. Average annual utility consumption weighted average of climate zone and building type**

| Case | Annual Electric Consumption | | | Annual Gas Consumption | | | Annual Total Consumption | | |
|---|---|---|---|---|---|---|---|---|---|
| | PG&E | SCE/SCG | SDG&E | PG&E | SCE/SCG | SDG&E | PG&E | SCE/SCG | SDG&E |
| CSW | -8% | -8% | -7% | -22% | -18% | -17% | -11% | -10% | -9% |

*Notes: Negative values indicate utility consumption savings. Savings are compared against the existing windows for the prototype building.*

The commercial building prototype models analyzed demonstrated varying degrees of energy savings achieved through CRAWS. Buildings with relatively high equipment loads and low ventilation requirements (such as offices) exhibited greater energy savings compared to buildings with high ventilation requirements (such as healthcare facilities). CRAWS provided significant savings for all the analyzed building types. Figure 1 illustrates the relative energy savings achieved by CRAWS for each of the 18 building types, broken down by fuel type.

**Figure 1. Average annual site energy savings, by building type**[59]

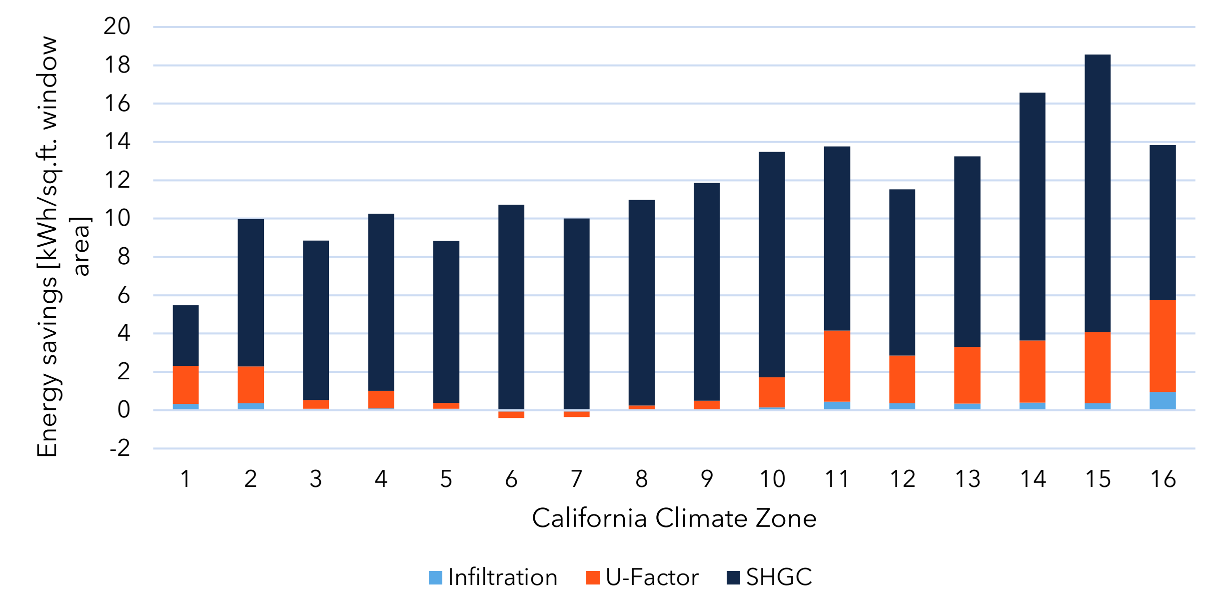



Energy cost savings from CRAWS vary depending on the climate zone. Inland climate zones with higher overall space conditioning loads (such as 14, 15, and 16) exhibit larger energy savings compared to mild coastal climate zones like 1 through 9. However, utility rates also significantly impact utility bills, so the savings are not directly proportional to space conditioning loads. CalMTA's analysis assigns utility rates based on utility service area.

The three factors that influence window energy savings are U-factor, SHGC, and infiltration. The impact of each factor varies depending on the building type and climate zone. For commercial buildings throughout California, however, the reduction in solar heat gains achieved through low-e coatings leads to overall energy savings. In mild coastal climate zones like 6 and 7, improvements in U-factor and infiltration rates can increase building energy consumption by eliminating some passive cooling. However, these penalties are relatively small compared to the savings generated from reducing solar heat gains. Figure 2 illustrates the savings contributed by each component in one example commercial building type, the small office (OfS).

[59] See Table 5 for definitions of the building type abbreviations.

**Figure 2. Average annual component energy savings for small office**




### 8.1.2 Peak demand reduction

CRAWS technologies reduce peak cooling demands by about 5% to 20% compared to existing windows.[60] Energy modeling indicates that maximum peak demand reduction generally occurs during summer months, when cooling loads are highest. Minimum peak demand reduction generally occurs during shoulder seasons, when HVAC usage is relatively low. The largest demand reductions were observed in Pacific Gas & Electric (PG&E) and Southern California Edison (SCE) service territories, with smaller impacts in the San Diego Gas & Electric (SDG&E) service territory.

### 8.1.3 Resilience

Buildings equipped with CRAWS technologies are better suited to accommodate load shifting events, as internal temperatures remain more stable and within a comfortable range for a longer period after the HVAC is set back or turned off in response to a demand-response signal or grid emergency. CalMTA performed energy modeling to assess the impact of improved commercial windows on interior space temperatures compared to buildings with SPC glass during a three-day power outage that coincided with extreme heat and cold events.[61] We found that CRAWS technologies delay the passing of major internal temperature thresholds (e.g., 85°F, 90°F) by 15-

[61] For this analysis, actual meteorological year (AMY) weather files were used: 2024 was chosen to represent a heat wave in Riverside (Sept. 9-15, 2024), and 2019 was chosen to represent cold in Lake Tahoe (March 1-11, 2019).

25 hours during a heat wave and delay the passing of major internal temperature thresholds (e.g., 60°F, 50°F) by 5-20 hours during a cold event.

### 8.1.4 Field installation

At the time of writing, CalMTA has a field installation of CSWs underway at Madison Elementary School in Madera, California. Classrooms at the school are the same size, with similar window and door configurations. Each classroom at the school is accessed from outside and is served by a packaged single-zone air conditioner with natural gas furnace. CalMTA installed CSWs on all windows in four classrooms and selected four classrooms to serve as a control group without CSWs.

Data collection started in September 2025 and will last for a year. CalMTA performed blower door testing on all eight classrooms and equipped each with air quality sensors that detect temperature, humidity, carbon dioxide ($CO_2$), volatile organic compounds (VOC), and particulate matter (PM). CalMTA also added door opening sensors and thermistors on the interior and exterior surfaces of windows and interior surfaces of CSWs. Energy data is also collected from the RTUs serving the classrooms, as well as supply and return air temperatures.

Preliminary blower door tests indicate that CSWs reduce infiltration rates in classrooms by roughly 8%-12%. Preliminary cooling season data observed during the month of September 2025 indicate that CSWs reduced HVAC cooling run time by 24% for classrooms with CSWs, while maintaining similar temperatures. During the month of January 2026, HVAC heating run time was reduced by 29% for classrooms with CSWs. CalMTA will share further data from the field study as it progresses.

## 8.2 Bill impacts

CalMTA used energy modeling to estimate the average annual total facility energy cost savings from adopting CRAWS technologies. We compared savings to a scenario where no action is taken, which was represented in this analysis using the SPC windows scenario. Annual utility cost savings were approximately 9% for each IOU as a weighted average of building type and climate zone.

Results summarized in Table 7 represent the total bill impacts for each modeled scenario. Negative values indicate bill savings. (All scenarios modeled resulted in bill savings.) Results are presented as a percentage reduction in the dollar amount of estimated customer bills on a whole-building basis. Since whole-building energy consumption includes lighting, water heating, plug loads, and miscellaneous loads, the percentages are lower than they would be if calculated solely for HVAC energy use.

**Table 7. Average annual whole-building cost savings, by fuel type and utility**

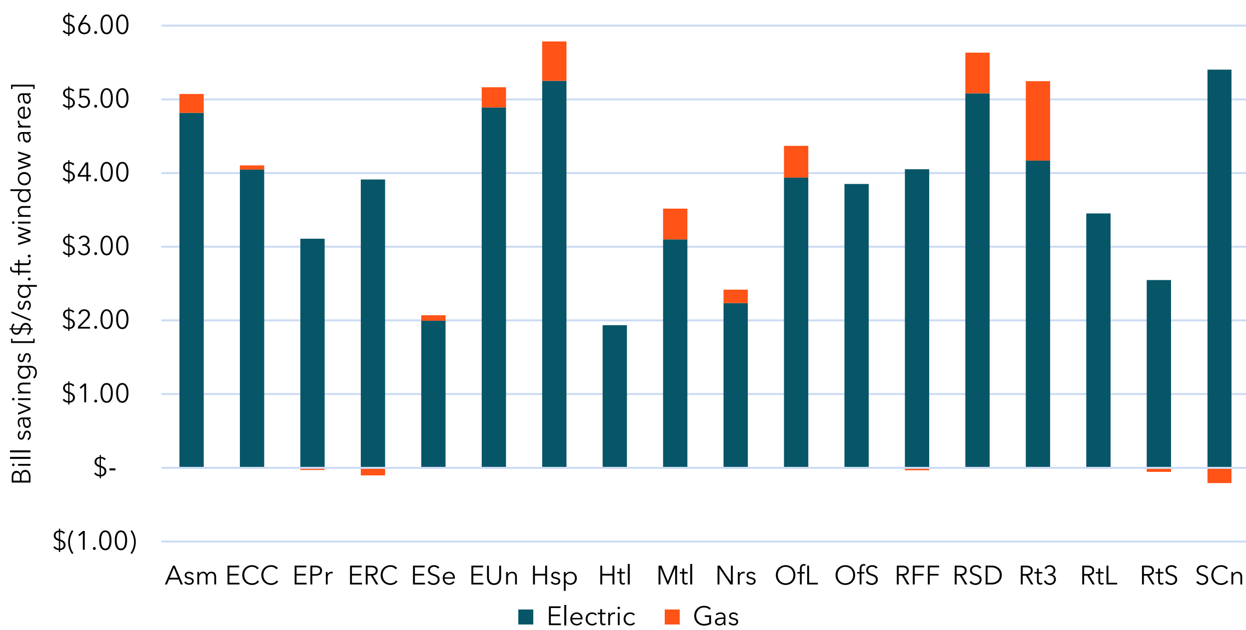
| Case | Electric | Gas | Total |
|---|---|---|---|

| | PG&E | SCE/SCG | SDG&E | PG&E | SCE/SCG | SDG&E | PG&E | SCE/SCG | SDG&E |
|---|---|---|---|---|---|---|---|---|---|
| CSW | -9% | -9% | -9% | -20% | -17% | -16% | -9% | -9% | -9% |

*Notes: Negative values indicate bill savings. Savings are compared against the existing windows for the prototype building.*

Bill impacts were calculated based on modeled energy consumption and peak demand in baseline and proposed models (Figure 3). For each energy model, the electric and gas bills were calculated using the mainstream commercial tariffs available in each model's particular climate zone.[62] Commercial gas utility rates are constant annually for SCG and SDG&E but vary by month for PG&E. Commercial electric rates are all time-of-use, so they vary by the hour of the day. These include a consumption charge ($/kWh) and in some cases a demand charge ($/kW, assessed monthly). The actual time-varying electric rates used by the three major IOUs in California were taken from CEC's MIDAS database for a calendar year (1/1/2025-12/31/2025).

**Figure 3. Average annual bill savings by building type**




Annual heating loads for commercial buildings in California are relatively low. Peak load reductions result in outsized bill reductions due to TOU rates and demand charges. Demand

[62] Nine electric rates and ten gas rates were used for this analysis. The electric rate IDs are as follows: USCA-PGPG-0600-0000, USCA-PGPG-0800-0000, USCA-PGPG-1100-0000, USCA-PGPG-1400-0000, USCA-SCSC-0800-0000, USCA-SCSC-1800-0000, USCA-SCSC-2400-0000, USCA-SDSD-1010-0000, USCA-SDSD-1020-0000. The gas rate IDs are as follows: PGE-GNR-1 Tier I, PGE-GNR-1 Tier II, PGE-GNR-2 Tier I, PGE-GNR-2 Tier II, SCE-GN10 Tier I, SCE-GN10 Tier II, SCE-GN10 Tier III, SDGE-GN03 Tier I, SDGE-GN03 Tier II, SDGE-GN03 Tier III.

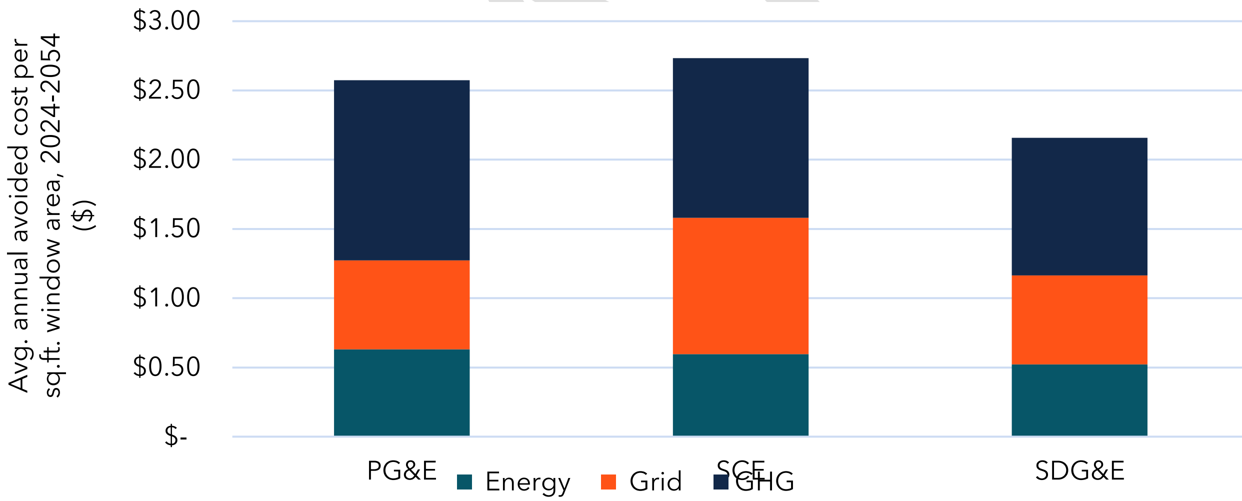
charges, which are driven primarily by cooling energy consumption, make up a large percentage of electricity bills for California commercial customers.

## 8.3 Avoided costs

CalMTA used CPUC's Avoided Cost Calculator (ACC), which provides a robust framework for evaluating the impact of fuel substitution and energy efficiency measures. The ACC estimates system-level utility costs of providing electric or gas on an hourly basis in $/kWh and $/therm. The avoided cost factors were multiplied by the modeled hourly unit energy savings (UES) outputs to develop annual avoided costs for each measure. The avoided costs were batched into three categories: energy benefits, grid benefits, and GHG benefits, which are the categories that are used for TSB reporting in the MTI Plan.

The avoided cost benefit for CSWs was calculated based on a start date of 2024 and extending through the estimated useful life of the product. The avoided cost benefit is shown in Figure 4, broken down by energy, grid, and GHG benefits.

**Figure 4. Annual average avoided cost per sq.ft. window area by IOU service territory, 2024-2054**




# 9 Product plan

## 9.1 Objectives

The CRAWS MTI aims to enhance availability, raise awareness, and establish consumer funding mechanisms for CRAWS technologies. The technical barriers for both CSWs and VIG for SPR primarily stem from low awareness, a lack of product performance data, performance ratings and reliability data, and an immature supply chain. VIG for SPR also faces technical barriers in effectively and reliably reducing infiltration, and the formation of condensation on poorly insulating existing window frames. While effective CSWs are already available, the supply chain for distributing and installing them in California is relatively immature. VIG technology performs well, but the scale of manufacturing and distribution is small and currently focuses on the new construction market. The lack of awareness within the building industry regarding VIG is reflected in the absence of test methods to evaluate and rate the performance of VIG for SPR when installed in existing window framing systems. Additionally, the lack of awareness is evident in the absence of ratings from programs like ENERGY STAR to inform consumer purchases of CSWs.

On the other hand, the past several years have seen advancements in readying the market to be able to adopt CRAWS technologies more widely. CalMTA aims to extend the momentum built by organizations such as the national laboratories, GSA, CEC, regional energy efficiency organizations (REEOs), and utilities that have actively tested and promoted window solutions.

### 9.1.1 Short-term objectives

In the short term (1-2 years), the MTI will seek to achieve the following objectives:

- ESCOs and utility energy efficiency program administrators are aware of the potential energy savings and NEBs of VIG for SPR and CSWs.
- AERC or a similar industry organization commits to developing a method for rating VIG for SPR.

### 9.1.2 Medium-term objectives

In the medium-term (3-5 years), the MTI will seek to achieve the following objectives:

- Municipalities will increasingly incorporate CRAWS technologies into their climate and energy action plans, recognizing them as a means to reduce emissions associated with operating their building stock.
- Utility energy efficiency programs increasingly provide incentives for CRAWS projects.
- Architects, design firms, ESCOs, CBOs, and HVAC installers increasingly evaluate and recommend CRAWS technologies as an upgrade option for consumers.
- AERC, or a similar industry organization, publishes a method for rating VIG for SPR, allowing an increasing number of VIG manufacturers and products to be rated by AERC.
- CRAWS technology is increasingly adopted by the CRE market, the MUSH market (municipalities, universities, schools, and hospitals), and by ESCO project portfolio.

### 9.1.3 Long-term objectives

In the long-term (6-10+ years), the MTI will seek to achieve the following objectives:

- The majority of commercial building owners in both ESJ and non-ESJ communities with SPC and DPC windows will recognize CRAWS technologies as an effective means to enhance building efficiency. During (or prior to) HVAC system upgrades, HVAC designers and installers will consider the potential of incorporating CRAWS technologies to reduce HVAC system sizing as part of standard practice, and by 2045, 50% of HVAC replacements or upgrades will include envelope evaluation.
- CalMTA will collaborate with ENERGY STAR to commence certification of CSWs, building off ENERGY STAR's certification program for residential storm windows.

## 9.2 Product plan actions

### 9.2.1 Field demonstration projects

*Short- to long-term action (1-10+ years)*

In-field demonstration projects, such as the one currently underway at Madison Elementary School in Madera, California, aim to raise awareness about the energy and non-energy benefits that CRAWS technologies can provide to buildings in California. Building on its current field demonstration, the CRAWS MTI will expand its field study sites to encompass a wider range of building types and climate zones. To achieve this, it will collaborate with other MTIs conducting field demonstrations, such as the CRTUs MTI. This collaboration will enhance efficiency and facilitate the assessment of the synergistic effects of CalMTA's MTIs. For instance, it will demonstrate how HVAC designers can utilize CRAWS technology to improve building envelope efficiency, thereby enabling them to downsize replacement systems.

In-field demonstration projects collect and share performance data, including energy performance and quantification of NEBs like thermal comfort, noise, and air quality. CalMTA will publish data from field demonstrations, including energy consumption, NEBs, and best practices to demonstrate the value proposition of CRAWS technologies and build upon lessons learned, with the aim of supporting ESCOs in evaluating or recommending CRAWS technologies as upgrade options for consumers.

*Medium-term action (3-5 years)*

Using case studies developed from field demonstrations to illustrate the business case for CRAWS technologies, CalMTA will collaborate with municipalities to incorporate CRAWS technologies into their climate and energy action plans, recognizing the potential to reduce GHG emissions associated with operating their building stock.

### 9.2.2 Stakeholder and industry collaboration

***Short-term actions (1-2 years)***

CalMTA will evaluate the need for expanded options for operable CSWs and will work with manufacturers and national labs to document the conditions that promote condensation and identify best practices for prevention and remediation. We will work with manufacturers to encourage them to submit products to AERC for rating.

***Short- to long-term action (1-10+ years)***

As outlined in the preceding section, CalMTA will collaborate with industry stakeholders, including the DOE, national laboratories, extra-regional energy efficiency organizations, and collaborative organizations, by establishing partnerships and sharing data from analysis and field installations. This initiative aims to enhance activity in the supply chain by encouraging HVAC designers to routinely consider the potential of CRAWS technologies in reducing HVAC system sizing during system upgrades, making it a standard practice.

***Medium-term action (3-5 years)***

CRAWS will collaborate with the DOE to expand the functionality of an existing CSW savings calculator to ensure applicability for California climate zones and building stock.

To further expand the VIG supply chain, CRAWS will collaborate with national laboratories, such as NLR, that are conducting research on VIG, to ensure that the latest research data informs industry standards as they are developed. For instance, NLR is leading studies to assess energy losses through existing window frames. This data can be used in part to design a system for rating the performance of VIG for SPR.

### 9.2.3 Certifying organization collaboration

***Long-term action (6-10+ years)***

VIG for SPR lacks a methodology for rating its performance in commercial applications. The CEC is currently developing a rating system for replacing SPC glass in residential applications. The CRAWS MTI will build off this momentum and serve as a catalyst to establish a rating system for commercial applications. A funding source will be established for AERC or a similar industry organization to develop a method for rating VIG for SPR. This method will enable an increasing number of VIG manufacturers and products to be rated by AERC.

CalMTA will collaborate with ENERGY STAR to certify CSWs, building off the precedent they established with their certification of residential storm windows. Uncertainty around future DOE funding for ENERGY STAR poses a risk that its ability to cover a new category of products would be limited. Additionally, there is a possibility that AERC may lack the capacity to develop a rating method for a new product type, given their significant commitments to other window attachment products.