# Thin Triple-Pane Windows

## Project Number ET25SWG0001

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## Acknowledgements

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## Disclaimer

# Executive Summary

Windows play a crucial role in residential building energy consumption, accounting for significant heat transfer despite their small surface area. The study's main objective is to evaluate emerging thin triple-pane window technologies in California's residential sector through literature review and subject matter expert (SME) interviews. California's residential landscape includes a diverse range of window types, with single-pane windows still prevalent in about 37% of the households.

Field and modeling studies by Lawrence Berkeley National Laboratory (LBNL), Northwest Energy Efficiency Alliance (NEEA) and Pacific Northwest National Laboratory (PNNL) demonstrate the efficacy of thin triple-pane windows, showcasing improved thermal performance compared to traditional double-pane windows. Thin triple-pane window have a central pane made up of thin glass sandwiched into a standard double-pane window with no key manufacturing and process modifications required, resulting in similar thickness and weight.  Key parameters such as U-factor and Solar Heat Gain Coefficient (SHGC) determine a window's energy efficiency. Thin triple-pane windows offer lower U-factors and SHGC than dual pane windows, resulting in better insulation and reduced heat loss.

SME interview findings highlighted energy efficiency as the primary driver for customer adoption, though market barriers such as limited manufacturers and high costs remain challenges. Thin triple-pane windows also provide substantial long-term non-energy benefits, including reduced sound transmission and decreased condensation. Economic analysis indicates favorable cost-effectiveness for only CZ01, CZ03 and CZ11 climate zones with an average Total Resource Cost (TRC) ratio of 0.85 and Total System Benefit (TSB) of $1,391 for all selected California climate zones that were evaluated (CZ01, CZ03, CZ06-07, CZ11-14).

## Introduction

Within residential building facades, windows make up about 7% of the outside surface area but account for 48% of envelope heat transfer. The energy required to heat and cool homes accounts for about 52% of the total building energy consumption, with the remainder allocated to plug loads, lighting, and water heating. Consequently, windows account for about 9% of the total energy use required for buildings and a total of 4% for total U.S. energy consumption [1]. To focus efforts on reduction in gas usage for space heating within California residential sector, including multifamily units and single-family homes, this emerging technology (ET) study was conducted to determine the energy-saving potential of thin triple-pane windows.

Various designs and strategies to increase window thermal performance have been developed and applied within the United States market, including emissivity coatings, low conductivity spacers and frames, gas buffers, and pane designs. These developments have reduced heat transfer between the atmosphere and building, reducing the load on both the home HVAC system and the grid during peak heating and cooling periods. Several field and modeling studies, including ones conducted by Lawrence Berkeley National Laboratory (LBNL) and the Pacific Northwest National Laboratory (PNNL), have demonstrated the efficacy of these designs, showcasing reduced heat transfer and greater usability of thin triple-pane windows over both previous designs of traditional thickness triple pane and the incumbent technology of double-pane windows [2, 3].

The attributes of thin triple-pane technologies were investigated through literature and subject matter expert interviews for application in the residential sector, including the physics behind the technology, advantages and disadvantages of the technology, and high-level energy savings.

## Background

California's residential landscape includes approximately 6.9 million single-family homes and 5.3 million multifamily units. The market for residential windows within California is diverse, with significant variation in the types of windows installed across homes. Single-pane windows are still prevalent in many older homes, with approximately 37% of households in the state still utilizing these windows with efficiency factors below recommended ratings [4]. In multifamily residences, the use of energy-efficient windows is becoming increasingly common. These buildings, especially those constructed before 1980, are often targeted for energy efficiency upgrades, including the installation of higher efficiency windows.

Double-pane windows, as the incumbent technology, are utilized in newer constructions and retrofitted homes, offering lower heat transfer and thus increased energy efficiency over single-pane designs. Triple-pane windows, particularly thin triple-pane windows, are gaining traction within manufacturing due to both their superior thermal performance and drop-in nature with the incumbent technology.

High efficiency windows are a fuel neutral measure which is reflected in both electric and gas savings, for customers and utilities. However, high efficiency thin triple pane windows have not been widely adopted in the residential market [4]. Some of the barriers include- limited availability of manufacturers, high incremental costs and low frequency of window retrofits. However, both working groups are resolving these market barriers through innovation and energy efficiency programs. The recent updates to the ENERGY STAR v7 Residential Windows Specification will also help to engage a stagnant market. This specification creates an opportunity for national alignment regarding high efficiency window products and can serve as a benchmark for utility programs across the country.

## Assessment Objectives

The main objective of this project is to collect market data and evaluate emerging thin triple-pane window technologies. To accomplish this task, an initial literature review was conducted to identify and summarize technology development and energy efficiency improvements. To build on this information, a list of three subject matter experts (SMEs) including researchers and market leaders was developed. Interviews were conducted to gather updated market data on thin triple-pane product offerings, efficiencies, and cost estimates.

### Key Parameters

Two key parameters dictate the energy efficiency of a window product and how well the units can regulate indoor temperature: U-factor and Solar Heat Gain Coefficient (SHGC). These variables indicate a window's resistance to conductive, convective and radiative heat transfer.

U-factor measures the rate of heat transfer through a window, including the glass, frame, and spacers. It indicates how well the window insulates against heat loss. A lower U-factor indicates lower heat loss and is the inverse of an R-value. This parameter is most impactful in heating-dominated climates with high thermal loads and is dictated primarily by the amount and type of material within the window unit.

Solar Heat Gain Coefficient (SHGC) measures a window's ability to block heat from sunlight. It is the ratio of solar radiation passing through the window to the total solar radiation incident on the unit. A lower SHGC indicates better blocking of solar heat, helping keep homes cooler. This is often achieved through low-emissivity (low-E) coatings that reflect infrared radiation. SHGC is most impactful in cooling-dominant or mixed climates with high solar loads and can be optimized per window by controlling the number and location of low-e coatings. While purchasing the windows, SHGC is a selectable parameter.

A modeling study by LBNL analyzed the impact of U-factor and SHGC on energy reduction in San Diego, CA, shown in Figure 1 below. Three current window products, including one thin triple-pane and two double-pane models, are plotted on each graph according to their rated U-factors and SHGC.

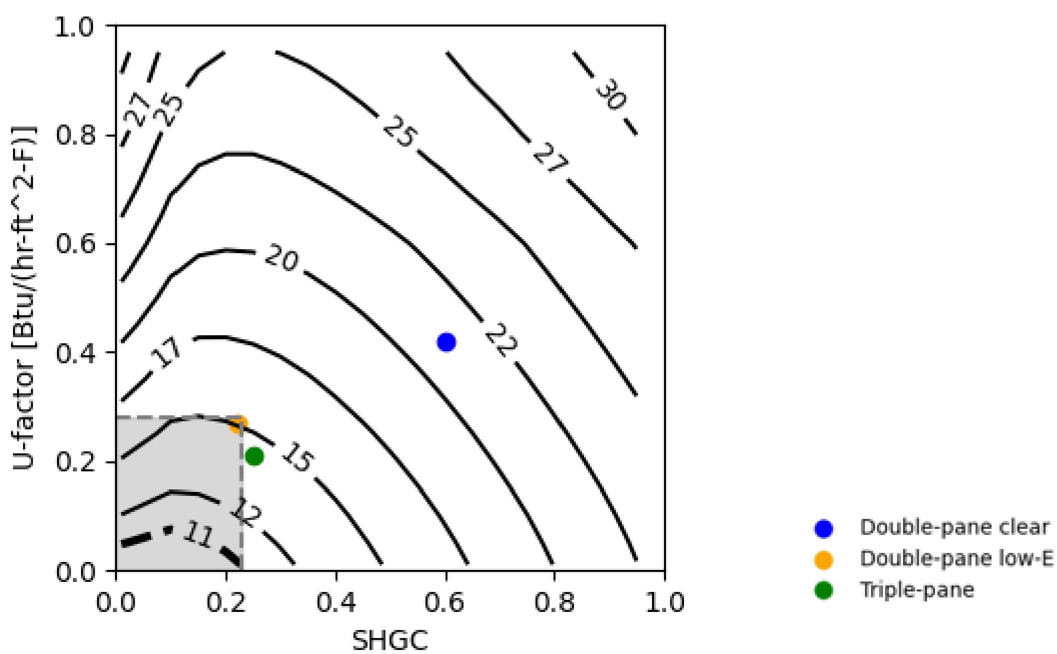


*Figure 1. Heating load requirements (MBTU) of varying U-factors and SHGC in San Diego, CA [4]*

# Technology Findings

## Product Assessment

### Incumbent Technology

Single-pane windows consist of one layer of glass placed within a wooden or metal frame. These have high U-factors and low insulation due to the increase in ability to transfer heat to the external environment, and decrease in sealing, allowing air transfer into and out of the home.

Windows with more than one pane are known as insulating glass units (IGU's). Double-pane windows are the current market and code standard in residential window technology and consist of two layers of glass separated by a spacer and a sealed air space, often filled with an inert gas. Typical thicknesses of these windows are under 0.75 inches and are the standard for production and installation into residential building facades. The U-factor for double-pane windows typically ranges from 0.30 to 0.50, and the SHGC for double-pane windows usually between 0.25 and 0.40.

The mean U-factor and SHGC for windows purchased within the U.S. market are 0.33 and 0.28, respectively [5]. However, California Title 24, Part 6 requires all new and replacement windows to have a U-factor of 0.30 and SHGC of 0.23 [6].

### Standard Triple-Pane

Standard triple-pane windows consist of three panes of glass with widths of 3 mm, separated by foam spacers and the two inner sealed spaces filled with an inert gas. These have varying dimensions depending on the manufacturer, but due to the added pane of and spacer, the dimensions of the frame of these windows are substantially larger than the incumbent technology, at about 1.25-1.5 inches thick. These windows are highly insulating, with U-factors below 0.2 and SHGC below 0.24 and visual transmittance (VT) levels similar to incumbent technology, due to low-emissivity coatings [5,7]. These can effectively reduce heat loss and energy consumption with an increase in insulation and decrease in overall heat transfer. However, due to the increase in both dimension and weight, these windows are more costly to produce and install. Thus, this technology is not able to be used as a drop-in replacement for the incumbent technology, and when combined with the increased price is not encouraged on the supply-push from manufacturers and builders.

**Thin Triple-Pane**

Thin triple-pane windows consist of three layers of glass: two outer panes with widths of 3 mm and a thin inner pane with a width between 0.7-1.2 mm. Foam spacers, about 7 mm wide, separate the outer and middle panes. The total width of the unit is comparable to double-pane windows, making it a drop-in replacement technology. The thin panes and spacers allow thin triple-pane windows to fit into standard window frames with a marginal increase in weight, suitable for both new constructions and retrofits [8].

Foam spacers maintain the correct distance between the panes and create sealed spaces for the gas fill, reducing convective and conductive heat transfer at the edges. Frames are typically made from materials with low thermal conductivity, such as vinyl or fiberglass. The spaces between the panes are filled with inert gases, usually krypton or argon. Krypton is preferred due to its density and lower thermal conductivity, resulting in better overall thermal performance. The configurations for standard double pane windows and thin triple pane windows are shown below in Figure 2, highlighting the locations of the low-emissivity coatings and location of thin glass within the foam spacer.

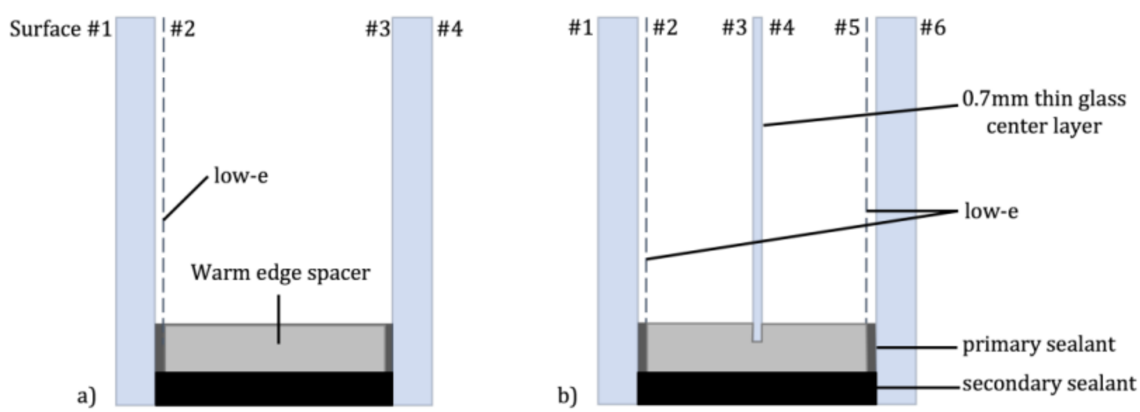


*Figure 2. a) Double-pane IGU; b) Thin-glass IGU [2,4]*

Thin triple-pane windows offer significantly lower U-factors than two pane windows, typically ranging from 0.15 to 0.25, indicating increased insulation and reduced heat loss. The SHGC for these windows can be as low as 0.20, effectively minimizing solar irradiance heat gain while maintaining good visible light transmittance [10]. These values achieve higher thermal performance than incumbent technology while overcoming manufacturing and installation barriers [12].

**Window Add-Ons**

Window add-ons or mounts are secondary enhancements installed on the exterior of existing windows to protect the window from damage, improve thermal performance, and overall efficiency. These add-ons provide an extra layer of solid material and a gas fill without replacing the entire window unit. An example of a storm window add-on is shown below in Figure 3.

*Figure 3. Storm Window Add-On [11]*

The additional layer and air space reduce heat loss, improving the U-factor and overall energy efficiency. These windows create seals over the current fenestration products, reducing air leakage by about 10-20% per window, further reducing heat loss. Extra layers also help dampen external noise, providing a quieter indoor environment. Furthermore, these add-ons protect the primary window from weather-related damage, extending its lifespan and offering seasonal flexibility by allowing ventilation during warmer months, and can either be a temporary or permanent installation depending on the requirements of the home. These add-ons can reduce thermal loads by 6-13% in heating (gas savings) and 8-13% in cooling (electric savings) within climate zone 6A in Minneapolis, MN, depending on initial sealing and window efficiency of the home [11].

The add-ons are often more affordable than full window replacements due to the ease of installation onto existing windows, making them a cost-effective option for upgrading existing windows. On average, each storm window-add on cost approximately $278 per window [11]. However, these windows do not offer the same level of performance as a complete higher efficiency window retrofit. In addition, they may sometimes affect the aesthetic appeal of the home, as they may not blend seamlessly with the existing window design. Maintenance can also be a concern, as the added layers may require regular cleaning and upkeep to ensure optimal performance due to the condensation build-up within the installation.

**Costs**

Estimated incremental increases in cost for thin triple-pane windows over standard windows come from manufacturing and material, as the dimensions of the technology create no difference in installation cost. The median increase in cost per square foot for thin triple-pane windows with U-factors below 0.22 was $3.70- $5.30 vs double-pane windows, according to an EPA market analysis [2]. However, a market transformation initiative by the Northwest Energy Efficiency Alliance (NEEA) indicates that after manufacturer stabilization with product lines, the incremental cost increase per square foot may reach $2-$4. This is in comparison to manufacturing cost increases of around $20 per square foot for standard triple-pane windows with U-factors below 0.25 currently available within the market [10].

## Literature Review

Several research institutions have conducted both modeling and field studies to provide an understanding of the potential energy savings of thin triple-pane windows across various climate zones. These institutions include the Pacific Northwest National Laboratory, Lawrence Berkeley National Laboratory, the U.S. Department of Energy, and various working groups aiming to transform the market and reduce heating and cooling energy consumption from the residential sector.

These studies have shown a substantial potential reduction in energy loss through building facade when utilizing thin triple-pane windows over standard dual pane code windows and high efficiency double-pane windows.

### PNNL Lab and Field Study

The performance benefits of thin triple-pane windows have been validated through various laboratory and field studies. One notable study conducted by the Pacific Northwest National Laboratory (PNNL) involved evaluating these windows in a field study within PNNL lab Homes, a matched pair of all electric homes located in Richland, WA [12]. The Lab Homes contain nine windows - three south-facing windows and two west-facing windows, with one of the south-facing windows and one of the west-facing windows being sliding glass doors. The experimental results included comparisons of heating, ventilation, and air-conditioning (HVAC) energy usage, condensation potential, occupant comfort, sound infiltration, and thermal performance.

During the heating season, the daily HVAC savings ranged from 3%-18% (0.2-18.7 kWh), with an average of 17% reduction at peak winter usage.  During the cooling season, the daily savings was 23%–41% (2.5-8.0 kWh), with the average of 33% reduction at peak summer usage.

These results highlight the increased savings for cooling. The higher thermal performance of the thin triple-pane windows also reduced the condensation potential on the interior surface during winter months and provided a more even distribution of temperatures throughout the home compared to the baseline.

The baseline U-factors and SHGC utilized for the PNNL study are given below in Table 1. The improvements in thermal performance of thin triple-pane over double-pane translate to substantial energy savings and enhanced comfort for occupants.

*Table 1.  U-Factors and SHGC for Baseline and Thin Triple Pane Windows Utilized in PNNL Study [12]*

| Parameter and Unit | Thin Triple-Pane | Double-Pane |
|---|---|---|
| **U-Factor (BTU/hr-ft$^2$-°F)** | 0.19 | 0.67 |
| **SHGC** | 0.27 | 0.68 |

In addition to the lab homes, PNNL conducted field tests in various residential buildings across the United States, including new construction and retrofit applications [12]. These tests aimed to validate the performance benefits and feasibility of thin triple-pane windows in real-world settings. The field studies included side-by-side comparisons of homes with thin triple-pane IGUs and standard windows, pre-retrofit and post-retrofit comparisons, and anecdotal comparisons through interviews with occupants, builders, and contractors. The results showed significant energy savings, improved interior surface temperatures, reduced condensation potential, and enhanced occupant comfort. Installation feasibility was demonstrated as the windows were successfully installed into standard double-pane frames without major modifications. These field sites confirmed the energy savings and additional benefits.

The field tests revealed varying levels of energy savings across different sites due to the overall thermal performance of the already existing sites. The site located in Yonkers, NY showed a 20% reduction in HVAC energy usage based on equipment runtimes, while the Helena, MT site demonstrated 1.5% savings due to already tight house conditions.

Table 2 below summarizes the heating season energy utility and HVAV equipment runtime savings and for the field demonstration sites with the U-factor and infiltration improvement of replaced windows between initial (baseline) and post-retrofit (test) values.

*Table 2. Utility and HVAC Runtime Savings Across PNNL Field Sites [12]*

| | U-Factor (Btu/hr/ft$^2$/F) | | U-Factor % Improvement | Utility Savings | HVAC Runtime Savings | Infiltration Measurements (ACH50) | | Infiltration % Improvement |
|---|---|---|---|---|---|---|---|---|
| **Site** | **Baseline** | **Test** | | | | **Baseline** | **Test** | |
| **Yonkers, NY** | 0.86 | 0.20 | 77% | 4.9% | 20.0% | 10.23 | 8.11 | 20.8% |
| **Helena, MT** | 0.50 | 0.20 | 60% | 2.3% | 1.5% | 1.33 | 1.3 | 2.2% |
| **St. Joseph, MI** | 0.86 | 0.20 | 77% | 14.5% | – | 9.34 | 8.52 | 8.8% |
| **Lab Homes** | 0.67 | 0.19 | 67% | 12.0% | – | 4.20 | 4.25 | NA |

## LBNL Modeling Study

Further research by Lawrence Berkeley National Laboratory (LBNL) involved modeling thin-glass triple-pane windows against existing double-pane products within various climate zones [13]. This study aimed to quantify the potential performance and energy savings opportunities.

The modeling setup included varying U-factor and SHGC within cooling-dominated, mixed, and heating-dominated climates to assess parameter impacts on energy usage and occupant comfort. The study found that thin triple-pane windows with lower U-values and SHGC significantly improved thermal performance with ultimate energy savings of 16% in heating-dominated climates like Minneapolis, MN, 12% in mixed climates like Washington, DC, and 7% in cooling-dominated climates like Houston, TX over double-pane windows as baseline.

During the heating season, the U-factor is crucial due to the temperature differential around the window. During the cooling season and for cooling loads, SHGC is more impactful due to reduced temperature differential but increased solar loads. The overall energy savings depend on the climate type and the ratio of temperature differential to solar loads. Three current window products, including one thin triple pane (3P-TG) and two double pane models (2P-LSG, 2P-LS4), were modeled within each climate zone and season according to their rated U-factors and SHGC, with thin triple pane showing decreased energy usage across each use case.

## PAWS Modeling Study

The energy saving potential of high efficiency windows is highly dependent on region. For example, climates with extremely cold winters will produce more favorable heating savings. A modeling study conducted by the Partnership for Advanced Window Solutions (PAWS) on potential energy and cost savings utilized a comparison of the most updated ENERGY STAR specifications on windows, version 7.0 over current standards for IECC climate zones 1-7 across United States cities [14]. The baseline U-Factor and SHGC for each region came from current code minimums within the jurisdiction, or a baseline of 0.35 and 0.30 respectively. Table 3 demonstrates energy savings for a 3’ X 5’ window, defined by ENERGY STAR version 7 criteria, over a code baseline for individual regions.

*Table 3. Electric and Gas Savings for Performance Parameters based on Climate Zone [14]*

| IECC Climate Zone (model city) | Baseline | | Performance | | Electric Savings | Gas Savings |
|---|---|---|---|---|---|---|
| | U-factor | SHGC | U-factor | SHGC | kWh/window | Therms/window |
| **1 (Miami, FL)** | 0.35 | 0.25 | 0.32 | 0.23 | 6.25 | 0.03 |
| **2 (Phoenix, AZ)** | 0.35 | 0.25 | 0.32 | 0.23 | 7.96 | 0.09 |
| **3 (Charleston, SC)** | 0.35 | 0.30 | 0.28 | 0.23 | 17.07 | 0.21 |
| **4 (Philadelphia, PA)** | 0.32 | 0.40 | 0.24 | 0.40 | 8.94 | 1.26 |
| **5 (Salt Lake City, UT)** | 0.32 | 0.30 | 0.22 | 0.30 | 1.45 | 2.3 |
| **6 (Minneapolis, MN)** | 0.32 | 0.30 | 0.22 | 0.30 | 2.60 | 2.98 |
| **7 (Anchorage, AK)** | 0.30 | 0.30 | 0.22 | 0.30 | 2.09 | 3.36 |

## CalNEXT Modeling Study

A report completed by CalNEXT aimed to evaluate the energy savings and cost-effectiveness of high-efficiency windows, characterized by improved U-factors and SHGC as the parameters of importance. Baseline energy use simulations were performed using the DEER Residential Prototypes, modified to reflect the 2022 California Energy Code mandatory U-factor requirements for new construction [15]. The measure case simulations utilized the same prototypes with the updated U-factors and SHGC values based on the ENERGY STAR Residential Windows v7.0 Specification Requirements.

The findings demonstrated significant energy savings and cost-effectiveness of high-efficiency windows across various residential building types and climate zones in California, including mobile homes, single family residences, and multifamily residences. For example, the measure case U-factors ranged from 0.25 to 0.28 (double pane windows), and SHGC values from 0.23 to 0.40, compared to baseline U-factors of 1.09 to 0.5 and SHGC values of 0.8 to 0.6 that exist in current vintages of homes within the California (market baseline).

The energy modeling results showed average savings of 1,093 kWh and 23 therms per window, with a Total System Benefit (TSB) of $2,204 and a Total Resource Cost (TRC) ratio of 1.23. TSB represents the dollar value of energy, capacity, and greenhouse gas benefits over the program's lifecycle, while TRC measures the relative costs and benefits to both participants and non-participants. These improvements translate to substantial energy savings and enhanced comfort for occupants, making double-paned windows a viable option for reducing energy consumption in residential buildings.

## SME Interview Findings

### Interview Questions and Response Rates

The objective of this section is to summarize the key findings from subject matter expert (SME) interviews. The interviews were conducted as a part of this emerging technology (ET) study to gain insights from various stakeholders on aspects of thin triple pane windows: understanding of emerging technology, market characteristics, and gas and electricity energy saving potential. The interviews were conducted from March to April 2025. The organizations interviewed are listed in Table 4, consisting of research institutions, working groups, and product manufacturers. The response rate is summarized in Table 5. The interview length was 45-60 minutes on average. Amazon gift cards worth $50 were shared with them after the interview, if accepted by the organization. As indicated in Table 5, both a response rate and participation rate of 100% were recorded.

*Table 4: List of organizations*

| Name of Organization |
|---|
| 1. Organization A |
| 2. Organization B |
| 3. Organization C |

*Table 5: Organization response rate*

| Number of organizations contacted | Number of organizations that responded | Target number of interviews | Actual participation | Response rate | Participation rate |
|---|---|---|---|---|---|
| 3 | 3 | 3 | 3 | 100% | 100% |

The focus of these SME interviews was centered around the understanding of thin triple pane window technology development, associated market barriers, usage pre-qualifications, range of cost impacts, energy efficiency, and market characteristics. Refer to Appendix A for the interview questionnaires for each SME. The individual SME responses and biographies can be found in Appendix B.

## Key Findings

Following is the summary of the key findings of (3) SME interviews:

### Market findings:

a) Energy Efficiency was cited as the most driver for customers purchasing high performance replacement windows, however the motivation is dependent on local climate conditions. All three SMEs cited that free ridership is not a concern for implementation of this measure in California.

b) Organization A's research suggests that window distributors and contractors tend to be uninterested in selling high performance window products, creating a significant barrier to broader adoption. According to other SME, limited manufacturers of thin triple windows is one of the main barriers in adoption.

**Best installation and usage practices:**

a) Thin triple pane windows don't have any customer pre-qualifications as such. Our study demonstrated that there is no noticeable difference in comparison to double pane windows. The architect SME confirmed that thin triples met the structural, dimensional, and aesthetic requirements of their project.

b) Some manufacturers reported that thin glass is easy to work with and manufacturing is less labor intensive. But this advantage may be manufacturer specific.

**Energy and efficiency savings:**

a) According to one SME, energy savings are primarily driven by SHGC, since the climate in California is mild and dominated by solar loads.

b) According to one SME and his experience in market transformation programs, U-factor of windows plays a significant role in determining energy savings. The value proposition becomes weak as the climate becomes warmer and warmer. A spreadsheet calculator created by PAWS team would be a valuable tool for estimating energy savings in different CA climate zones.

**Cost observations table:**

These costs are range estimates, as the market share for thin triple pane windows is still relatively small as compared to the incumbent technology. Due to the ongoing development of technology and manufacturing prices, these estimates are expected to continue to change.

*Table 6: Incremental cost table*

| Incremental cost premium of thin triple pane window over code minimum double pane window | Reference |
|---|---|
| $6 per sq. ft. | SME interview- Organization A |
| $2-$7 sq. ft. | SME interview- Organization B |
| $48/$54 for 15 sq. ft. window depending on the U-factor [13] | ENERGY STAR v7 reference and cited by all SMEs |

## Cost Effectiveness Analysis

To determine the energy saving potential of thin triple pane windows in select CA climate zones, this study leveraged existing high performance window incentive calculator created by PAWS working group. The following were the assumptions of U-factor and SHGC for baseline and measure cases. The baseline values refer to new construction baseline noted in Title 24, Part 6. The measure case values represent a typical thin triple pane window.

*Table 7: Assumptions for Baseline and Measure Cases*

| **Baseline Double Pane Window** | | **Performance Thin Triple Pane Window** | |
|---|---|---|---|
| U-Factor | SHGC | U-Factor | SHGC |
| 0.3 | 0.23 | 0.2 | 0.23 |

Assumptions:

1) According to previous research, the national building stock market baseline is much lower performing than our assumption for baseline. The potential gas and kWh savings for these climate zones could be different if market baseline is used instead of new construction baseline. However, we cannot go above a U-factor of 0.35 or a SHGC of 0.5, while selecting baseline window in the spreadsheet calculator created by PAWS. The electric savings are primarily SHGC/cooling dominated, whereas the gas savings are lower for higher SHGC window products.
2) The following CA climate zones are available for selection in PAWS tool: CZ01, CZ03, CZ06-07, CZ11-14.
3) The PAWS calculator assumes 2006 IECC single family detached house, (23.8) 15 sq.ft. windows per home and common building characteristics for building envelopes.
4) The incremental cost is assumed to be $48 per 15 sq.ft. window, which is equivalent to $3.2 per sq.ft. [14].

Table 8 shows the annual gas energy savings and customer payback for select CA climate zones. The utility rates are based a recent GET study and are included in appendix C. The payback period without any end user rebate ranges from 10.3 years to 39.04 years. The percentage annual gas savings varies from 8-12% depending on climate zone.

*Table 8: Annual Gas Energy Savings and Simple Payback*

| CA Climate Zone | City | % Annual Gas Savings | Therm Savings/ Window | Therm Savings/Home | Therm Savings/sq.ft | Total Annual Cost Savings | Simple Payback w/o rebate (yrs) |
|---|---|---|---|---|---|---|---|
| CZ01 | Arcata | 11 | 2.77 | 66 | 0.18 | $111 | 10.30 |
| CZ03 | Oakland | 9 | 1.79 | 43 | 0.12 | $72 | 15.81 |
| CZ06 | Torrance | 12 | 0.81 | 19 | 0.05 | $29 | 39.04 |
| CZ07 | San Diego | 12 | 0.68 | 16 | 0.05 | $35 | 32.31 |
| CZ11 | Red Bluff | 8 | 1.8 | 43 | 0.12 | $75 | 15.18 |
| CZ12 | Sacramento | 8 | 1.59 | 38 | 0.11 | $66 | 17.28 |
| CZ13 | Fresno | 8 | 1.25 | 30 | 0.08 | $53 | 21.64 |
| CZ14 | Palmdale | 9 | 1.05 | 25 | 0.07 | $38 | 30.06 |

This study also used the Cost Effectiveness Tool (CET) for determining cost effectiveness and the feasibility of offering thin triple pane windows as a new measure. The CET selections are summarized in Table 9. The therm savings from Table 8 per sq.ft. were used as an input to the CET tool. The analysis assumed no kWh savings as SHGC was not changed in measure case. The end user rebate was also not considered. Refer Appendix C for utility rate assumptions.

*Table 9: CET Selections*

| Category | Selection |
|---|---|
| Proposed Measure Name | Thin Triple Pane Window, U-value 0.2 and SHGC 0.23 |
| Avoided Costs and Market Effects | 2024, 5% |
| Use Category | BldgEnv |
| Use Subcategory | HeatCool |
| Technology Group | Fenest |
| Technology Type | WinFilm |
| Building Type | SFm |
| Climate Zone | Available selections in PAWS tool- CZ01, CZ03B, CZ6-7, CZ11-14 |
| Sector | Residential |
| Measure Application Type | New Construction |
| Normalized Unit | Area-100Win (per 100 sq.ft. window) |
| EUL (Equipment Useful Life) | 20 years |
| NTG (Net-to-Gross Ratio) | 0.6 |

The TRC (Total Resource Cost) ratio of 0.85 and TSB (Total System Benefit) of $1,391 is obtained assuming equal distribution of one house for each climate zone. TRC and TSB vary with climate zone as shown in Table 10. As summarized in SME interviews, the value proposition of this emerging technology becomes weak as climate becomes warmer and warmer. However, more accurate computation can be done by leveraging residential prototype models specific to California, such as Database for Energy Efficient Resources (DEER).

*Table 10: Summary of TRC and TSB values*

| CA Climate Zone | City | % Annual Gas Savings | TRC Ratio | TSB |
|---|---|---|---|---|
| CZ01 | Arcata | 11 | 1.62 | $330.09 |
| CZ03 | Oakland | 9 | 1.04 | $213.21 |
| CZ06 | Torrance | 12 | 0.46 | $94.08 |
| CZ07 | San Diego | 12 | 0.41 | $83.10 |
| CZ11 | Red Bluff | 8 | 1.05 | $214.46 |
| CZ12 | Sacramento | 8 | 0.93 | $189.44 |
| CZ13 | Fresno | 8 | 0.71 | $145.13 |
| CZ14 | Palmdale | 9 | 0.6 | $121.95 |

## Conclusions

Previous research conducted by various institutions, including Pacific Northwest National Laboratory (PNNL), Lawrence Berkeley National Laboratory (LBNL), and other working groups have demonstrated the substantial energy efficiency and benefits of thin triple-pane windows compared to code minimum double pane windows. The studies on thin triple-pane windows show significant modeled energy savings and improved thermal performance compared to double-pane windows across every climate zone within the US, while providing several non-energy occupant comfort benefits. The impact of SHGC and U-factor varies by region, with SHGC being more critical in warmer climates to reduce solar heat gain, while U-factor is more important in colder climates to prevent heat loss. For California climate zones, optimizing both SHGC and U-factor is essential.

From the SME interviews, energy efficiency was cited as the most driver for customers purchasing high performance replacement windows, however the motivation is dependent on local climate conditions. Some of the barriers in adoption of this measure include limited availability of manufacturers of thin triple-pane windows, high incremental costs, and lack of interest by contractors and distributors.

This study also conducted economic and cost effectiveness analysis by leveraging the existing window incentive calculator created by PAWS working group. The percentage annual gas savings vary between 8-12% depending on the climate zone. Overall, a TRC ratio of 0.85 and TSB of $1,391 is obtained for the CA climate zones selected (CZ01, CZ03, CZ06-07, CZ11-14).

In addition to energy savings, thin triple-pane windows offer several non-energy benefits, including reduced sound transmission, decreased condensation within the inner panes of glass, and increased occupant comfort due to more consistent building temperature maps.

**Appendix A: SME Interview Questionnaire**

1. What has your experience with window programs been to date and what opportunities do you foresee for high efficiency windows?

2. Can you share the most impactful research findings related to triple pane windows?

3. What would be the expected heating savings for CA as a mixed and cooling dominated climate?

4. Do you have insights on how the U-factor and SHGC would differ for the climates within CA compared to the studied locations?

5. What are some market challenges preventing the adoption of triple pane windows?

6. Can you share your insights on pre-qualifications for triple pane windows?

7. What is a general comparison of measure cost estimation for material and installation of standard code windows vs triple pane – would there be a difference CA markets?
    a. Can you share your perspective on free ridership as far as a thin triple pane measure is concerned (Program participants would have implemented the measure in absence of the program – done it even if there is no incentive)?

8. What is a general estimate for cost effectiveness and utility savings of thin triple pane windows over code minimum windows?

9. What are the best installation and usage practices of triple pane windows?

## Appendix B: Individual SME Responses & Biographies

**1) Interviewee:** SME 1

**Organization:** Organization A

**Date of interview:** 3/21/2025

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**Background information:** SME 1 is currently working as a Principal Scientific Engineering Associate at Organization A. He is licensed Professional Mechanical Engineer in California and experienced in Product Design, Development, Testing with expertise in HVAC system and fenestration design.

**Interview Questions and Notes:**

1.What has your experience with window programs to date and what opportunities do you foresee for high efficiency windows (previous experience)?

A: I have been working at Organization A for over 15 years. My primary focus area of research is windows. Prior to this, I also worked at a windows manufacturing company.

2. Can you share the most impactful research findings related to triple pane windows?

A: We are actively doing analysis for the CEC project, and the final project report will be released around October 2025. The following are the key takeaways from the interim project report (published in October 2022):

a) The study estimates that there are at least 7 million homes (single and multifamily) in California which have windows that don't meet current minimum performance standards (maximum U-factor of 0.3 and maximum SHGC of 0.23). About 14,000 homes choose triple pane windows every year, including thin triples.
b) Incremental purchase price increases for triple pane windows are around $2-$7 per sq. ft.
c) Energy Efficiency was cited as the most driver for customers purchasing high performance replacement windows, however some interviewees said that motivation is dependent on local climate conditions.

3. What would be the expected heating savings for CA (a mixed and cooling dominated climate)?

A: I expect less energy savings due to mild cold climate in CA, but higher cost savings as utility rates in CA are on the higher side. Triple pane windows would be easy to sell for New Construction (NC) compared to Normal Replacement (NR) market.

4. Do you have insights into how the U-factor and SHGC would differ for the climates within CA compared to the studied locations?

A: Since solar loads are more dominant than thermal loads in CA climate zones, performance or energy saving potential will be more sensitive to change in SHGC (Solar Heat Gain Coefficient).

5. Can you share your insights into pre-qualifications for triple pane windows?

A: Nothing as such, triple pane windows are slightly heavier than double pane windows.

6. What is a general comparison of measure cost estimation for material and installation of standard code window vs triple pane – would there be a difference CA markets?

A: Incremental purchase price increases for triple pane windows are around $5 per sq. ft.

7. Can you share your perspective on free ridership as far as a thin triple pane measure is concerned (Program participants would have implemented the measure in absence of the program – done it even if there is no incentive)?

A: I don't think free ridership is of concern for high efficiency windows measure implementation in CA. Our study indicates that Energy Efficiency is one of the top drivers for purchasing and installing high efficiency windows.

8. Barriers specific to CA for market adoption & cost effectiveness?

A: Our research suggests that window distributors and contractors tend to be uninterested in selling high performance window products, creating a significant barrier to broader adoption.

**2) Interviewee:** SME 2

**Organization:** Organization B

**Date of interview:** 4/1/2025

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**Background information:** SME 2 has over 15 years of experience in Project Management and R&D. He brings in knowledge base of the residential windows and doors industry alongside a broader view of the adoption of emerging energy efficient technologies.

**Interview Questions and Notes:**

1.What has your experience with window programs to date and what opportunities do you foresee for high efficiency windows (previous experience)?

A: I have been in this market transformation role in Minnesota for about 1.5 years now. I have worked in the R&D of Cardinal Glass Industries for more than 10 years.

2. Can you share the most impactful research findings related to triple-pane or high efficiency windows?

A:

a) Windows measure is fuel agnostic or neutral from an energy savings standpoint.
b) Our market transformation study indicates that windows stay installed for about 40-50 years and it may survive two cycles of HVAC replacement. This can also help to downsize the HVAC equipment.
c) High efficiency windows add more shelter-in-place capacity during power outages in peak winters.

3. What would be the expected heating savings for CA (a mixed and cooling dominated climate)?

A: You can refer to spreadsheet created by PAWS (Partnership for Advanced Window Solutions) for estimating gas and kWh savings specific to different climate zones in California. However, the value proposition becomes weak for warmer climates like California compared to states like Minnesota. But high utility rates in California might help to nullify this effect. The energy saving potential of both standard and thin triple pane windows are comparable. However, thin triples are associated with non-energy benefits such as sound mitigation. The energy saving potential of this measure would be more if compared to the market baseline, compared to the new construction baseline.

4. Do you have insights into how the U-factor and SHGC would differ for the climates within CA compared to the studied locations?

A: We normally focus less on SHGC in our market transformation programs. SHGC is selectable. We believe that U-factor is a more significant parameter, and our market transformation programs focus on U-value compared to SHGC. SHGC is more significant in cooling dominated climate zones.

5. Can you share your insights into pre-qualifications for triple pane windows?

A: Thin triple pane windows don't have any customer pre-qualifications as such.

6. What is a general comparison of measure cost estimation for material and installation of standard code window vs triple pane – would there be a difference CA markets?

A: ENERGY STAR conducted a nationwide study of material costs of high efficiency windows. For standard triple pane windows, the incremental cost is $54/window. For thin triple, the incremental cost is somewhere between $54-100/window.

7. Can you share your perspective on free ridership as far as a thin triple pane measure is concerned (Program participants would have implemented the measure in absence of the program – done it even if there is no incentive)?

A: I don't think free ridership is of concern for high efficiency windows measure implementation in CA.

8. Barriers specific to CA for market adoption & cost effectiveness?

A: Thin triple pane window represents a smaller market compared to standard triple pane window. According to my research, there are hardly 2-3 manufacturers making thin glass triples. Limited availability of manufacturers and options could be one of the significant barriers in adoption. However, there are several manufacturers (~80-100 ENERGY STAR certified) making standard triple windows.

**3) Interviewee:** SME 3

**Organization:** Organization C

**Date of interview:** 4/8/2025

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**Background information:** SME 3 is a research economist at Organization C.

**Interview Questions and Notes:**

1. What has your experience with window programs to date and what opportunities do you foresee for high efficiency windows (previous experience)?

A: I am a research economist at Organization C, and my focus area is windows and window attachments for residential sector.

2. Can you share the most impactful research findings related to triple-pane or high efficiency windows?

A:

a) Our lab home studies showed improved energy savings, enhanced comfort, and moisture resilience for thin triple pane windows (heating energy savings of 12% and cooling energy savings of 27% if compared to double pane clear glass windows in eastern Washington State CZ- 5B)
b) Average U-value for new thin triples is taken to be approximately 0.2.
c) Thin triples also helped to reduce HVAC peak power reduction by approximately 17% during the winter heating season.

3. What would be the expected heating savings for CA (a mixed and cooling dominated climate)?

A: The potential gas energy savings for CA climate zones would be dependent on utility rates, average outdoor air temperatures, and what baseline you are considering (existing market baseline or new construction baseline).

4. Do you have insights into how the U-factor and SHGC would differ for the climates within CA compared to the studied locations?

A: I am not a windows expert, but U-factor is a more important parameter for heating dominated climate zones and SHGC for cooling dominated climate zones.

5. Can you share your insights into pre-qualifications for triple pane windows?

A: Thin triple pane windows don’t have any customer pre-qualifications as such. Our study demonstrated that there is no noticeable difference in comparison to double pane windows. The architect confirmed that thin triples met the structural, dimensional, and aesthetic requirements of their project.

6. What is a general comparison of measure cost estimation for material and installation of standard code window vs triple pane – would there be a difference CA markets?

A: Our study indicated that incremental cost for thin triple-pane windows is $6/sq.ft. compared to code minimum double-pane windows. The incremental cost premium is $54/window (15 sq.ft.) for triple pane windows if compared to double pane windows.

7. Can you share your perspective on free ridership as far as a thin triple pane measure is concerned (Program participants would have implemented the measure in absence of the program – done it even if there is no incentive)?

A: I don’t think free ridership is of concern for high efficiency windows measure implementation in CA.

8. Barriers specific to CA for market adoption & cost effectiveness?

A: Some manufacturers reported that thin glass is easy to work with and manufacturing is less labor intensive. But this advantage may be manufacturer specific.

## Appendix C: Utility Rate Assumptions (2023) [16]

| Climate Zone | Name of electric utility | Name of gas utility | Average rate [$/kWh] | Average rate [$/therm] |
|---|---|---|---|---|
| CZ01 | PG&E | PG&E | $0.41 | $1.68 |
| CZ02 | PG&E | PG&E | $0.40 | $1.70 |
| CZ03 | PG&E | PG&E | $0.41 | $1.68 |
| CZ04 | PG&E | PG&E | $0.40 | $1.70 |
| CZ05 | PG&E | PG&E | $0.41 | $1.68 |
| CZ06 | SCE | SoCalGas | $0.34 | $1.54 |
| CZ07 | SDG&E | SDG&E | $0.49 | $2.21 |
| CZ08 | SCE | SoCalGas | $0.34 | $1.54 |
| CZ09 | SCE | SoCalGas | $0.33 | $1.53 |
| CZ10 | SCE | SoCalGas | $0.33 | $1.55 |
| CZ11 | PG&E | PG&E | $0.39 | $1.75 |
| CZ12 | PG&E | PG&E | $0.39 | $1.74 |
| CZ13 | PG&E | PG&E | $0.39 | $1.76 |
| CZ14 | SCE | SoCalGas | $0.34 | $1.52 |
| CZ15 | SCE | SoCalGas | $0.32 | $1.55 |
| CZ16 | SCE | SoCalGas | $0.33 | $1.54 |

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