Title

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Advancing Building Performance: Field Results of Thin-Glass Triple-Pane Window Demonstrations

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ABSTRACT

To meet California and the nation's ambitious energy targets, energy use in the building sector must drop dramatically. Windows continue to be the lowest thermally performing envelope system in the nation's buildings, resulting in poor overall envelope performance and potential impacts to human health and comfort. Current best practice new window performance is typically met by double-pane low-solar-gain glazing. Thin-glass triple-pane windows are a highly promising next step forward in performance and have been deployed in two California multi-family sites to quantify field performance and building energy savings. The technology assessed offers the performance benefits of traditional triple-pane but with little increase in weight or cost, enabling incremental costs competitive with alternative energy reduction solutions for the building envelope. This paper covers a detailed investigation into the demonstration project and measured performance benefits of the windows after a full year of data collection.

INTRODUCTION

California aims to achieve aggressive energy efficiency goals, including Zero Net Energy (ZNE) residential and low-rise multi-family construction by 2020 and a 40% reduction in energy demand through retrofits (California 2015). Windows have historically been, and continue to be, the lowest thermally performing envelope system in California residences. Wall and attic insulation levels have increased significantly through the years, to the point where wall surface-to-surface thermal resistance is approximately R-15 $h \cdot ft^2 \cdot °F/Btu$ ($2.6\ m^2 \cdot K/W$) when accounting for framing and facing materials, while standard windows installed today achieve a surface-to-surface resistance of only R-2.3 $h \cdot ft^2 \cdot °F/Btu$ ($0.41\ m^2 \cdot K/W$). The overall effective thermal performance of a typical new construction wall in California with 15-20% window-to-wall ratio is reduced to around R-7.5 $h \cdot ft^2 \cdot °F/Btu$ ($1.3\ m^2 \cdot K/W$), or half of the performance of a windowless wall. This thermal imbalance is exacerbated in 6.5 million, or ~50%, of California homes (US EIA 2009) where walls containing single-pane windows result in an opaque-plus-window overall wall thermal performance of less than R-2 $h \cdot ft^2 \cdot °F/Btu$ ($0.35\ m^2 \cdot K/W$). This discrepancy leads to condensation issues, mold growth, and structural damage, especially in low-income homes with aluminum windows, which have a low Condensation Resistance Index rating (CR 12), whereas the current industry standard double-pane windows have CR of 56, and triple-pane windows have a CR of 65.

However, increasing the thermal performance of windows is typically expensive since currently available high-performance products require heavy glazing, leading to heavier and wider frames than industry standard. These changes result in difficulty and greater expense to install in both new and retrofit construction. Reducing the cost of high-performance windows to a point where they meet cost demands of the market requires reduced material costs, increased installation

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efficiency by maintaining window weight and frame sizing comparable to existing windows for retrofit applications and maintaining long-term air filtration and structural performance. High thermal performance triple-pane windows have existed in the market since the early 1980s, but adoption of the technology has been minimal. Sales of these windows have never reached higher than 2-3 percent of market share in the US and are even lower in California where less than 100,000 of the more than 12.2 million homes have triple-pane glazing. Thin-glass triple-pane IGUs are an emerging technology that can deliver high-performance windows at incremental costs competitive with other building envelope solutions, such as high-performance attics and walls.

This project demonstrates thin-glass triple-pane insulating glazing units (IGUs), which offer comparable thermal performance to traditional triple-pane windows but have a potential for lower costs and with similar weight and frame size. This innovation allows manufacturers to lower costs by utilizing existing frames designed for double-glazing, making installation easier and more affordable for both new and retrofit projects, as the weight and dimensions of the frames are well understood by existing contractors. The demonstration involves installations of baseline code-compliant double-pane windows and high-performance thin-triple windows in single-family homes and two multi-family sites, verifying the product's effective performance. This report will focus on one multifamily site, consisting of 16 individual dwelling units.

METHODOLOGY

Window Products

The double-pane baseline and thin-triple demonstration performance levels used, and the rationales, are as follows. The current residential standard in California (California 2019) requires a U-factor of 0.30 BTU/hr-ft2-F (1.7 W/m²·K) and SHGC ≤ 0.25, and is the performance level we consider the baseline installation for retrofit glazing in California. This performance level is typically met by double-pane low-solar-gain glazing with warm-edge spacers and vinyl frames. The thin-glass triple-pane IGU selected for demonstration in this project allows for up to a NFRC certified U=0.20 BTU/hr-ft2-F (1.1 W/m²·K) in a foam filled vinyl sliding window frame designed for double-pane glazing. The performance metrics utilized for this demonstration project are shown in Table 1 for evaluated performance. These performance levels are determined at NFRC specified conditions (NFRC 2025a, NFRC 2025b), actual performance will vary based on instantaneous environmental conditions and sun angles.

Table 1. Window Performance Metrics for the Demonstration Project

Performance Metric	Baseline Performance	Demonstration Performance	Evaluation Method
Installed window cost ($/window)	$800 - $900	$900 - $1300	Purchase price paid for demonstration windows
U-Factor (BTU/hr-ft2-F (W/m²·K))	Sliding: 0.30 (1.70)	Sliding: 0.21 (1.19)	NFRC certification
Solar Heat Gain Coefficient (-)	Sliding: 0.23	Sliding: 0.23	NFRC certification
Visible Light Transmittance (-)	Sliding: 0.54	Sliding: 0.41	NFRC certification

The demonstrated thin-triple design uses a traditional double-pane IGU as a basis, adds a thin-glass (0.028-0.063 in (0.7-1.6 mm)) center layer, a second low-e coating, and Argon gas in both gas cavities. The vinyl window frame is manufactured in Sacramento, Ca by a large volume new construction focused manufacturer. While typically supplied with double-pane glass, the frame design allows for up to a 1-inch (25.4 mm) IGU width, which is ideal for the thin-glass IGU design in this project.

The incremental cost for the prototype windows in this study came out to be between $100 and $400 per window. The lower end of incremental cost came on standard XO sliding window with annealed glass, which is the most common product sold in the California market, and the upper end of incremental cost came on a large three panel XOX slider that required tempered safety glazing on all glass lites. The $100 incremental cost to the consumer on the XO slider came to $6 per sf ($65 per sq m), which compares to the $1-$3 per sf ($11-$32 per sq m) incremental cost to the manufacturer of a typical triple pane upgrade (Energy Star 2021). The products utilized for this demonstration were prototypes and based on manufacturer feedback we expect the incremental price to go down to $3-$5 at volume.

There are several configuration possibilities with thin-triple glazing. This project utilizes the configuration shown in Figure 1(b). This construction is technology readiness level (TRL) 8 and is constructed with two spacers and glass thicknesses already in common practice within the window industry. Market success with this product will incentivize manufacturers to invest in the technology needed to reduce costs and increase durability. Figure 1(c) shows an example of a thin-glass triple-pane IGU concept currently in development with multiple manufacturers that optimizes potential manufacturing cost and durability. The cost of IGUs utilizing this configuration was not yet low enough for this project, and is currently TRL 5-7, depending on the specific technologies implemented.

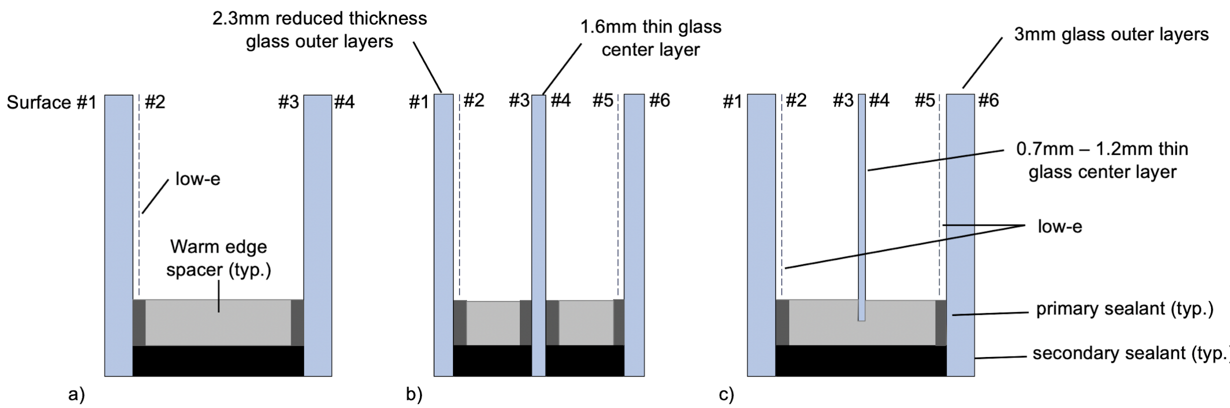

Figure 1 (a) Typical double-pane IGU with 1/8-inch (3 mm) glass; (b) Thin-glass IGU proposed fir this project (TRL 8) with 0.063-inch (1.6 mm) glass center layer and two spacers; and c) Thin-glass IGU concept with 0.028-0.047-inch (0.7-1.2 mm) center-pane and single spacer (TRL 5-7).

Demonstration Site

For this project thin triple windows were retrofitted into two multi-family sites, each with at least eight tenant units within low-income communities in California. Final site selection was made based on engagement with property managers and respective communities. This report concentrates on one of those sites. Examples of typical units at the site are shown from above in Figure 2a and with the exterior wall in Figure 2b. The development was built in 1971 and is in California climate zone 2 (HDD: 1750, CDD: 650). The site consists of 206 apartment units, of which five 500 sq ft (46 sq m) studio apartments with one existing aluminum single-pane 117 in x 57 in (2917 mm x 1448 mm) XOX slider and eleven 640 sq ft (59 sq m) one-bedroom apartments with an additional 70 in x 34 in (1778 mm x 864 mm) XO slider participated in this study. All windows on the site face East or West and have a 4-foot (1.2 m) overhang.

Two formal presentations on the study were held in the common area of the site and participation in the study was offered to all residents. Of the units choosing to participate in the study, seven face East and nine face West. Wall construction is uninsulated CMU and shared on three sides, except for end units, which have two shared walls. The roof is wood framed with gravel ballast and a thin layer of blown-in cellulose insulation on the ceiling deck. Heating is accomplished through a single wall mounted gas heater in each unit controlled by a wall mounted thermostat and cooling is through a stand-alone 120v plug-in through-the-wall air-conditioner with an internal thermostat. The models and vintages of heaters and air-conditioners vary between housing units.

Figure 2 Typical demonstration site building with approximate location of shared walls identified of right, and example of a one-bedroom exterior wall with XOX and XO sliders and 4-foot (1.2 m) overhang.

Measurements

The Measurement and Verification (M&V) methodology employed for this project is consistent with Option B as described in the International Performance Measurement and Verification Protocol (IPMVP) Core 2016. This option involves isolating the retrofit, in this case the windows, and measuring their effect on HVAC energy consumption as well as the performance of the windows by themselves. The intent of this M&V plan was to verify the window retrofits' ability to reduce heat transfer through the window. Thereby improving energy performance and reducing associated energy consumption (heating and cooling) of the overall dwelling, while delivering improved occupant comfort. All measurements, data collection, surveys, and interactions with demonstration participants were IRB reviewed and approved before any action was taken.

At each pilot site, the team surveyed building characteristics including window and envelope properties, HVAC system types and capacity, and installed sensors to monitor energy, thermal heat transfer, and comfort-related parameters. Pre-retrofit baseline conditions were continuously monitored for at least 12 months at each site and the team administered an occupant survey during this time. The occupant survey gathered information on household characteristics, occupancy patterns, space conditioning use, and occupant experience and comfort (across seasons) of the tenant units in their current conditions. Post-retrofit monitoring was for 12 months, and the team administered a second occupant survey at the completion of this phase. The post-retrofit occupant survey gathered information on space conditioning usage, occupant experience and comfort in the home since the retrofit, as well as any changes in household characteristics or occupancy patterns since the baseline. A site M&V plan including all monitoring equipment was customized by site based on the initial surveys. A list of typical monitoring points is included in Table 1. The specific monitoring points and data collection intervals varied based on the individual requirements of the units.

Table 1. Typical Data Collected from Each Test Site

Data Point	Data type (unit)
HVAC fan and compressor	Energy (W)
Supply air	Temperature (°F/°C)
Return air	Temperature (°F/°C)
Furnace natural gas consumption	Valve position (on/off)
Room air	Temperature (°F/°C)
Heating setpoint	Temperature (°F/°C)
Cooling setpoint	Temperature (°F/°C)
Room relative humidity	RH (%)

Occupancy	(on/off)
Exterior air	Temperature (°F/°C)
Exterior relative humidity	Temperature (°F/°C)
Site energy	Monthly utility bill (kWh)
Exterior glass	Temperature (°F/°C)
Interior glass	Temperature (°F/°C)
Window sash position	(open/closed)

RESULTS & DISCUSSION

Thermal Performance

The key metric evaluated in this project is the energy savings of the high-performance window upgrade, and the incremental value (energy and non-energy) the windows provide. There were data collection issues in several of the units over the monitoring period, primarily due to unintentional occupant tampering. Of the 16 total sites in the study, we were able to collect what we consider valid cooling energy data from 10 sites and valid heating energy data from 11 sites. This data is presented below in Figure 3 in a weather normalized form. Normalization was performed to account for variations in weather conditions between pre-retrofit and post-retrofit periods by cooling degree days (CDD) with a baseline of 65 °F (18.3 °C). This format provides the most accurate direct comparison of the pre and post conditions.

In all but three cases less energy was utilized in the post retrofit scenario, with an average energy use reduction of 25%. Despite all these units having very similar sizes, occupancy, and configurations there is significant variation in energy use between units, with a range of 250 - 1850 kWh per year in the pre-retrofit case and 200 - 1700 kWh per year in the post retrofit case. This wide variation is likely primarily due to occupant behavior variations. For instance, S107, which utilized the most cooling energy in the study, maintained a cooling setpoint of 68 °F (20 °C), while unit S116, which utilized the least cooling energy, maintained a cooling setpoint of 78 °F (25.6 °C). We did not see a significant difference between east and west orientations or between double and triple pane retrofit options. The latter is not surprising since the SHGC for both double and triple pane units was similar.

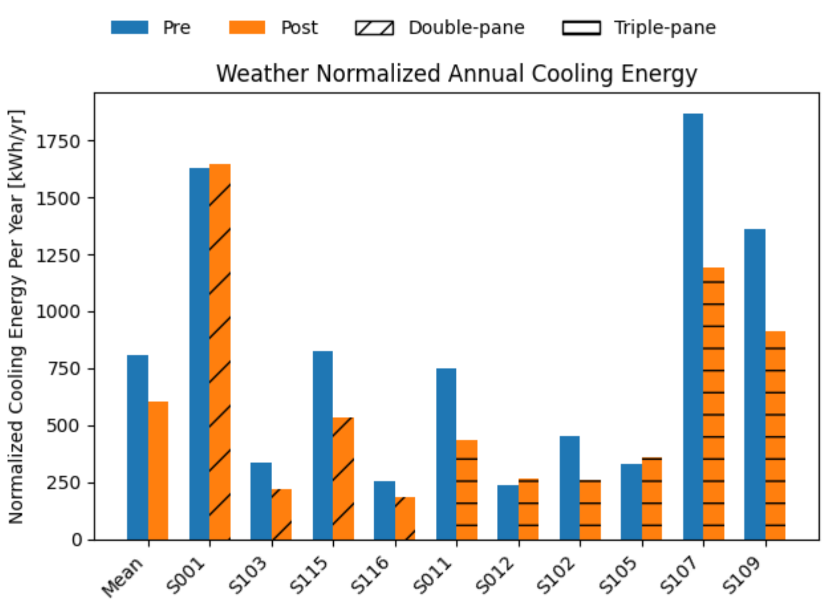

Figure 3 Weather normalized annual cooling energy use by dwelling unit, showing a mean decrease of 25% in energy over the monitored period.

Heating use for each unit was similarly monitored and is presented below in Figure 4 in a weather normalized form. Normalization was performed to account for variations in weather conditions between pre-retrofit and post-retrofit periods by heating degree days (HDD) with a baseline of 65 °F (18.3 °C). Due to the configuration of the heaters at this site, we were unable to directly measure the gas flow, so the time each heater was on is used as our metric for evaluation. This is a reasonable proxy for energy savings since all heaters in this study function with constant gas flow. The results show that the mean heating energy was reduced by 4% and generally increased for 4 units, decreased for 5 units and two units had negligible heat use pre and post retrofit. These results conflict somewhat with the occupant survey, which generally report reduced perceived heating use, and an increase in thermal comfort during the heating season. There are numerous potential reasons for this discrepancy including variations in unit configurations, occupant behaviors, and the reduction of solar load due to the low solar gain windows utilized in the demonstration. Units with increased heating energy consumption can be explained by unexpected occupant usage of the heating system. In addition, the 33.6% increase in heating energy consumption observed in unit S104 may be inaccurate, potentially due to constantly open windows to accommodate pet access, which could significantly skew heating usage data.

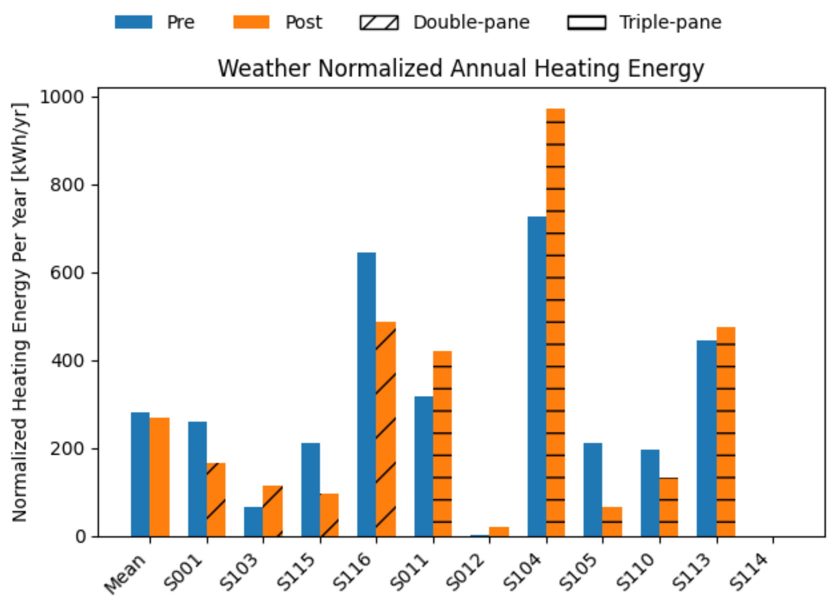

Figure 4 Weather normalized annual heating energy use by dwelling unit, showing a mean decrease of 4% in energy over the monitored period.

Overall, comparing the pre-retrofit and post-retrofit energy consumption, there is a 19.5% decrease in the weather-normalized annual heating and cooling energy consumption total. However, there is a diverse magnitude of energy savings across the 14 apartment units, ranging from a 42.3% decrease to 33.6% increase total annual heating and cooling energy consumption after weather normalization. As previously noted, there are numerous potential reasons for wide variations in unit energy use, but primarily due to occupant behaviors.

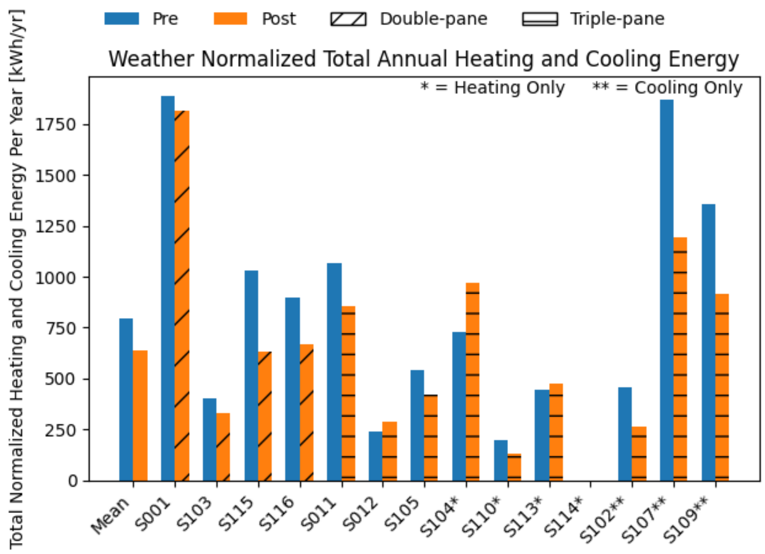

Figure 5 Weather normalized total annual heating and cooling energy use by dwelling unit, showing a mean decrease of 19.5% in energy use over the monitored period.

Occupant Comfort

A pre-retrofit occupant survey was conducted at the start of the project during monitoring equipment installation and a post-retrofit survey was conducted at the conclusion of the project when monitoring equipment was removed, approximately 2 years after the initial survey. Based on these self-reported results we can conclude that most respondents value comfort highly, both for themselves and family members. However, prior to the retrofit satisfaction with temperature in their home varies, with some respondents expressing dissatisfaction initially while others reported being satisfied. There was a general dissatisfaction with the baseline window performance though, in terms of keeping the home warm/cool and blocking outside noise.

80% of occupants noted external noise, both from vehicles and neighbors as a significant point of discomfort in our pre-retrofit survey. Figure 4 illustrates the high density of the housing and proximity of the complex to a nearby freeway, which are the primary causes of this discomfort. In the post retrofit survey, these same occupants noted significant reductions in noise. One occupant noted: “Before windows went in, I hear everything, now [it’s] so silent.”

Thermal comfort responses from occupants were very positive, with 90% reporting significant improvements in keeping their apartment warm during the heating season and cool during summer. 75% of participants noted reduced need for heater and air conditioner after the retrofit.

Figure 5 The demonstration site is located near a busy freeway. The noise from the freeway and from the dense occupancy of the site contributed to noise complaints from nearly all occupants. All occupants reported significant noise reductions in their units after the retrofit.

CONCLUSIONS

The deployment of thin-glass triple-pane windows in a California multi-family site has demonstrated significant potential for improving thermal performance, occupant comfort, and energy savings. The innovative window technology provides the benefits of traditional triple-pane windows without the associated increase in weight and cost, making it a feasible option for both new constructions and retrofits. The measured data over a year-long period showed a 25% average reduction in cooling energy usage, a 4% reduction in heating energy use and a 20% combined heating and cooling energy use reduction. Although heating and cooling energy results were mixed, possibly due to variations in unit configurations, occupant behaviors, and the reduction of solar load due to the low solar gain windows utilized in the demonstration. Occupant surveys revealed substantial improvements in thermal comfort and noise reduction post-retrofit, highlighting the windows' effectiveness in enhancing living conditions. These findings underscore the importance of adopting high-performance window technologies to meet California's ambitious energy efficiency goals improve the overall performance of the building envelope.

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