

Energy Savings Potential and Cost-Effectiveness Analysis of High Efficiency Windows in California

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ABBREVIATIONS, ACRONYMS, AND SYMBOLS

°F	Degrees Fahrenheit
Ar	argon
BCR	Benefit-to-cost ratio
Btu	British Thermal Unit
CZ	climate zone
ft.	foot, feet
ft ²	square feet
hr	hour
in.	inch, inches
Kr	krypton
LBNL	Lawrence Berkeley National Laboratory
LED	light-emitting diode
Low-E	Low emissivity
NREL	National Renewable Energy Laboratory
NREMD	National Residential Efficiency Measures Database
PG&E	Pacific Gas and Electric
PNNL	Pacific Northwest National Laboratory
PV	present value
SHGC	Solar Heat Gain Coefficient
SW	state-wide
TDV	Time Dependent Valuation
U-factor	Thermal conductance, Btu/hr-ft ² -°F
VT	visible light transmittance
WVP	Windows Volume Purchase
ZNE	Zero Net Energy

EXECUTIVE SUMMARY

High efficiency windows with U-factors below 0.25 Btu/hr-ft²-°F have historically been dismissed in California because most climate zones in the State are relatively mild, and the potential reduction in energy use has not been viewed as significant enough to justify the higher cost. Although energy efficiency programs have established various criteria for high efficiency windows, this study used $U \leq 0.25$, because it represents a cost pivot point where standard low-E double-pane windows are inadequate, and more expensive options must be considered. These options include double-pane windows with a second low-E coating on the room-side surface, triple-pane windows with insulating gas fill, multi-pane windows that use one or more suspended films instead of glass, and a few advanced technologies, such as aerogel or vacuum-insulated windows. For this study, four high efficiency options were analyzed in detail to determine their technological, cost, and market readiness:

1. Double-pane, argon fill, low-e on Surfaces 2 and 4, low Solar Heat Gain Coefficient (SHGC)
2. Triple-pane, argon fill, two low-e coatings, low SHGC
3. Triple-pane, krypton fill, two low-e coatings, low SHGC
4. Triple-pane, argon fill, two low-e coatings, high SHGC

All four high efficiency window types appear to have overcome any major technical barriers when produced by a reputable manufacturer, but the high costs of manufacturing, installation, and warranty remain serious hurdles, especially when combined with manufacturer and builder mark-ups. Estimated installed cost increments for the four options evaluated in this study are summarized in Table ES-1, and are expressed as a percentage of window area. These costs were developed based on reputable publications, price quotes for actual products, and rough estimates from window manufacturers and other industry experts. However, there were large variations in estimated costs depending on the source, and there may be scenarios where builders can obtain and install high efficiency windows for significantly less cost than indicated in Table ES-1. All incremental costs are relative to a 2019 Title 24, Part 6 code minimum standard design as defined in the Alternative Calculation Method (ACM) Reference Manual, which will include a U-factor of 0.30 and an SHGC of 0.35 in Climate Zones (CZs) 1, 3, 5, and 16, or an SHGC of 0.23 in all other CZs.

Time Dependent Valuation (TDV) regulated energy savings for each option in each California CZ was modeled in accordance with Title 24, Part 6 by Enercomp using the California Building Energy Code Compliance (CBECC-Res) software and California Energy Commission approved methods for evaluating potential new code requirements. The present value (PV) of TDV energy savings over a 30-year time horizon provides a target price for marginal cost-effectiveness. The target price (equal to the PV of energy cost savings) divided by the actual price provides an estimated benefit-to-cost ratio (BCR) under present technical and market conditions. Options with $BCR > 1.0$ meet the cost-effectiveness threshold. BCRs for each of the four high efficiency options applied to a blended 2,430 ft² single-family prototype house in each of the 16 California CZs are presented in Figure ES-1, along with

simple-average BCRs and construction-weighted average state-wide BCRs¹. The prototype houses have window areas equal to 20% of the floor area, and the windows are equally distributed on each side of the house. The blended prototype BCRs were calculated based on the weighted average of the results for the 2,100 ft² single-family prototype (45%) and the 2,700 ft² prototype (55%), which were modeled separately. Several other scenarios were modeled, including a 6,960 ft² eight-unit multi-family prototype, a single-family prototype with reduced window area, and a single-family prototype with realistic window distributions rotated in each of the four primary orientations.

TABLE ES- 1. ESTIMATED INCREMENTAL INSTALLED COST OF REPRESENTATIVE HIGH EFFICIENCY WINDOWS RELATIVE TO PROPOSED 2019 TITLE 24 CODE MINIMUM DOUBLE-PANE WINDOWS

Window Characteristics	Incremental Installed Cost normalized by window area (\$/ft ²)
Baseline: Low SHGC (U-0.30/S-0.23), High SHGC (U-0.30/SHGC-0.35)	\$0.00
Double-pane, argon fill, low-e on surfaces 2 and 4, low SHGC (U-0.25/SHGC-0.23)	\$4.23
Triple-pane, argon fill, two low-e coatings, low SHGC (U-0.21/SHGC-0.21)	\$7.00
Triple-pane, krypton fill, two low-e coatings, low SHGC (U-0.18/SHGC-0.21)	\$14.31
Triple-pane, argon fill, two low-e coatings, high SHGC (U-0.22/SHGC-0.44)	\$7.00

¹ Weighting based on CZ construction estimates used in Title 24 Part 6 Standards development activities.

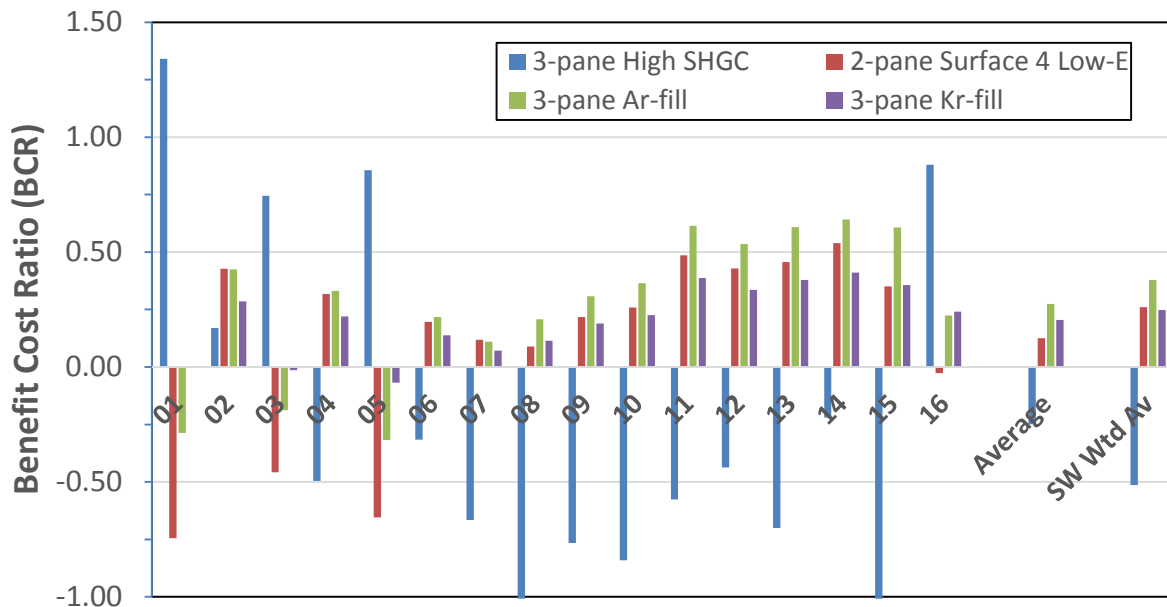


FIGURE ES- 1. ADVANCED GLAZING BENEFIT TO COST RATIO BY CZ AND WINDOW TYPE (2,430 FT² SINGLE-FAMILY, PV OF TDV OVER 30-YEAR LIFE CYCLE DIVIDED BY INSTALLED COST)

The results suggest that none of the high efficiency options are ready for broad deployment in California with the current cost structure. The triple-pane, argon-filled, high SHGC option may be cost-effective in CZ 1, but much of the savings is attributable to the choice of SHGC=0.44, which is higher than the proposed 2019 Title 24 code minimum of 0.35. This higher SHGC is similarly achievable with double-pane windows, but additional savings is provided by the low U-factor of triple-panes.

Despite the BCR results, there may still be opportunities for utilities and others to significantly lower the installed cost of high efficiency windows by stimulating demand through financial incentives and education about non-energy benefits, such as noise reduction and improved comfort. Such efforts could overcome re-tooling and low volume hurdles facing manufacturers, and instill higher confidence in high efficiency windows among California builders.

INTRODUCTION

As California continues to push toward Zero Net Energy (ZNE) in new residential construction and the number of new energy savings options declines, the potential for technologies previously viewed as nonviable for the California market should be revisited to determine if technological advances and market forces have significantly changed the landscape. One of these technologies is high efficiency windows with U-factors at or below 0.25 Btu/hr-ft²-°F, and solar heat gain characteristics tailored to the local climate. New products with higher performance have become available in recent years, costs have decreased for at least some features of high efficiency windows, and durability has improved significantly. The focus of this project was on insulated, multi-pane windows with gas fill and passive coatings to control heat and solar gains. Advanced technologies such as vacuum insulated glazing, electrochromic windows, and thermochromic windows, were not considered viable for large-scale deployment in the near-term due to cost, availability, and technical challenges, and are addressed only briefly in this report.

The production housing market for triple-pane windows remains elusive in the United States (U.S.), despite a prosperous market in Europe. The current market share of triple-pane windows is estimated by experts to be 2-3% of residential window sales in the U.S. (Ducker 2016), about 5% in the western region, and less than 1% in California. Market penetration in the U.S. was limited to 1.4% for windows meeting the Energy Star Most Efficient Windows criterion of $U \leq 0.20$ (Ducker 2016), despite the availability of 444 triple-pane window models (Evergreen Economics 2017), although many of the triple-pane windows listed in the National Fenestration Rating Council (NFRC) database are not actually produced at significant levels. Most sales in North America have occurred in Canada, and to a lesser extent in the colder U.S. climate regions. In California, there are very few documented applications of triple-pane windows except in custom applications.

Frontier Energy and Enercomp investigated the technical characteristics of high efficiency window options in 2017, cost drivers associated with high efficiency windows, and cost-effective applications in California based on Time Dependent Valuation (TDV). Triple-pane windows were the primary emphasis of the study, and are featured in this report, but some insights into the highest performing double-pane windows and quadruple glazed windows will also be presented. Our investigation leveraged work previously done by Evergreen Economics to assess the California market for triple-pane windows, supplemented by additional interviews with window and glass manufacturers, builders, and other industry experts to fill in a few gaps. It should be noted that no California production builders were found that had actually installed triple-pane windows, but several of them had obtained prices in the past, and followed the window industry closely. A full list of stakeholders interviewed for this project is provided in the Acknowledgments section.

Additional background information about high efficiency windows programs and the current state of the market in California and nationwide can be found in the Evergreen Economics memo to PG&E entitled “PG&E Codes and Standards Efficient Windows Market Study” (Evergreen Economics 2017). Market barriers, builder attitudes, lifecycle costs, and other topics related to the long-term market viability of high efficiency windows will be the focus of an upcoming Master Builder study led by TRC, and are addressed only at a high level in this report.

TECHNICAL DISCUSSION

There is no formal definition of high efficiency windows that establishes a particular set of window features or minimum performance characteristics. For this study, we chose to limit our analysis to windows with U-factors less than or equal to 0.25 Btu/hr-ft²-°F, and Solar Heat Gain Coefficient (SHGC) tailored to the specific climate. This U-factor generally rules out all double-pane windows, which typically have only one low-E coating, except for a few models with enhanced thermal resistance using low-E coatings on both Surface 2 (inside the exterior pane) and Surface 4 (the surface facing the interior of the house). Triple-pane windows can have a range of U-factors above and below 0.25, depending on the insulating glass package width, coatings, and gas fill, but a third glazing layer (either glass or suspended thin film) is typically necessary to achieve U-factors below 0.24. The range of U-factors published by four manufacturers is shown in Figure 1 for a sampling of 1,326 commercially available triple-pane window products of all styles and sizes meeting the $U \leq 0.25$ criterion. Another 1,716 triple-pane products (and tens of thousands of double-pane products) from the same manufacturers had U-factors above 0.25, and therefore weren't included in our working definition of high efficiency windows. Although many triple-pane glass door products were also available from these manufacturers, we focused exclusively on windows in our analysis of cost and energy efficiency.

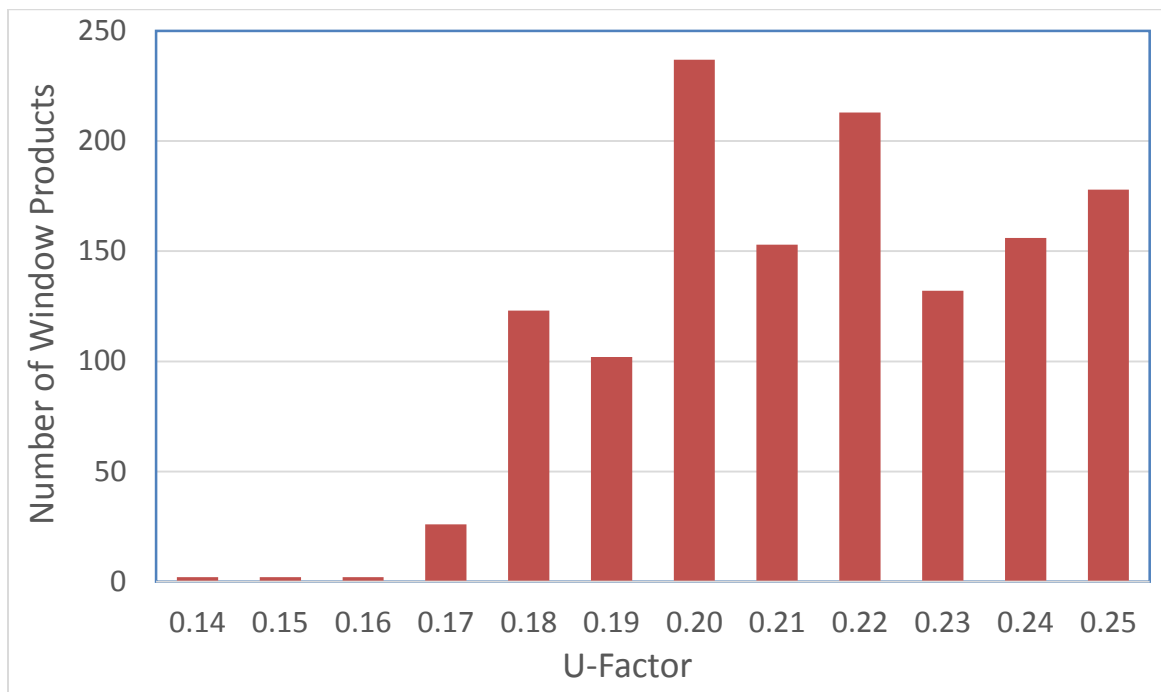


FIGURE 1. DISTRIBUTION OF U-FACTORS FOR HIGH EFFICIENCY ($U \leq 0.25$) TRIPLE-PANE WINDOWS

The third glazing in triple-pane windows provides an important opportunity to reduce U-factor by lowering conduction heat transfer through an additional gas layer, and allowing the use of an additional low-E coating. There are a broad range of coatings used by manufacturers to fine tune U-factor and SHGC, and they can be applied to the glass

surfaces in a variety of combinations. Additional low-E coatings are beneficial for reducing U-factor, but SHGC is only marginally affected by either the third pane or the extra low-E coating. Low SHGC is generally produced using a spectrally selective low-E coating on Surface 2 with two or three layers of silver. In addition to controlling thermal performance, these coatings can also be used to manage thermal stresses on windows that can cause breakage, and to limit the potential for condensation that can impede visibility and cause long-term damage to the windows.

Measures that decrease the amount of solar heat gain, including a third pane of glass or additional low SHGC coatings, tend to have a detrimental effect on visible light transmittance (VT), which can lead to an unacceptable degradation in window view quality for occupants. Although VT is not currently regulated by Title 24, it is an important consideration for homeowner acceptance. VT is occasionally addressed in this report to provide context when SHGC reduction measures are discussed.

In some cases, including one manufacturer's full line of triple-glazed windows, a suspended film is used instead of a third layer of glass. This film technology provides U-factors comparable to triple-pane windows, with reduced weight and thinner overall assemblies. Additional films can be used to create a quadruple or even quintuple-glazed window with ultra-low U-factors, but these products are not readily available in the U.S.

Overall window U-factor is strongly affected by the gas used for reducing the conductance through the gaps between panes. Argon is a common gas fill for insulating double-pane windows. However, argon achieves optimal performance with a gap thickness of about 1/2 in. (see Figure 2), which is impossible to achieve with three panes of glass in standard 1 in. insulating glass packages. Thicker assemblies closer to 1-3/8 in. optimize the efficiency of argon, even with small variations in gap width. These thicker frames can be used with either double or triple-glazing, and can more readily be filled with insulation, but they are heavier and require expensive retooling by manufacturers. For this study, triple-pane window thicknesses were assumed to be in the standard 7/8 in. to 1 in. range, limiting the insulating ability of argon.

Krypton provides 25% better center-of-glass U-factors with smaller gap widths in the range of 1/4 to 3/8 in., but is more expensive than argon gas. Because of its cost, krypton can also require more expensive fill techniques to minimize the loss of gas during the process. Krypton also does not displace other gases cleanly, and may require additional volume changes to achieve the desired 90% concentration. Xenon is marginally more efficient than krypton (~10% better for a 7/8 in. assembly), but is significantly more expensive, and is therefore not viewed as a realistic near-term option for high efficiency windows. Mixtures of various gases are sometimes used to obtain a more optimal combination of performance and cost in thinner windows, but such mixtures are difficult to price reliably, and consequently are not included in this study.

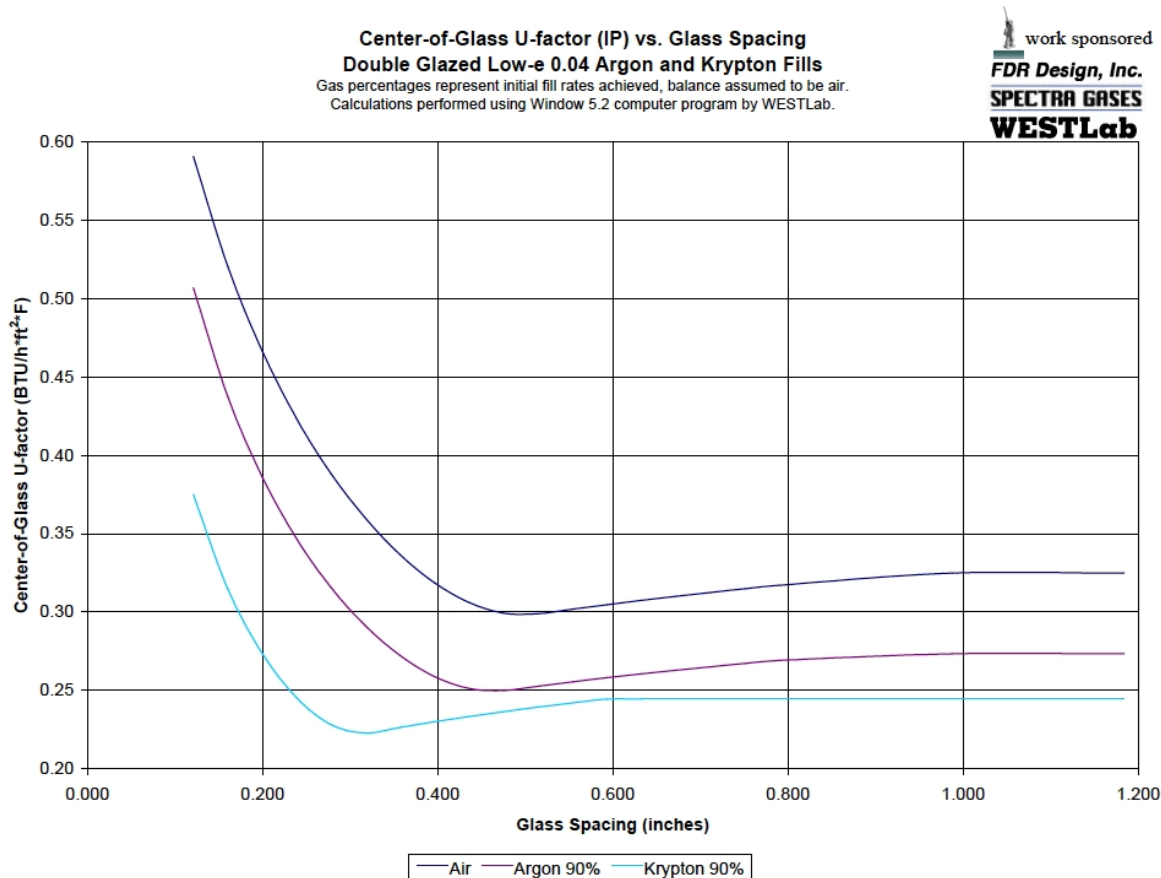


FIGURE 2. CENTER-OF-GLASS U-FACTORS FOR ALTERNATIVE GAS FILLS IN DOUBLE-PANE WINDOWS (CREDIT: FDR DESIGN INC.)

Window frames and spacers are also important components of high efficiency windows. Insulated vinyl frames typically have the lowest conductivity among commonly available frame materials, and are the option most frequently associated with very low U-factor windows, though cellular PVC may be a superior long-term option. Better quality insulated foam spacers are often used instead of traditional aluminum spacers to achieve the lowest possible U-factors in triple-pane windows, though potential outgassing from foam spacers has been identified as a durability concern. For this study, our analysis will focus primarily on the cost-effectiveness of advanced window glazing options, and highly efficient frames and spacers will be accepted as a given.

Low U-factors can be more difficult to achieve in certain window types with larger edge losses, such as double-hung sliders which typically have much smaller glazed area to frame ratios than fixed picture windows. In addition, sliders are usually constrained in terms of allowable window thickness, because the sashes must have room to slide past each other within a standard assembly size. This limits the ability of sliders to use window thicknesses closer to 1-3/8 in., which would optimize the gap width between panes, and achieve the maximum U-factor in argon-filled triple-pane windows.

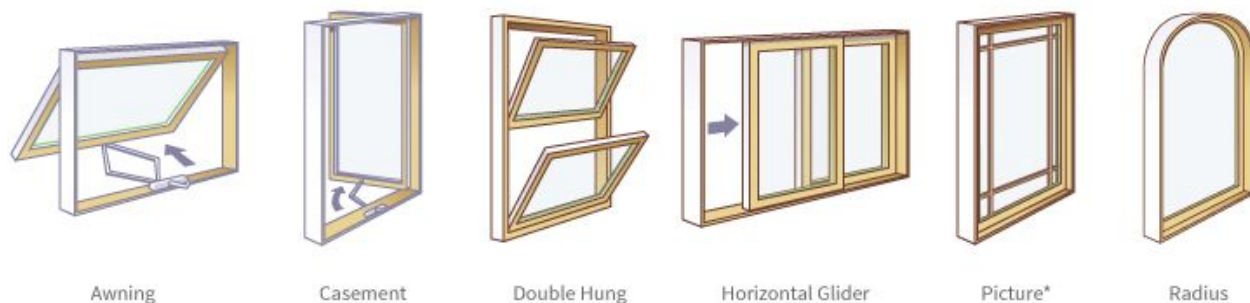


FIGURE 3: WINDOW OPERATING STYLES (IMAGE CREDIT: MILGARD WINDOWS)

The Efficient Windows Collaborative has the following to say about some of the more common operator types shown in Figure 3 (EWC 2017a):

“Casement windows are hinged at the sides. Hinged windows such as casements generally have lower air leakage rates than sliding windows from the same manufacturer because the sash closes by pressing against the frame. Casement windows project outward, providing significantly better ventilation than sliders of equal size. Because the sash protrudes from the plane of the wall, it can be controlled to catch passing breezes, but screens must be placed on the interior side. Virtually the entire casement window area can be opened, while sliders are limited to less than half of the window area.

Both sashes slide horizontally in a double-sliding window. Only one sash slides in a single-sliding window. Ventilation area can vary from a small crack to an opening of one-half the total glass area. Screens can be placed on the exterior or interior of the window unit. Horizontally sliding windows generally have higher air leakage rates than projecting or hinged windows.

In double-hung units, both sashes slide vertically. Only the bottom sash slides upward in a single-hung window. Ventilation area can vary from a small crack to an opening of one-half the total glass area. Screens can be placed on the exterior or interior of the window unit. Sliding windows, such as single- or double-hung units generally have higher air leakage rates than projecting or hinged windows.”

Figure 4 provides average U-factors for various combinations of triple-pane window features that meet the high efficiency criterion of $U \leq 0.25$. Published NFRC data for commercially available windows from four manufacturers were used: Andersen, Alpen, Milgard, and Pella. The results indicate that the most efficient options include krypton fill and vinyl frames in casement or fixed windows, which can have U-factors as low as 0.14. However, because the data were restricted to windows with $U \leq 0.25$, and there are strong correlations among the various window characteristics, the results in Figure 4 should be viewed in a qualitative manner.

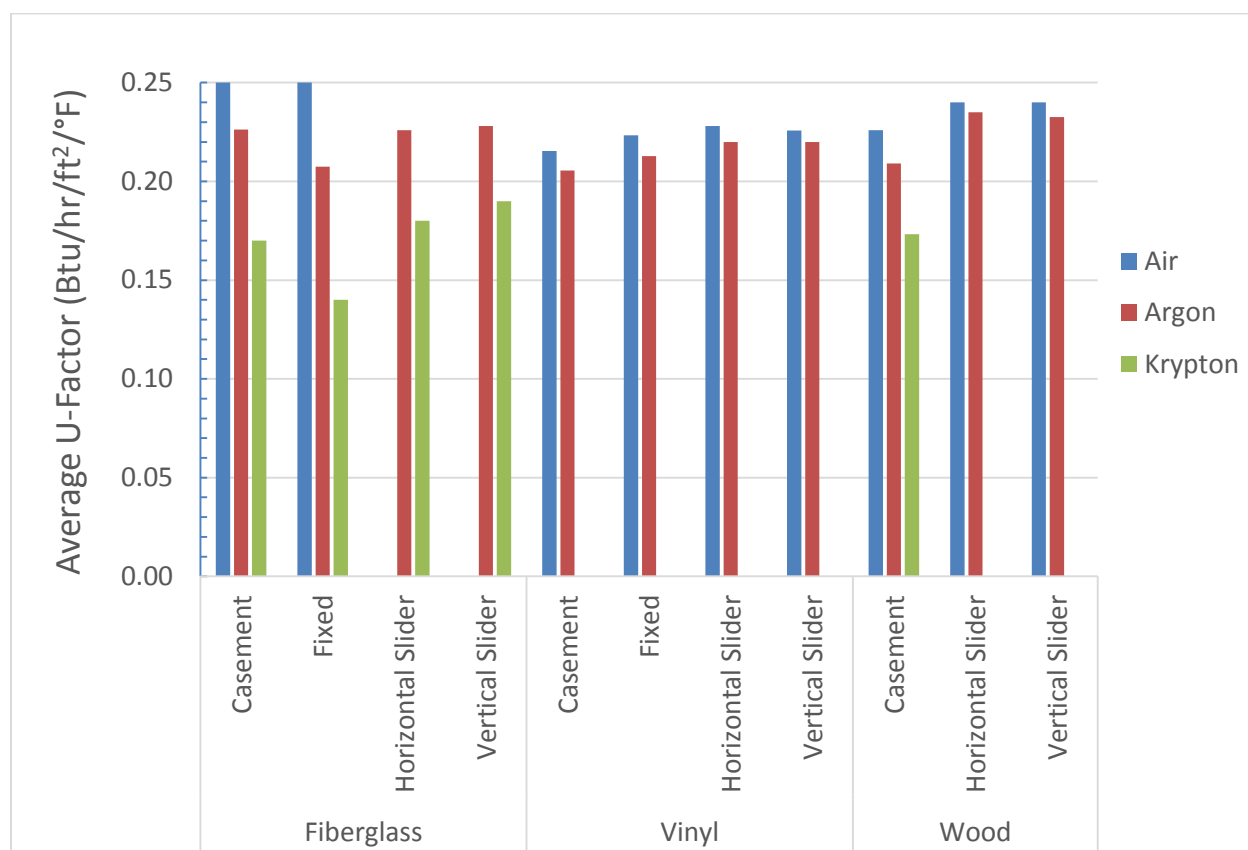


FIGURE 4. AVERAGE U-FACTORS FOR A RANGE OF COMMERCIALY AVAILABLE TRIPLE-PANE WINDOWS

Other attributes of high efficiency windows can be strongly correlated with those included in Figure 4. For example, it is very unlikely that insulated spacers or three low-E coatings will be used in windows filled with air. As a result, the database of triple-pane windows was further analyzed to identify the individual impacts of specific design characteristics compared to a baseline, with all other window features held constant.

Table 1 summarizes the characteristics of the reference window, which includes the features most commonly associated with triple-pane windows available from the four manufacturers. The incremental effects on U-factor, SHGC, and VT, for various window features are shown in Table 2. The “delta” values represent the expected deviation from the reference value. Sufficient incremental data were only available for gas fill, operator type, and low versus high SHGC. For frame material, low-E coatings, gap width, spacer insulation, and thermally enhanced frames, the published data were not specific enough to compare across manufacturers. Further details of the calculated values in Table 2 are included in Appendix A.

TABLE 1. CHARACTERISTICS OF REFERENCE TRIPLE-PANE WINDOWS

Triple-Glazed Window Characteristic	Reference Value
Gas fill	Argon
Frame material	Vinyl
Operator type	Vertical slider
Number of low-E coatings	Two
Solar heat gain	Low SHGC
Spacer	Foam spacer
Grille	None

TABLE 2. INCREMENTAL EFFECTS OF ALTERNATIVE TRIPLE-PANE WINDOW CHARACTERISTICS

Triple-Glazed Window Characteristic	U-Factor	SHGC	VT
Reference value	0.21	0.23	0.42
Delta air	0.03	0	0
Delta krypton	-0.03	0	0
Delta horizontal slider	0	0	0
Delta casement	-0.01	-0.02	-0.05
Delta fixed	-0.02	0.01	0.03
Delta high SHGC	0.01	0.21	0.11

The final window characteristics for the two baseline code-minimum windows and four high efficiency windows used in the CBECC-Res building simulations and cost-effectiveness calculations are listed in Table 3. Many other combinations of high efficiency options were possible, but a manageable number was needed for the cost analysis and simulation phase, and the four windows we selected cover the range of performance fairly well. These representative properties were primarily based on the analysis of commercially available triple-pane windows discussed above, along with the proposed 2019 Title 24, Part 6 requirements for residential buildings, data published by the Efficient Windows Collaborative

(EWC 2017), and the inputs of industry experts interviewed for this project. It should be noted that the SHGC and VT for triple-pane windows were lowered slightly from the statistical average of published data (from 0.23 and 0.42, respectively, to 0.21 and 0.40) to better reflect typical triple-pane window attributes that would be installed in warmer California climates, and provide a more realistic SHGC differential between double-pane and triple-pane options.

TABLE 3. CHARACTERISTICS OF REPRESENTATIVE HIGH EFFICIENCY WINDOWS USED IN COST-EFFECTIVENESS ANALYSIS

Window Type	U-Factor	SHGC	VT
Baseline code minimum, double-pane, low SHGC	0.30	0.23	0.42
Baseline code minimum, double-pane, high SHGC	0.30	0.35	0.59
Double-pane, argon fill, low-E on surfaces 2 and 4, low SHGC	0.25	0.23	0.42
Triple-pane, argon fill, two low-E coatings, low SHGC	0.21	0.21	0.40
Triple-pane, krypton fill, two low-E coatings, low SHGC	0.18	0.21	0.40
Triple-pane, argon fill, two low-E coatings, high SHGC	0.22	0.44	0.53

There are several benefits associated with triple-pane windows beyond simple energy savings. During colder weather, radiative heat transfer between the window and the exposed skin of occupants is reduced because the interior window surface can be 4-8°F warmer than typical insulating double-pane windows (Lyons and Arasteh 1999). This creates approximately 5% reduced probability of discomfort for occupants (EWC 2017c), perhaps higher in rooms with large picture windows. The higher window surface temperature with triple pane windows also reduces the chance of condensation, as discussed earlier. An additional non-energy benefit is reduced noise transmittance, which can be valuable for minimizing distractions from nearby construction work, traffic sounds, or loud neighbors. The Sound Transmission Class appears to improve by 2 points for triple-pane windows with other attributes held constant (which is a discernible, but modest improvement), while other noise reduction characteristics like dissimilar window thicknesses have an impact closer to 4 points (JELD-WEN 2017). We were unable to discern for certain whether triple-pane windows are inherently more or less able to resist air leakage. It appears that manufacturing and installation quality are the primary drivers for window air tightness, but some experts feel that the additional seals associated with triple-pane windows increase the likelihood of air leakage. Based on expert opinions, triple-pane windows may be better able to resist wind damage, but we were unable to find a study proving this assertion. Finally,

high efficiency windows reduce heating and cooling loads, allowing reduced equipment size in some situations, and saving money on first cost for homebuyers.

Several advanced technology options may offer alternatives to triple-pane windows, or offer enhanced performance capabilities in combination with triple-pane windows. In vacuum sealed windows, all gas is removed from between the panes, eliminating heat losses associated with convective loops within the windows, but affordability and long-term durability remain unproven. Aerogel windows use an extremely porous solid material to achieve low U-factors in a lightweight package, but the cost of transparent aerogel windows remains high. Thermochromic windows can increase or decrease the level of tinting based on the outside temperature and amount of direct sunlight. Electrochromic windows can be controlled electronically to let in more or less sunlight depending on the weather conditions and operating mode of the space conditioning equipment. Each of these technologies has significant engineering, market, or cost barriers that must be overcome before they become viable options in residential new construction.

COST ANALYSIS

It is challenging to obtain reliable cost data for relatively new technologies when there are limited applications and insufficient production levels to fully understand current cost drivers and their future trajectory. In such cases, it is most appropriate to draw from a variety of sources, exclude outliers, and adjust for differing assumptions. For this study, we used past studies, manufacturer and retailer data, and interviews with industry experts to estimate typical costs for all four high efficiency windows and two baseline code minimum windows. The references are listed in Table 4, and the results are summarized in Table 5. Further details and assumptions used for calculating representative costs are provided in Appendix B. It should be remembered that actual costs for specific applications are highly variable, and may well be much higher or lower than our estimates. For this reason, much of the cost-effectiveness discussion is presented in the context of target costs, allowing users of this report to compare their own window cost estimates to the PV of saved energy, which is embodied in the target cost.

These cost estimates represent a snapshot in time. Stricter building codes planned in Canada over the next three to five years are likely to result in greater production levels for triple-pane windows in North America, much as they drove market demand for low-E double-pane windows in the 1980s. In Ontario, triple-pane windows will likely be required in new construction to meet a strict $U < 0.21$ requirement planned for 2022, and double-pane windows may not be produced at all after 2025. In Vancouver, British Columbia, the U-factor requirement is already at 0.25. This Canadian activity will provide manufacturers with greater knowledge of re-tooling requirements to produce triple-pane windows more efficiently, and help expedite the testing needed for NFRC certification. If California window manufacturing plants begin producing triple-pane windows at significant volumes, some industry experts that were contacted anticipate that the cost could drop by 20-30%. If this speculative estimate turns out to be accurate from a retail perspective, triple-pane windows could potentially be available at nearly the same price that double-pane windows cost now. Another data point is the historical decrease in incremental cost of low-E, argon-filled windows from approximately 50% in the early 1990s (Popular Mechanics 1993) to 17% in 2018 (NREL 2018). The manufacturing challenges are different for triple-pane windows, but perhaps a similar trend is possible, leading to future incremental prices that may be less than half what they are now.

TABLE 4. COST REFERENCE SUMMARY

References
BEopt (NREL 2017)
NREL Report (Farese et al. 2011)
National Residential Efficiency Measures Database (NREL 2013)
PNNL R-5 WVP Program (PNNL 2013)
RSMeans Residential Cost Data (RSMeans 2014)
Angie's List
Home Advisor
Manufacturer 1 estimate
Manufacturer 2 estimate
Expert 1 estimate
Expert 2 multi-family study
Expert 3 estimate
Expert 4 estimate
Builder 1 estimate
Builder 2 estimate
Builder 3 estimate
Evergreen Economics expert sources
Evergreen Economics manufacturer source
Home Depot (Manufacturer 3)
Home Depot (Manufacturer 4)
Home Depot (Manufacturer 5)

TABLE 5. ESTIMATED INSTALLED COST OF REPRESENTATIVE HIGH EFFICIENCY WINDOWS

Window Characteristics (4ft x 4ft Double-hung Vertical Sliders)	Incremental Installed Cost normalized by window area (\$/ft ²)	Total Installed Cost normalized by window area (\$/ft ²)	Sample Size*
Baseline code minimum, double-pane, low SHGC	\$0	\$25.00	2 new home; 8 retrofit
Baseline code minimum, double-pane, high SHGC	\$0	\$25.00	6
Double-pane, argon fill, low-E on surfaces 2 and 4, low SHGC	\$4.23	\$29.23	2
Triple-pane, argon fill, two low-E coatings, low SHGC	\$7.00	\$32.00	19
Triple-pane, krypton fill, two low-E coatings, low SHGC	\$14.31	\$39.31	6
Triple-pane, argon fill, two low-E coatings, high SHGC	\$7.00	\$32.00	4

* The "samples" include actual quotes, published reports, and expert interviews.

The added cost for the 4th surface low-E double-pane window is associated with the cost of the hard coating used for the room-side surface, which is about twice as expensive as the more common soft-coat low-E used for the protected interior glazing surfaces.

In recent years, the cost of krypton gas has decreased substantially as its use in fluorescent lamps has expanded. The cost is likely to trend further downward in the coming years, although there has been a strong shift in the lighting market from fluorescent to LED in most applications, which could slow the downward trend. Very little public data is available about the cost of krypton compared to argon, but the consensus among experts is that it remains too expensive to be cost-effective in windows. The best estimate is that the cost of the krypton filling process to a window manufacturer is about 5-10 times the cost of argon.

Low SHGC windows tend to be more expensive to produce, because of the silver used in spectrally selective coatings. However, low SHGC windows are produced at higher volumes in California than high SHGC windows, which tends to lower the cost to builders. On balance, most experts believe the incremental cost for high SHGC windows could go in either direction, so we assumed the cost would be about the same on average.

The incremental costs for all high efficiency windows are likely to include some additional features that enhance overall thermal resistance, including insulated vinyl frames, insulated spacers, and high-quality, low-E coatings. Incremental costs for these features are

significant, but extremely difficult to isolate, and we have accepted them as intrinsic components of high efficiency triple-pane windows.

Some of the experts interviewed for this study felt that window manufacturers may be using markups that far exceed the proportional cost of manufacturing triple-pane windows for the purpose of discouraging their adoption. Greater demand for triple-pane windows would force manufacturers to engage in expensive retooling efforts, changes to marketing materials, and additional NFRC testing of new product lines that they may prefer to avoid in the near-term. We do not have specific evidence of this issue, but it was an opinion expressed by multiple experts.

When installation costs and builder mark-up costs were not included in an estimate, we added 20% to the material cost based on RS Means 2014. In some cases, installation costs will increase substantially if the extra weight requires an additional worker to handle, or if a larger number of smaller windows are installed to avoid the need for an additional worker. In other cases where windows are smaller by design, there may be no significant change in installation cost. For example, the window installers for a recent Meritage Homes showcase house in Roseville did not report any installation challenges with triple-pane windows that led to additional labor costs. On balance, a simple installation multiplier seemed appropriate.

Window costs can also vary depending on the window area, assembly thickness, and operator type. It is probably reasonable to assume that the wide cost per square foot variation based on window size and operator type for double pane windows in retail stores (~50% relative to the mean was observed during this study for a small sample of about 10 windows) would be present for triple-pane units as well. For consistency, we used 1 in. thick 4 ft. x 4 ft. double-hung windows when cost data were available for multiple window types.

We did not investigate life-cycle costs for triple-pane windows following initial installation, such as repair and replacement costs. There is currently insufficient data to establish whether triple-pane windows suffer early failures at a higher rate than double-pane windows, but according to several of the industry experts we spoke with, durability was a more significant issue in the 1980s before many modern window manufacturing improvements became available.

ENERGY SAVINGS POTENTIAL

Energy savings for the four high efficiency window options defined in Table 3 were analyzed in all 16 California CZs using the CBECC-Res building simulation software and the 2019 Title 24 TDV values (E3 2016). Simulations included the current 2019 Title 24 prescriptive package of measures as part of the standard design model. Other code-minimum packages are possible, and may affect the results to some extent, but we have assumed that the prescriptive packages provide a reasonable characterization of the space conditioning loads and a representative set of building attributes for a code-compliant house. Ken Nittler of Enercomp performed the parametric simulations in accordance with standard methods and assumptions used by the California Energy Commission, and using the latest draft CBECC-Res 2019 software (r987) available at the time of the analysis. The three standard prototype house configurations (Hedrick et al. 2013) with proposed 2019 code-minimum features were analyzed separately:

- 2,100 ft² single-family
- 2,700 ft² single-family

- 6,960 ft² multi-family (8-unit building)

Window area was set at 20% of conditioned floor area for single-family cases and 15% for multi-family. Window distribution was solar-neutral, with equal areas on all four sides. In CZs 1, 3, 5, and 16, where heating loads dominate, the reference window was the high SHGC code-minimum option. In all other CZs, the low SHGC baseline was used as the reference.

The annual regulated TDV percentage savings for all four high efficiency windows when applied to the blended single-family prototype (weighted as 55% 2,700 ft² two-story, 45% 2,100 ft² one-story) in all 16 CZs are shown in Figure 5. The simple average savings across all CZs, and the statewide construction-weighted average (identified as “SW Wtd Av”) are also included. The corresponding results for the multi-family prototype are somewhat less interesting, because the energy savings are lower for the vast majority of climate/window combinations, but those results are included in Appendix C for completeness. Further details on site energy savings for both gas and electricity are provided Appendix D.

The TDV regulated energy savings for low-SHGC triple panes with argon or krypton-fill are generally in the 5-10% range (or 2.5-5% of whole-house TDV), which is quite significant when targeting ZNE. The savings potential for high-SHGC triple panes appears to be much higher (ranging from 13% to 26% of TDV for regulated end-uses) when applied in colder CZs (1, 3, 5, and 16), and not surprisingly, the high-SHGC option is quite detrimental in warmer CZs, increasing TDV more than 20% in some cases.

An important note to consider is that we assumed the baseline windows in colder CZs have SHGC=0.35 based on the minimum prescriptive value in the proposed 2019 Title 24, Part 6 Standards. Our assumption is SHGC=0.44 for the high-SHGC triple panes, which does result in energy savings versus the code minimum due to additional solar heating gains in the winter, but that component of the savings is not inherently related to the addition of a third pane of glass or second low-E coating. Double-pane windows could be selected with SHGC=0.44 just as easily. As a result, the energy savings (or lack thereof) for high-SHGC triple panes is a combination of a lower U-factor creditable to high efficiency windows, and a higher SHGC that could be required in colder climates in future revisions to the Title 24, Part 6 Standards.

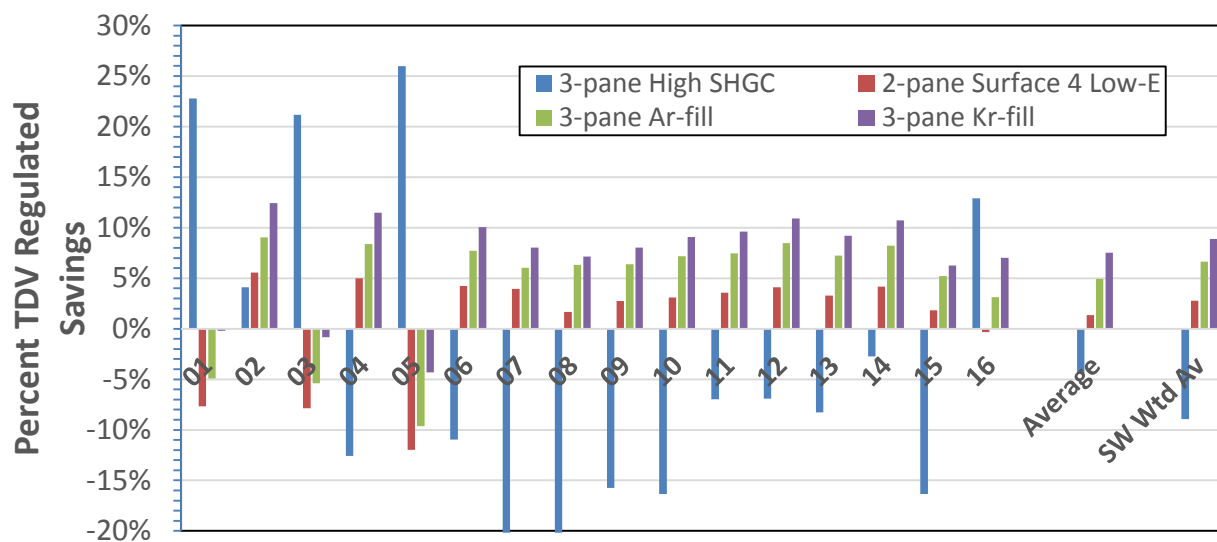


FIGURE 5. ADVANCED GLAZING IMPACT ON REGULATED TDV BY CZ (WEIGHTED AVERAGE SINGLE-FAMILY)

Using the PV of TDV savings over a 30-year time horizon, we can establish a target value for the incremental cost of each high efficiency window type. This would be the price that results in a benefit-to-cost ratio of 1.0. These target costs are shown in Figure 6 for the blended 2,100 ft² and 2,700 ft² single-family prototype house. Window/CZ combinations that result in negative energy savings are not included. Numerically average statewide and construction weighted statewide values are shown as well.

The results indicate that an incremental target cost in the range of \$4/ft² for low SHGC argon-filled triple-pane windows would result in marginal cost-effectiveness in several of the warmer CZs in California. For krypton-filled triple-panes and high SHGC argon-filled triple-panes, the target value is about \$5/ft², and for Surface 4 low-E double-panes, the target is about \$1.50/ft².

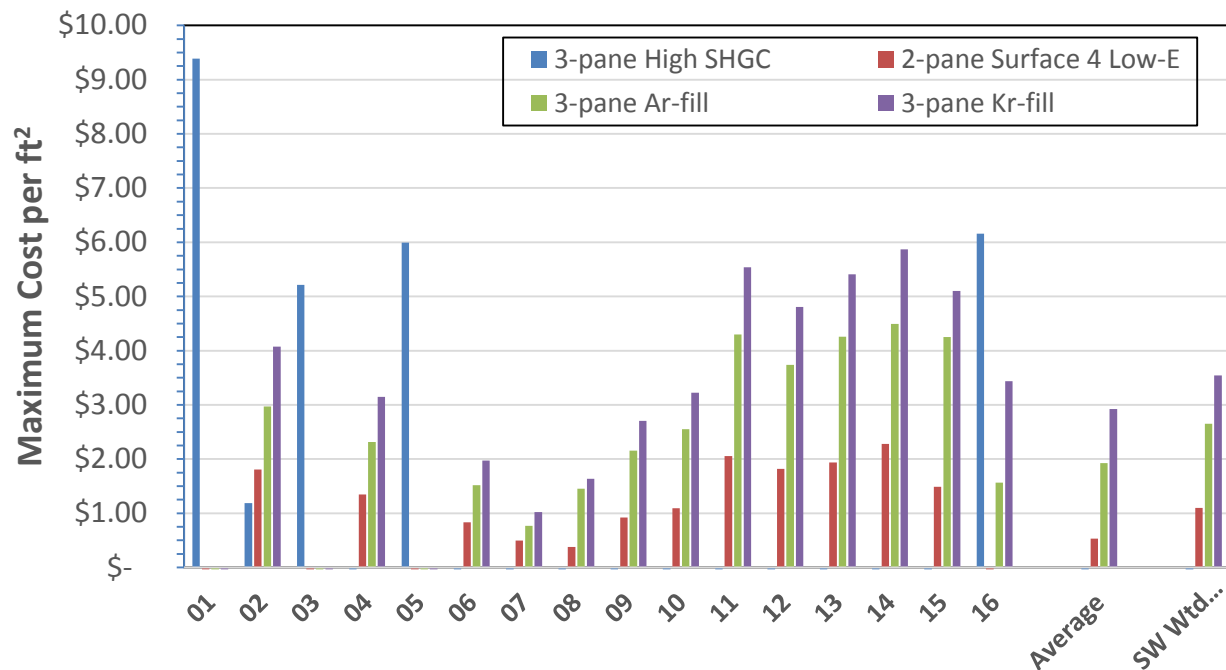


FIGURE 6. ADVANCED GLAZING MAXIMUM COST FOR BREAKEVEN COST EFFECTIVENESS (2,430 FT² SINGLE-FAMILY)

COST-EFFECTIVENESS

Using the estimated incremental costs for the four high efficiency windows considered in this study, combined with the energy savings analysis in the preceding section, we can evaluate the overall cost-effectiveness of high efficiency windows across the state, and identify target markets for specific window types where the current price is less than the PV of energy savings. Figure 7 shows the projected benefit-to-cost ratio (BCR) for each window and CZ combination in California, along with the simple average and statewide construction weighted average for the blended 2,430 ft² single-family home. Similar graphs for the multi-family prototype are included in Appendix C.

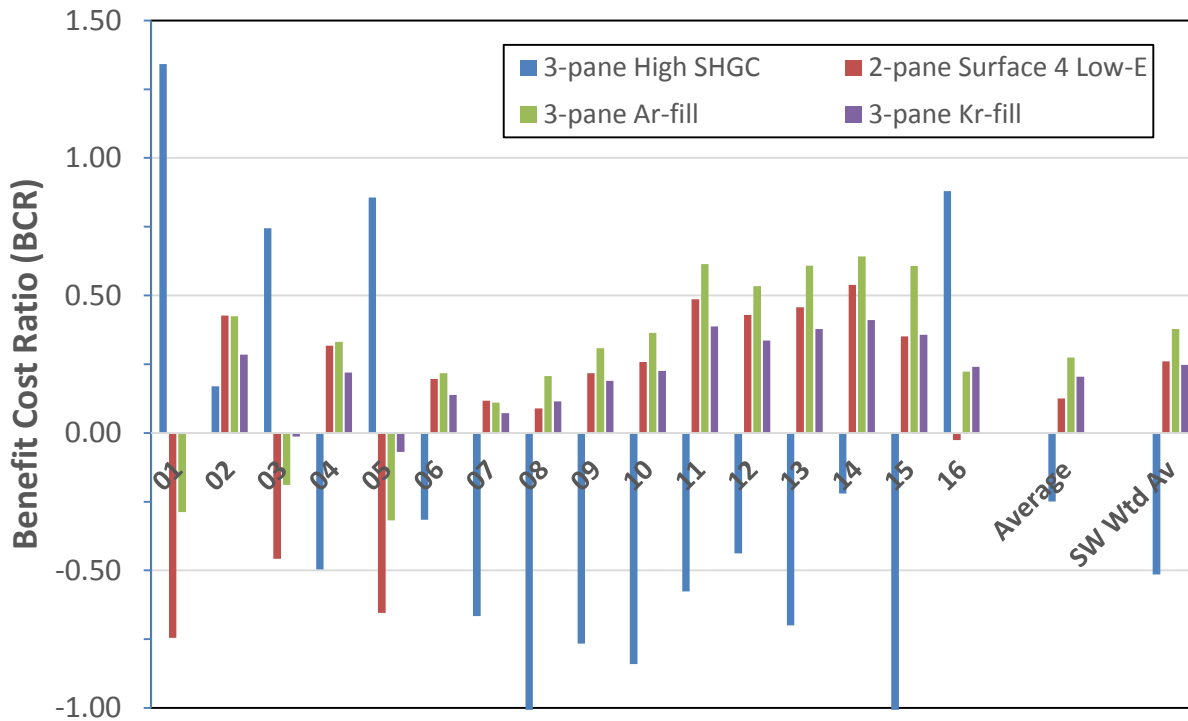


FIGURE 7. ADVANCED GLAZING BENEFIT TO COST RATIO BY CZ AND WINDOW TYPE (2,430 FT² SINGLE-FAMILY, PV OF TDV OVER 30-YEAR LIFE CYCLE DIVIDED BY INSTALLED COST)

Only one window/CZ combination exceeds the threshold criterion of BCR>1.0 that defines cost-effectiveness under 2019 Title 24 assumptions. That combination is high-SHGC triple-pane windows in CZ 1. As discussed earlier, the benefits of both greater “free” solar heating and reduced conductive heat losses contribute to this outcome, and it is possible that the same level of savings could be attained in cold climates with high SHGC double-pane windows. Many other options have BCRs in the 0.4-0.8 range, which indicates that potential volume discounts and utility incentives could push the technology over the cost-effectiveness hurdle, stimulating demand enough to propel production levels that could lead to further cost reduction in the future. However, it appears at the present time that high efficiency windows are generally not cost-effective in California without a substantial change to the existing cost structure. As a point of reference, the estimated BCR for photovoltaic systems is over 2.0 in most CZs (E3 2017). It is important to note that a lack of cases near 1.0 does not exclude the technology from consideration as a viable measure in some applications, as often builders must choose marginally cost-effective measures to demonstrate compliance. For example, window area and orientation can change the economics considerably, as will be discussed later in the report.

Figure 8 shows the PV of TDV savings over a 30-year horizon for three of the high efficiency window types. Bars are shown for two deployment scenarios: 1) when applied only in the CZs where that product is the best option, and 2) in all CZs when weighted by construction starts. Krypton-filled windows are not included, because they currently aren't the best high efficiency option in any climates based on the cost-effectiveness analysis. This graph gives

an indication of the potential for broad market adoption at current prices. Unfortunately, none of the window types show this potential at the present time.

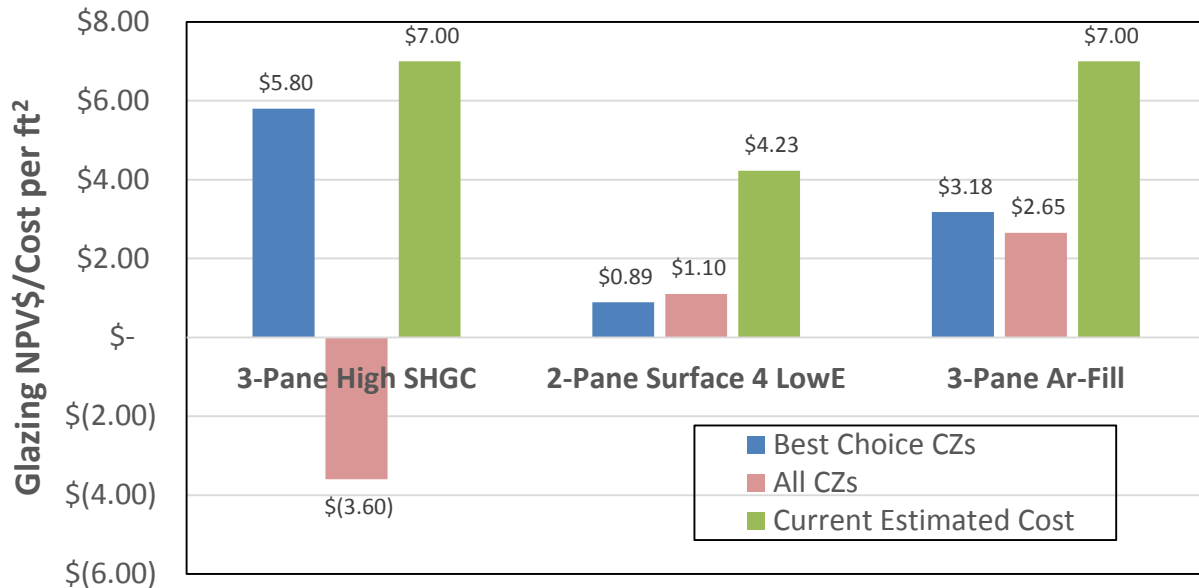


FIGURE 8. PV OF TDV SAVINGS FOR HIGH EFFICIENCY WINDOWS IN TARGET MARKETS VERSUS ALL MARKETS (2,430 FT² SINGLE-FAMILY)

Figure 9 shows the potential energy savings for alternative methods of increasing the energy efficiency of houses by reducing conductive heat losses and gains from windows, and increasing beneficial solar gains. Although not a Title 24, Part 6 recognized savings opportunity², reducing window area will generally reduce the energy consumption and construction cost in most California climates, and may warrant consideration in future code cycles. It should be noted that prior to the 2005 Title 24 Standards, builders did receive credit for less window area; however, the baseline back then was 20% window area in the coastal CZs and 16% window area in the north coast, central valley and mountains. The belief at the time was that typical window fractions were 14% of floor area, but this is worth revisiting in the Home Energy Rating System (HERS) data registry. To illustrate the magnitude of the effect, Figure 9 indicates that reducing window area by 10% (from 20% of floor area to 18% in the single-family case) leads to TDV energy savings in regulated end-uses of about 2.3% statewide, assuming prescriptive wall assemblies are installed. This includes some CZs where reducing window area is detrimental in the context of a code-minimum house, as well as a few CZs where savings over 3% can be achieved.

² Title 24 Alternative Calculation Method (ACM) modeling rules assign the Proposed Home's glazing percentage to the Standard Home comparison case when glazing area is below 20% for single-family (15% for multi-family).

Also shown in Figure 9 is the very large TDV impact of window orientation. When modeling “real world” versions of the single-family prototypes, where glazing is more realistically distributed (for illustrative purposes, we assumed 50% of total area on the back, 25% on the front, and 12.5% each on the left and right), the results provide a very different picture compared to equal window distribution. CZ variations ranging from 12% higher to 12% lower TDV energy use can occur with “real” glazing distribution rather than a solar-neutral distribution of windows. This effect is significantly larger than the savings associated with most of the high efficiency window options and raises issues as to how glazing performance is handled within the Alternative Calculation Method Reference Manual. Production builders will run compliance in all four cardinal orientations, and will therefore need to demonstrate compliance in the worst orientation (typically Front East), while a custom builder may have the flexibility to optimize orientation, and therefore be rewarded with the benefits of the most favorable orientation (typically Front North). This inconsistent handling is tied to the standard design assumption of uniformly distributed glazing used for code development, which we believe should be studied in more detail.

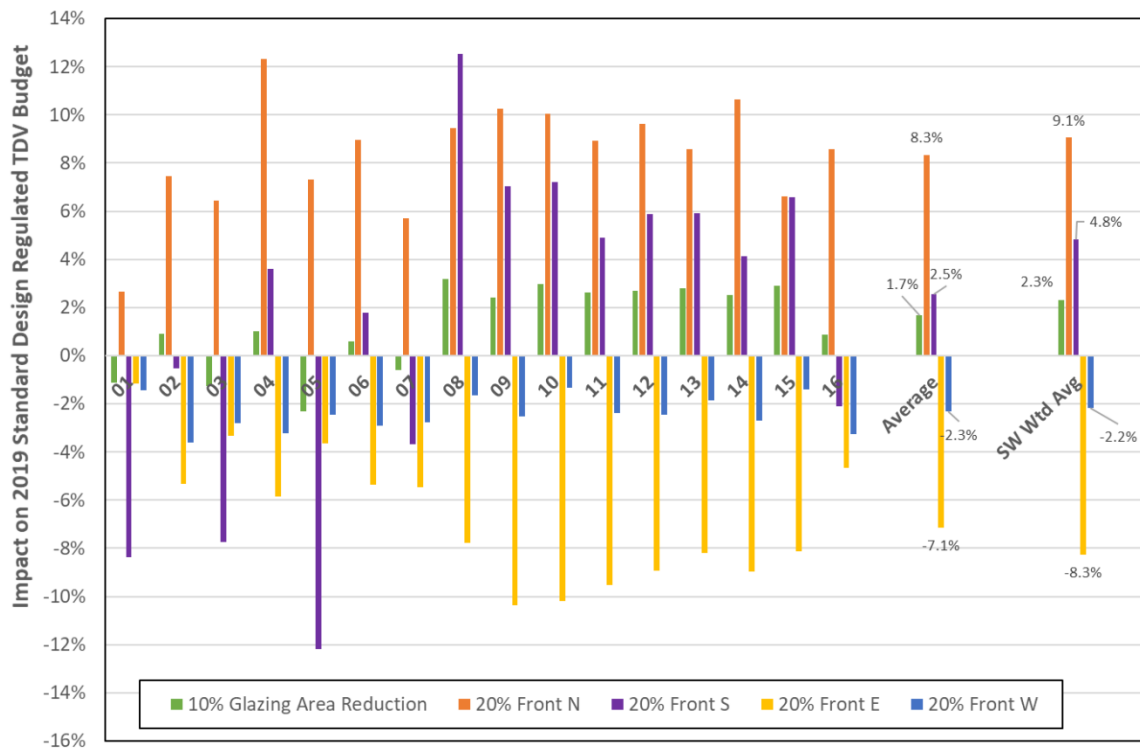


FIGURE 9. IMPACT OF GLAZING REDUCTION AND ORIENTATION DISTRIBUTION ON TDV REGULATED BUDGET (2,430 FT² SINGLE-FAMILY)

It is difficult to fully evaluate the potential energy savings for high efficiency windows without separating the effects of window properties from glazing orientation. It is important to remember that the best-case benefit-to-cost ratio for high efficiency windows occurs when applied to the worst-case orientation (front facing east, with most of the glass facing west). The results in this scenario are shown in Figure 10. The BCR is 10-15% better on average than for the solar-neutral analysis in Figure 6, but still falls short of cost-effectiveness based on TDV.

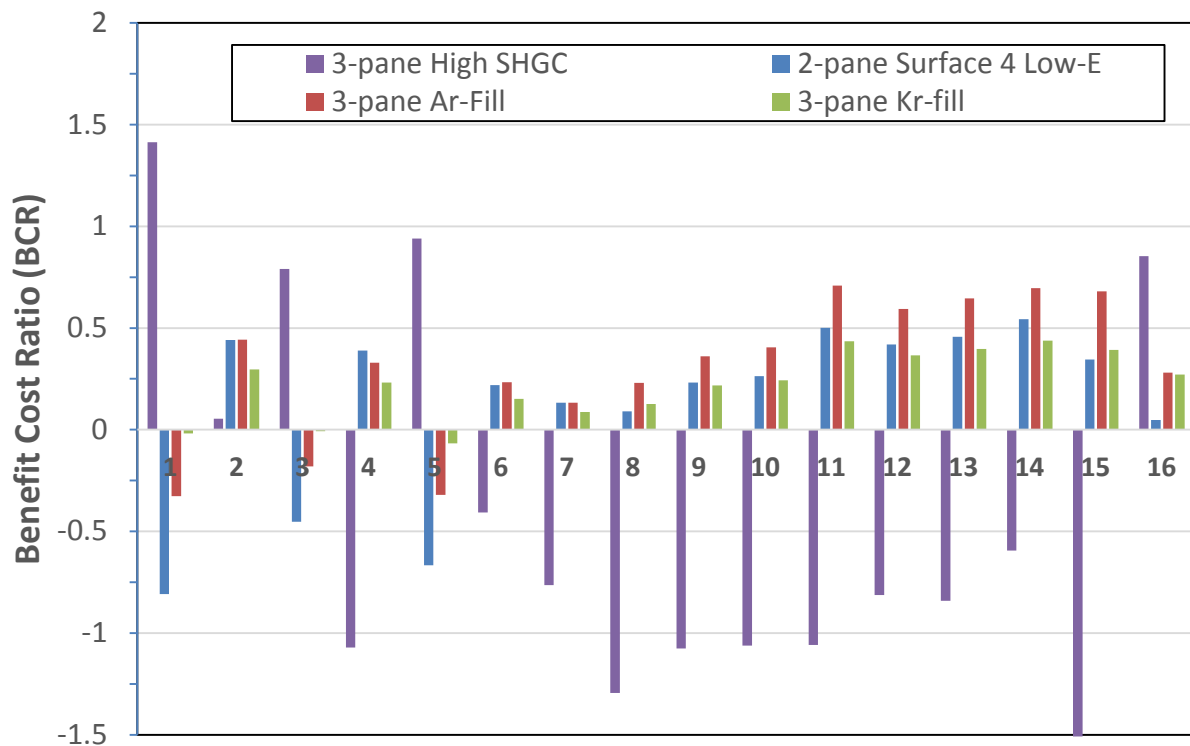


FIGURE 10. BENEFIT TO COST RATIO FOR HIGH EFFICIENCY WINDOWS COMPARED TO CODE MINIMUM WINDOWS IN THE WORST CASE ORIENTATION IN EACH CZ (2,100 FT² SINGLE-FAMILY)

MARKET BARRIERS AND OPPORTUNITIES

There are a variety of barriers that inhibit market penetration for high efficiency windows, including triple-panes. Technology and cost barriers were discussed earlier in the report, but there are also market barriers that must ultimately be overcome even when the technology is cost-effective. Because the Master Builder program is planning a more extensive study of market barriers and counter-strategies led by TRC, we will provide only a few high-level discussion points that arose during conversations with industry experts.

One important barrier is a concern over durability associated with triple-pane windows, which largely dates back to the 1980s when clear glass was used in most windows. Lower U-factors inherently mean large differential temperature gradients within the window assembly, which can introduce thermal stresses that can damage seals or fracture the glazing over time. Overheating may also be a concern in windows that use suspended films. It is generally believed by experts that window manufacturers have overcome these durability issues through research and testing. Many of the hundreds of commercially available triple-pane window models have never actually been constructed and installed in the field, but the industry has a fair amount of experience with all the basic window types discussed in this report. Given that some individual triple-pane window models have never been produced, there may be additional concerns about product availability for production housing. The broader production builder market may not be convinced to use high efficiency

windows, especially those with krypton-fill, until manufacturers have demonstrated availability and high durability in a much larger number of houses.

Double-pane windows with 4th surface low-E coatings have the potential for condensation on the room-side of the interior pane due to its lower surface temperature in cold weather. In warmer and dryer regions throughout most of California, this is unlikely to be a significant concern, but it may be a problem in some geographic areas or applications where indoor humidity can be higher. Hazing can also be an issue with the hard coating typically used for the 4th surface.

Another concern associated with triple-pane windows is the potential need to modify sashes and frames for heavier, and potentially thicker, window assemblies. Until enough manufacturers and builders have demonstrated inexpensive methods for mounting heavier windows with larger physical dimensions in standard window openings, especially in retrofit applications, market acceptance for triple-pane windows may be limited.

Finally, high altitude applications may not be suitable for argon or krypton-filled windows because the pressure difference can cause the gas to leak out over time, severely degrading window U-factor. Gas leakage can also be an issue if the windows must be transported through high altitude regions to reach the distributor or installation site. Breather tubes can be used to equalize pressure between the inside and outside of gas-filled windows, but also increase the cost.

Several opportunities exist for California utilities and other stakeholders to help overcome the technical, cost, and market barriers for high efficiency windows, both as a compliance option for new homes, and as a retrofit option to help achieve 50% savings in existing homes by 2030. Rebates that are sized to offset the BCR shortfall in several California CZs could result in a critical mass of triple-pane window demand that prompts window manufacturers to re-tool for triple-pane production and begin broader promotional efforts. Educating builders and homeowners about the non-energy benefits and target costs described in this report could also be beneficial in stimulating demand if they are able to procure high efficiency windows at a price much lower than we have assumed. Investment in emerging technologies, such as “skinny triple-pane windows” being developed by Lawrence Berkeley National Laboratory (LBNL), which use a very thin layer of glass suspended between two standard panes, could enhance the efficiency of argon-filled windows and lower the cost at the same time.

CONCLUSIONS/FUTURE RESEARCH

This study utilized a variety of public data sources, building simulations, and expert insights to evaluate the cost-effectiveness and near-term market viability of high efficiency windows in California new construction. The results indicate that based on our current estimate of incremental cost, none of the triple-pane options are cost-effective in any California CZs, except for the high SHGC triple-pane window in CZ 1 when compared to a medium SHGC code-minimum double-pane window. The low SHGC argon-filled triple-pane option may become cost-effective in several CZs if production levels increase to the point where the price difference compared to code-minimum double pane windows drops by about 50%, which may be possible based on some expert predictions of a 20-30% total price decrease for triple-pane windows (virtually eliminating the price difference compared to double-pane), and based on the historical price trend of low-E insulated glazing in the 1980s-90s. In some situations, this price may even be feasible now, given the right application and a motivated window manufacturer. Other options have limited potential based on the 2019

Title 24 TDV definition and ACM rules, unless the cost to builders decreases dramatically in the coming years. In cases where realistic glazing distribution and worst-case orientation are considered, the cost-effectiveness improves for many options, but not enough to change our conclusions.

If cost-effectiveness is not considered, triple-pane windows do offer significant TDV regulated energy savings of 5-10%. There are also several non-energy benefits that could factor into window selection decisions, including noise reduction and comfort enhancement. The technology has also been well enough established that builders should have high confidence in the long-term durability of triple-pane windows.

Future studies should focus on some of the more uncertain inputs to our analysis, and aspects that weren't investigated in detail, including the following:

- Future manufacturing cost implications once plants have re-tooled for large-scale triple pane production. Cost trends in Canada and Europe, which may shed light on future trends in the U.S.
- Rebate amounts necessary to drive demand to the “tipping point” where manufacturers are motivated to re-tool.
- Potential advances in krypton capture and fill technology that could change the cost structure.
- Incremental cost differences for alternative features, such as framing material and operator type, which could help identify a market segment that makes sense to target first.
- Long-term warranty costs for repair and replacement.
- Costs and benefits from the homeowner perspective, including the implications of potential time-of-use rates, which may dictate the future of high efficiency windows in the retrofit market.
- Potential cost reductions associated with suspended films and skinny window technologies.
- Alternative high efficiency window technologies such as vacuum and aerogel insulated windows, and windows featuring variable tinting, such as thermochromic and electrochromic windows.
- Potential market transformation benefits of sound transmission ratings specifically developed for windows instead of those developed for general building components, such as Sound Transmission Class. Increasing the availability of existing noise transmission data for residential products.

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APPENDIX A: ONE-OFF EFFECTS OF ALTERNATE SPECS FOR TRIPLE GLAZED WINDOWS

REFERENCE WINDOWS

	U-Factor	SHGC	VLT
Milgard - Montecito 8220	0.24	0.24	0.41
Milgard - Quiet Line 7220, SunCoatMAX	0.19	0.18	0.42
Milgard - Quiet Line 7220, SunCoat	0.2	0.25	0.45
Milgard - Tuscany 8220	0.24	0.24	0.41
Milgard - Tuscany 8240	0.25	0.24	0.4
Pella 350 Series Double Hung	0.18	0.24	0.41
Pella 350 Series Single Hung	0.17	0.24	0.41
Average for Baseline	0.21	0.23	0.42

GAS FILL ANALYSIS: U-FACTOR

	Exceptions to Baseline	Argon	Air	Krypton		Delta Air	Delta Krypton
Milgard - Quiet Line 7220	EdgeGard spacer	0.20	0.22			0.02	
Milgard - Quiet Line 7220	EdgeGardMAX	0.20	0.22			0.02	
Milgard - Quiet Line 7220	None	0.21	0.23			0.02	
Pella - 350 Series	None	0.18	0.20			0.02	
Milgard - Essence 9200	None	0.21	0.24			0.03	
Milgard - Thermally Improved Aluminum 420	Aluminum frame, horizontal slider	0.21	0.25			0.04	
Alpen - ZR-6/7 Balanced	Fiberglass frame, suspended film	0.19		0.18			-0.01
Pella - Architect Series	Wood frame, awning	0.21		0.17			-0.04
Pella - Architect Series	Aluminum frame, casement	0.22		0.19			-0.03
Pella - Architect Series	Wood frame, casement, higher SHGC	0.19		0.16			-0.03
Pella - Architect Series	Wood frame, casement	0.21		0.17			-0.04
Alpen - ZR-6/7 Balanced	Fiberglass frame, casement, suspended film	0.17		0.15			-0.02
						Air	Krypton
Incremental Effect		U-Factor				0.03	-0.03

GAS FILL ANALYSIS: SHGC

	Exceptions to Baseline	Argon	Air	Krypton		Delta Air	Delta Krypton
Milgard - Quiet Line 7220	EdgeGard spacer	0.25	0.25			0.00	
Milgard - Quiet Line 7220	EdgeGardMAX	0.25	0.25			0.00	
Milgard - Quiet Line 7220	None	0.25	0.25			0.00	
Pella - 350 Series	None	0.24	0.24			0.00	
Milgard - Essence 9200	None	0.22	0.22			0.00	
Milgard - Thermally Improved Aluminum 420	Aluminum frame, horizontal slider	0.24	0.24			0.00	
Alpen - ZR-6/7 Balanced	Fiberglass frame, suspended film	0.26		0.26			0.00
Pella - Architect Series	Wood frame, awning	0.23		0.23			0.00
Pella - Architect Series	Aluminum frame, casement	0.23		0.23			0.00
Pella - Architect Series	Wood frame, casement, higher SHGC	0.27		0.27			0.00
Pella - Architect Series	Wood frame, casement	0.23		0.23			0.00
Alpen - ZR-6/7 Balanced	Fiberglass frame, casement, suspended film	0.24		0.24			0.00
						Air	Krypton
Incremental Effect		SHGC				0.00	0.00

GAS FILL ANALYSIS: VT

	Exceptions to Baseline	Argon	Air	Krypton		Delta Air	Delta Krypton
Milgard - Quiet Line 7220	EdgeGard spacer	0.46	0.46			0.00	
Milgard - Quiet Line 7220	EdgeGardMAX	0.46	0.46			0.00	
Milgard - Quiet Line 7220	None	0.45	0.45			0.00	
Pella - 350 Series	None	0.41	0.41			0.00	
Milgard - Essence 9200	None	0.38	0.38			0.00	
Milgard - Thermally Improved Aluminum 420	Aluminum frame, horizontal slider	0.42	0.42			0.00	
Alpen - ZR-6/7 Balanced	Fiberglass frame, suspended film	0.42		0.42			0.00
Pella - Architect Series	Wood frame, awning	0.42		0.42			0.00
Pella - Architect Series	Aluminum frame, casement	0.42		0.42			0.00
Pella - Architect Series	Wood frame, casement, higher SHGC	0.49		0.49			0.00
Pella - Architect Series	Wood frame, casement	0.42		0.42			0.00
Alpen - ZR-6/7 Balanced	Fiberglass frame, casement, suspended film	0.38		0.38			0.00
						Air	Krypton
Incremental Effect		VLT				0.00	0.00

OPERATOR ANALYSIS: U-FACTOR

	Exceptions to Baseline	Vert Slider	Horiz Slider	Casement	Fixed	Delta Horiz	Delta Csmt	Delta Fixed
Alpen - ZR-6 Balanced-6	Fiberglass frame, suspended film	0.19	0.19	0.19	0.16	0.00	0.00	-0.03
Alpen - ZR-6 SolarControl-6	Fiberglass frame, suspended film	0.19	0.19	0.20	0.17	0.00	0.01	-0.02
Andersen - A - Heatlock	Composite	0.20		0.20	0.18		0.00	-0.02
Milgard - Essence 9200	Wood	0.22	0.22	0.22		0.00	0.00	
Milgard - Montecito 8220	None	0.25	0.25	0.23	0.24	0.00	-0.02	-0.01
Milgard - Quiet Line 7220	None	0.20	0.20	0.17	0.18	0.00	-0.03	-0.02
Milgard - Tuscany 8220	None	0.25	0.25	0.23	0.24	0.00	-0.02	-0.01
Pella 350 Series Single Hung	None	0.17	0.17	0.16		0.00	-0.01	
Pella - Designer Series	Aluminum frame	0.25		0.23			-0.02	
						Horiz Slider	Casement	Fixed
Incremental Effect		U-Factor				0.00	-0.01	-0.02

OPERATOR ANALYSIS: SHGC

	Exceptions to Baseline	Vert Slider	Horiz Slider	Casement	Fixed	Delta Horiz	Delta Csmnt	Delta Fixed
Alpen - ZR-6 Balanced-6	Fiberglass frame, suspended film	0.26	0.27	0.24	0.27	0.01	-0.02	0.01
Alpen - ZR-6 SolarControl-6	Fiberglass frame, suspended film	0.19	0.19	0.17	0.20	0.00	-0.02	0.01
Andersen - A - Heatlock	Composite	0.18		0.15	0.18		-0.03	0.00
Milgard - Essence 9200	Wood	0.22	0.22	0.19		0.00	-0.03	
Milgard - Montecito 8220	None	0.24	0.24	0.22	0.25	0.00	-0.02	0.01
Milgard - Quiet Line 7220	None	0.18	0.18	0.15	0.22	0.00	-0.03	0.04
Milgard - Tuscany 8220	None	0.24	0.24	0.22	0.25	0.00	-0.02	0.01
Pella 350 Series Single Hung	None	0.24	0.24	0.19		0.00	-0.05	
Pella - Designer Series	Aluminum frame	0.19		0.20			0.01	
						Horiz Slider	Casement	Fixed
Incremental Effect						0.00	-0.02	0.01

OPERATOR ANALYSIS: VT

	Exceptions to Baseline	Vert Slider	Horiz Slider	Casement	Fixed	Delta Horiz	Delta Csmt	Delta Fixed
Alpen - ZR-6 Balanced-6	Fiberglass frame, suspended film	0.42	0.43	0.38	0.44	0.01	-0.04	0.02
Alpen - ZR-6 SolarControl-6	Fiberglass frame, suspended film	0.43	0.44	0.39	0.45	0.01	-0.04	0.02
Andersen - A - Heatlock	Composite	0.40		0.35	0.41		-0.05	0.01
Milgard - Essence 9200	Wood	0.37	0.37	0.33		0.00	-0.04	
Milgard - Montecito 8220	None	0.41	0.41	0.37	0.43	0.00	-0.04	0.02
Milgard - Quiet Line 7220	None	0.43	0.43	0.33	0.51	0.00	-0.10	0.08
Milgard - Tuscany 8220	None	0.41	0.41	0.37	0.43	0.00	-0.04	0.02
Pella 350 Series Single Hung	None	0.41	0.41	0.33		0.00	-0.08	
Pella - Designer Series	Aluminum frame	0.43		0.45			0.02	
						Horiz Slider	Casement	Fixed
Incremental Effect						0.00	-0.05	0.03

SHGC ANALYSIS: U-FACTOR

	Exceptions to Baseline	Low SHGC	High SHGC	Delta High SHGC
Alpen - ZR-6	Fiberglass frame, suspended film	0.19	0.20	0.01
Milgard - Essence 9200	Wood	0.22	0.23	0.01
Milgard - Montecito 8220	None	0.24	0.23	-0.01
Milgard - Style Line 6510	Casement	0.23	0.24	0.01
Milgard - Tuscany 8220	None	0.24	0.23	-0.01
Milgard - Ultra 3210	Fiberglass	0.23	0.24	0.01
Pella 350 Series Single Hung	None	0.17	0.22	0.05
Pella - Designer Series	Aluminum frame	0.25	0.25	0.00
Pella - Architect Series	Wood frame, casement	0.19	0.20	0.01
				High SHGC
Incremental Effect			U-Factor	0.01

SHGC ANALYSIS: SHGC

	Exceptions to Baseline	Low SHGC	High SHGC	Delta High SHGC
Alpen - ZR-6	Fiberglass frame, suspended film	0.19	0.41	0.22
Milgard - Essence 9200	Wood	0.22	0.38	0.16
Milgard - Montecito 8220	None	0.24	0.43	0.19
Milgard - Style Line 6510	Casement	0.22	0.38	0.16
Milgard - Tuscany 8220	None	0.24	0.43	0.19
Milgard - Ultra 3210	Fiberglass	0.25	0.45	0.20
Pella 350 Series Single Hung	None	0.24	0.47	0.23
Pella - Designer Series	Aluminum frame	0.19	0.46	0.27
Pella - Architect Series	Wood frame, casement	0.20	0.45	0.25
				High SHGC
Incremental Effect			SHGC	0.21

SHGC ANALYSIS: VT

	Exceptions to Baseline	Low SHGC	High SHGC	Delta High SHGC
Alpen - ZR-6	Fiberglass frame, suspended film	0.43	0.53	0.10
Milgard - Essence 9200	Wood	0.37	0.48	0.11
Milgard - Montecito 8220	None	0.41	0.53	0.12
Milgard - Style Line 6510	Casement	0.37	0.47	0.10
Milgard - Tuscany 8220	None	0.41	0.53	0.12
Milgard - Ultra 3210	Fiberglass	0.43	0.56	0.13
Pella 350 Series Single Hung	None	0.41	0.55	0.14
Pella - Designer Series	Aluminum frame	0.43	0.53	0.10
Pella - Architect Series	Wood frame, casement	0.45	0.55	0.10
				High SHGC
Incremental Effect			VT	0.11

APPENDIX B: DETAILED COST ANALYSIS

THIRD PANE COST

Source	% Increase for 4ft x 4ft Window *	Incremental Cost per 2,700 ft ² House (540 ft ²)	Incremental Cost / 4ft x 4ft Window	Total Cost for Triple Pane (\$ / ft ²)	Incremental Cost for Double to Triple Pane (\$ / ft ²) *	Notes
BEopt	30%	\$3,699.00	\$109.60	\$29.92	\$6.85	Vinyl frames, installation included
BEopt	78%	\$13,975.20	\$414.08	\$58.94	\$25.88	Insulated vinyl frames, installation included. NREL has proposed revisions for the upcoming version of BEopt that reduce large cost interactions.
Builder 1 estimate	5%	\$650.00	\$19.26	\$26.20	\$1.20	Builder price, installation included
Manufacturer 1 estimate	14%	\$1,518.75	\$45.00	\$28.38	\$3.38	List price, 20% installation and markup assumed, upgraded coatings and spacer
Manufacturer 2 estimate	17%	\$1,856.25	\$55.00	\$29.13	\$4.13	Triple Glazing, LowE(2), Argon, undiscounted, 20% installation and markup assumed
Farese et al. 2011	20%	\$973.44	\$81.12	\$30.07	\$5.07	R-5 windows vs code minimum
National Residential Efficiency Measures Database (NREMD)	20%	\$3,780.00	\$112.00	\$42.00	\$7.00	Vinyl frames, installation included
NREMD	144%	\$35,100.00	\$1,040.00	\$110.00	\$65.00	Insulated vinyl frames, installation included
Expert 1 estimate	35%	\$4,725.00	\$140.00	\$33.75	\$8.75	Double pane to 1-3/8" argon filled triple pane
Expert 2 study	26%	\$3,504.60	\$103.84	\$31.49	\$6.49	Average for argon filled windows (sample of 2)
Expert 3 estimate	33%	\$4,387.50	\$130.00	\$33.13	\$8.13	Standard double pane to triple pane estimate
Builder 1 estimate	35%	\$4,725.00	\$140.00	\$33.75	\$8.75	Standard double pane to triple pane recollection based on an actual project
Builder 2 estimate	30%	\$4,050.00	\$120.00	\$32.50	\$7.50	Standard double pane to triple pane estimate. Estimated \$1000/home as well, but window area is unknown.

Evergreen experts	94%	\$12,656.25	\$375.00	\$48.44	\$23.44	Range for R-5 incremental cost estimated to be \$150-\$600 more than a typical Energy Star® window.
Evergreen manufacturer	60%	\$8,100.00	\$240.00	\$40.00	\$15.00	R-5 incremental cost estimated to be 60% more than a typical Energy Star window.
Home Depot (Manufacturer 3)	16%	\$1,255.84	\$37.21	\$20.44	\$2.79	Argon fill, 20% installation and markup assumed
Home Depot (Manufacturer 4)	50%	\$7,582.28	\$224.66	\$50.79	\$16.85	Double hung price with two sashes, 20% installation and markup assumed
Expert 4 estimate	16%	\$2,160.00	\$64.00	\$29.00	\$4.00	\$4-\$6 for third pane, third coating, and krypton fill. Each about 1/3 of cost increase, 20% installation and markup assumed.
PNNL R-5 WVP Program	19%	\$2,507.76	\$74.30	\$29.64	\$4.64	2012 average incremental cost from Energy Star to R-5. Goal was \$4/ft ² , 20% installation and markup assumed
				Median	\$7.00	

* If the reference cost was unknown, \$25/ft² was used

KRYPTON FILL COST

Source	% Increase for 4ft x 4ft Window*	Incremental Cost per 2,700 ft ² House (540 ft ²)	Incremental Cost / 4ft x 4ft Window	Incremental Cost (\$/ft ²)	Notes
Expert 2 study	28%	\$3,839.40	\$113.76	\$7.11	Average for triple pane windows (sample of 2)
Manufacturer 2 estimate	44%	\$5,934.60	\$175.84	\$10.99	Estimated that krypton historically costed 10x argon fill, but the cost is declining. Assumed 7x current BEopt incremental cost for argon fill (\$1.57), 20% installation and markup assumed.
Alternate Manufacturer 2 estimate	24%	\$3,234.74	\$95.84	\$5.99	Estimated that krypton historically costed 10x argon fill, but the cost is declining. Assumed 7x Home Depot incremental cost for argon fill in Manufacturer 3 windows (\$0.71), 20% installation and markup assumed.

Expert 1 estimate	30%	\$4,050.00	\$120.00	\$7.50	Last time he checked, may not be up-to-date
Expert 4 estimate	8%	\$1,080.00	\$32.00	\$2.00	Estimated as \$0.50 for glass manufacturer, with roughly 5/1.5 markup, 20% installation and markup assumed
Home Depot (Manufacturer 3)	76%	\$8,574.19	\$254.05	\$19.05	R-5 window incremental cost for triple panes, krypton included, but may include better spaces and frames, 20% installation and markup assumed
			Median	\$7.31	

4TH SURFACE LOW-E DOUBLE-PANE COST

Source	% Increase for 4ft x 4ft Window*	Incremental Cost per 2,700 ft ² House (540 ft ²)	Incremental Cost / 4ft x 4ft Window	Incremental Cost (\$ / ft ²)	Notes
Manufacturer 2 estimate	14%	\$1,552.50	\$46.00	\$3.45	Double Glazing, LowE(2), Argon, undiscounted, 20% installation and markup assumed
Expert 4 estimate	20%	\$2,700.00	\$80.00	\$5.00	Estimated \$1.25/ft ² at window manufacturer, with estimated 5/1.5 markup, 20% installation and markup assumed
			Average	\$4.23	

Low SHGC Cost

Source	% Increase for 4ft x 4ft Window*	Incremental Cost per 2,700 ft ² House (540 ft ²)	Incremental Cost / 4ft x 4ft Window	Incremental Cost (\$ / ft ²)	Notes
Beopt	3%	\$340.20	\$10.08	\$0.63	Average for triple pane windows.
Three experts interviewed	0%	\$0.00	\$0.00	\$0.00	Could be higher or lower cost, depending on volume

			Average	\$0.00	
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BASELINE DOUBLE-PANE COST

Source	Incremental Cost per 2,700 ft ² House (540 ft ²)	Incremental Cost / 4ft x 4ft Window	Incremental Cost (\$ / ft ²)	Notes
BEopt	\$12,457.80	\$369.12	\$23.07	New construction, vinyl frame, argon fill, installation included
Home Depot (Manufacturer 5)	\$9,185.00	\$226.79	\$17.01	Retail price for Energy Star window, 20% installation and markup assumed
RSMeans 2014	\$14,916.39	\$441.97	\$27.62	New construction, insulating glass, plastic clad wood, horizontal slider, installed not including caulking, paint, etc.
Angie's List	\$17,718.75	\$525.00	\$32.81	Energy efficient, "standard size", replacement including installation
Home Advisor	\$22,180.50	\$657.20	\$41.08	Replacement including installation, mix of sizes
NREMD	\$18,900.00	\$560.00	\$35.00	Replacement, vinyl frames, installation included
NREMD	\$24,300.00	\$720.00	\$45.00	Replacement, insulated frames, installation included
Home Depot (Manufacturer 3)	\$11,736.09	\$289.78	\$21.73	Replacement, argon fill, most basic options, 20% installation and markup assumed
Home Depot (Manufacturer 4)	\$23,810.36	\$587.91	\$44.09	Replacement, argon fill, low-SHGC, 20% installation and markup assumed
PNNL R-5 WVP Program	\$15,350.69	\$454.84	\$28.43	2012 average incremental cost for code minimum windows. Includes installation cost.
Average for new construction only			\$25.35	

APPENDIX C: MULTI-FAMILY ENERGY SAVINGS ANALYSIS

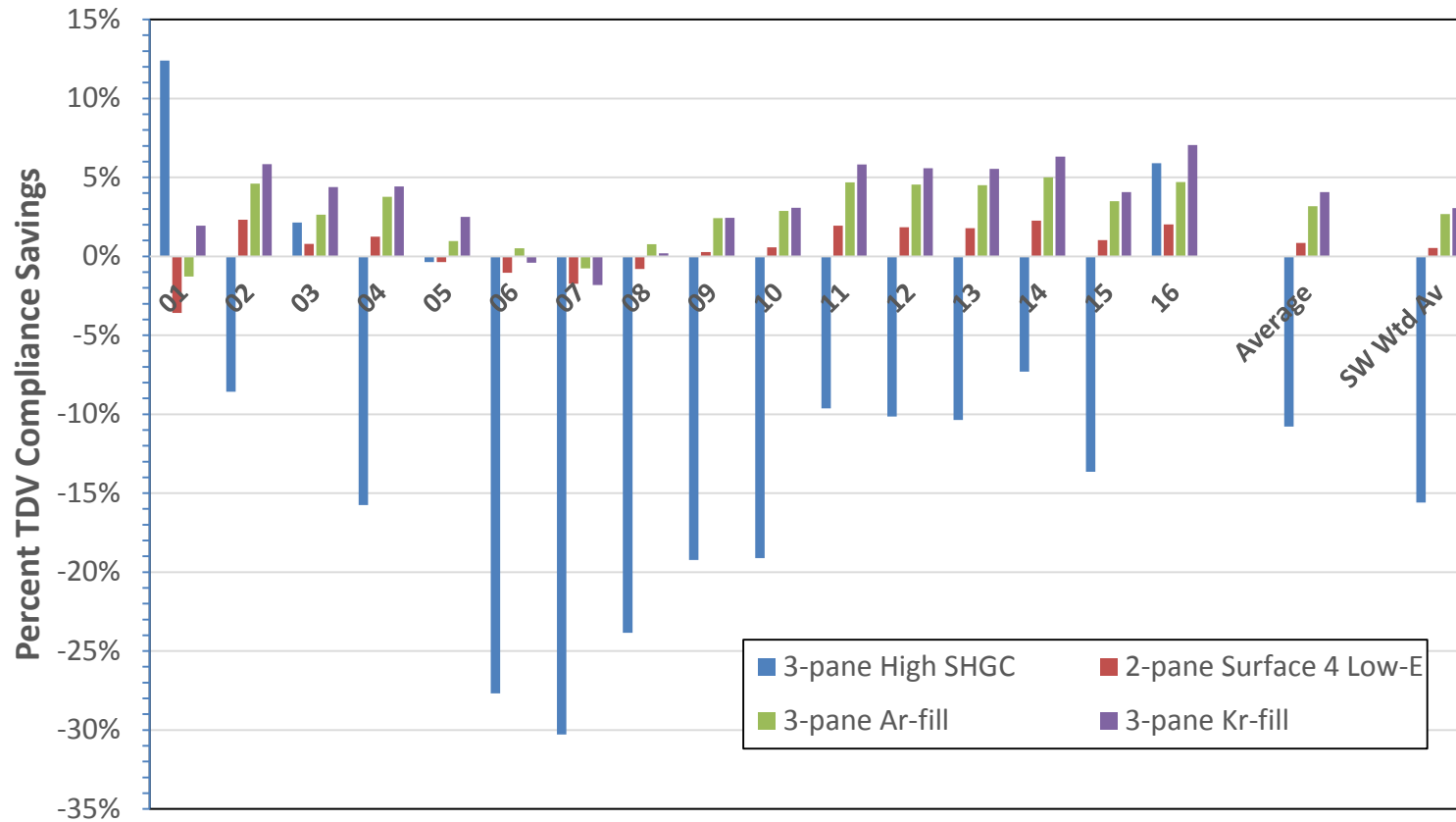


FIGURE C- 1. ADVANCED GLAZING IMPACT ON REGULATED TDV BY CZ (6,960 FT² MULTI-FAMILY)

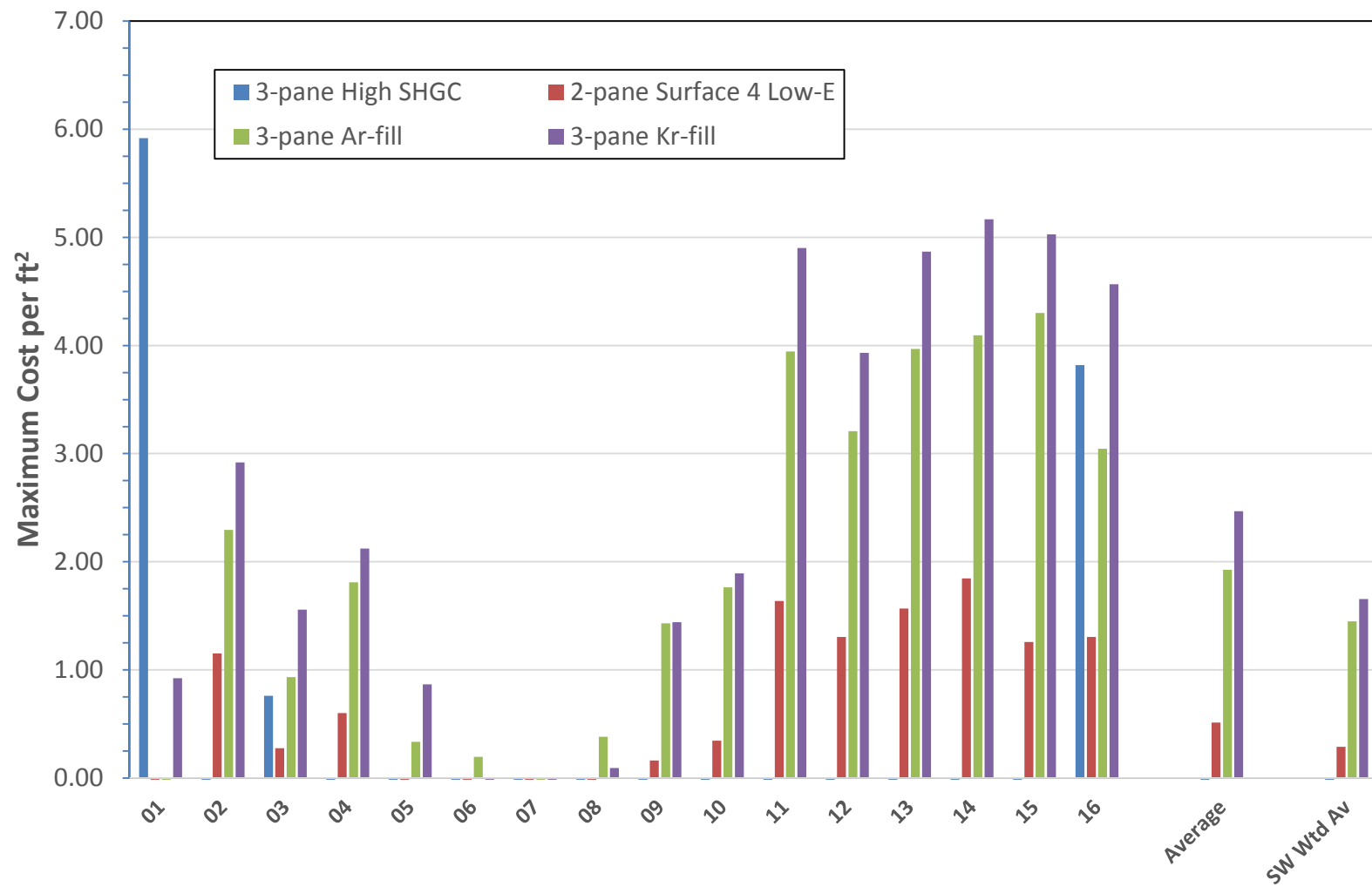


FIGURE C- 2. ADVANCED GLAZING MAXIMUM COST FOR BREAKEVEN COST EFFECTIVENESS (6,960 FT² MULTI-FAMILY)

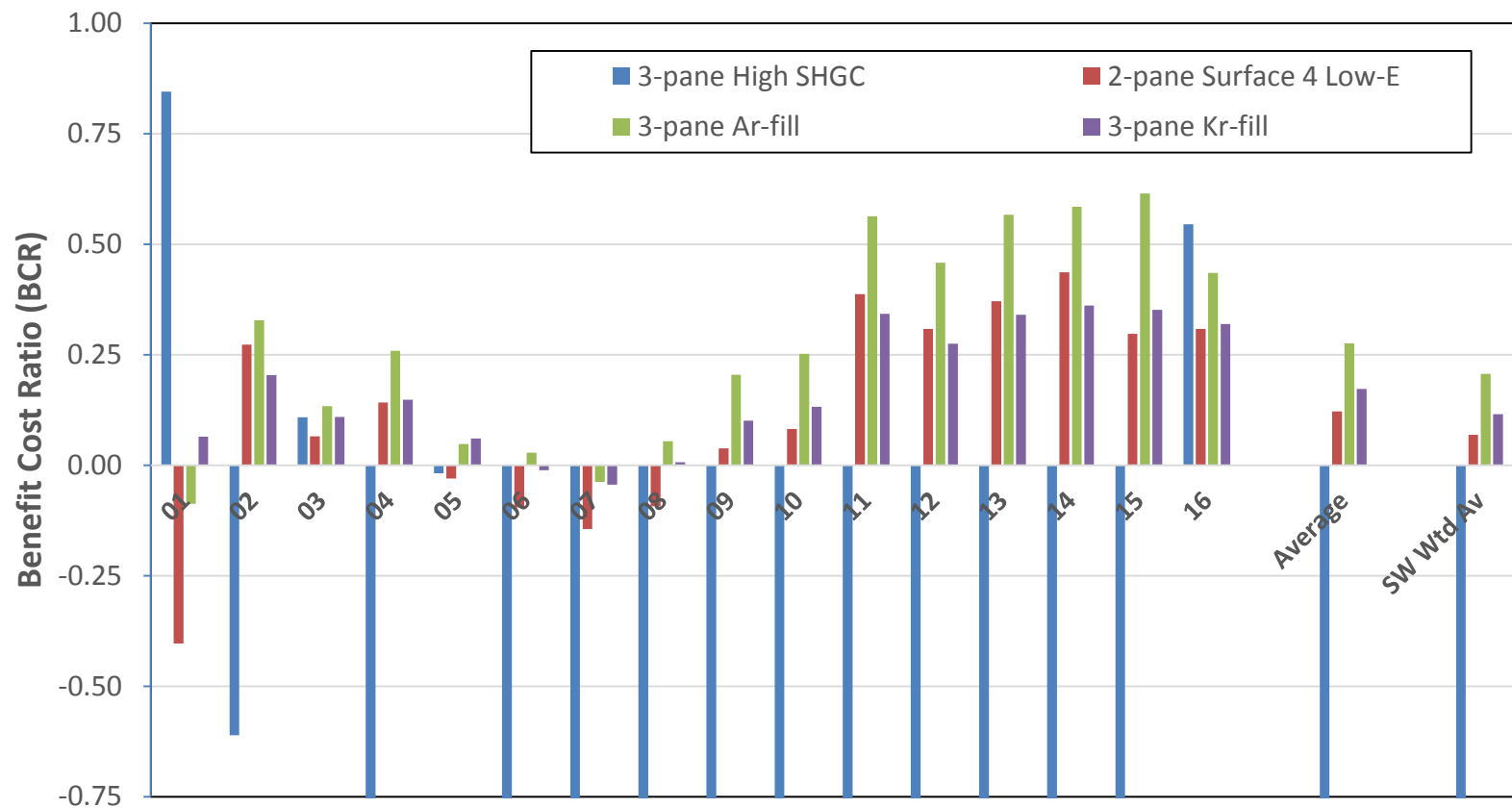


FIGURE C- 3. ADVANCED GLAZING BENEFIT TO COST RATIO BY CZ AND WINDOW TYPE (6,960 FT² MULTI-FAMILY, INSTALLED COST DIVIDED BY PV OF TDV OVER 30-YEAR LIFE CYCLE)

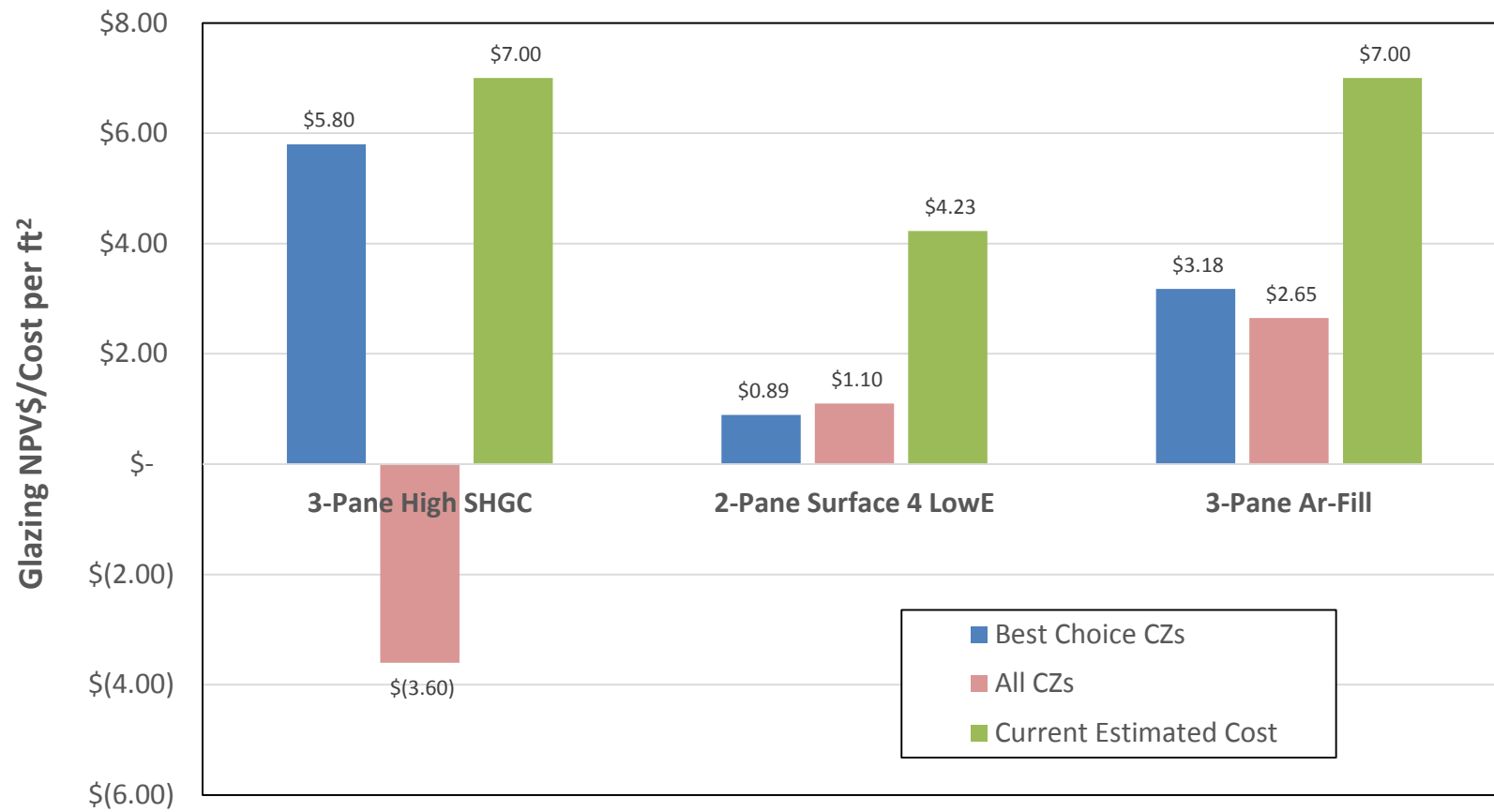


FIGURE C- 4. PV OF TDV SAVINGS FOR HIGH EFFICIENCY WINDOWS IN TARGET MARKETS VERSUS ALL MARKETS (6,960 FT² MULTI-FAMILY)

APPENDIX D: ANNUAL SITE ENERGY SAVINGS ANALYSIS

		SF 2,430 ft ² prototype			MF per apartment			SF 2,430 ft ² prototype			MF per apartment		
	Climate Zone	3-pane High SHGC			3-pane High SHGC			2-pane Surface 4 Low-E			2-pane Surface 4 Low-E		
		kWh Total	kWh Clg	therms	kWh Total	kWh Clg	therms	kWh Total	kWh Clg	therms	kWh Total	kWh Clg	therms
	1	71	-	119	(6)	(10)	22	(28)	-	(42)	(0)	-	(6)
	2	(91)	(147)	110	(113)	(110)	19	15	(2)	24	(3)	(5)	5
	3	32	(1)	63	(25)	(20)	9	(15)	-	(24)	9	6	(3)
	4	(159)	(207)	96	(140)	(133)	15	12	(4)	20	(6)	(7)	4
	5	35	(2)	74	(38)	(31)	9	(21)	-	(34)	8	5	(4)
	6	(163)	(182)	59	(164)	(145)	3	6	(6)	13	(11)	(8)	1
	7	(122)	(115)	27	(139)	(118)	0	4	(2)	8	(8)	(5)	0
	8	(406)	(408)	35	(220)	(203)	1	(0)	(17)	9	(17)	(14)	1
	9	(499)	(515)	51	(233)	(217)	3	1	(17)	12	(14)	(12)	1
	10	(585)	(607)	59	(244)	(230)	4	2	(19)	13	(13)	(11)	1
	11	(664)	(715)	95	(244)	(242)	17	12	(7)	22	(3)	(4)	5
	12	(451)	(498)	92	(210)	(208)	16	11	(11)	21	(8)	(10)	5
	13	(687)	(729)	79	(251)	(250)	15	11	(5)	19	(4)	(5)	4
	14	(621)	(685)	116	(226)	(226)	22	13	(7)	24	(2)	(4)	5
	15	(1,081)	(1,072)	9	(374)	(364)	0	22	54	3	10	11	0
	16	(117)	(185)	113	(75)	(84)	26	13	86	(23)	43	43	(4)
	Average	(344)	(379)	75	(169)	(162)	11	4	3	4	(1)	(1)	1
	Statewide Wtd Avg	(442)	(475)	72	(180)	(168)	7	6	(5)	12	(7)	(6)	1

		SF 2,430 ft ² prototype			MF per apartment			SF 2,430 ft ² prototype			MF per apartment		
	Climate Zone	3-pane, Ar-fill			3-pane, Ar-fill			3-pane, Kr-fill			3-pane, Kr-fill		
		kWh Total	kWh Clg	therms	kWh Total	kWh Clg	therms	kWh Total	kWh Clg	therms	kWh Total	kWh Clg	therms
	1	(16)	-	(28)	2	-	(2)	(0)	-	(3)	4	-	3
	2	24	3	33	1	(2)	7	31	1	47	(2)	(5)	10
	3	(7)	-	(17)	10	6	(1)	1	-	(3)	9	6	1
	4	19	1	27	(1)	(2)	6	24	(1)	39	(5)	(7)	8
	5	(13)	-	(28)	9	5	(3)	(4)	-	(12)	8	4	(0)
	6	10	0	17	(8)	(5)	2	10	(4)	24	(15)	(11)	2
	7	5	0	9	(6)	(3)	0	5	(1)	13	(11)	(7)	0
	8	6	(1)	12	(12)	(9)	1	(2)	(11)	18	(23)	(18)	1
	9	21	12	16	(5)	(3)	2	14	1	22	(14)	(11)	2
	10	30	20	17	(1)	1	2	22	8	25	(9)	(6)	3
	11	84	64	31	19	16	7	87	59	44	16	13	9
	12	39	20	30	4	1	7	41	13	43	(1)	(5)	9
	13	85	67	27	18	16	6	89	64	39	15	12	9
	14	80	59	32	18	15	7	84	54	47	17	13	10
	15	223	221	5	59	61	0	254	253	6	63	67	0
	16	95	94	(6)	50	46	1	103	86	19	46	40	7
	Average	43	35	11	10	9	3	47	33	23	6	5	5
	Statewide Wtd Avg	44	32	19	1	2	2	45	27	29	(5)	(4)	3