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Transforming Windows from Energy Liabilities to Zero-Energy Assets: Next-Generation Solutions for Buildings

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Transforming Windows from Energy Liabilities to Zero-Energy Assets

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ABSTRACT

Windows have traditionally contributed to a building's HVAC load, but they can also become a source of net energy gain or even operate as zero-energy components. For heating applications, highly insulating windows can harness more solar heat than the energy lost through them, transforming windows from energy liabilities to assets. Dynamic glazings provide further benefits by regulating solar heat gain, reducing cooling loads in summer and heating demands in winter. This simulation study focuses on developing the next generation of zero-energy windows (ZEW) for residential new construction. Through annual energy simulations across climate zones 1-8, ZEW performance benchmarks were established based on current code-level buildings, and we've identified the regions where meeting ZEW standards are most achievable. This work evaluates both static and dynamic window technologies, assessing their effects on annual energy use and cost. Key findings demonstrate that ZEW performance is achievable across diverse climate zones, with specific regional requirements. Most climate zones from 3-8 can achieve ZEW with specific configurations, while some warm climates (1-2) appear challenging for ZEW implementation. Climate zones 4-6 consistently allow for zero energy window implementation, offering multiple pathways through either static or dynamic window technologies. Colder climate zones (7-8) ZEW products allow for higher SHGC values while requiring low U-values.

INTRODUCTION

Windows have traditionally been considered as energy liabilities in buildings, contributing to the heating and cooling loads and underperforming relative to insulated walls. They account for about 4 Quads of US energy consumption, or 12% of building energy use (Selkowitz et al., 2018; Arasteh et al., 2006). However, advances in glazing technology, and dynamic control systems provide opportunities to transform windows from energy consumers to energy-neutral or even energy-positive building components (Hart et al., 2019; Carmody et al., 2007; Arasteh et al., 2003;).

The concept of zero energy buildings (ZEBs) has evolved significantly over the past two decades, with various definitions emerging to address different aspects of building energy performance. Torcellin et al (2006) established four fundamental definitions based on site energy, source energy, energy cost, and emissions (Table 1). Further studies have expanded this framework to include nearly zero energy buildings (Kurnitski et al, 2011), net positive energy buildings (Kolokotsa et al, 2011), or plus zero energy buildings (Voss et al, 2012).

Extending these concepts to building components, Zero Energy Windows (ZEWs) represent an advancement in fenestration performance. While ZEBs address whole-home energy efficiency and utilize on-site renewable energy generation for energy use offset, ZEWs focus on transforming one of the most critical elements of the building envelope. Unlike the extensive research on ZEBs, studies specifically addressing ZEW concepts and definitions have been relatively limited. Arasteh et al. (2006) were among the first to propose a definition for ZEWs, describing them as windows that achieve net energy gain rather than loss, with "neutral" performance equivalent to a building with no windows, measured through annual heating and cooling source energy. Earlier work by Maccari et al (2001) approached the concept through heating and cooling load reductions, establishing "neutral" performance based on reference windows using ISO 9050 standards for light transmittance, solar factor, overall U-value, and air leakage factor. They evaluated performance using

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normalized heating and cooling load reduction coefficients. Grynning et al. (2013) expanded on these concepts by proposing three rating methods: the ISO 18292 method defining "neutral" as a cooling/heating factor of zero (essentially an adiabatic element); a useful gain method balancing solar gain and conduction heat loss; and a cooling and heating demand method comparing window performance to an opaque wall. Their metrics included cooling/heating factors, useful energy balance, and effects on combined heating and cooling demand. More recently, Harris (2022) emphasized the significance of windows in building energy performance and reviewed the pathway for achieving zero energy windows, though without explicitly quantifying ZEW performance criteria.

For this study, fundamental definitions for Zero Energy Windows were established that align with the ZEB framework proposed by Torcellini et al. (2006). Through comprehensive energy simulations, both static and dynamic window technologies were evaluated to determine specific performance thresholds for achieving zero energy status. The analysis identified the thermal performance criteria for homes across climate zones in United States, to inform the future window development tailored to specific regional conditions.

The remainder of this paper is organized as follows. The detailed definitions of Zero Energy Windows are presented. Next, the methodology is described, including simulation parameters, climate zone selection, and specifications for both static and dynamic window technologies evaluated. The simulation results are then presented, detailing the performance requirements for static and dynamic windows to achieve zero energy status across different metrics. Following this, the implications of these findings are discussed. Key conclusions are summarized and recommendations for future ZEW implementation are provided based on the analysis.

METHODOLOGY

Definitions of Zero Energy Window

Zero Energy Windows are defined using the metrics that parallel with Torcellini et al.’s (2006) framework for Zero Energy Buildings. Unlike ZEBs, these definitions for ZEWs establish performance benchmarks where windows achieve equivalent energy performance compared to opaque walls.

Table 1. Definitions for Zero Energy Windows compared to Zero Energy Buildings

Metric	Zero Energy Building	Zero Energy Window
Zero Site Energy Use	The site produces at least as much energy as it uses in a year, when accounted for at the site in a year.	The annual site energy consumed with windows is equal to the site energy consumed without windows
Zero Source Energy Use	The site produces at least as much energy as it uses in a year, when accounted for at the source in a year.	The annual source energy consumed with windows is equal to the source energy consumed without windows
Zero Energy Cost	The amount of money the utility pays the building owner for the energy the building exports to the grid is equal to the amount the owner pays the utility for the energy used over the year.	The annual energy cost of the building with windows is equal to the energy cost without windows

Window Technologies

Both static and dynamic window technologies were evaluated in this study. A parametric analysis was conducted by varying:

1. U-factor: 0.01 to 1.00 Btu/h·ft²·°F (0.06 to 5.68 W/m²·K) in 0.05 increments;
2. Solar Heat Gain Coefficient (SHGC): 0.01 to 1.00 in 0.05 increments

Dynamic windows were modeled using the same parametric grid of U-factor and SHGC values as static windows, but with an additional HVAC-responsive shading control algorithm implemented. The control logic operated as follows:

1. When heating mode is on: shade up (maximum SHGC state);
2. When cooling mode is on: shade down (minimum SHGC state);
3. When both heating and cooling are inactive: no change in shading position.

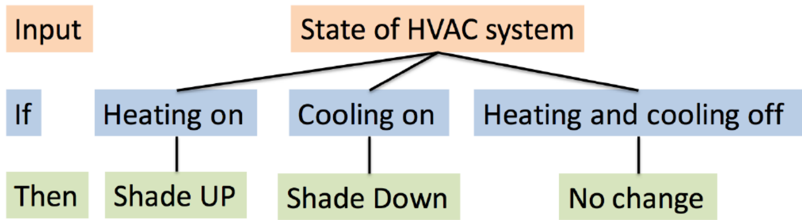

Figure 1 The HVAC-responsive shading control algorithm for dynamic window simulation.

This HVAC-responsive control strategy was selected for its simplicity and practicality in residential applications. The approach requires minimal sensing infrastructure, as it relies only on HVAC operational state information that is readily available in most modern residential systems. This control strategy optimizes solar heat gain based on real-time building thermal needs, allowing solar energy to enter the building during heating periods while minimizing it during cooling periods.

For each maximum SHGC value (shade up state), multiple minimum SHGC values (shade down state) were modeled at 0.05 decrements from the maximum value. For example, a window with a maximum SHGC of 0.65 was simulated with minimum SHGC states of 0.60, 0.55, 0.50, and so on, down to 0.05. This approach allowed for evaluation of various dynamic ranges to determine optimal performance.

Simulation Methodology

Building energy simulations were conducted using EnergyPlus. DOE prototype building models for single family detached houses in 2021 IECC version (Department of Energy, 2024) were selected to represent typical new construction in the U.S. The model has 2,400 ft^2 (223 m^2) of conditioned floor area and a window-to-wall ratio of 15% evenly distributed in each orientation. Window performance was simulated as complete fenestration systems, including both glazing and frame components, to capture the thermal performance of the entire window assembly. Simulations were performed across all U.S. climate zones (1-8) and moisture regimes (A=Moist, B=Dry, C=Marine) using the Typical Meteorological Year (TMY3) weather data for representative cities. A selection of key simulation inputs for the prototype models are listed in Table 2.

Table 2. Simulation Inputs for Prototype Residential Building Models in the Analysis

	Climate Zone 1,2	Climate Zone 3, 4A, 4B	Climate Zone 5, 6, 7, 8
Furnace AFUE	80%	80%	80%
HSPF	8.2	8.2	8.2
SEER	14	14	13
Ceiling Insulation R-value $ft^2\cdot°F\cdot hr$ ($m^2\cdot K/W$)	30 (5.3)	49 (8.6)	60 (10.6)
Above Grade Wall Insulation R-value $ft^2\cdot°F\cdot hr$ ($m^2\cdot K/W$)	13 (2.3)	20 (3.5)	20 +5ci (4.4)
Infiltration (ACH50*)	5	3	3

* ACH50: Air Change per Hour at 50 Pa (1 psf).

The key metrics following the three definitions of Zero Energy Windows were calculated as below:

1. Site Energy Use: total annual site energy consumption;
2. Source Energy Use: site energy converted to source energy using national average conversion factors (electricity: 3.167; natural gas: 1.084);

3. Energy Cost: calculated using EIA residential annual average electricity and gas price data in 2023 (U.S. Energy Information Administration, 2024) for the states that each representative city resides in.

RESULTS AND DISCUSSIONS

Static Window Performance Requirements for Zero Energy Windows

A detailed analysis of climate zone 5B (Denver, Colorado) serves as a representative case study for understanding the performance requirements of static Zero Energy Windows. Climate Zone 5B features a cool and dry climate with significant heating demands and moderate cooling requirements.

Figure 2 presents the cooling electric energy consumption, heating gas energy consumption, and total source energy use for each combination of U-factor and SHGC through contour plots. The cooling energy increases with higher SHGC values regardless of U-factor, with the contour lines running nearly vertical. This indicates that solar heat gain has a dominant effect on cooling loads. The heating gas energy subplot shows a different pattern – the contour lines slope upward from left to right. This indicates that both U-factor and SHGC significantly influence the heating energy use. Lower U-factor and increased SHGC both contribute to reduced heating energy consumption.

The total source energy plot shows the overall energy performance and reveals the Zero Energy Window performance threshold under the Zero Source Energy Use definition, represented by the black dashed line. Points along this line represent window configurations that achieve equivalent source energy use performance as an opaque wall. The simplest combination of U-factor and SHGC along this line for manufacturability is when U-factor reach its maximum at 0.18 Btu/h·ft²·°F (1.02 W/m²·K) with an associated SHGC of 0.35.

To better understand where the market stands and the possibility to achieve ZEW, the plot also displays some typical window products including double-pane clear window (blue dot), double-pane low-E window (yellow dot), and triple-pane windows (green dot). The gray shaded region indicates the window qualification for ENERGY STAR Northern zone that Denver resides in. None of the most common market products achieve zero energy performance in Climate Zone 5B, indicating that advanced technologies such as vacuum glazing or dynamic capabilities would be necessary to achieve zero source energy performance in this climate zone.

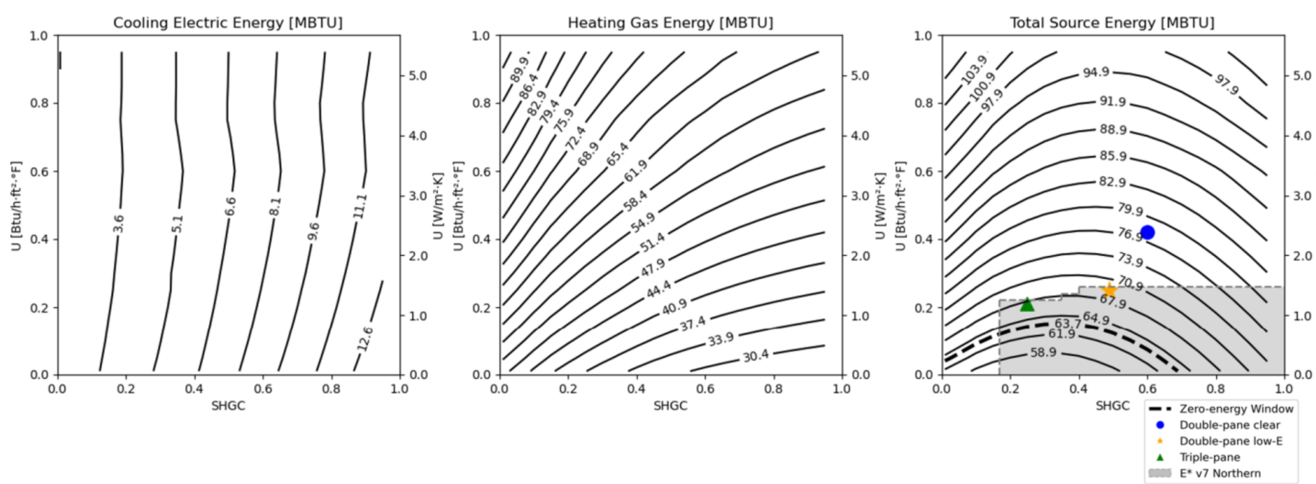

Figure 2 Cooling electric energy, heating gas energy, and total source energy use for static window in climate zone 5B (Denver, Colorado). The Zero Energy Window performance energy level is shown with dashed line in the total source energy figure, along with typical performance levels for common window configurations. (1 MBTU = 1.055 GJ)

Dynamic Window Performance Requirements for Zero Energy Windows

The same climate zone 5B example is used to understand the potential for achieving zero source energy window performance through adaptive shading control. Figure 3 presents the comprehensive evaluation of dynamic windows with varying minimum SHGC states (shade down), compared to the static (no shade) window. The six contour plots on the top illustrate the total source energy use as a function of U-factor and maximum SHGC (shade up). Each plot maintains the same U-factor on the vertical axis and maximum SHGC on the horizontal axis, while the minimum SHGC value (shade down) varies across plots from 0.1 to 0.55. As the minimum SHGC value decreases (moving from SHGC_low=0.1 to SHGC_low=0.55), the zero energy performance line shifts upward, indicating that windows with greater dynamic range can 1) reduce energy use more extensively and 2) achieve zero energy status with less stringent U-factor requirements. For example, in the SHGC_low = 0.1 and SHGC_low = 0.15 subplots, the double-pane low-E window falls below the zero energy line, indicating it meets the ZEW criteria. In contrast, when examining the SHGC_low = 0.45 subplot, while the double-pane low-E window sits just below the ZEW line, the performance margin is significantly reduced. This indicates that windows with greater dynamic range demonstrate better performance by optimizing solar gain seasonally – maximizing beneficial solar heat gain during heating periods while minimizing unwanted solar gain during cooling periods.

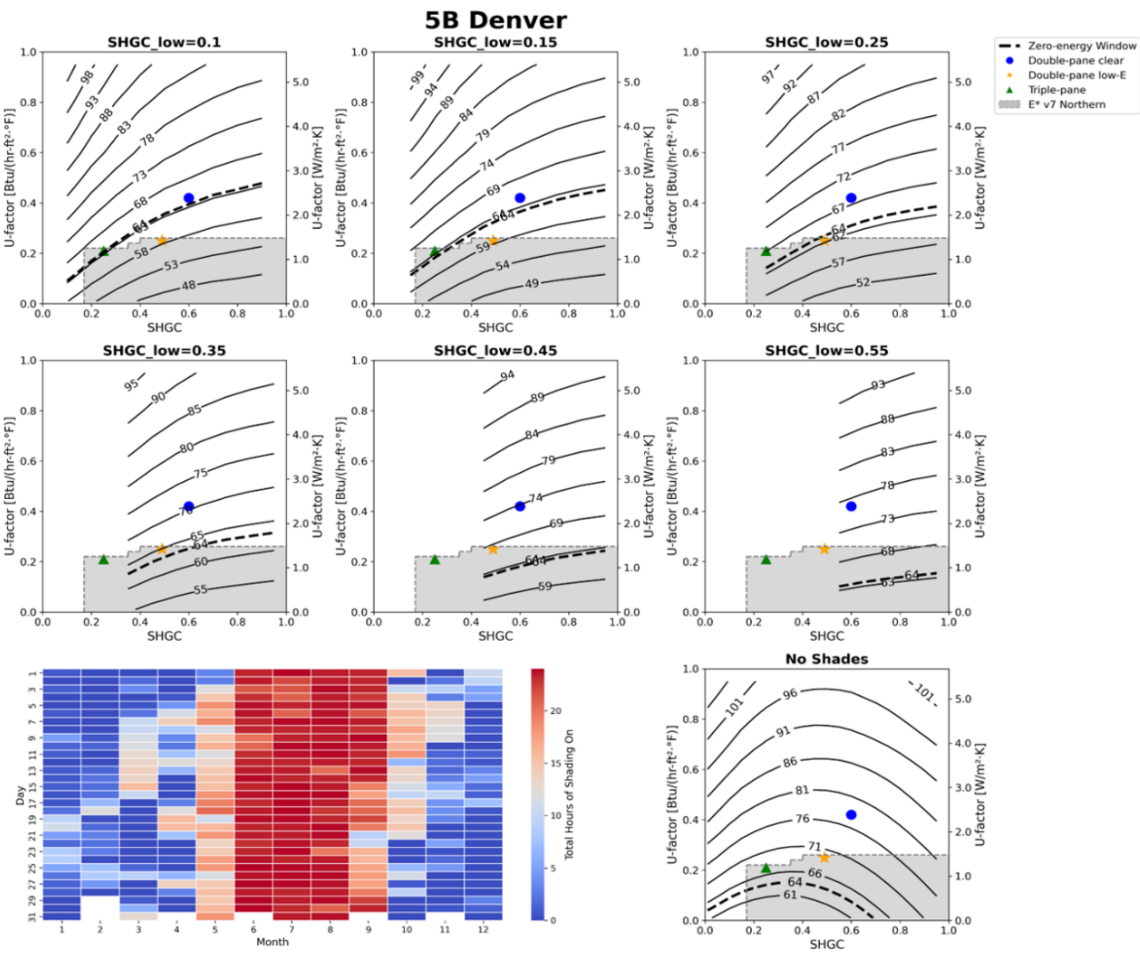

Figure 3 Top six plots: dynamic window total source energy performance in climate zone 5B (Denver, Colorado); Bottom right: static window total source energy performance; Bottom left: hourly shade operation patterns in a year. (1 MBTU = 1.055 GJ)

The static window (no shades) case on the bottom right is used for comparison. When compared to the dynamic window plots, several observations can be made: Dynamic windows significantly expand the range of window configurations capable of achieving zero energy performance. While static window require U-factors below 0.18 Btu/h·ft²·°F (1.02 W/m²·K), dynamic window with SHGC_low = 0.1 can achieve zero energy performance with U-factors up to 0.40 Btu/h·ft²·°F (2.27 W/m²·K). The performance gap between current market products and zero source energy line is narrowed with dynamic operation. Double-pane low-E window achieve and go beyond zero energy performance when operated dynamically with minimum SHGC values lower than 0.25. The double-pane clear and trip-pane window approaches the zero energy threshold when operated dynamically with low minimum SHGC values, indicating that medium to high SHGC baseline windows are better suited for this climate to minimize annual source energy use. Dynamic operation delivers the greatest benefits for SHGC between 0.4 - 0.6, where the zero energy threshold line shifts upward indicating that windows with higher U-factors now can achieve zero energy status; the expanded area below the zero energy threshold line represents a broader range of viable window configurations.

The heat map in the bottom left provides insights into the shade operation patterns throughout the year in this climate zone. Strong seasonal patterns are evident. The shades are predominantly in the down position in summer months (May-Sep). During winter months (Nov-Mar), shades are mostly in the up position especially in daylight hours when solar radiation is strong, allowing maximum solar heat gain to offset heating loads. This demonstrates how this HVAC-responsive control algorithm optimizes solar heat gain in Climate Zone 5B by effectively adapting to both seasonal and daily variations.

National Mapping of Zero Energy Window Requirements

Figure 4 presents a comprehensive mapping of Zero Energy Window requirements across all U.S. climate zones. This tabular analysis provides an overview of the specific performance criteria necessary to achieve zero energy status under three key metrics: source energy use, site energy use, and energy cost. The checkmark (✓) in the ZEW column indicates whether zero energy window performance is actually achievable in that climate zone. For regions without a checkmark, the listed specifications represent the optimum performance, even though these configurations do not reach true zero energy status. For climate zones labeled with "Alternative" for static windows, both static and dynamic window configurations can achieve zero energy performance, providing multiple pathways to zero energy status.

In the warm climate zones dominated by cooling demands (1A-2B), Zero Energy Window performance is hard to achieve. Only 1A can achieve ZEW with static windows having extremely low SHGC values (0.08-0.13 Btu/h·ft²·°F; 0.45-0.74 W/m²·K) regardless of U-factor. The mixed climate zones (3A-4B) show varying ZEW feasibility. Climate Zone 3B can achieve ZEW status only with dynamic windows (U-0.11). For Climate Zone 4A and 4B, ZEW is achievable with both static and dynamic window configurations, as indicated by the "Alternative" designation and checkmarks for both options. The heating-dominated regions (climate zone 5-7) offer multiple pathways to ZEW. Climate Zones 5A, 5B, 6A, 6B, and 7 can all achieve zero energy performance with both static alternatives (U-factors between 0.18-0.22 Btu/h·ft²·°F; 1.02-1.25 W/m²·K) and dynamic windows (U-factors between 0.18-0.25 Btu/h·ft²·°F; 1.02-1.42 W/m²·K). In the most extreme cold climate (climate zone 8), ZEW is achievable with both static windows and dynamic windows. But the requirement on U-factor is stringent (0.11-0.16 Btu/h·ft²·°F; 0.62-0.91 W/m²·K).

It's worth noting that in the climate zones where both static and dynamic windows can achieve zero energy performance, the dynamic windows consistently allow for higher U-factors (typically 0.05-0.10 improvement) compared to static windows with equivalent performance. This represents more flexibility in window configurations and potentially lower manufacturing complexity. Additionally, across many climate zones (4A through 7), dynamic windows show consistent performance requirements (U-factor ≈ 0.25 Btu/h·ft²·°F (1.42 W/m²·K), SHGC_low = 0.1, SHGC_high = 0.49), potentially enabling more standardized manufacturing approaches for dynamic Zero Energy Windows.

The ZEW performance requirements vary slightly across the three metrics. The source energy use generally imposes the most stringent requirements due to the higher primary energy factors for electricity compared to natural gas. The site energy use shows similar patterns to source energy, but with slightly less stringent U-factor requirements in certain climate zones. The energy cost tracks with source energy requirements in most climate zones, reflecting the correlation between energy consumption and cost. However, in regions where the relative prices of electricity and natural gas differ significantly from national averages, energy cost-based requirements diverge from source energy-based requirements.

Table 3. National mapping of window performance requirements across U.S. climate zones for static and dynamic windows

	Source Energy Use				Site Energy Use				Energy Cost			
	ZEW	Operation	U [Btu/h·ft^2·°F (W/m^2·K)]	SHGC	ZEW	Operation	U [Btu/h·ft^2·°F (W/m^2·K)]	SHGC	ZEW	Operation	U [Btu/h·ft^2·°F (W/m^2·K)]	SHGC
1A	✓	Static	Any	0.08	✓	Static	Any	0.13	✓	Static	Any	0.08
2A		Dynamic	0.30 (1.70)	0.5		Dynamic	0.18 (1.02)	0.5		Dynamic	0.18 (1.02)	0.5
2B		Dynamic	0.20 (1.14)	0.5		Dynamic	0.18 (1.02)	0.5		Dynamic	0.18 (1.02)	0.5
3A	✓	Dynamic	0.14 (0.79)	0.5	✓	Dynamic	0.20 (1.14)	0.5	✓	Dynamic	0.12 (0.68)	0.5
3B	✓	Dynamic	0.11 (0.62)	0.5	✓	Dynamic	0.22 (1.25)	0.5	✓	Dynamic	0.13 (0.74)	0.5
3C		Dynamic	0.20 (1.14)	0.5		Dynamic	0.14 (0.79)	0.5		Dynamic	0.20 (1.14)	0.5
4A	✓	Dynamic	0.25 (1.42)	0.4	✓	Dynamic	0.25 (1.42)	0.4	✓	Dynamic	0.25 (1.42)	0.4
4A	✓	Static	0.18 (1.02)	0.4	✓	Static	0.25 (1.42)	0.36	✓	Static	0.10 (0.57)	0.3
4B	✓	Dynamic	0.33 (1.87)	0.4	✓	Dynamic	0.36 (2.04)	0.4	✓	Dynamic	0.34 (1.93)	0.4
4B	✓	Static	0.14 (0.79)	0.25	✓	Static	0.23 (1.31)	0.25	✓	Static	-	-
5A	✓	Dynamic	0.25 (1.42)	0.49	✓	Dynamic	0.25 (1.42)	0.49	✓	Dynamic	0.25 (1.42)	0.49
5A	✓	Static	0.23 (1.31)	0.49	✓	Static	0.25 (1.42)	0.49	✓	Static	0.18 (1.02)	0.49
5B	✓	Dynamic	0.25 (1.42)	0.49	✓	Dynamic	0.25 (1.42)	0.49	✓	Dynamic	0.25 (1.42)	0.49
5B	✓	Static	0.18 (1.02)	0.35	✓	Static	0.25 (1.42)	0.49		Static	-	-
5C	✓	Dynamic	0.25 (1.42)	0.49	✓	Dynamic	0.25 (1.42)	0.49	✓	Dynamic	0.25 (1.42)	0.49
5C	✓	Static	0.18 (1.02)	0.39		Static	0.25 (1.42)	0.49	✓	Static	0.18 (1.02)	0.49
6A	✓	Dynamic	0.25 (1.42)	0.49	✓	Dynamic	0.25 (1.42)	0.49	✓	Dynamic	0.25 (1.42)	0.49
6A	✓	Static	0.19 (1.08)	0.49	✓	Static	0.25 (1.42)	0.49	✓	Static	0.11 (0.62)	0.49
6B	✓	Dynamic	0.25 (1.42)	0.49	✓	Dynamic	0.25 (1.42)	0.49	✓	Dynamic	0.25 (1.42)	0.49
6B	✓	Static	0.22 (1.25)	0.49		Static	0.25 (1.42)	0.49	✓	Static	0.11 (0.62)	0.49
7	✓	Dynamic	0.20 (1.14)	0.49	✓	Dynamic	0.24 (1.36)	0.49	✓	Dynamic	0.22 (1.25)	0.49
7	✓	Static	0.18 (1.02)	0.49	✓	Static	0.23 (1.31)	0.49	✓	Static	0.12 (0.68)	0.49
8	✓	Dynamic	0.14 (0.79)	0.49	✓	Dynamic	0.14 (0.79)	0.49	✓	Dynamic	0.13 (0.74)	0.49
8	✓	Static	0.11 (0.62)	0.49	✓	Static	0.16 (0.91)	0.49		Static	-	-

Note: The checkmark (✓) in the ZEW column indicates whether zero energy window performance is achievable in that climate zone. For all the dynamic window, the SHGC_low is 0.1 in this table.

CONCLUSION

This analysis of Zero Energy Window (ZEW) requirements across U.S. climate zones suggests several findings that may have implications for window technology development and building energy efficiency.

The results indicate that zero energy window performance appears achievable in many U.S. climate zones, though with varying levels of difficulty. In cold and mixed climates (zones 4B-8), ZEW status can be achieved through either static or dynamic window technologies. The performance criteria for these regions generally require U-factors below 0.25 Btu/h·ft^2·°F (1.42 W/m^2·K) combined with moderate to high SHGC values (typically 0.4-0.5) to balance beneficial winter solar gain with summer cooling penalties. These requirements become more stringent in colder climates, with climate zone 8 demanding U-factors below 0.16. In hot climate zones (particularly 2A and 2B), true zero energy performance seems to remain beyond the capabilities of current window technologies, suggesting an area where further research may be beneficial. The analysis of Climate Zone 1A indicates that zero energy performance may be achievable, but only with extremely low SHGC values (below 0.10) that would limit visible light transmission and compromise daylighting benefits.

The analysis suggests that dynamic windows may offer performance advantages over static windows across climate zones. The ability to adjust solar heat gain could potentially expand the range of viable zero energy window configurations, allowing for less stringent U-factor requirements compared to static windows. This operational difference appears most notable in climate zones with distinct heating and cooling seasons. In Climate Zone 5B, for example, dynamic windows with a minimum SHGC (shade down) of 0.1 could achieve zero energy performance with U-factors approximately 0.05-0.10 Btu/h·ft^2·°F (0.28-0.57 W/m^2·K) higher than static alternatives. The heat map analysis reveals the seasonal operation patterns that contribute to this advantage, with shading deployed predominantly during summer months to reduce cooling loads while maximizing beneficial solar gain during winter months. This adaptation enables dynamic windows to overcome some of the performance limitations of static windows.

The examination on multiple metrics (site energy use, source energy use, and energy cost) provides different perspectives on window performance. The source energy use and energy cost metrics generally result in more stringent requirements than site energy, particularly in regions with electricity-dominated cooling loads, likely reflecting the higher primary energy factors associated with electricity generation and regional utility rate structures. The variation among the requirements highlights the importance of metric selection when establishing performance targets. The source energy providing a more comprehensive assessment of environmental impact but potentially imposing more challenging requirements. The energy cost metric reveals how regional energy price variations can influence the economic optimization of windows.

Based on these findings, future industry efforts could focus on improving thermal performance of windows with advanced technologies like VIG. Applying thin-film low-E coatings with improved solar control properties may help address challenges in hot climates. Further refinement of affordable dynamic glazing technologies could expand ZEW feasibility across more climate zones as well. Utility incentive programs could target dynamic window technologies in appropriate climate zones, while education programs for consumers and building professionals might highlight the long-term energy benefits of high-performance windows.

From the researcher side, further research to refine these findings would be valuable, particularly addressing cost-effectiveness considerations, and the interaction between window performance and whole-building design strategies. Demonstration projects showcasing Zero Energy Window technologies in different climate contexts could validate the simulation results in actual operation and accelerate market adoption with visible evidence of their effectiveness.

This study employs an idealized modeling framework that has several limitations that should be acknowledged. The analysis assumes unobstructed solar access and does not account for contextual shading from adjacent buildings, landscaping, or other obstructions. Future research should incorporate contextual shading scenarios to better understand ZEW performance in urban and suburban settings. Additionally, while this residential-focused analysis emphasizes HVAC loads given the minimal lighting energy trade-offs in homes with LED lighting, commercial applications would require more comprehensive end use energy analysis.

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