Quantifying Energy Benefits from Window Improvement Strategies for Commercial Buildings

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Abstract

This study investigates the feasibility of net positive windows (NPWs) for office buildings. Specifically, a series of parametric and optimization analyses is conducted to determine the main design and operation parameters that affect energy efficiency of windows for prototypical office buildings across various U.S. climate zones. The analyses evaluate the impacts of glazing thermal and optical properties, window sizes, and shading strategies on the energy performance of office buildings with and without daylighting controls. It is found that achieving NPWs is challenging especially for office building with large windows located in hot climates. The analysis indicates that achieving NPWs can only be feasible for static windows when a combination of integrated design and operation strategies are considered including optimized thermal and optical properties for the glazing coupled with tight air leakage and enhanced daylighting controls. For retrofit applications on static glazing, secondary windows provide 6% and 5% energy saving when applied to single pane and double pane windows, respectively. Energy saving for Low-E film applications are estimated to be 8% for single-pane windows and 7% for double-pane windows. Internal shades reduce the annual energy use of the office building by 8% for single pane and 3% for double pane windows, whereas external shading provided 8% annual energy saving for single pane windows and 7.9% for double pane windows.

Keywords: Net positive window; Office buildings; Static glazing; Energy efficiency

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Nomenclature

Abbreviations	
ACH	Air Changes per Hour
AL	Air Leakage
HVAC	Heating, Ventilation, and Air-Conditioning
MZVAV	Multiple Zone Variable Air Volume
NPW	Net Positive Window
PSZ	Prescribed System Zoning
SHG	Solar Heat Gain
SHGC	Solar Heat Gain Coefficient
VT	Visible Transmittance
WWR	Window-To-Wall Ratio

1. Introduction

Windows are recognized as a critical component in building energy performance, historically viewed as a source of energy inefficiency for both residential and commercial buildings. Although windows account for only 8% of building surface area, they represent 45% of thermal energy transmission through the building envelope [1]. Fenestration systems are responsible directly for 8.6% and indirectly for 43.0% of annual energy consumption of buildings [1]. Fenestration systems have even larger impacts on peak energy demand and on occupant comfort [2]. However, advancements in window technologies over the past few decades have transformed windows from energy liabilities into potential energy assets [3]. Although current windows are more energy efficient than those from previous decades, they still represent substantial energy burdens for buildings.

Window glazing has been categorized into several forms; static, dynamic, and thermotropic glazing windows [4], static and dynamic windows [5]. The conventional static windows are traditional windows constructed with fixed glazing that does not change their optical properties or performance in response to light, temperature, or an applied electrical current. Static windows include traditional single glazing double, triple, and multi-layer glazing [6]. Recent advancements in static window technologies include passive technologies that can improve thermal and optical window performance such as low-E glazing [7], tinted glazing [8], and anti-reflective glass [9]. Other static window enhancement adaptabilities include solar infrared blocking coatings, and the availability of various cavities including air, argon, krypton, and xenon gases have been added [6].

Dynamic or active windows are other improved window technology with the ability to adjust their tint levels; these include thermochromic, electrochromic, photochromic, gasochromic, and liquid crystal glazing [10],[11]. While commercialization of dynamic windows is growing, its market value and projected growth by 2027 is 10.4% [12], which is a small share compared to the overall window market. Therefore, many studies have focused on studying optical and thermal properties that could enhance the performance of static windows. Indeed, previous studies clearly reveal that utilizing low-E coating for static windows can provide approximately 10% annual energy savings compared to double pane clear glass windows [7], and can save up to about 9% of daily energy consumption of Air conditioners [13]. Several reported analyses have examined the impact of window parameters and applications on energy-saving for static windows including building orientation, window-to-wall ratio (WWR), glazing type, window size, window opening, shading systems, daylighting control on static window performance [14],[15],[16],[17],[18], [19],[20]. Nevertheless, these existing studies have basically analyzed the impact of window properties or parameters on energy saving. However, there is a lack of a comprehensive analysis on how these strategies could achieve net zero or net positive energy operation for static windows. Indeed, high performance windows can achieve net zero-energy and even net positive energy operation for some building types and climatic conditions [21].

The concept of Net Positive Windows (NPWs) describes window systems that enable sufficient solar heat gains during winter to reduce heating demands, while minimizing heat gains during summer to lower cooling loads [21]. In this context, windows shift from being energy liabilities to active contributors to a building's energy efficiency. NPWs are typically evaluated by comparing their energy savings to their energy losses, leading to their classification as net energy gainers or zero-energy products [21], [22]. These systems integrate high insulative materials with effective solar controls, optimizing thermal behavior based on climate and building use [23]. NPWs may utilize advanced static glazing, dynamic glazing technologies, or photovoltaic (PV) integration, and contributes to the overall goal of achieving net zero or net positive energy buildings [22],[23],[24].

Some reported studies have explored the potential of NPWs in enhancing energy performance of buildings. For instance, Arasteh et al. [25] examined annual energy peak demand of nine representative window products deployed for residential buildings in eight US climates. The study revealed that windows with dynamic solar heat gain (SHG) properties are found to offer significant potential in reducing energy use and peak demands in northern and central climates, while windows

with very low (static) SHG properties offer the most energy benefits in southern climates. Arasteh et al. [21] conducted an energy performance analysis for window types for residential buildings and found that in heating dominated climates, static high-solar-gain windows with a U-factor of about 0.68 W/m^2-K (0.12 Btu/hr-ft^2-°F) can achieve energy neutrality. However, they noted that in mixed heating/cooling climates static windows with low U-factors are not as effective to reach energy neutrality as dynamic fenestration systems with the ability to modulate from high solar heat gain coefficient (SHGC) (heating season) to low SHGC (cooling season). Ihm et al. [26] analyzed the impacts of window-to-wall ratios (WWR), glazing U-factor and SHGC on heating, cooling, and total energy use for prototypical residential housing units in Korea. The analysis results indicated that windows can be energy neutral and even achieve positive energy operation for residential buildings in most Korean cities. Moreover, Arasteh et al. [3] analyzed the energy performance of existing residential and commercial building stocks and found that high performance windows have significant potential for energy and peak electricity and natural gas demand savings. They identified three technologies that can achieve substantial demand savings including high insulating window with U-factor of 0.1 Btu/(hr-ft²-°F), dynamic windows, and integrated façades for commercial buildings to control/redirect daylight. Based a large scale analysis of window-related energy consumption for US residential and commercial building stocks, it is estimated that retrofitting existing window stock with improved fenestration technologies offers significant energy savings potentials of about 3.9 Quads [27].

Although these earlier studies provide useful insights into the energy-saving potential of window systems, there is a need to investigate the potential of current window technologies to achieve net zero neutrality when deployed for commercial buildings. Indeed, there are very limited comprehensive studies on the required specifications to achieve NPWs for commercial buildings. Hong and Selkowitz [28] examined the energy performance of window technologies for prototypical large office buildings across five US climates. Their findings indicated that triple-pane low-E and double-pane low-E windows can provide significant energy-saving potential for office buildings. Moreover, their study revealed that the deployment of daylighting controls can contribute a 5-7% reduction in annual energy needs for the office buildings. Recently, Wheeler et al. [29] have evaluated the energy benefits of deploying transparent photovoltaic windows for office buildings. Their analysis has indicated that highly glazed buildings could achieve net-zero energy performance depending on the building specifications and the climatic conditions [29]. In summary, existing

reported studies specific to NPWs are limited and do not provide specific guidelines on the potential for static fenestration systems to achieve net positive energy performance when deployed for commercial buildings. Energy use associated with windows varies widely among buildings depending on climate, building vintage, window and glazing characteristics, window/wall ratios, and other factors [2]. Because commercial buildings often have larger WWR, different occupancy patterns, and more complex HVAC systems, they present unique challenges for their fenestration systems to achieve net positive energy performance. Additionally, the use of daylighting controls offer a particularly significant benefit for commercial spaces with fenestration systems [3].

This study aims to analyze the required thermal and optical properties as well as operating conditions for statically glazed windows to achieve net zero energy performance when deployed for commercial buildings. Specifically, the study has two main objectives: (i) to determine the combinations of thermal and optical properties for windows with static glazing to achieve a net zero or positive performance; and (ii) to examine the operation strategies and the climatic conditions required to achieve NPWs. The outcome of the study could provide useful design and operation guidelines required to develop net positive windows suitable for both new and existing office buildings.

2. Analysis approach

The analysis considered for this study is carried out using prototypical US office buildings with a wide range of fenestration specifications. The parametric analysis is based on a state-of-the-art whole building energy simulation tool [30]. Fig. 1 outlines the general analysis approach considered for the study. First, the main characteristics of the prototypical office buildings are described. Then, the range of window design and operation parameters considered for the study are described. A series of sensitivity analyses are conducted to establish the main guidelines for static fenestration systems to achieve net-zero energy performance for office buildings. Finally, various window improvement strategies were examined. The results from various analyses encompass cooling, heating, and total source energy use relative to the baseline case. The primary location of this analysis is Boulder Colorado characterized by cool dry climate (5B) with high heating load as well as considerable demand for cooling. Three additional representative US climate zones are further analyzed through sensitivity analysis; 2B (Phoenix, AZ), 3C (San Francisco, CA), 5A (Chicago, IL).
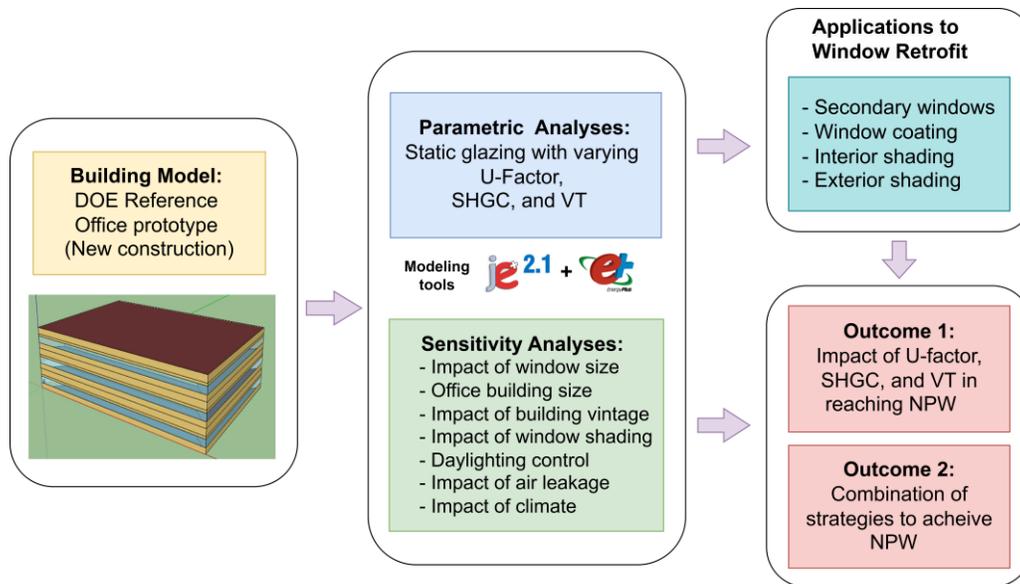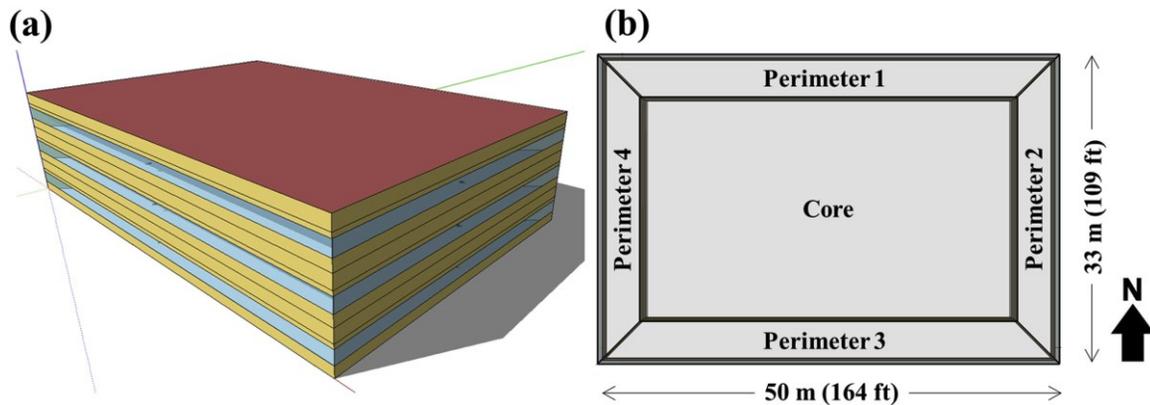
Fig. 1. General analysis approach

2.1. Prototype building model

The study is based on a prototypical US Department of Energy (DOE) commercial reference medium office building model for new constructions using the specifications from the ASHRAE standard 90.1 2019 [31]. The DOE prototype building model represents a standardized, fully specified digital building designed by DOE and Pacific Northwest National Laboratory (PNNL) to serve as research and benchmarking reference for energy performance analysis [31]. The office prototype is a robust, validated, and transparent model that effectively generalizes medium-sized office buildings in the U.S. [32]. It is based on real-world data, representative operational practices, and is used extensively for both research and policy [33],[34],[35]. The Medium office is oriented so that the window area facing the north and south is greater than the window area facing east and west. Table 1 presents a summary of the key characteristics of the prototypical building model used in the analysis.

Table 1. Characteristics of the energy model for the prototypical medium office building

| Parameter	Description
Total floor area	4,982 m^2 (53,628 ft^2)
Aspect ratio	1.5
Number of floors	3
Shading Geometry	None
Azimuth	Non-directional

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Thermal Zoning	Perimeter zone depth: 15 ft. Each floor has four perimeter zones and one core zone. Percentages of floor area: Perimeter 40%, Core 60%
Floor to floor height	13 ft
Floor to ceiling height	9 ft (4 ft above-ceiling plenum)
Exterior wall construction	Steel-framed wall, 25 mm Stucco/Gypsum Board/R-13.45 Insulation
Roof construction	Roof emissivity = 0.9; roof solar absorptance = 0.7; Typical IEAD R-20.83 Roof w/ metal exterior surface
Window construction	Simple glazing system, equal distribution of windows on all four orientations;
Window-to-wall ratio	33%
Thermal Zones	15 Total Zones (5 per floor) plus additional plenum space per floor
Infiltration Rate	AL= 0.5905 cfm/ft^2 (3.0 L/s·m²) at 0.30 inches of water column pressure)
HVAC	Heating type: Gas furnace inside the packaged air conditioning unit Cooling type: Packaged air conditioning unit; Packaged multiple zone variable air volume (MZVAV) system, Gas furnace, Gas-fired boiler, Air-cooled chiller; Differential dry bulb economizer enabled; Service hot water system: High-efficiency (thermal efficiency ≈80%)
Internal gains	Lighting power density = 6.66 W/m^2 (0.62 W/ft^2) Electric plug loads = 7937 W per core zone Gas plug load = 0 W/m^2 (0 W/ft^2) People = 268 total; 5.38/100 m^2 (5.0/1000 ft^2) Elevators = 2 @ 20 HP each, 91% motor efficiency
Thermostat setpoint	75°F Cooling/70°F Heating
Thermostat Setback	80°F Cooling/60°F Heating

Fig. 2. Rendering of the DOE prototypical medium office building: (a) 3D view and (b) floor plan [36].

2.2. Baseline description

The analysis uses the office building model with adiabatic windows (i.e., with SHGC = 0, U-factor = 0, VT = 0, and AL=0) as the baseline against which the energy performance of various glazing configurations is evaluated. Such adiabatic windows have no solar gain, no daylighting, no air leakage, and no heat transfer between the interior and exterior environments since representing the ideal energy neutral fenestration systems for the office building. Moreover, these adiabatic windows allow for systematic and fair comparative analyses between different glazing types as well as design and operation configurations for the prototypical office building as noted in previous studies [21], [26]. The annual end-use energy distribution of the baseline medium office building in Boulder, CO, is shown in Fig. 3. The annual source energy use intensity for the baseline case building prototype (i.e., with adiabatic windows) is estimated to be 246.88 kWh/m². The annual source energy end-use distribution indicates that plug loads consume the most source energy (43%), followed by interior lighting (17%), heating (16%), domestic hot water (8%), and cooling (7%). Fig. 4 shows the monthly energy consumption profiles for both electricity (kWh/m²) and natural gas (therms) for the baseline office building. As indicated by the results of Fig. 4, electricity use of the baseline office building remains relatively steady throughout the year, ranging between approximately 4 and 8 kWh/m², with a slight increase during the summer months due to air conditioning. Natural gas consumption, however, shows a distinct seasonal pattern, peaking during the winter months (January, February, and December) at over 500 therms, due to high space heating needs and decreasing below 150 therms, during the summer months (June through September) when no space heating is required. The monthly energy use shows a consistent pattern expected for a heating dominated climate of Boulder, CO.
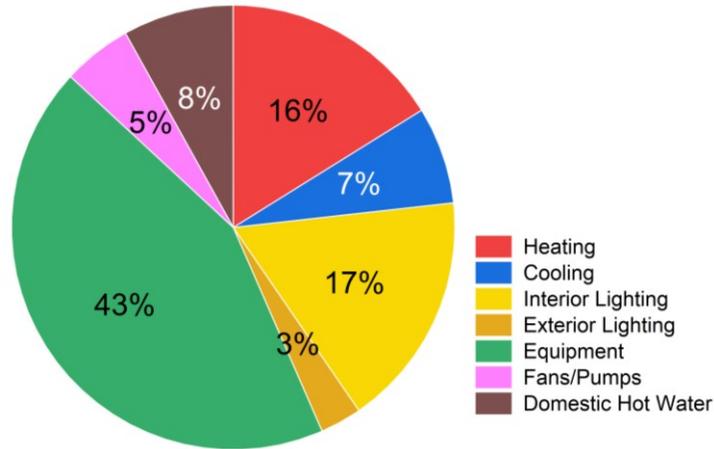
Fig. 3. Total annual energy end-use breakdown for the baseline model of the medium office building in Boulder, CO.
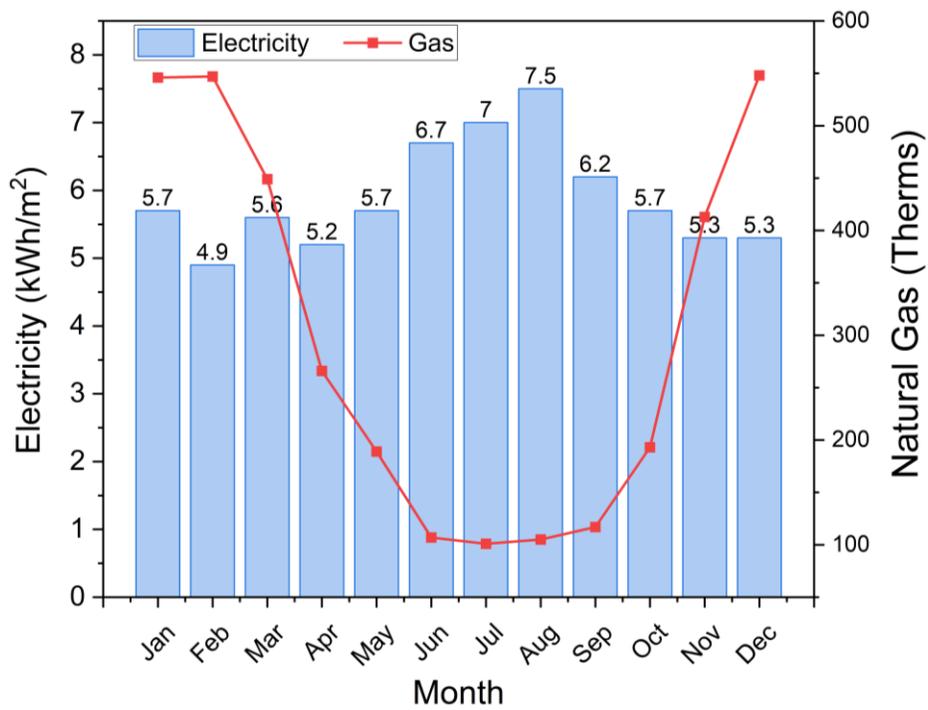
Fig. 4. Monthly variations of electricity and natural gas consumptions for the baseline model of the medium office building in Boulder, CO.

2.3. Simulation analysis

In this study, various window configurations are modeled to assess their potential for achieving net energy positive performance. The study systematically varies the glazing thermal properties, specifically the SHGC and U-factor, from 0 to 0.9 in 0.1 increments. The glazing visible transmittance (VT) is set to be 1.10*SHGC, suitable for static glazed windows [37]. Additionally, an infiltration rate of 0.50 cfm/ft^2 for the medium office building is used in the simulations [31]. Initially, windows with window to wall ratio of 33% are considered and are uniformly distributed across all four orientations. A parametric analysis with 100 window configurations is evaluated and compared against a baseline adiabatic model (i.e., SHGC = U-factor = VT = 0). The results are expressed using the percentage reduction in annual total source energy use of the office building relative to that obtained for the baseline case. Thus, a negative energy reduction indicates that the windows are energy liabilities for the office building since they increase its annual energy use. Furthermore, the study incorporates existing window glazing types with SHGC and U-factor values as outlined in Table 2.

Table 2. Properties of six window glazing types

Glazing	U-factor		SHGC	VT	Description
	Btu/h ft^2 °F	W/m^2 K			
#1	0.83	4.71	0.78	0.85	Single Low-E Clear
#2	0.59	3.35	0.76	0.81	Double Clear, air, vinyl frame
#3	0.37	2.10	0.60	0.77	Double Low-E Clear, air, vinyl frame
#4	0.34	1.93	0.29	0.41	Double Low-E Tint, air, vinyl frame
#5	0.33	1.87	0.68	0.74	Triple Clear, argon, vinyl frame
#6	0.24	1.36	0.47	0.66	Triple Low-E Clear, air, vinyl frame

2.4. Sensitivity analysis

Several sensitivity analyses were performed to evaluate how key factors, including WWR, air leakage, climate, daylighting controls, building size, vintage, and shading strategies influence energy savings in buildings with static glazing windows. These parameters are well-established as having a significant impact on window performance and overall energy efficiency.

2.4.1. Window size

The DOE medium office prototype has a 33% window-to-wall ratio (WWR), defined as the portion of above-grade wall area covered by windows. WWR significantly influences energy use and occupant comfort through heat transfer, solar gain, infiltration, and daylighting [38]. Studies show WWR strongly predicts cooling energy use [16], with poor configurations increasing total energy demand by 5–25% compared to optimal ones [39]. Ideal WWRs typically fall between 0.30 and 0.45, except for south-facing façades in extreme climates [39]. In addition to the 33% WWR, this analysis also considers WWRs of 15% and 45% to assess the impact of smaller or larger WWR on the medium office building.

2.4.2. Building size

The size of a building is proportional to the area to heat, cool and light. Several studies have shown the significant impact of building size on thermal performance from space heating and cooling [40],[41]. The DOE classified office buildings into small (1 floor), medium (3 floors), and large (12 floors). Therefore, to cover the broader office building stock, the energy performance of small and large office building was analyzed in addition to the medium office prototype. Small offices have floor area of 510 m^2 (5,500 ft^2) and WWR of 21% whereas large office floor area is 46,316 m^2 (498,588 ft^2) with 40% WWR [31].

2.4.3. Building Vintage

DOE classifies building energy models into three categories depending on their vintage: pre-1980, post-1980 (1980-2004), and new constructions. Since office buildings make up about 18% of total floor area of the US commercial building stock with those constructed before 1980 representing nearly a third of the existing office building stock [42], the evaluation of window performance for various building vintages is considered in this section. Therefore, in addition to the new construction, medium office pre-1980 and post-1980 models for the medium office buildings are analyzed. Table 3 summarizes the main differentiating features for two additional medium office building vintages analyzed.

Table 3. Characteristics of the energy model for the pre-1980 and post-1980 prototypical medium office building in Boulder, CO.

| Parameter	Description (pre-1980)	Description (post-1980)
Total floor area	4,982 m^2 (53,628 ft^2)	4,982 m^2 (53,628 ft^2)
Window construction	WWR=33%; Simple glazing U-factor=3.52; SHGC=0.41; VT= 0.32	WWR=33%, Simple glazing U-factor=3.55, SHGC=0.39,
Roof Construction	Fiberglass batt insulation placed above the roof deck; R-value: R11 to R-19	Fiberglass batt insulation placed above the roof deck; R-20 to R-30
Wall construction	Minimal insulation in cavity walls (no continuous insulation layers); R-7 to R-11	R-13+ cavity insulation with R-5 to R-10 continuous exterior insulation
Air Infiltration	1.5 cfm/ft^2 above grade wall area at 0.3 in wc (75 Pa)	1.5 cfm/ft^2 above grade wall area at 0.3 in wc (75 Pa)
HVAC	PSZ with plenum zones, gas furnace, hot water reheat (with associated boiler)	PSZ with plenum zones, gas furnace, hot water reheat (with associated boiler)
Light power density	16.89 W/m^2 (1.6 W/ft^2)	16.89 W/m^2 (1.6 W/ft^2)
Electric plug loads	8.07 W/m^2 (0.75 W/ft^2)	8.07 W/m^2 (0.75 W/ft^2)

2.4.4. Shading

The impacts of window shading on the medium office building energy use are analyzed using operable window interior and exterior shading devices. In this analysis, horizontal slat-type blinds are considered for interior shading and exterior roller shades in office buildings, incorporating daylighting controls. Interior roller shades are controlled with slat angles ranging from 0° (fully open, horizontal slats) to 180° (fully closed, vertical slats), with a nominal operating angle of 45° to extend/retract based on exterior conditions (e.g., solar irradiance, glare). Exterior window shading options include awnings, blinds, solar screens, overhangs, shutters, and roller shades, each offering varying levels of sun protection and energy efficiency. Retractable window awnings are often deployed because of their potential to reduce solar heat gains by up to 65% on south-facing windows and 77% on west-facing windows [43]. In this analysis, a sequential multiple surface control using outdoor air temperature is considered for controlling the exterior shading device. Fig. 5 shows the illustrations of both the interior and exterior shading devices
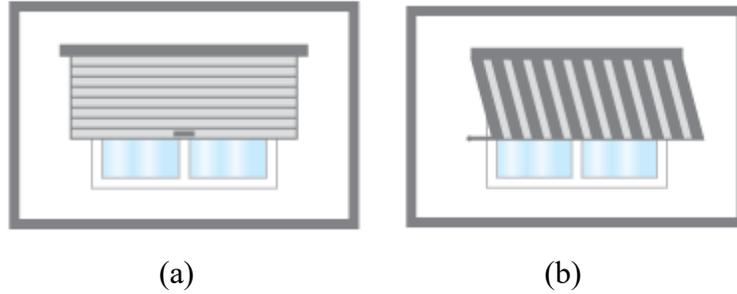
Fig. 5. Illustrations of two window attachments: (a) interior blind shade and (b) exterior awning

2.4.5. Daylighting controls

Several studies show that proper daylighting schemes can help reduce the electrical demand [44],[45],[46]. It is believed that daylighting can reduce artificial lighting consumption from 50 to 80% and even up to 85% [44],[46]. SplitFlux daylighting method with continuous, stepped, and continuous/off (gradual) controls are considered in this analysis [47]. For continuous control, lights dim linearly, and continuously as indoor daylight illuminance increases, down to a minimum level and remain at this level even with more daylight intake. The stepped control has 3 settings which ensure that lights drop in equal steps as daylight illuminance level increases. The continuous/off gradual control is similar to the continuous control except that the lights turn off completely when the minimum dimming point is reached. Fig. 6 illustrates the basic operation including the relationship between electric light output and daylight illuminance level for the three daylighting controls [47].
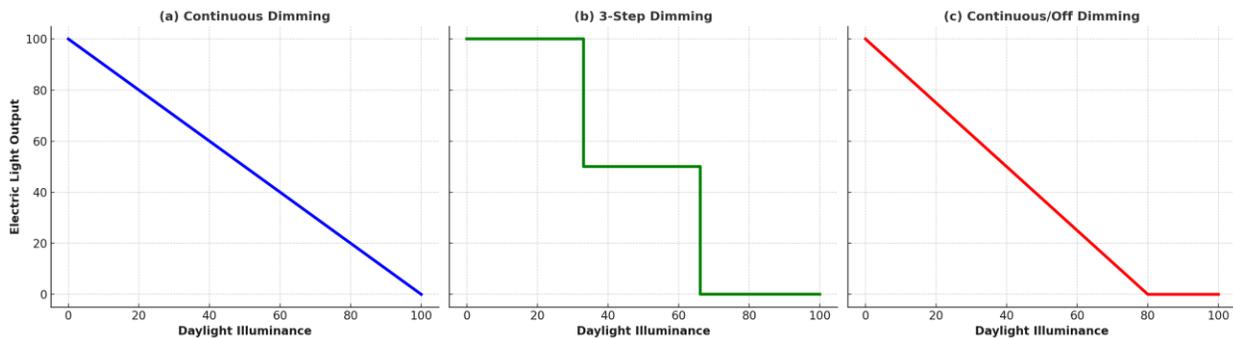
Fig. 6. Illustration of daylighting controls: (a) continuous control, (b) stepped control, (c) continuous/off control.

2.4.6. Air Leakage

Air leakage through building envelopes has considerable impacts on heating and cooling thermal loads and consequently energy use of buildings [48]. It is reported that heat gains from air leakage can account for 10%–33% of the overall building envelope heat transmissions [49]. Moreover, it is estimated that air leakage through envelope elements of US commercial buildings is responsible for about 6% of their annual energy use and mainly affects space heating [50]. Specifically, previous studies show that air infiltration accounts for 33% of the total heating energy use but lowers by 3.3 % the total cooling energy use [51]. ASHRAE 90.1 specifies that for more efficient building energy performance, air leakage rate from various building components including windows, should not exceed 0.40 cfm/ft^2 (2.03 L/s/m^2) at 75 Pa indoor-outdoor pressure difference [52]. In this section, the impacts of window air leakage are estimated for three different air infiltration target rates of 0.40, 0.25, and 0.06 cfm/ft^2, when compared with the base case air leakage of 0.5905 cfm/ft^2 (3.0 L/s·m²) set for the prototypical US medium office building.

2.4.7. Climate

The analysis examines the impacts of window thermal and optical properties on the energy performance for a medium office located in Boulder, CO in addition to three other cities with different climatic characteristics, including San Francisco, CA (mild climate), Chicago, IL (cool humid) and Phoenix, AZ (hot climate. These range of climate zones considered provide a representative of the US climate. The climate characteristics of the three cities in addition to Boulder, CO, are summarized in Table 4 [53].

Table 4. Climate features for four US cities considered in the study [53].

City	ASHRAE Climate Zone	Thermal zone	HDD (ºC-days)	CDD (ºC-days)	Average daily solar radiation (kWh/m²/day)
Phoenix, AZ	2 B	Hot	523	2532	5.7
San Francisco, CA	3C	Mild	1504	79	4.4
Chicago, IL	5A	Cool Humid	5974	1003	6.5
Boulder, CO	5B	Cool Dry	3301	432	4.4

## 3. Discussion of analysis results

Fig. 6 summarizes the impact of window glazing U-factor and SHGC on annual total source energy use for the prototypical medium office building in Boulder, CO, operated without daylighting controls. In Fig. 5, the contour lines represent energy performance relative to the baseline case, with negative values indicating the relative energy penalties that the windows present for the office building. The performance of six common glazing types is also estimated as identified by their number within the contour lines. The thermal and optical specifications for the six glazed windows are listed in Table 2.

Fig. 7 demonstrates that both U-factor and SHGC significantly influence overall building energy performance. The contour lines indicate that the office building consumes less annual source energy as the U-factor of its windows decreases. However, the steeper gradients along with the SHGC variation compared to those associated with the U-factor change suggest that the SHGC specification has more pronounced effects on energy performance of the office building in Boulder, CO, than the U-factor of the windows. This result suggests that prioritizing SHGC selection may yield greater energy reductions compared to focusing solely on U-factor improvement when the office building is in cool and dry climate zones such as that of Boulder, CO. As anticipated, glazing type #1 (Single Low-E Clear) results in the least energy savings due to its high U-factor and SHGC, which lead to poor thermal and solar control properties. In contrast, glazing type #6 (Triple Low-E Clear), with its low U-factor and SHGC, achieves the highest energy savings, demonstrating higher performance in reducing total thermal heating and cooling needs for the office building. Interestingly, glazing types #3 (Double Low-E Clear) and #5 (Triple Low-E Clear) exhibit similar thermal performance despite their different characteristics, indicating that both glazing types can provide comparable energy benefits under certain conditions. The analysis also highlights that achieving net-zero or positive energy window remains challenging for static glazing systems without incorporating advanced technologies or daylighting controls. This underscores the need for innovative glazing solutions and complementary design strategies, such as dynamic shading devices and integrated attachment systems.
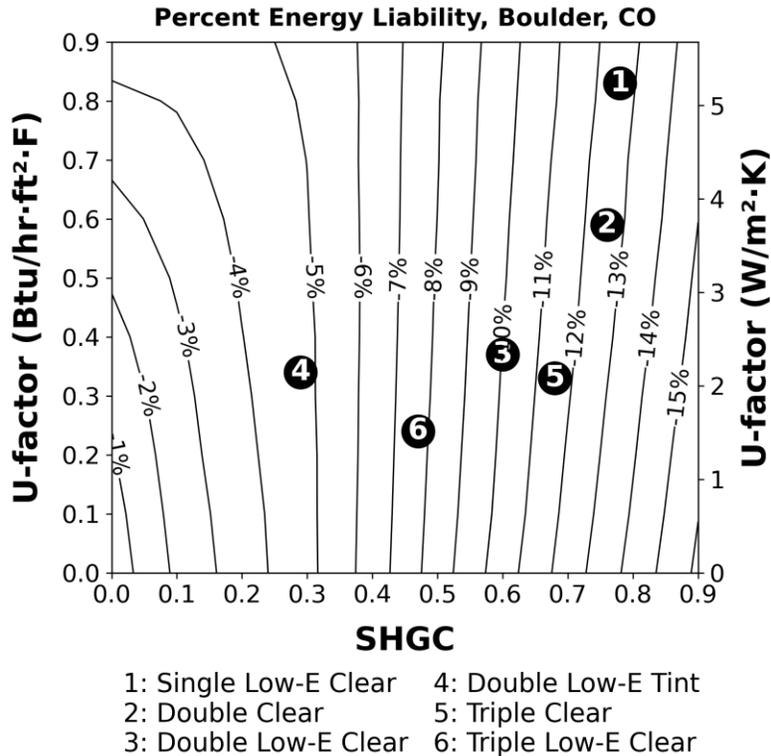
Fig. 7. Window energy penalty contours relative to the baseline (SHGC = U-factor = VT = 0, and AL = 0) for the medium office building in Boulder, CO.

Fig. 8 shows the energy consumption breakdown (kWh/m²) for six glazing systems, for which thermal and optical properties are detailed in Table 2. Fig. 8 confirms that high performance glazing systems, particularly Triple Low-E Clear, achieve significant energy savings due to their low U-factor and SHGC values. This performance contrasts sharply with Single Low-E Clear and Double Clear glazing, which exhibit comparatively high values for both U-factor and SHGC, resulting in higher energy penalties, as shown in Fig. 7. The energy performance variations between the six glazing types are most pronounced for heating and cooling end uses. Specifically, the heating energy demand decreases markedly as glazing performance improves, with Triple Low-E Clear demonstrating the lowest heating energy need due to its superior insulating properties. Annual cooling energy end-use, while relatively low across all glazing types, shows a slight increase with higher-performance glazing. This counterintuitive trend is likely attributable to reduced heat transfer, which can trap internal heat gains during warmer months.
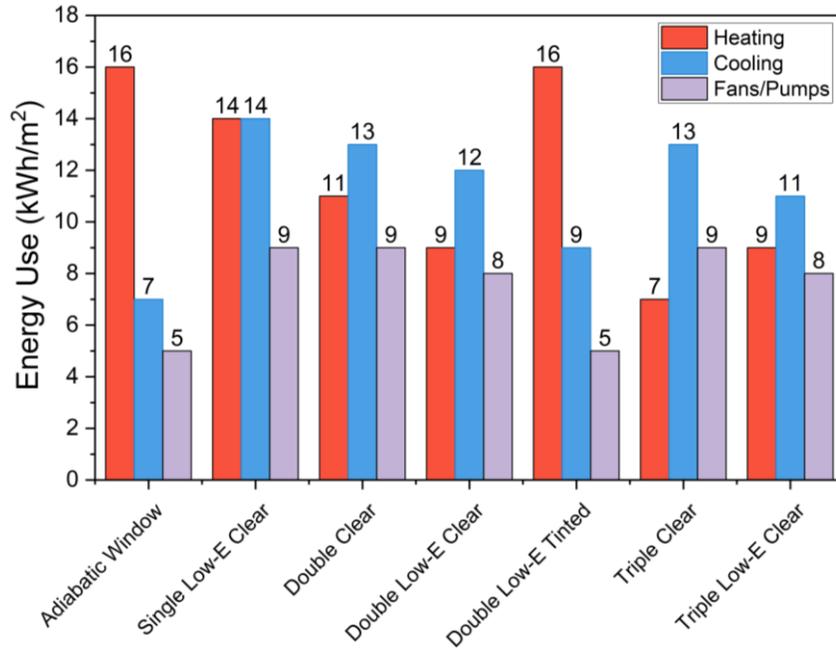
Fig. 8. Annual energy end use distributions for the office building in Boulder, CO, with different window types compared with baseline adiabatic.

3.1. Sensitivity analysis results

In this section, the results of several sensitivity analyses outlined in section 2.4 are discussed. The discussion includes the impact of WWR, air leakage, climate, daylighting controls, building size, building vintage, and shading strategies. The analysis results provide insights into how each factor affects energy consumption of the office building and identify the best design and operation conditions that favor windows to achieve net energy positive performance
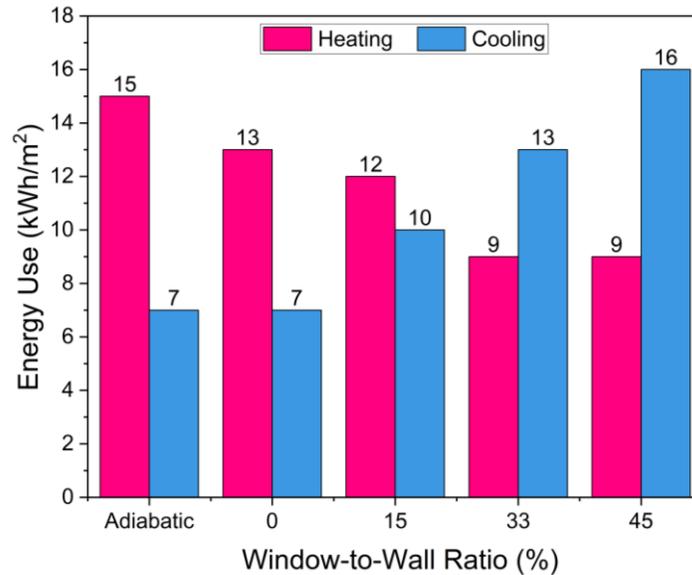
3.1.1. Impact of Window Size

First, a parametric analysis is carried out to assess the impact of window size on the energy performance of the office building by varying its WWR from 15% and 45%. Specifically, office buildings with three WWR values are considered in the analysis including WWR = 0.15, WWR=0.33, and WWR = 0.45. Fig. 9 summarizes the results of the impact of window size on the energy performance of the medium office building in Boulder, CO. As expected, the results indicate that as the window size increases, the annual energy needs for the office building increase independently of the glazing thermal and optical properties. Indeed, the window energy liabilities become noticeably higher for WWR = 45% compared to those for WWR = 15% and even for WWR

= 33%. The increase in window size magnifies the impact of SHGC on the annual energy use of the office building due to higher solar heat gains which increase the building's thermal cooling load as clearly depicted in Fig. 10 for the case of single low-E windows. Conversely, the thermal heating load of the office building reduces as the window size increases since more solar heat gains are harvested. This passive solar heating benefits from larger windows reduces the heating load on the building's HVAC system. However, larger windows increase overall annual energy use for the office building, making the goal of reaching net-zero energy performance even more challenging compared to smaller windows.
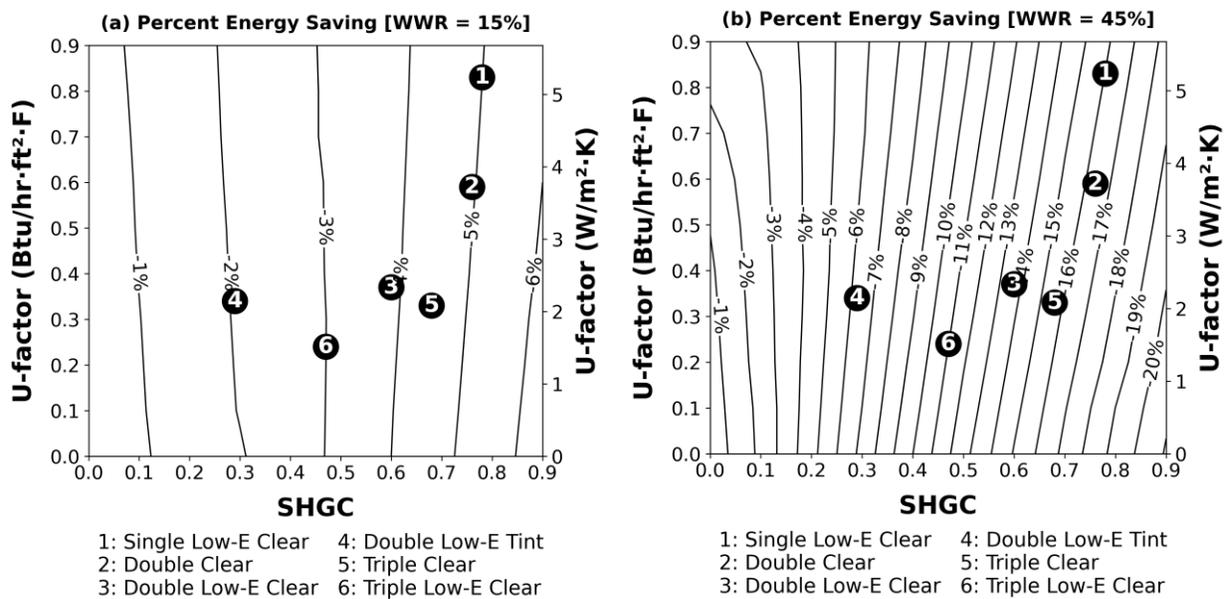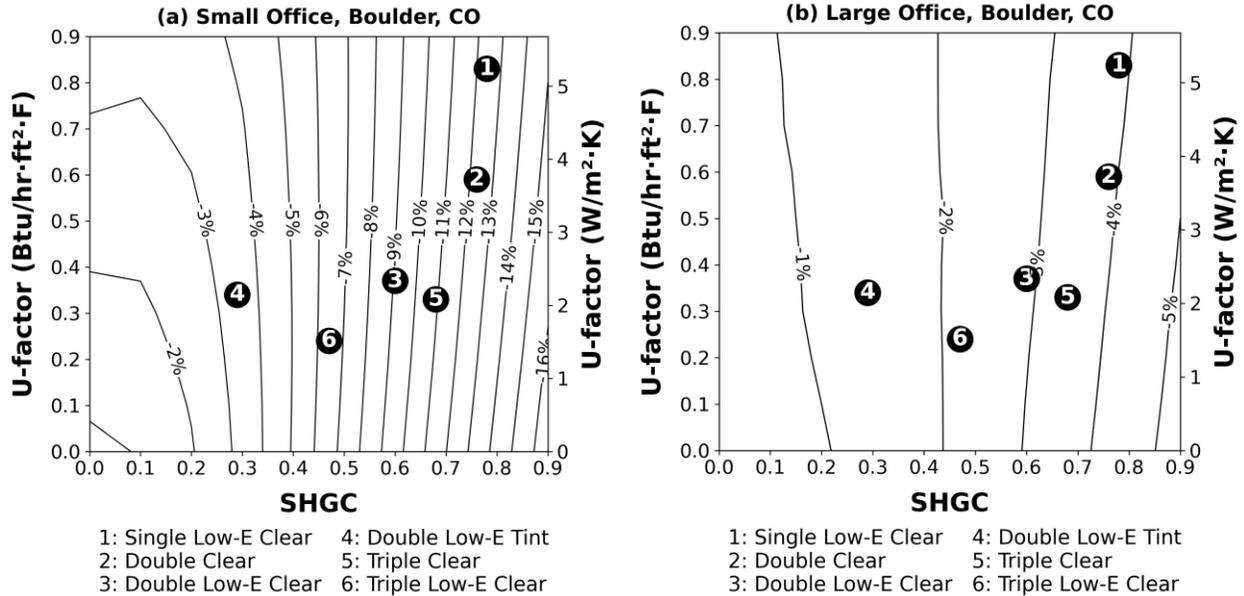

Fig. 9. Window energy penalty contours for the medium office building in Boulder, CO, with (a) WWR=15% and (b) WWR=45%.

Fig. 10. Impact of window size on annual heating and cooling energy end uses for the prototypical medium office building in Boulder, CO.

3.1.2. Impact of Office Building Size

In addition to the medium-sized office building, small and large office buildings are considered to assess the energy liabilities of windows relative to the associated baseline cases (i.e., same size buildings but with adiabatic windows). The effects of both thermal and optical properties of windows on annual building energy performance of both small and large office buildings in Boulder, CO, are illustrated in Fig. 11. The results of Fig. 11 show that large office buildings exhibit lower relative energy penalties compared with small office buildings. Previous studies have reported that small offices (less than 5,000 ft^2) and large office buildings (over 500,000 ft^2) have about the same electricity intensity [54]. However, the contributions of windows on both heating and cooling needs are higher for small compared to large buildings that are dominated by their core spaces rather than their perimeter spaces. Therefore, the annual energy performance of small office buildings is highly sensitive to the window properties as depicted in Fig. 11. For both office building sizes, the SHGC specification has more impact than the U-factor selection on the annual energy performance as found for the case of the medium office building.

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Fig. 11. Window energy penalty contours for (a) small office, (b) large office buildings in Boulder, CO.

3.1.3. Impact of Building Vintage

The results illustrated in Fig. 11 show the relative energy performance of medium office buildings constructed pre-1980 [Fig.12(a)] and post-1980 [Fig. 12(b)]. As expected, the annual source energy use for the baseline with adiabatic windows (i.e., U-factor=SHGC=VT=AL=0) is higher for pre-1980 benchmark model [486.5 kWh/m^2 (8727.41 GJ)] compared with post-1980 benchmark [471.54 kWh/m^2 (8457.02)]. However, the window energy liabilities are more pronounced for post-1980 compared to pre-1980 buildings, especially for windows with high SHGC values. This is due to improved thermal insulation in post-1980 buildings, where excessive solar heat gains through the windows become significant energy liabilities due to substantial increases in space cooling needs. Thus, improvements in building envelopes make the contributions of windows even more pronounced on the overall energy needs of the office buildings. Fig 13 summarizes the annual energy end use breakdown for the two baseline office building vintages with the post-1980 model having cooling (9%) and heating (3%) end-uses higher than those of the pre-1980 model.
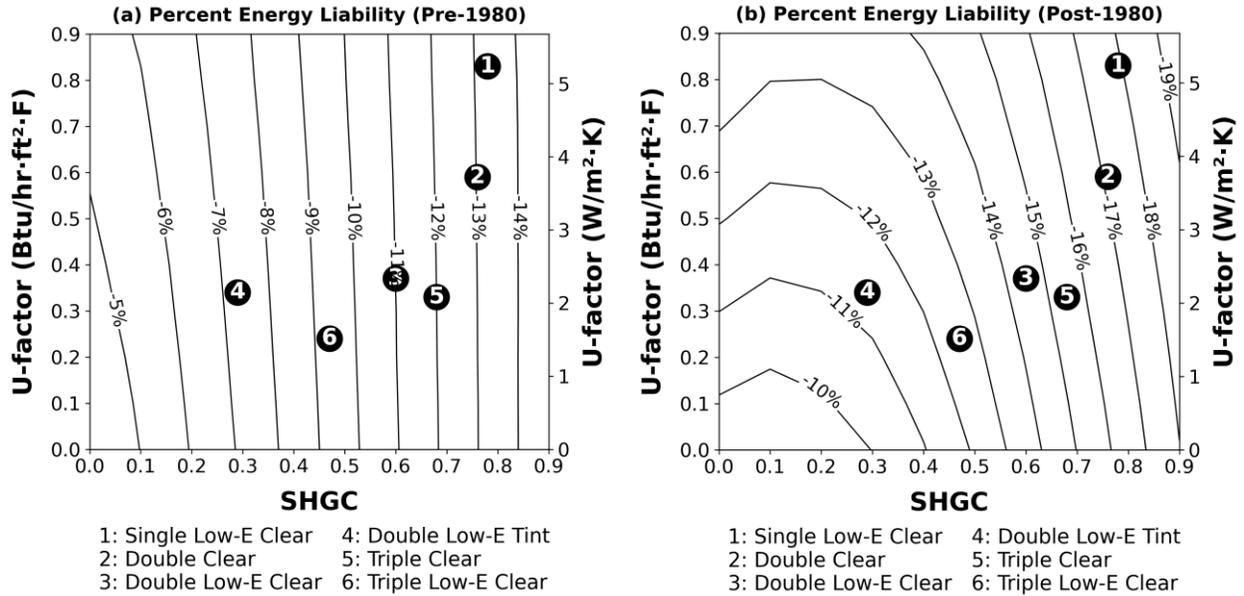
Fig. 12. Window energy penalty contours for (a) pre-1980 and (b) post-1980 medium office buildings in Boulder, CO.
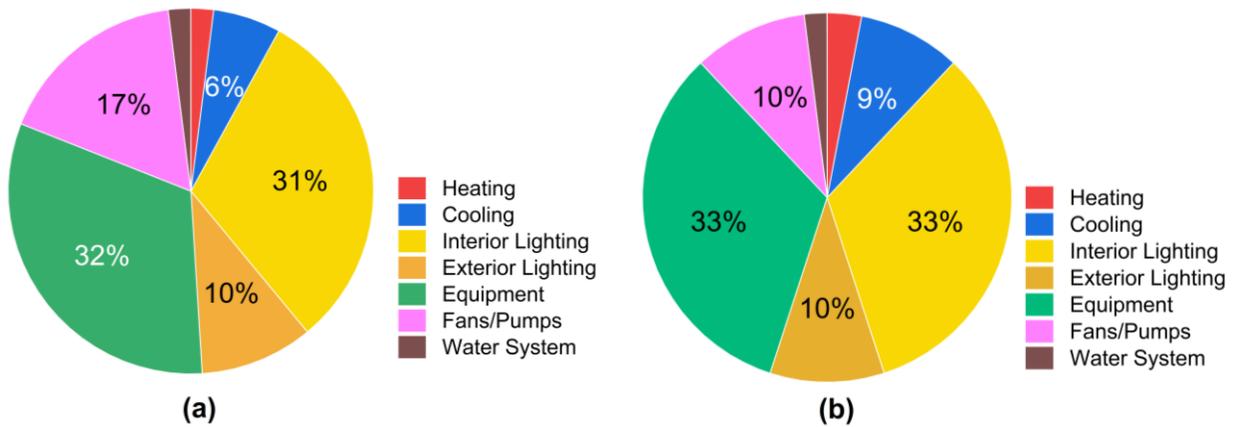

Fig. 13. Annual energy end-use breakdowns for the baseline models of (a) pre-1980 and (b) post-1980 medium office buildings in Boulder, CO.

3.1.4. Window shading

Fig. 14 shows the results of the deployment of interior and exterior dynamic shading devices coupled with daylighting controls for the medium office building in Boulder, CO. The results of Fig. 14 indicate that the exterior shading system performs better than the roller shade by reducing the window energy penalties by up to 4% for high SHGC glazing. Previous studies have found that

exterior shading devices can reduce cooling loads by up to 40%, outperforming interior shading systems [17], [18]. For both shading systems, the results of Fig. 14 confirm that the influence of U-factor is less pronounced compared to that of SHGC, with minimal variation in energy savings across different U-factor levels regardless of the window attachment type.
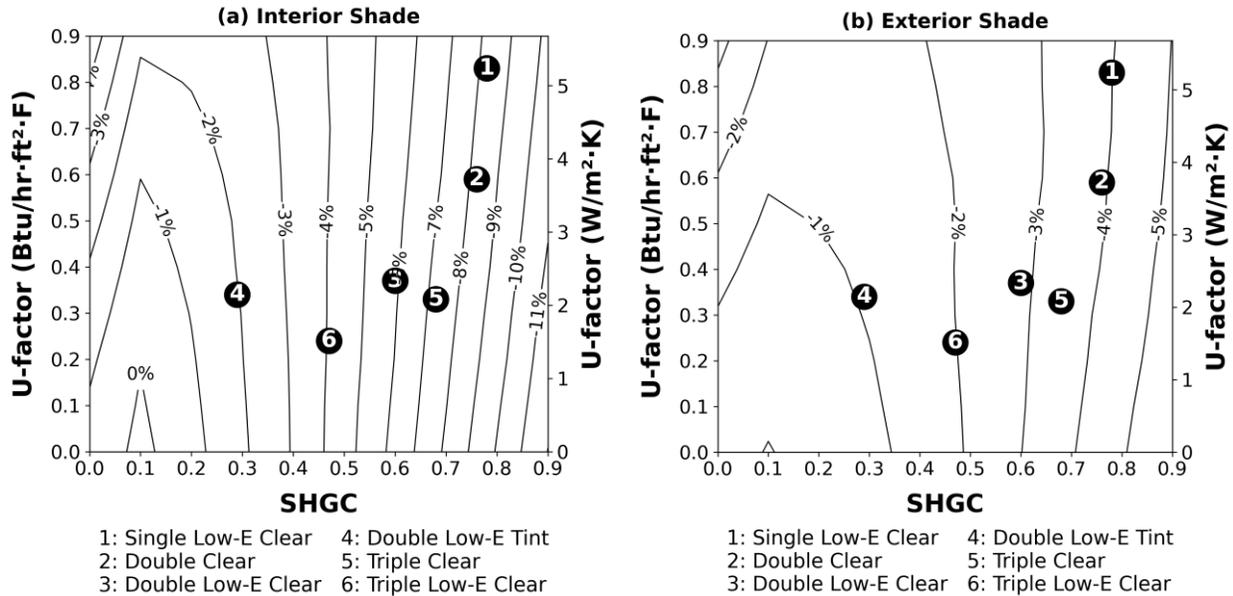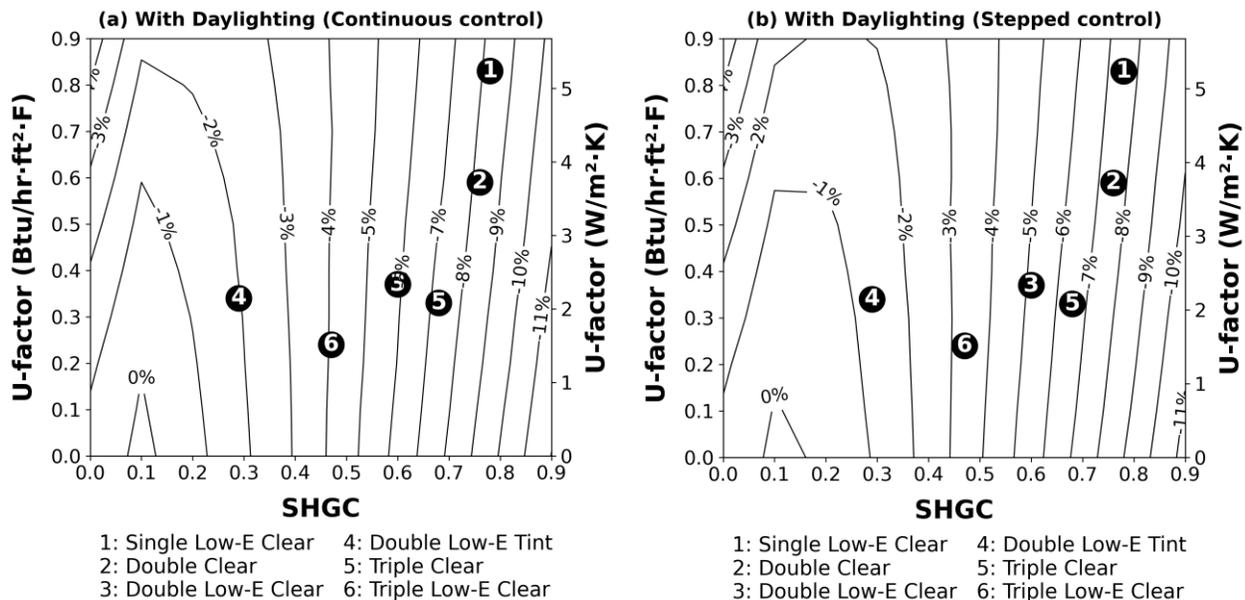

Fig. 14. Window energy penalty contours for the medium office building in Boulder, CO, with (a) interior shading (b) exterior shading.

3.1.5. Impact of daylighting controls

In this analysis, daylighting controls are deployed for perimeter spaces exposed to natural light through the fenestration systems. To implement daylighting controls, the prototypical medium office building is equipped with twenty-four networks of photosensors, two per perimeter zone. The photosensors regulate the output of the electrical lighting systems to ensure a consistent illuminance setpoint of 377 lux across all perimeter spaces [31]. Each photosensor is positioned at a desk height of 0.75 m (2.5 ft), centrally located within each perimeter zone. Fraction of lights controlled is 0.52 (52% of light controlled) for each building zone. SplitFlux daylighting method with continuous, stepped, and continuous/off controls are considered in this analysis as described in section 2.4. The minimum input power fraction and minimum light output fraction for continuous or Continuous/off dimming control are set to 0.2 for all zones.

Fig. 15 summarizes the relative variations in the annual source energy required for the medium office building in Boulder, CO, equipped with daylighting controls when the thermal and optical properties of the windows are varied. The results indicate that the addition of daylighting controls reduces the energy penalties of the windows regardless of their thermal and optical properties. For instance, the energy penalty for single low-e clear glazing is reduced from 18% (refer Fig. 7) to 16% when daylighting controls are deployed. Specifically, the total annual source energy use of the medium office having single low-e clear glazed windows (refer to Table 1) is reduced from 3,203,056 kWh/yr to 3,153,611 kWh/yr with the use of daylighting controls. Thus, the deployment of daylighting controls allows the single low-e clear glazed windows to be more energy efficient and reduces by 3% the annual source of energy needed for the medium-sized office building in Boulder, CO. Fig. 16 presents the annual energy end-use breakdown for the office building having single low-e static glazed windows for cases with and without daylighting controls. Specifically, the implementation of daylighting controls results in a substantial reduction of 21.4% in interior lighting annual energy end-use. Additionally, annual energy end-uses associated with cooling and fans decrease by 3.9% and 4.3%, respectively. The reductions in cooling and fans/pump annual energy needs are attributed to lower internal heat gains resulting from reduced electrical lighting usage.
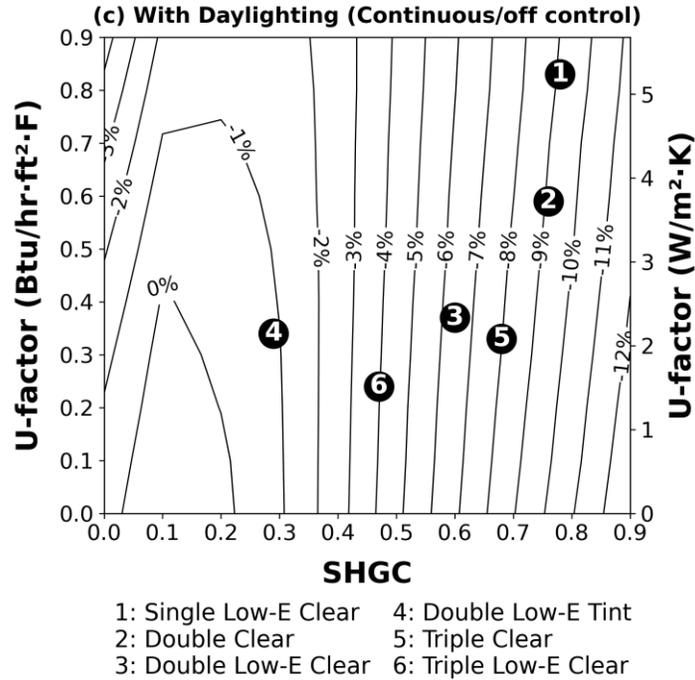

(a) With Daylighting (Continuous control)

(b) With Daylighting (Stepped control)

1: Single Low-E Clear   4: Double Low-E Tint
2: Double Clear   5: Triple Clear
3: Double Low-E Clear   6: Triple Low-E Clear

Fig. 15. Impact of daylighting controls on energy performance of a prototypical office building in Boulder, CO.
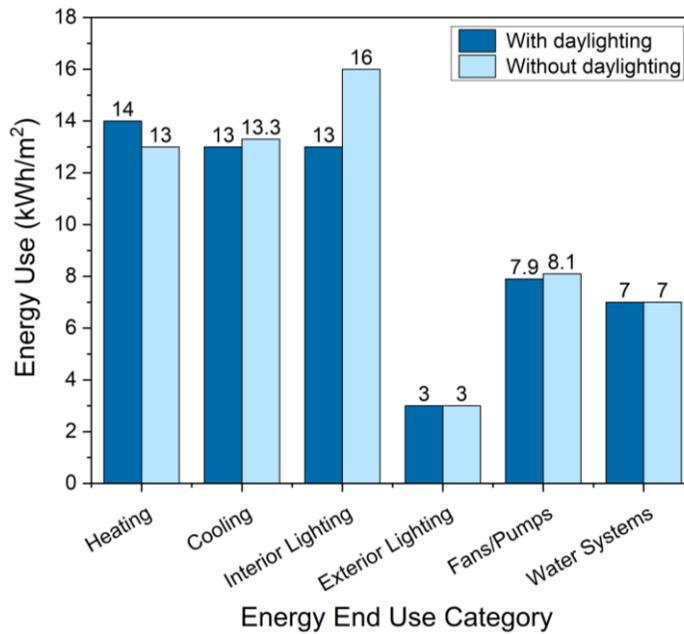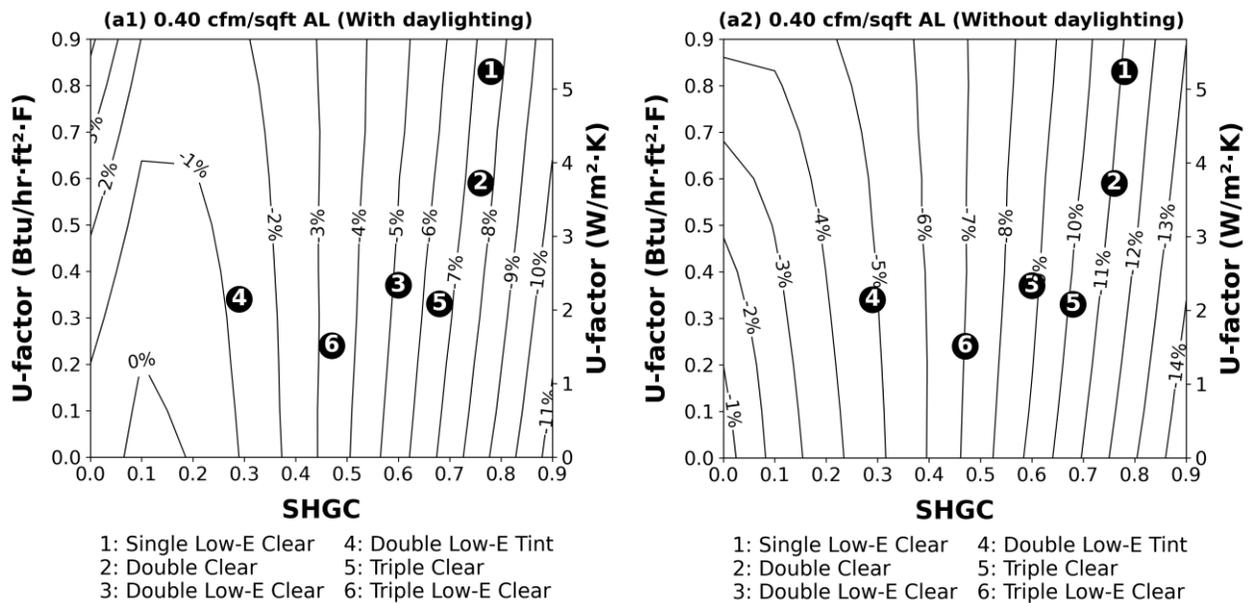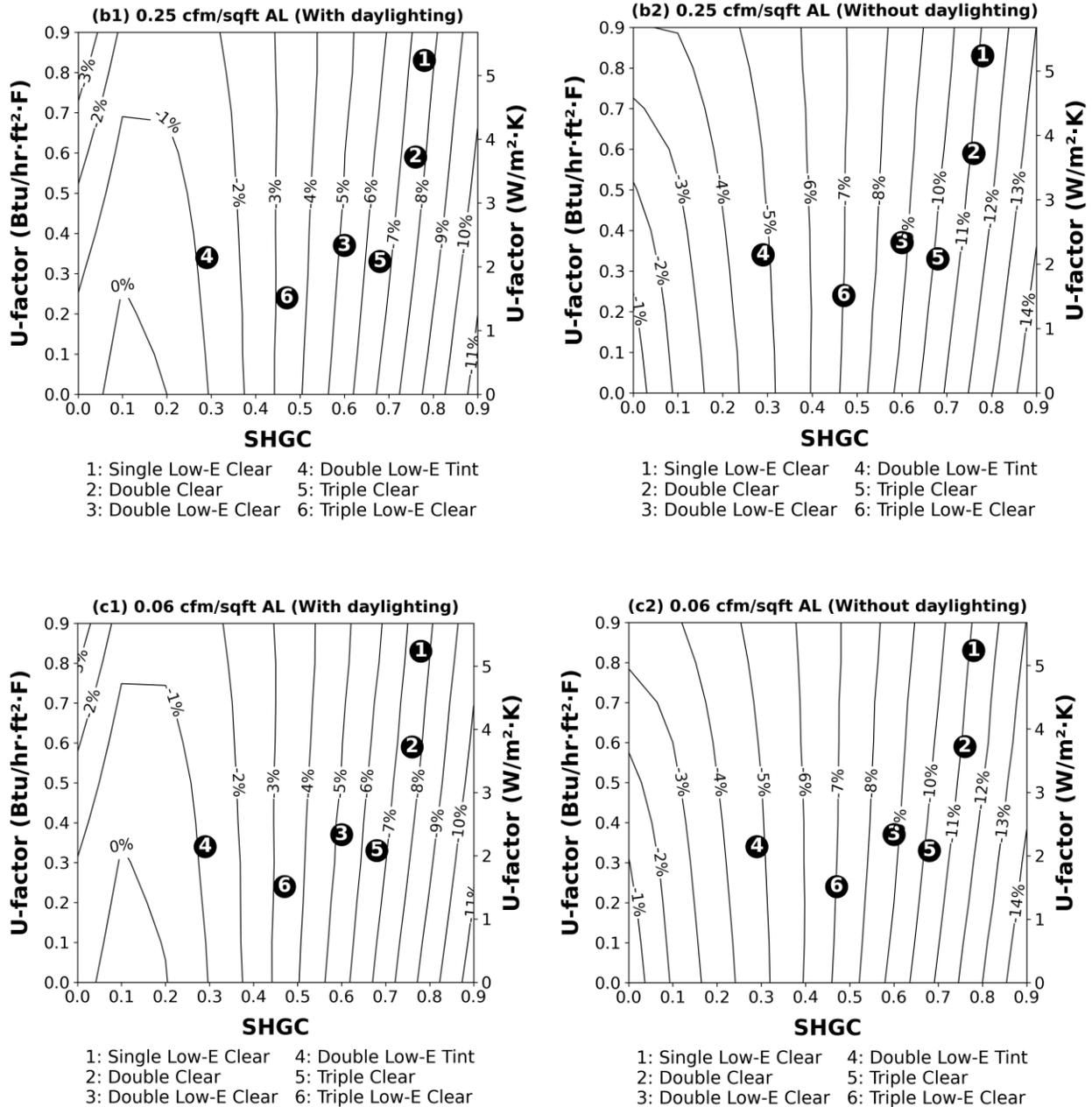

Fig. 16. Annual energy end-use distribution for the office building with single low-e clear glazed windows with and without daylighting controls.
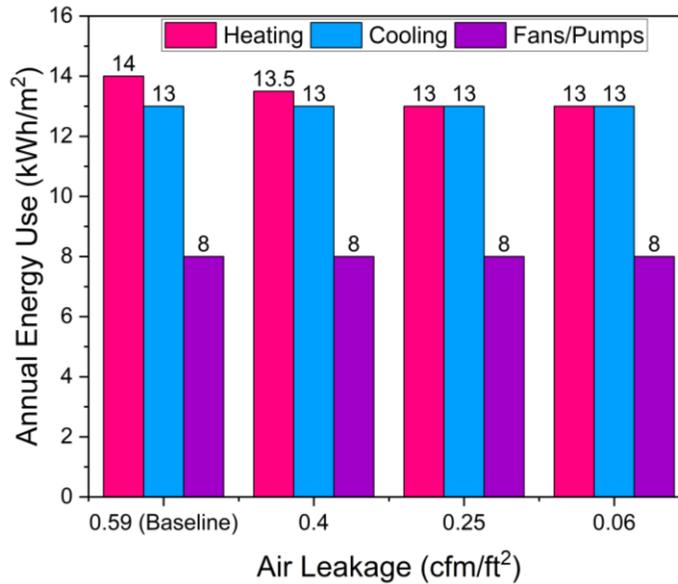
3.1.6. Impact of Air Leakage

Fig. 17 illustrates the relative window energy liability for various air leakage levels including 0.40 cfm/ft² [Fig. 17(a)], 0.25 cfm/ft² [Fig. 17(b)], and 0.06 cfm/ft² [Fig. 17(c)] for medium office with and without daylighting control. In all cases, the contour lines show a clear linear relationship between window energy liability and SHGC value. As air leakage decreases, the window energy liability is noticeably reduced, particularly in the case with daylighting, indicating improved overall energy performance for the windows and thus the office building. This underscores the critical importance of air leakage when assessing the energy performance of windows. Reduced air leakage decreases the uncontrolled heat losses and gains and thus both heating and cooling needs for the office building. However, there are no significant changes in energy use with the air leakage level for the cases without daylighting controls. Fig. 18 illustrates the annual energy use for heating, cooling, and fans for the three air leakage rates: 0.40 cfm/ft², 0.25 cfm/ft², and 0.06 cfm/ft² compared with baseline of 0.59 cfm/ft² for single low-e clear glazed windows. As air leakage decreases, heating energy use decreases, cooling energy use remains relatively stable, and fan energy use decreases slightly. Lower air leakage rates generally lead to reduced energy needs for heating and fan operation, while cooling energy end-use is less affected by the air leakage level.

1: Single Low-E Clear   4: Double Low-E Tint
2: Double Clear   5: Triple Clear
3: Double Low-E Clear   6: Triple Low-E Clear

Fig. 17. Window energy penalty contours for the medium office building in Boulder, CO, with different air leakage rates (a) AL=0.40 cfm/ft², (b) AL=0.25 cfm/ft², and (c) AL=0.06 cfm/ft².
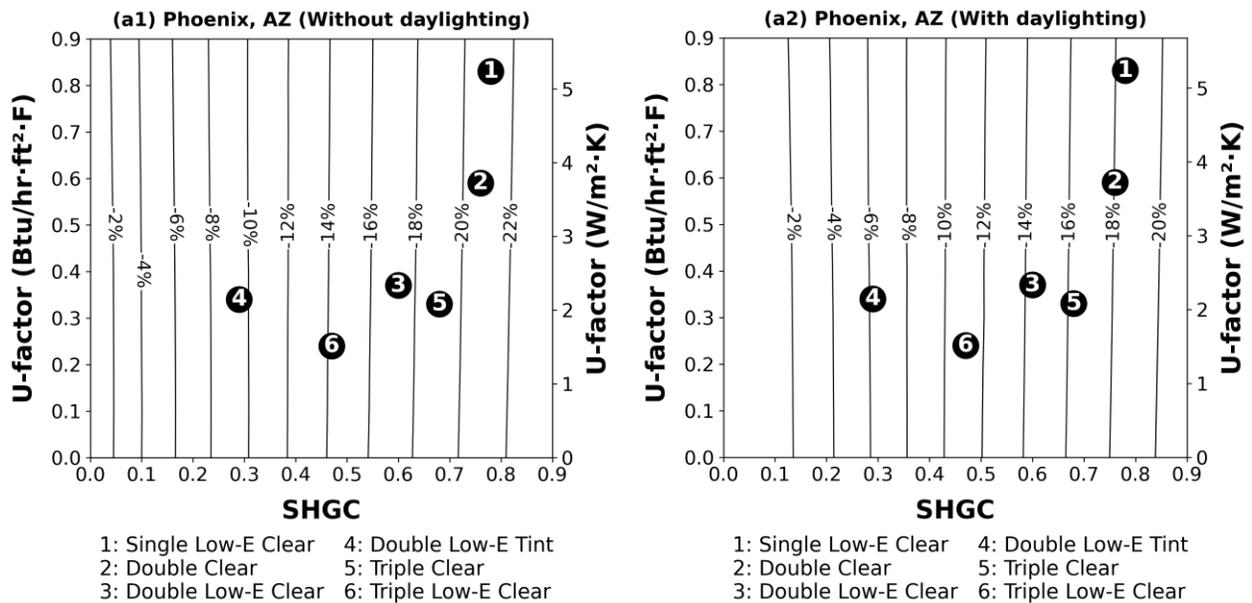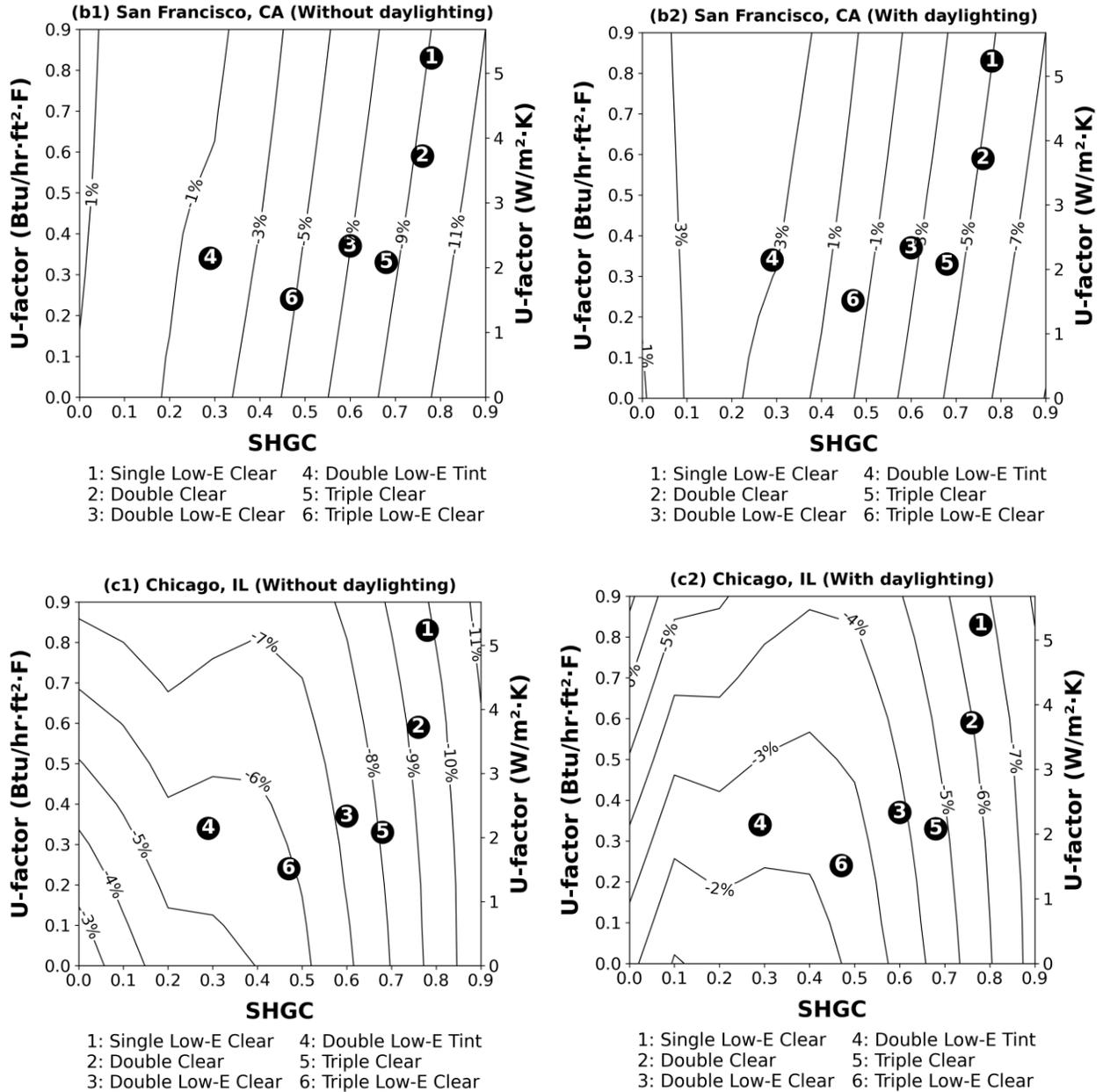
Fig. 18. Annual heating, cooling, and fan energy end-use variations for the medium office building in Boulder, CO, with different air leakage rates with daylighting control.

3.1.7. Impact of Climate

The contour plots of Fig. 19 reveal significant variations in energy performance patterns across these three climate zones, demonstrating that the impacts of windows depend significantly on the climate Indeed, the energy liability contour lines are almost vertical when the office building is in San Francisco, CA, and Phoenix, AZ. These vertical lines indicate that U-factor has a minimal impact while SHGC has a significant influence on the energy impact of the windows for the office building. A small reduction in SHGC value results in a larger percentage of energy reductions, as shown by the closer spacing of the contour lines along the SHGC axis. Conversely, changes in the U-factor have a less pronounced impact on energy changes, as indicated by the low gradients along the U-factor axis. For example, glazing with low SHGC value, such as #4 (Double Low-E Tint) and #6 (Triple Low-E Clear), achieve higher energy savings compared to those with high SHGC value, as is the case for #1 (Single Low-E Clear) and #2 (Double Clear), even if their U-factor is significantly different. These results demonstrate that SHGC is more critical for improving energy performance of windows than their U-value. This observation is consistent with the results reported previously for residential buildings [21].

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On the other hand, the window energy liability contours when the medium office building is in Chicago, IL, are affected by both window SHGC and U-values similar to the results obtained for Boulder, CO [i.e., Fig. 5]. Indeed, Chicago, IL, and Boulder, CO, are characterized by cold climates with heating needs more dominant than cooling requirements. Arasteh et al. [21] found that in heating dominated climates, windows with a low U-factor of about 0.68 W/m^2-K (0.12 Btu/hr ft^2-F) and high SHGC values can approach the net-zero energy use operation when deployed for homes. However, windows cannot achieve net zero energy performance for a medium office building in Chicago, IL, even with low U-factor and higher SHGC. Other design and operating conditions need to be considered to improve the energy performance of windows, especially in cold climates.

(a1) Phoenix, AZ (Without daylighting)   (a2) Phoenix, AZ (With daylighting)

1: Single Low-E Clear   4: Double Low-E Tint
2: Double Clear   5: Triple Clear
3: Double Low-E Clear   6: Triple Low-E Clear

1: Single Low-E Clear   4: Double Low-E Tint
2: Double Clear   5: Triple Clear
3: Double Low-E Clear   6: Triple Low-E Clear

Fig. 19. Window energy penalty contours for the medium office building located in three cities: (a) Phoenix, AZ, (b) San Francisco, CA, (c) Chicago, IL.

3.2. Applications to Window Retrofits

The results of the set of sensitivity analyses indicate that it is difficult for static glazed windows to achieve net energy positive performance, especially for office building with large fenestration systems and high air leakages (Fig. 5-10). Instead of replacing windows, low cost retrofit options

to improve the energy performance of static glazed fenestration systems can be considered including the applications of secondary windows, coating films, and shading devices. Previous studies have reported that double-pane secondary windows can achieve annual energy savings of 11-18% when applied to single-pane clear windows for medium-sized office buildings [56]. Secondary windows contribute to 24-38% heating energy reduction for single-pane and 43-94% for double-pane secondary windows [57]. Moreover, secondary windows can result in annual cooling energy reduction of 6-10% when deployed for single-pane and 16-26% for double-pane secondary windows [57]. In addition, secondary windows can reduce air infiltration from 2.0 cfm/ft² for a single-pane window to 0.06 cfm/ft², representing 35% - 55% reduction in a whole building air leakage [57].

In addition, window coating can be deployed for existing fenestration systems to better manage solar heat gains and improve the energy performance of buildings. Window coatings are thin films applied to the existing glazing systems to adjust their optical properties. Spectrally selective coatings can enhance both natural illumination and thermal comfort within buildings [58]. There are several coatings available in the market. Low-emissivity (low-E) film is the most common type of energy-efficient coating suitable for windows. These low-E films can have different SHGC ranges: high solar gain low-e (SHGC of 0.40-0.65), best suited for cold climates to enhance solar heat gains through the windows, moderate solar gain low-e (SHGC of 0.25-0.40), effective for mixed climates, and low solar gain low-e (SHGC of generally 0.20-0.27), ideal for hot climates to minimize heat gains [59], [60]. Specifically, silver-based low-E coatings account for over 90% of the low-E window coating market today and can provide significant energy savings [61]. These coatings can achieve about 35% energy savings for sealed double low-E windows. The deployment of silver-based low-E window coatings are generally a cost-effective energy-saving solution for retrofitting fenestration systems [62].

Window attachments including shading devices have been reported to reduce noticeably the energy needs for buildings. For instance, insulated cellular shades could lower heat losses through windows by 40% during the winter season and reduce unwanted solar heat through windows by 60% during the summer season [63]. Exterior shades have been known to be highly efficient in reducing solar heat gains through windows for commercial buildings. For example, a study reported that exterior shading could reduce window related annual energy use by 70-86% [64]. Other studies

have shown that fixed exterior shading systems, such as louvers and vertical fins, can reduce direct solar radiation and overheating periods, especially in cooling-dominated climates [65].

This section highlights the applications of the analysis results summarized in the previous sections to estimate the energy benefits of various window retrofit options for medium office buildings. Specifically, the energy savings associated with the following window retrofits are evaluated: secondary windows, low-E coatings, interior shading attachments, and exterior shades.

To determine the percentage energy savings for any window retrofit option, ΔEU_R, using the results of the contour plots, the following expression can be used:

$$\Delta EU_R(\%) = \frac{\Delta EU_a - \Delta EU_b}{1 - \Delta EU_b} \tag{1}$$

Where ΔEU_b and ΔEU_a represent the window energy penalties before and after the deployment of the retrofit measure.

3.2.1 Deployment of Secondary Windows

The thermal and optical properties when secondary windows are applied to both single and double pane windows are listed in Table 3 using commercially available inserts [28]. The single-pane window with the insert has its SHGC value lowered from 0.78 to 0.41 and its U-factor reduced from 0.83 to 0.5 Btu/hr·ft²·°F. Meanwhile, the double-pane window with the insert achieves slightly lower relative reductions in SHGC (from 0.76 to 0.35) and U-factor (0.59 to 0.4 Btu/hr·ft²·°F). Fig. 20 illustrates using the contour plots the percentage energy savings as a function of SHGC for secondary windows applied to single-pane and double-pane windows.

In Fig. 20, after retrofitting existing windows with inserts, significant improvements are observed for both single and double pane windows. The energy savings due to the deployment of secondary windows are estimated using Eq. (1) to be 6% for single pane windows, and 5% for double pane windows. Indeed, using secondary windows reduced the energy penalty of single glazed windows from 12.5% before retrofit to 6.5% after retrofit which achieved the estimated reduction of 6%. The impact of secondary windows on any type of glazing can be estimated using both Eq. (1) and the energy penalty contours of Fig. 20. As shown in Fig. 21, both graphs show

similar trends in energy penalty reduction as SHGC increases, but post-retrofit configurations achieve lower overall penalties due to better thermal performance.

Table 3. Properties of existing windows without and with inserts [66]

Static glazing	Baseline Window Before Retrofit				Window Performance After Retrofit (Secondary Window)			
	U-factor	SHGC	VT	AL	U-factor	SHGC	VT	AL
Single pane, clear	0.83	0.78	0.85	2.0	0.47	0.41	0.57	0.06
Double pane, clear	0.59	0.76	0.81	2.0	0.33	0.42	0.52	0.06

1: Single pane, clear   2: Double pane, clear
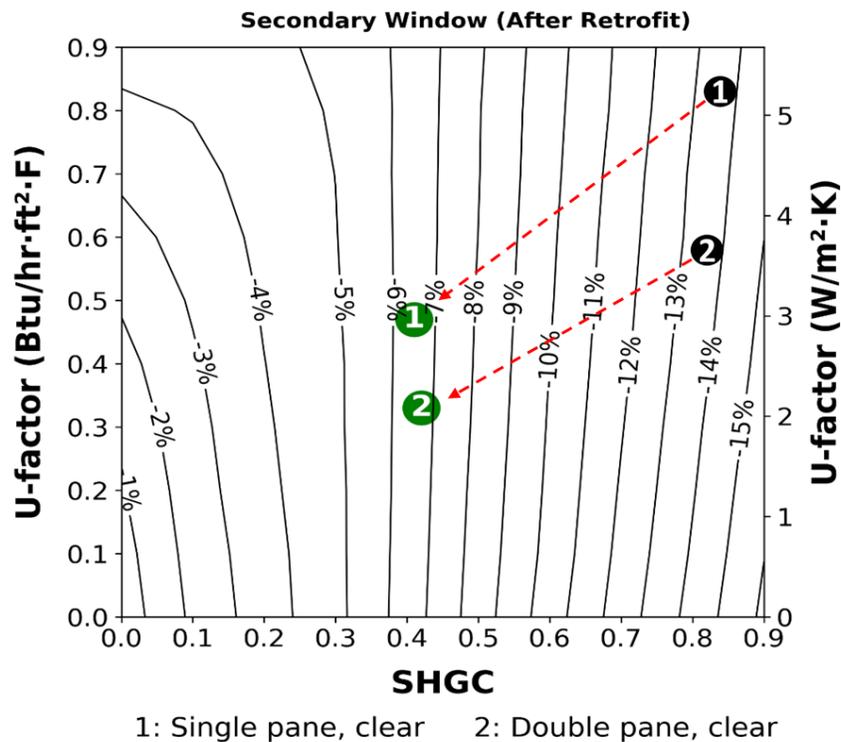
Fig. 20. Estimation of annual energy savings achieved by deploying secondary windows for single and double clear glazed windows of the medium office building in Boulder, CO.
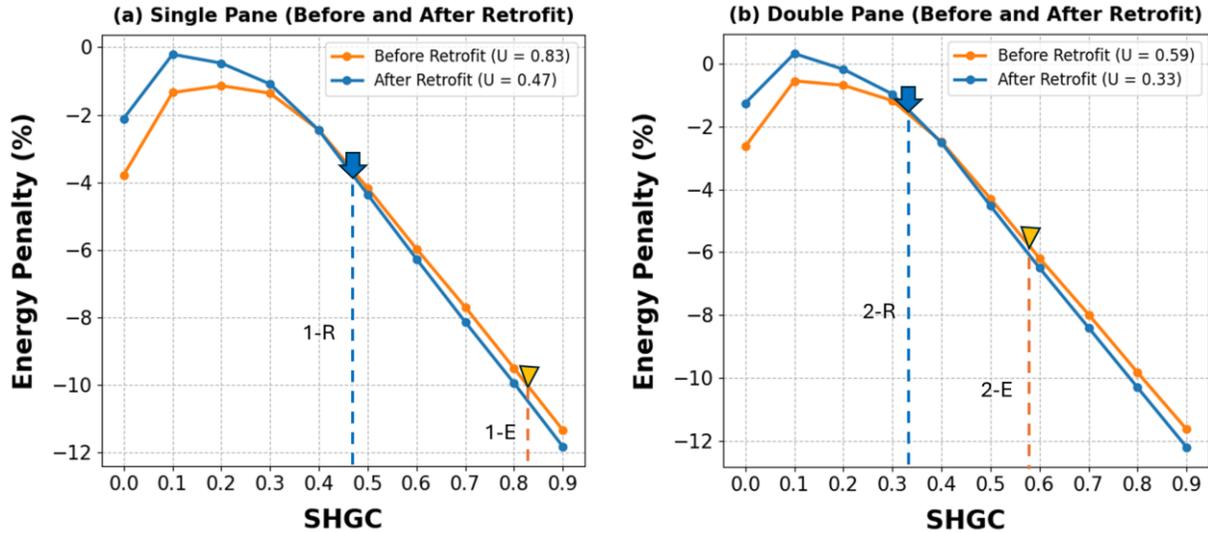
Fig. 21. Energy penalty as a function with SHGC for U-factors for before retrofit and after retrofitting with secondary window for (a) single-pane and (b) double-pane windows.

3.2.2 Use of Window Coatings

In this section, the energy performance of windows retrofitted with low-emissivity (low-e) films is evaluated. Low-e coatings affect heat transfer within the insulated glazing to lower the U-factor of windows and change their optical properties to manage daylight transmittance as well as solar heat gains to reduce their energy impact by as much as 30% to 50% [67]. It has been reported that low-e coating types such as Low-E 20 film can reduce U-factor by 18% and 67% of SHGC for single glazing and 8% of U-factor and 50% of SHGC for double glazing when applied internally [68]. However, for exterior applications, prestige exterior Low-E 20 film shows 0% impact on U-factor for both single and double pane clear glazing but 55% change in SHGC for single pane and 62% in SHGC for double pane [68]. Moreover, Low-E 20 film reduced VT from 0.75 of single pane to 0.17 and reduced VT from 0.67 to 0.15 for double pane glazing representing about 77% reduction in VT across all climate zones [68]. For this analysis, the application of the Low-E film is set to lower by 18% the U-factor, SHGC by 67%, and VT by 81% for single glazing and by 8% the U-factor, 50% SHGC and 77% VT for double glazing as summarized in Table 3.

Fig. 21 illustrates the impact of applying low-E 20 films to single-pane and double-pane windows. Using equation (1), the annual energy savings incurred from the deployment of the low-E 20 films are estimated to be 8% for single-pane windows and 7% for double-pane windows.

Table 4. Window properties with and without low-E 20 films

Glazing	Baseline Window Performance			Retrofitted Window Performance		
	U-value	SHGC	VT	U-value	SHGC	VT
Single pane	0.83	0.78	0.85	0.68	0.26	0.20
Double pane	0.59	0.76	0.81	0.59	0.36	0.19
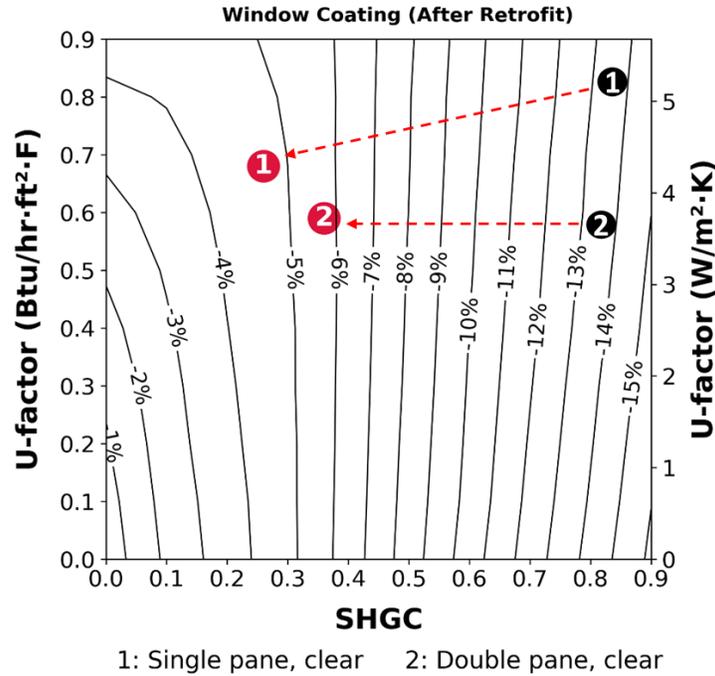
Fig. 21. Estimation of energy savings achieved by adding low-E films on single and double pane windows for the medium office building in Boulder, CO without daylighting control.

3.2.3. Application of Interior shading

Internal shading devices provide significant reduction of both SHGC and U-factor [69], [70]. Indeed, SHGC values as low as 0.2 can be achieved with the application of internal blinds on a single clear glazing [69]. Moreover, interior shades applied for single glazed windows can improve their U-factor by about 19% [70]. When deployed for double pane windows, interior shades can low their U-factor from 0.32 to 0.27, a decrease of approximately 16% [71]. Previous studies have reported that the effectiveness of internal blinds depends on the window type [72], [73]. Table 5 summarizes the impact of selected internal shades on the SHGC values of single and double pane windows.

For this illustrative analysis, roller shades with reflective white translucent coating are considered as internal shades for both single and double pane windows as shown in Fig. 22 and a U-factor reduction of 19% for single glazing and 16% for double glazing are considered [70] [71]. The results indicate that adding the interior shades provides moderate reductions in window energy penalties. Based on Eq. (1), the addition of internal shades reduces the annual energy use of the office building by 8% for single pane and 3% for double pane windows.

**Table 5**. Effects of Internal Shades on SHGC values for single and double pane windows [73]

Shading category	Single clear glazing (SHGC)	Double clear glazing (SHGC)
SHGC of Draperies and Roller shades	*Baseline (SHGC=0.81)*	*Baseline (SHGC=0.37)*
Dark Closed Weave	0.71	0.89
Light Closed Weave	0.46	0.72
Dark Open Weave	0.80	0.90
Light Open Weave	0.65	0.82
SHGC of Roller shades	*Baseline (SHGC=0.81)*	*Baseline (SHGC=0.37)*
White Opaque	0.35	0.66
Dark Opaque	0.65	0.86
Reflective White Opaque	0.32	0.61
Reflective White Translucent	0.25	0.57
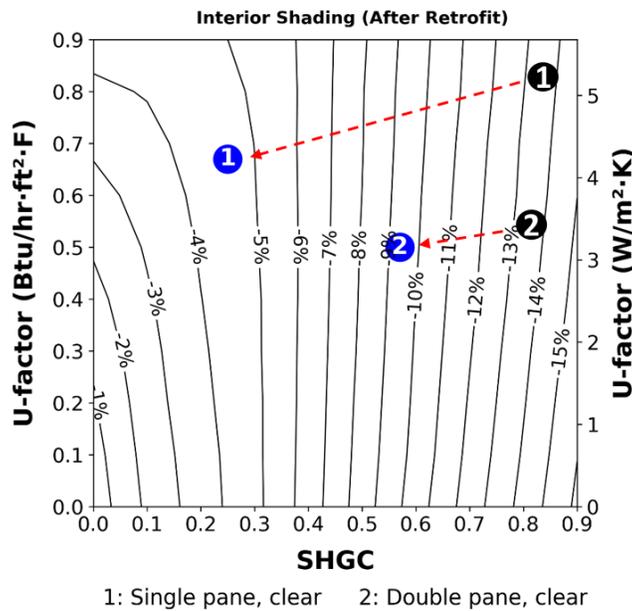
Fig. 22. Estimation of energy savings achieved by installing interior shades on single and double pane windows of the medium office building in Boulder, CO.

3.2.4. Installation of Exterior shading

While exterior shading primarily targets the reduction of solar heat gains, it can also marginally reduce the U-factor by limiting radiative heat exchange. Studies show that the deployment of exterior shades can lead to a U-factor reduction of approximately 5–10% and 3–7% for double-pane windows. However, reductions of 60% to 90% in SGHC can be achieved when installing exterior shades for single-pane window and 50% and 80% for double-pane [43]. In this section, window awnings are deployed as exterior shading devices for the windows to assess their impact on the annual energy performance of the medium office building in Boulder, CO, as illustrated in Fig. 23. The results show that after deploying the exterior shades, the window energy penalties have been lowered for both single and double pane windows. The annual energy savings due to the installation of exterior shades are determined using Eq. (1) and are estimated to be 8% for single pane windows and 7.9% for double pane windows.
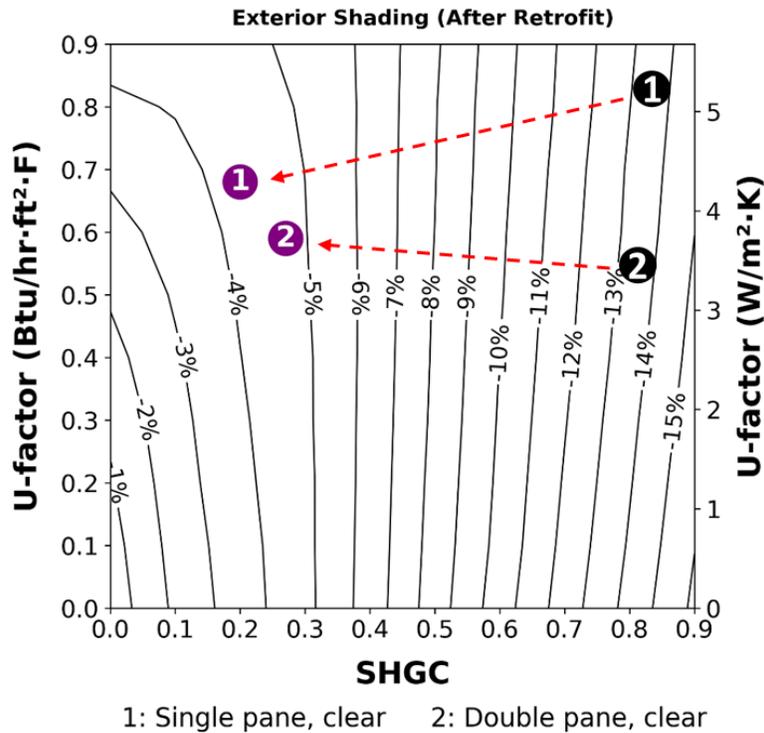
Fig. 23. Estimation of annual energy savings due to the installation of exterior shades on single and double pane windows of the medium office building in Boulder, CO.

4. Summary and Conclusions

This study investigates the feasibility of net positive windows (NPWs) for static fenestration systems of office buildings. A series of sensitivity analyses has explored the impacts of a wide range of window design specifications and operation conditions on the energy performance of US office buildings. The evaluated factors include glazing properties, window sizes, window air leakages, window attachments, and daylighting controls. Moreover, the analysis results have been applied to assess the impacts of common retrofit options for existing windows on the annual energy performance of office buildings. The evaluated window retrofit measures include the addition of secondary windows, the application of low-E coatings, as well as the installation of interior and exterior shading attachments. Key findings from the study include:

- Both U-factor and SHGC significantly influence window energy performance, with SHGC exhibiting the most pronounced impacts. However, lower SHGC values (0.2-0.4) combined with low U-factors (0.2-0.3) allow static glazing systems to approach energy neutrality when applied to office buildings, especially those equipped with daylighting controls.

- In Boulder's cool-dry climate, interior blinds, daylighting control, and reduced air leakage enabled net-zero energy. With a combination of these optimized measures, window retrofit can potentially achieve net-positive energy.

- The optimal combination of U-factor and SHGC varies considerably across climates, building types, and window sizes. It was found that for large windows more stringent glazing specifications are required to achieve energy neutrality-. Moreover, climate-specific analysis reveals distinct patterns, with hot climates showing extreme sensitivity to the SHGC selection.

- Achieving net positive energy performance remains challenging for static glazing systems without incorporating daylighting controls for all US climates.

- The results show that various retrofit measures for windows can significantly enhance the energy performance of office buildings. The addition of secondary windows can significantly enhance the energy efficiency of windows by lowering their thermal conduction (U-factor), solar heat gains, their (SHGC), and air leakage (AL). However, the relative improvement is more pronounced for single-pane rather than double-pane windows due to their initially poor energy performance. Moreover, the application of low-e coatings is found to be most effective for simple clear glazing systems with higher SHGC values.

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For double-pane and low-e windows, the use of coatings is less effective. When window attachments are considered, it is found that the use of reflective internal blinds is effective for only single clear glazed fenestration systems. However, the application of external shading devices enhances energy performance for most window types.

While achieving net-zero or positive energy performance proves challenging for static glazed windows of office buildings, our results suggest that integrating several design specifications and operation conditions are needed to achieve net positive windows. In addition to optimizing their thermal and optical properties, windows need to be properly sized and protected by shading attachments to achieve energy neutrality for office buildings equipped with daylighting controls. The study also highlights the potential benefits of dynamic façade systems and emerging glazing technologies in further enhancing energy performance. Thus, a future analysis should consider the role of advanced glazing technologies including dynamic windows and transparent photovoltaic systems in achieving energy neutrality for fenestrations systems under a wider range of design and operation conditions for office buildings.

Disclosure

MDM is a cofounder of Tynt Technologies.

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