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Review Article

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Contribution of advanced windows and façades to buildings decarbonization: A comprehensive review

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ABSTRACT

On a global level the building sector consumes about 45.00% of energy consumption, contributes about 40.00% to emission, uses 30.00% of water and impacts the environment by generating 30.00% of waste. Although windows are important components of a building that provide natural lighting and ventilation and establish necessary contact with the external environment necessary for healthy indoor ambient, they permit entry of undesirable solar heat in summer and allow escaping heat from the indoor ambient in cold seasons, which aggravate the building needs for energy and increase its contribution to atmospheric emissions. The present investigation provides a review on research, development, and applications of advanced windows in the building sector. The introduction highlights the importance and contribution of advanced glazing technology to improving energy, comfort, and thermal performance of buildings. The review includes natural illumination and ventilation, thermal comfort and discusses the effects of window to wall ratio on natural illumination and ventilation of windows and façades. The review also covers recent developments in glazed windows and façades including performance enhancements by using reflective solar films, vacuum glazing, windows with filling materials, windows with water flow, window with phase change material, window with stagnant inert gas filling, ventilated windows and façades and windows with aerogel. A special section was also included on smart glazing for windows and façades showing the new tendencies and applications in the building industry. Since commercial programs and open access codes are handy tools for simulation and performance calculations a section is dedicated to these codes. The conclusion section contains the most relevant conclusion of the review as well as future trends in research and developments in the area. The topics included in this review can be helpful for experienced and young researchers, practicing engineers and general readers interested in windows and façades.

Keywords: thermally efficient windows, simple window, window with phase change material, window with absorbing gases, evacuated windows, commercial simulations codes

INTRODUCTION

Windows and façades are important components of a building that provide natural lighting and ventilation and establish necessary contact with the external environment necessary for healthy indoor ambient, but they also permit entry of undesirable solar heat in hot seasons and permit heat escape from the indoor ambient in cold seasons, which increase the building energy demands to cope with these inefficiencies and augment its contribution to offensive emissions. This scenario led to tremendous increase in research and developments of windows and façades to cope with their deficiencies and increase their capabilities to handle the ever-changing ambient conditions to keep the indoor ambient comfort and healthy.

Windows and façades are glazed areas whose U-values are high in comparison to other components of the building. **Figure 1** shows the U-values of some of the commercially available glazing systems (Akram et al., 2023). Irrespective of this deficiency, large, glazed areas are widely used in modern and contemporary architecture. Several studies were dedicated to improving the thermal performance of glazed windows and façades by increasing the thermal resistance of the glazed system by using phase change material (PCM), inert gases and vacuum glazing, etc., and using smart windows to better

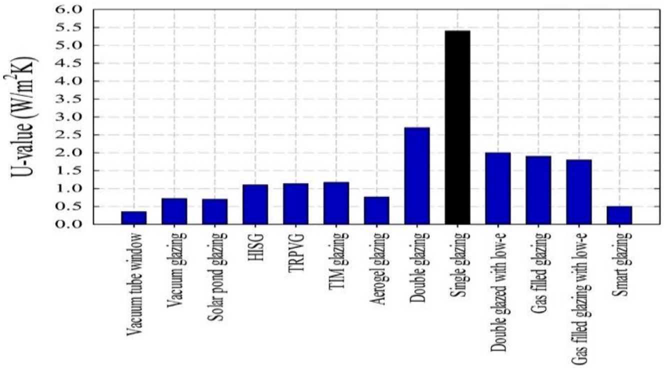


Figure 1. U- & g-value of some commercial glazing systems (Akram et al., 2023)

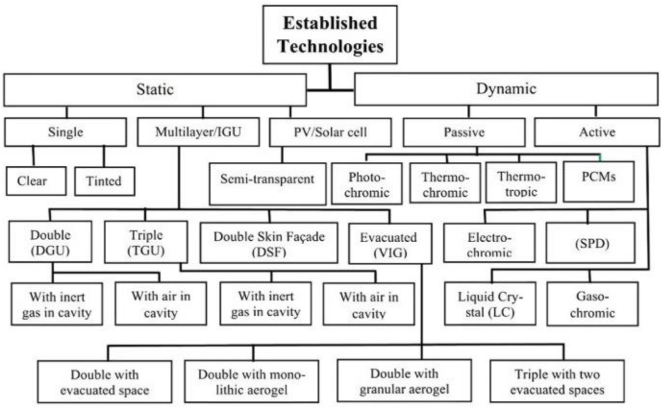


Figure 2. Classification of established glazing technologies (Michael et al., 2023)

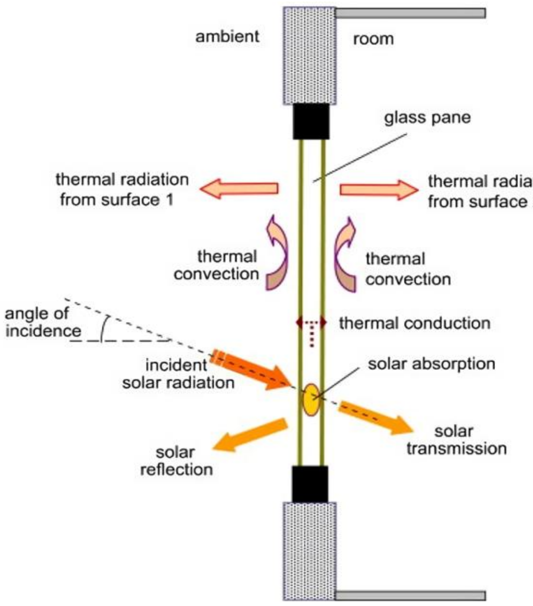


Figure 3. Energy flow paths in single pane glazing (Chow et al., 2010)

control indoor heat and luminance. Smart technologies include active dynamic glazing, which modulates the entering amount of visible light, reduce energy demands, and enhance thermal and visual comfort (Casin, 2018).

Figure 2 shows the classification of established glazing technologies (Michael et al., 2023).

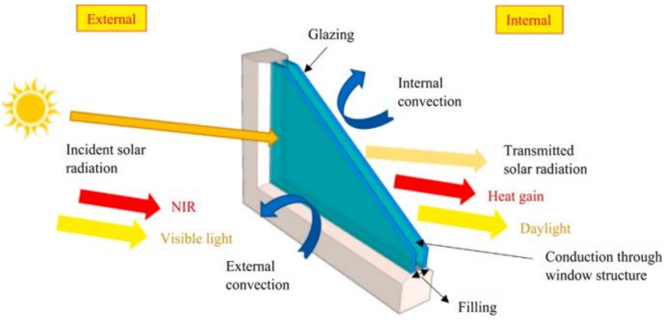


Figure 4. Schematic view of a double-glazing unit with mechanisms of heat & daylight (Mohammad & Ghosh, 2023)

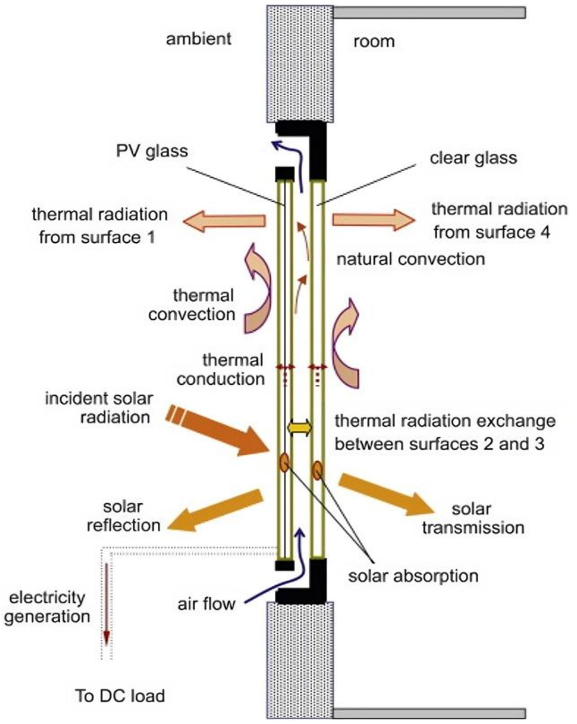


Figure 5. Energy flow paths at natural-ventilated PV double-pane window (Chow et al., 2010)

In regions of moderate winter and summer single glass windows are still in use mainly because of the cost ability to effectively reduce entering solar radiation, luminance, and glare besides promoting cooling energy savings. **Figure 3** shows the energy flow for a single-pane window glass (Chow et al., 2010).

Low-e coatings are almost fully developed and widely applied in many applications. Investigations on electro thermal coatings to convert electricity to heat by the Joule effect are ongoing but limited by the need of power supply, while photo thermal coatings were investigated to improve the glazing performance by absorbing ultraviolet radiation (UV) and infrared radiation (IR). **Figure 4** shows the mechanisms of heat transfer and daylight through a double-glazing unit (Mohammad & Ghosh, 2023).

Further improvements were incorporated in double glass windows including forced and induced airflow in the spacing separating the glass sheets, **Figure 5** (Chow et al., 2010).

Another improvement was incorporated using liquid flow, especially water to avoid heat flow to the interior ambience.

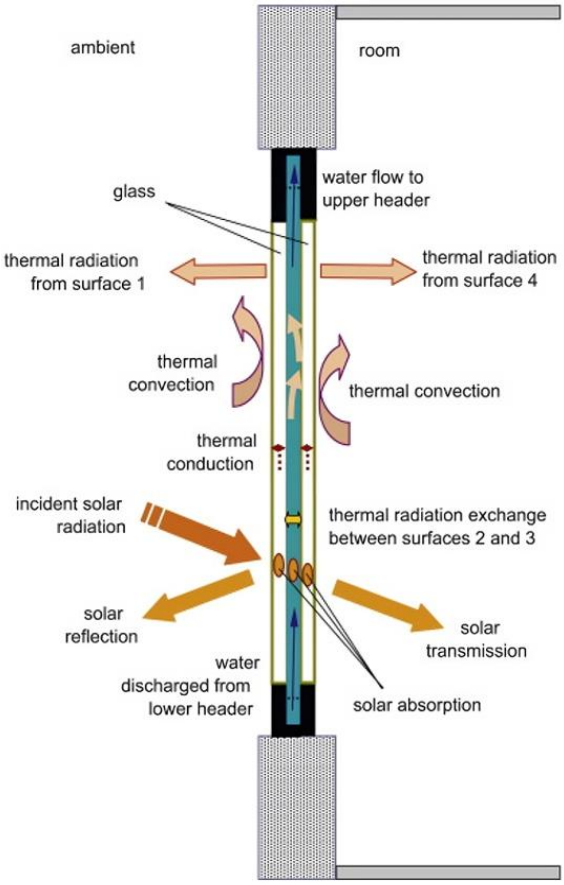


Figure 6. Schematic illustration of solar absorbing glazing (Chow et al., 2010)

Figure 6 shows water cooled double glass window (Chow et al., 2010). The reported results indicated a big reduction of heat gain and enhancement of indoor comfort.

Aerogel is a silica-based, porous material composed of 4.00% silica and 96.00% air prevents convection heat transfer, has a thermal conductivity of about 0.013 W/mK, but allows light transmission.

Studies showed that the inclusion of PCM in glazed units can decrease the building energy demands, enhance the indoor comfort and delay and attenuate temperature but has the drawback of possible leakage and overheating.

Vacuum glazing is widely used in very cold countries because of low heat loss and high visible transmittance. Heat radiation is the only mode of heat transfer through these windows. **Figure 7** shows a general layout of the vacuum window.

The above highlights show that the glazed windows and façades received were and still are subject to intense research activities and dedicated developments to make them efficient, safe, affordable, and astatically attractive.

The main objective of this work is to present an updated review of the state of research, development and applications of windows and façades in the building sector. The review covers natural illumination and visual comfort, natural ventilation, thermal comfort, and the influence of window area on natural illumination and visual and thermal comfort. The review also covers the performance enhancements of windows and façades including reflective solar films, vacuum glazing, double glass windows with filling materials such as windows with water flow, window with PCM, window with stagnant inert gas filling, ventilated windows (VWs) and façades, windows with aerogel and smart glazing.

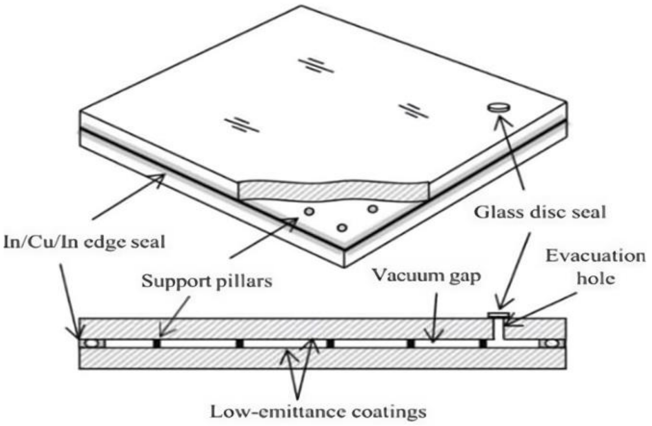


Figure 7. Schematic of double evacuated glazing unit (Michael et al., 2023)

Since commercial programs and computational codes are handy tools for simulation and thermal performance calculations of components and buildings, a section is dedicated to these simulations codes and relevant publications that used these tools in the analysis and simulations. The conclusion section contains the most relevant conclusion of the present review as well as future trends in research and developments in windows and façades.

The novelty of this paper is that besides energy reduction and avoidance of emissions usually treated in most papers and reviews, this paper relates explicitly natural illumination, natural ventilation and window and façade geometry to thermal and visual comfort, stress reduction, and overall health and well-being of the occupants of the building.

The main contributions of this paper to the area include addressing explicitly natural illumination, natural ventilation and their positive impact on attention restoration, stress reduction, and overall health and well-being. As passive strategies they can significantly help increase the liveliness, performance, and visual comfort of the residents, besides reducing the overall electrical energy consumption of a building. The paper also highlights the importance of the appropriate configuration of windows to improve visual and thermal comfort, reducing glare, distributing light, and controlling solar energy gain. Also, the paper provides an updated review on the stage of research, development and applications of windows and façades in the building sector.

This review is organized in five sections, as below:

1. **Introduction:** The actual scenario in window and façades technologies are presented and commented on. The section ends by presenting the objectives of the review, contribution of the review to the area and finally the basic contents of the review.
2. **Illumination, visual comfort, thermal comfort, & natural ventilation:** In this section natural illumination, visual comfort, natural ventilation, thermal comfort are treated and studies reporting scientific research and results are presented. Impact of

the window to wall ratio on visual and thermal comfort are presented.

3. **Performance enhancements of windows & façades:** In this section windows with water flow, window with PCM, window with stagnant inert gas filling, VWs and façades, windows with aerogel and smart glazing.
4. **Commercial programs & codes:** In this section most used commercial codes for simulating the thermal performance of buildings and components are presented and commented on.
5. **Conclusions, future trends in research, & developments:** In this section the main findings of the review are reported and the gaps for future research and developments are highlighted.

ILLUMINATION, VISUAL COMFORT, THERMAL COMFORT, & NATURAL VENTILATION

Windows provides the contact between the internal space of a building and external surroundings. Internal natural illumination, natural ventilation, and reduction of heat transfer to and from the building can be achieved partially by traditional glazed windows under severe and sudden variations. Hence it is necessary to improve windows and façades to provide quick and adequate response to the momentary changes and to ensure continuously comfortable and healthy ambience for the occupants.

Natural Illumination & Visual Comfort

Daylight is a free energy and cost-effective alternative to artificial lighting and has favorable effects on comfort, health, well-being, and productivity. A fair amount of research work was done to evaluate natural daylight effects on occupants, and work efficiency.

Yao (2014) conducted a study to investigate the effects of movable solar shades on energy consumption, indoor thermal and visual comfort. Results showed that movable solar shades provided 30.87% energy savings, improved thermal comfort by 21.00% and visual comfort by 19.90%. Carlucci et al. (2015) provided a review of indices for assessing visual comfort and presented recommendations and suggestions for improvement. Nasrollahi and Shokri (2016) reviewed the basic concepts of daylighting, and the architectural parameters in an urban context. The results indicate that these factors are of high significance. Hoffmann et al. (2016) investigated coplanar shades with different geometry and material. Energy use increased substantially when an additional interior shade was used for glare control. Acosta et al. (2016) conducted a study to investigate the impact of window design on energy savings for lighting and visual comfort in residential spaces.

Silva et al. (2016) provided a literature review on the use of PCMs in glazing and shading solutions focused on PCM technologies developed for translucent and transparent building envelopes to improve energy efficiency. Costanzo et al. (2016) investigated the application of thermo-chromic windows to an existing office building for energy savings, daylighting, and thermal comfort. The results showed an overall energy savings from around 5.00% for cold climates to around 20.00% in warm climates.

Vlachokostas and Madamopoulos (2017) conducted a study to investigate the thermal performance of a liquid filled prismatic louver façade and concluded that the liquid filled louver system enhanced the indoor natural light by 9.00%, reduced the glare by 20.00% and enhanced absorption of solar radiation by 52.40%. Shen and Tzempelikos (2017) presented details of a simplified model-based shading control. The method was generalized and can be applied to any shading/glazing properties, location, orientation, and room configuration.

Makaremi et al. (2018) examined the influence of reflectance of surfaces and lighting strategies on energy consumption and visual comfort. The results show the possibility of electrical energy savings up to 45.00% by increasing surface reflectance properties. Eisazadeh et al. (2019) investigated the influence of glazing characteristics and shading device configuration and concluded that they severely impact energy cost, daylighting, and visual comfort. Gutiérrez et al. (2019) examined the design and daylight performance of a new louver screen for office buildings and concluded that it can provide adequate daylight levels and visual comfort. Dogan and Barch (2019) provided a review on daylighting metrics for residential architecture and introduced a concept for a new climate-based, annual evaluation framework.

Zhang et al. (2019) presented the results of a human experiment of the effects of glazing types (color and transmittance) on participants' alertness, mood and working performance. For a high Circadian Stimulus CS level (≥0.3), glazing color and transmittance did not significantly affect human alertness. A low CS level (<0.3) caused significant negative mood to occupants. Day et al. (2019) reported similar results from a large-scale study in the US. Ke et al. (2019) provided a review on recent progress in smart windows including functional materials, device design and performance. Kaasalainen et al. (2020) investigated the direct and combined energy impacts of window related architectural design and concluded that cooling can be a significant factor and that energy efficiency should always be evaluated. Onubogu et al. (2021) presented a review on the existing technologies of daylighting systems covering both passive and active daylighting systems, besides providing recommendation for future research.

Khaled and Berardi (2021) presented a review on coating technologies for glazing applications and commented that both static and dynamic technologies contribute to enhance optical and thermal performances. Foroughi et al. (2021) developed an optimization model to identify the optimum window design parameters. The results show that selecting optimum window dimensions and locations can reduce the total building energy consumption. Feng et al. (2021) reviewed and analyzed window design studies to achieve high performance, presented simulation-based optimization methods, and identified potential challenges and future research trends.

Eleanor et al. (2022) identified critical needs in research, tools, and technologies to enable more effective use of

Table 1. Summary of some reference results on natural illumination & visual comfort

Reference	Work nature	Research objective	Main findings
Yao (2014)	Numerical	Solar shades	Movable solar shades can reduce building energy demand by 30.87% & improve indoor thermal comfort by 21.00% in summer.
Hoffmann et al. (2016)	Numerical	Coplanar shades	Energy use increased substantially when an additional interior shade was used for glare control.
Acosta et a. (2016)		Window	Energy consumption does not depend on window shape.
Costanzo et al. (2016)	Numerical	Thermochromic windows	Overall energy savings compared to clear glazing can range from around 5.00% for cold climates to around 20.00% in warm climates.
Vlachokostas and Madamopoulos (2017)	Numerical	Prismatic louver façade	LFPL system enhances indoor natural light by 9.00% & reduces glare by 20.00%, shows a 52.40% enhanced solar radiation absorption.
Makaremi et al. (2018)	Numerical	Artificial lighting	Possibility of electrical energy savings up to 45.00% by increasing surface reflectance properties.
Eisazadeh et al. (2019)		Glazing & shading device	Glazing characteristics and shading device configuration have major impact on energy cost, daylighting, & visual comfort.
Gutiérreza et al. (2019)	Numerical	Louvre screen for office buildings	Proposed louvre system can provide satisfactory daylight levels & visual comfort within the room.
Chen et al. (2019)	Experimental	Glazing types	Improvement of occupants' mood would be achieved through increasing glazing visual transmittance &/or decreasing its colour saturation.
Foroughi et al. (2021)	Numerical	Window design	Selecting optimum window dimensions & locations can reduce total building energy consumption by 2.00 & 15.00% in cold & hot climate zones, respectively.
Lee et al. (2022)	Experimental	Light shelf	Energy consumption of proposed system is reduced by 3.50%-32.70% compared with existing light shelf technologies.

daylight. Advanced window technologies and integrated design can enable achieving health, comfort, and net zero energy goals. Lee et al. (2022) proposed a technique for improving the efficiency of the light shelf using a solar module and evaluated experimentally its performance. The results showed that the energy consumption of the proposed system is reduced by 3.50%-32.70%. Li et al. (2022) provided an overview of research advances in optical transmittance, thermal resistance, and thermal inertia along with photo-thermal transmittance in glazing envelopes, with a special focus on the integration of PCMs. Li and Tang (2024) provided a review on PCM window for thermal and light dynamic regulation and identified the potential of these concepts to improve light and thermal regulation. **Table 1** presents a summary of some studies on natural illumination and visual comfort in buildings.

Comments

Visual connection to nature has been demonstrated to have a positive impact on attention restoration, stress reduction, and overall health and well-being. Inside buildings, windows are the primary means of providing a connection to the outdoors, and nature views may have similar effects on the occupants.

Glazed envelopes suffer from the defects of high solar transmittance, poor thermal insulation, and low thermal inertia, while traditional windows, as the major source of daylight, have a common problem, which is uneven distribution of daylight in the room besides possible glaring. Day lighting is a passive strategy, which is significant in increasing the liveliness, performance, and visual comfort of the residents. It helps to reduce the overall electrical energy consumption of a building. Since day lighting is essential for the general comfort of the occupants and considering that artificial lighting accounts for a considerable part of electrical energy consumption in buildings, there is a need to design appropriate lighting scenarios for buildings in a way to reduce energy while meeting visual comfort requirements.

Natural Ventilation

Natural ventilation can provide occupants with thermal comfort and a healthy indoor environment, besides being an effective strategy for reducing energy consumption especially for commercial and office buildings.

Aflaki et al. (2014) presented a review on ventilation techniques. Results showed that building orientation and apertures size are effective to increase indoor air ratio. Zhang et al. (2014) presented a review on diffuse ceiling ventilation (DCV) and examined thermal comfort, air quality, pressure drop as well as radiant cooling potential. Yu et al. (2015) provided a review on cooling and ventilation in office buildings including natural ventilation, building thermal mass activation, DCV and proposed a system combining the three technologies. Kasima et al. (2016) conducted a computational fluid dynamics (CFD) study to investigate the effect of different opening positions on wind-induced ventilation performance.

Salcido et al. (2016) presented a review to analyze the use of mixed mode ventilation systems in office buildings. The authors showed the progress made and future challenges for use in office buildings. Nomura and Hiyama (2017) provided a review on natural ventilation performance of office buildings in Japan and indicated that natural ventilation performance depends considerably on the building design. Omrani et al. (2017) conducted a study to analyze the effects of natural ventilation mode on thermal comfort. Results highlighted better performance of cross ventilation over single-sided ventilation. Elshafei et al. (2017) investigated the effects of window parameters on indoor natural ventilation in a residential building. Modifications in window size, window placement, and shades improved the air temperature and the air velocity. Palme et al. (2017) presented natural ventilation as a mitigation strategy to reduce overheating in buildings. The overheating risk of a small house is evaluated with and without considering urban heat island effect. Results show that an important portion of the indoor heat can be removed.

Remion et al. (2018) presented a review on performance of natural ventilation systems. Results can help to build a new protocol more suited to the assessment of the performance of hybrid and natural ventilation systems. Solgi et al. (2018) presented a review on night ventilation strategies in buildings, indicated that night ventilation strategies are effective but there is a need for design strategies and optimization, besides the fact that future research should include computer simulations, testing full-scale prototypes, and monitoring of case studies. Cuce et al. (2019) evaluated the possibility of using natural ventilation in school buildings and concluded that the strategy was viable, and that single-side ventilation and cross-ventilation can improve cooling and air quality in school buildings.

Chen et al. (2019) examined various types of control including spontaneous, manual, and the fully automatic window/heating, ventilation, and air-conditioning control system and concluded that the fully automatic system was more adequate and showed energy savings of 17.00-80.00% with zero discomfort. Guo et al. (2019) developed an approach integrating sensitivity and parametric simulation analysis and showed that the climatic conditions and night ventilation have strong effect. Wu et al. (2019) presented a review on DCV, highlighted the research findings, and proposed simplified modeling methods for DCV system design tool. Yang et al. (2019) reviewed advanced air distribution methods, limitations and solutions and analyzed measuring and evaluating methods for ventilation and air distribution. Solgi et al. (2019) studied PCM behavior when used with night ventilation and showed that insulated envelopes increase night ventilation efficiency and stabilize PCM transition temperature. Rahnama et al. (2020) evaluated the cooling capacity of DCV system and indicated that the highest cooling capacity is achievable with evenly distributed heat load in the room and active diffuse panels in the ceiling.

Hu et al. (2020) experimentally investigated the performance of a phase change material enhanced ventilated window (PCMEVW) and found that the room inlet air temperature was 1.4 °C lower compared to the normal VW and the average energy saving was 1.6 MJ/day. Hu et al. (2020) proposed a PCMEVW system for ventilation preheating/precooling purposes and showed that the proposed system greatly decreases the energy demands for summer and winter applications. Piselli et al. (2020) investigated possible improvements from using natural ventilation on PCM performance in cooling application and showed that PCM inclusion in the building envelope resulted in significant cooling savings. Guo et al. (2020) evaluated the resulting thermal performance from coupling a cool roof with night ventilation and concluded this can result in 27.00% savings in the annual cooling energy.

Hati (2021) presented a review on ventilation systems, variable speed drive and discussed various energy efficiency strategies and artificial intelligence-based models. Zhang et al. (2021) presented a review of combined natural ventilation and commented that the coupling between different natural ventilation systems still requires more future research. Zhong et al. (2022) reviewed research on single-sided natural ventilation and commented that in future investigations, different methodologies should be coupled. Maghrabie et al. (2022) presented a review of natural ventilation of buildings based on solar chimney (SC) and concluded that combined SC-based cooling/heating energy systems can be an effective strategy for energy efficient buildings. Sadeghian et al. (2022) investigated the role of design parameters on the performance of DCV systems and concluded that dispersed configuration had the highest draft rate of 14.00%. Zaniboni et al. (2022) presented a review on natural and mechanical ventilation concepts and concluded that thermo-hygrometric comfort is an important parameter. Mateus et al. (2023) reviewed the methodologies applied to study the natural ventilation of large air masses and techniques used for the validation of CFD models and commented that greater agreements were found in the models´ formulations. **Table 2** presents a summary of some studies on natural ventilation in buildings.

Comments

Buildings consume more than 40.00% of global energy use and ventilation is one of the largest sources of energy consumption. Also, the high cost of energy has intensified research interest in passive energy saving strategies for buildings. Night ventilation has been shown to reduce the energy demand for cooling buildings as well as significantly improve thermal comfort. DCV also has great energy saving potential and can handle high cooling loads without inducing thermal discomfort. PCMs have a big potential to be used as passive strategy for improving energy efficiency and occupants' thermal comfort in buildings. However, their performance still needs to be enhanced to have them effectively used.

Thermal Comfort

ASHRAE (2017) defines thermal comfort as "*that condition of mind that expresses satisfaction with the thermal environment*". The six factors considered in ASHRAE are temperature, thermal radiation, humidity, airspeed, activity level (metabolic rate), and occupant clothing (degree of insulation).

Saadatjoo et al. (2019) investigated the effect of porosity distribution pattern on natural ventilation and concluded that porosity could be changed to fulfill most of the building environmental requirements. Hawila et al. (2019) conducted a study to quantify the interactions and optimize building glass façades. The results indicated that the optimized design enhanced thermal comfort and energy-savings.

Krstic-Furundzic et al. (2019) presented the estimation of energy performance of different hypothetical models of façade design. Results showed the effects of the various alternatives of shadings on the reduction of environmental pollution and energy demands. Fahmy et al. (2020) simulated an educational building and concluded that shading the roofs and southern façade of building envelope were the most effective.

Abd El-Rahman et al. (2020) commented that a significant part of the building energy is consumed for achieving thermal and optical comfort. The important parameters include building shape, orientation and the window to wall ratio and need to be adequately combined to achieve thermal comfort and energy efficiency. Ko et al. (2020) investigated the influence of a window on the thermal and emotional aspects of the occupants and concluded this strategy is important for

Table 2. Summary of some reference results on natural ventilation

Reference	Work nature	Research objective	Main findings
Kasima et al. (2016)	Numerical	Opening positions	Mixed-mode buildings ventilation have potential to save 40.00% HVAC energy.
Omrani et al. (2017)	Numerical	Single-sided & cross ventilation	Better performance of cross ventilation over single-sided ventilation.
Elshafei et al. (2017)	Numerical & experimental	Window	Decrease in air temperature by 2.50% & an increase in air velocity by six times.
Cuce et al. (2019)	Numerical	School buildings	Single-side ventilation & cross-ventilation can have good effect on cooling & improving air quality in school buildings.
Guo et al. (2019)	Numerical	Night ventilation	Climatic conditions & night ventilation modes strongly affect influence of design parameters on performance indicators.
Solgi et al. (2019)	Numerical	Night ventilation	Use of well-insulated envelopes increases night ventilation efficiency & stabilizes optimal PCM transition temperature.
Rahnama et al. (2020)	Numerical	Ceiling ventilation system	Highest cooling capacity inscenario with evenly distributed heat load in room & compact distribution of active diffuse panels in ceiling.
Hu et al. (2020a)	Experimental	Ventilated window	Ventilation pre-cooling application, room inlet air temperature is by average 1.4 °C lower compared to normal ventilated window.
Hu et al. (2020b)	Numerical	PCM enhanced ventilated window	PCMVW can enhance building energy saving by 62.30% & 9.40% compared to primitive summer & winter control strategies.
Guo et al. (2020)	Numerical	Coupling a cool roof with night ventilation	Combining a cool roof with night ventilation can significantly decrease annual cooling energy consumption by 27.00% compared to using a black roof without night ventilation and by 13.00% compared to using a cool roof without night ventilation.
Sadeghian et al. (2022)	Numerical	Ceiling ventilation systems	Local thermal comfort assessment revealed that dispersed configuration had highest draft rate of 14.00%.

Table 3. Summary of some reference results on thermal comfort

Reference	Work nature	Research objective	Main findings
Saadatjoo et al. (2019)	Numerical	Thermal performance & ventilation	To save energy, it is possible to reduce air changes in a room to minimum, enhancing both local thermal performance & comfort.
Hawila et al. (2019)	Numerical	Glass facades	Optimized design improved thermal comfort conditions as well as energy-savings.
Krstic-Furundzic et al. (2019)	Numerical	Façade design	Various alternatives of shadings reduce total energy demands & reduce environmental pollution.
Fahmy et al. (2020)	Numerical	Wind catchers, shading devices, low e-glass windows, double skin façade, & double roof	Shading roofs & southern facade of building envelope are most efficient scenarios for passively modified version of building.
Ko et al. (2020)	Numerical	Window	Providing a window with a view in a workplace is important for comfort, emotion, & working memory & concentration of occupants.
Yang et al. (2021)	Numerical	Building-integrated photovoltaic/thermal double-skin façade	Solar heat gain coefficient of BIPV/T-DSF's external window possessed highest importance affecting indoor thermal comfort & energy consumption.
Shahrzad and Umberto (2022)	Numerical	Opaque dynamic façade	Thermal resistance in façade could be increased & decreased as a function of airflow in façade.
Jiang et al. (2022)	Experimental	Visual windows	Visual window improved occupants' tolerance to thermal environment.

their comfort and concentration. Yang et al. (2021) performed sensitivity analysis on the correlations between indoor thermal comfort, energy consumption and design parameters of BIPV/T-double skin façades (DSFs) and concluded that solar heat gain coefficient (SHGC) of the BIPV/T-DSF's external window significantly affects indoor thermal comfort and energy consumption.

Bahri et al. (2022) presented a review on tools and techniques used to improve thermal comfort in a double skin façade for residential buildings. Results suggest that simulation is the most accurate in comparison with other methodologies. Shahrzad and Umberto (2022) investigated the optimization of a novel opaque dynamic façade and concluded that the thermal resistance in the façade could be varied as a function of airflow in the façade. Jiang et al. (2022) conducted a study to explore the influence of natural views and daylight on health, thermal perception and energy savings and concluded that visual window improved the occupants' tolerance to the thermal environment. **Table 3** presents a summary of some studies on thermal comfort in buildings.

Comments

Natural illumination and natural ventilation can reduce energy demands and improve the thermal comfort. One can also observe the recent concern about visual comfort especially in working areas and impacts human comfort and efficiency. The important parameters of buildings such as building shape, orientation, and the window to wall ratio, need to be adequately combined to achieve thermal comfort and energy efficiency.

Table 4. Standard requirement for WWR (ASHRAE, 2017)

WRR	Less than 0.24	Equal to 0.24	More than 0.30
Performance	Poor	Good	Overheat

Effect of Window to Wall Ratio

Window-wall ratio (WWR) is an important building design parameter that has significant effects on the fashionable appearance of the building as well as on the internal thermal, visual, and acoustic comforts. ASHRAE (2017) has established that WWR of 0.24 is considered ideal for indoor daylight and natural ventilation. **Table 4** shows the summary of WWR values and their effects on building performance. Also, the ratio of glass area to floor area is relevant in building design. A value in the range of 20.00-30.00% of the floor area is considered adequate.

Goia (2016) conducted a study to seek for the optimal WWR in European climates and concluded that these values occur in the range (0.30<WWR<0.45) and that the total energy use may increase by 5.00-25.00% for the worst WWR configuration.

Carlos and Corvacho (2017) assessed the influence of thermal performance and ventilation on human comfort and found that it was possible to minimize the air changes without compromising air quality and enhance thermal performance and comfort. Fang and Cho (2019) proposed a building performance optimization process that can evaluate daylight and energy performance of building design. Troup et al. (2019) conducted a study to evaluate the effects of WWR in actual office buildings and the results showed increased median total energy use intensity with increasing fenestration due to increasing cooling loads.

Alwetaishi (2019) assessed the influence of WWR in various microclimate regions and suggested WWR of 10% in hot and dry and hot and humid climates. Ashrafian and Moazzen (2019) focused their study on the impact of different transparency ratios and window combinations on occupants' comfort and the energy demands of a classroom. The results indicated that a WWR of 50.00% can decrease artificial lighting by 15.00% and ensure indoor comfort. Phuong et al. (2019) proposed an integrated approach to determine window to floor ratio to provide the target Daylight Factor, energy efficiency for the tropical climate. The results showed that the recommended window to floor ratio is 15.20% to 18.50% for Daylight Factor of 1.35%.

Ozel and Ozel (2020) investigated the effect of WWR on the thermal performance of different wall materials and concluded that for the case of bare wall the wall material affected the glazed area, whereas in the case of the insulated wall, the effect was marginal. Shao et al. (2020) used the Design builder software to determine the optimum value for WWR for rural house design considering other parameters such as building orientation and thermal performance among others. Their recommendation is that the effect of various factors should be considered in the design to determine the WWR of rural houses. Sayadi et al. (2021) investigated different cases in various climatic conditions to obtain the optimal WWR based on the minimum energy use of a building during a complete year. Boutet and Hernández (2021) focused his study on determining an optimized design proposal that achieves thermal and daylighting habitability conditions. The results showed significant thermal and daylighting behavior enhancements with important reductions in the cooling loads. Saber (2021) investigated the effects of the WWR and recycled panels on energy consumption. All panel cases showed that the least energy consumption with lighting included occurred for WWR of 45.00-55.00%. They recommended the use of recycled materials-based panels for the envelope with WWR less than 50%.

ASHRAE has established that window to wall ratio of 0.24 is considered ideal to allow optimum indoor daylight and natural ventilation, which reduces energy costs. The larger the window, the more heat or light will penetrate the room, which causes overheating and glare. An appropriate configuration of windows can effectively improve visual and thermal comfort by reducing glare, distributing light, and controlling solar energy gain.

PERFORMANCE ENHANCEMENTS OF WINDOWS & FAÇADES

Since glazed windows and façades are the weakest elements for heat transfer between the building and exterior ambient, many studies and developments were devoted to enhancing their thermal and optical characteristics to make them not only more efficient, but also dynamic enough to cope with ever-changing climatic conditions.

Reflective Solar Films

Sustainability and energy conservation are essential for buildings management together with satisfactory indoor environment and comfort. Windows and translucent elements are responsible for maintaining comfortable indoor thermal and visual environment (**Figure 8**). Many window geometries and attachments were developed to improve the performance of windows. Among these possible solutions solar control films (SCFs) outstanding as a cheap and effective solution that controls light and heat penetration, filters out UV and IR, reduces glare and minimizes the use of electric lighting. **Figure 9** shows possible arrangements for windows with reflective film for summer and winter operations.

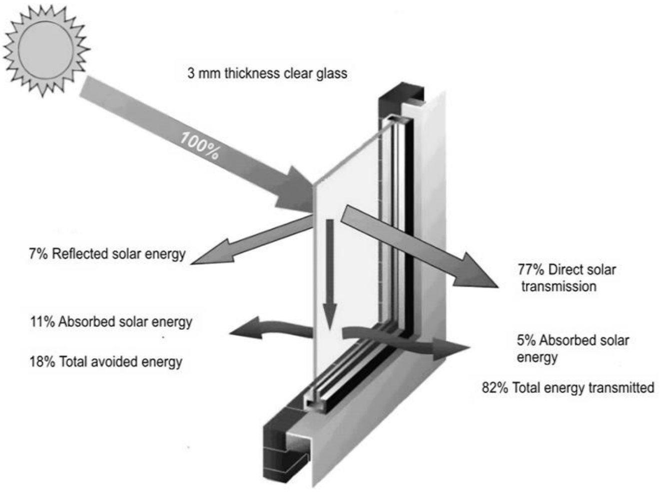


Figure 8. Incident & transmitted solar energy through a clear glass window (Sureguard, 2023)

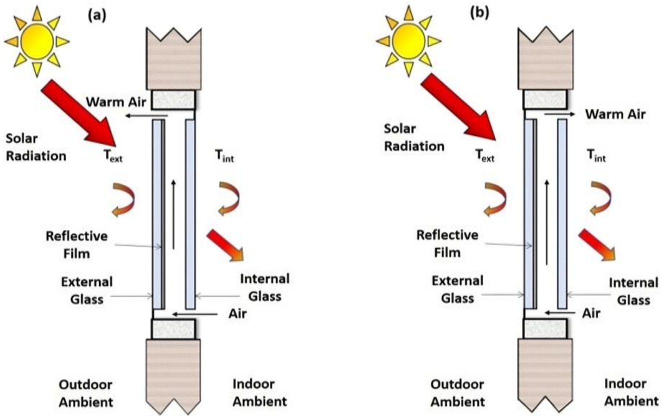


Figure 9. Modes of operation of investigated window: (a) arrangement for hot climate & (b) arrangement for cold climate (Ismail et al., 2021)

Yu and Su (2015) presented a review of methods for indoor daylight assessment, and methods used for predicting energy savings from daylight to make available information for sustainable design and energy management. Hee et al. (2015) reviewed the impacts of window glazing on the energy and daylight performance and the optimization techniques used in choosing the emerging glazing technologies. Moretti and Belloni (2015), in their study to evaluate the effects of SCFs on the thermal, and daylight performance for moderate climate, reported a reduction of 60.00% in the incoming radiation, about two to three ^{o}C of the indoor temperature, increase of artificial lighting, decrease of the cooling demand by 29.00% while the heating demand increased by 15.00%. Li et al. (2015) investigated the effect of solar films on building energy consumption and concluded that solar films have good potential for energy saving.

Rezaei et al. (2017) presented a review on various types of glass coatings and glazing systems and evaluated the potential of using different window technologies for hot, cool, and temperate climates. Xamán et al. (2017) presented the results of thermal evaluation of a room fitted with a double glass window and SCF. The results showed a reduction of 62.00% of the energy gains for hot climate, and insignificant effect on the indoor temperature in the cold climate. Teixeira et al. (2020) conducted a study to investigate the thermal and visual comfort performance of different types of SCFs and concluded that the highly reflective SCF has the highest thermal and optical performance, while the spectrally selective film showed an annual reduction of 38% of energy consumption. Abundiz-Cisneros et al. (2020) investigated alternative materials to substitute silver (Ag) in a low-e filter coated and concluded that an aluminum-based filter has a good cost-benefit performance.

Tong et al. (2021) provided a review of transparent-reflective switchable glass (TRSGs) technologies for application in building façades, while El-Eshmawy et al. (2021) reviewed the different types of glazing, categorized them into conventional and advanced and showed their thermal and lighting performance. Pereira et al. (2021) investigated different SCFs applied on existing windows of a building. SCF considered as the best retrofitting solution showed an annual carbon footprint of 4,447 MJ/m^2/40 y and 380 kgCO$_2$eq/m^2/40 y, respectively. Calama-González et al. (2019) evaluated the influence of SCF on natural luminance of a public hospital building in a Mediterranean climate and commented a reduction of 12.20% of the electric consumption of the artificial lighting system, **Figure 10**. The room with solar film showed a reduction of 3.30% in energy cooling demand. In contrast, heating energy demand increased by 6.50% in comparison with the room with no solar film.

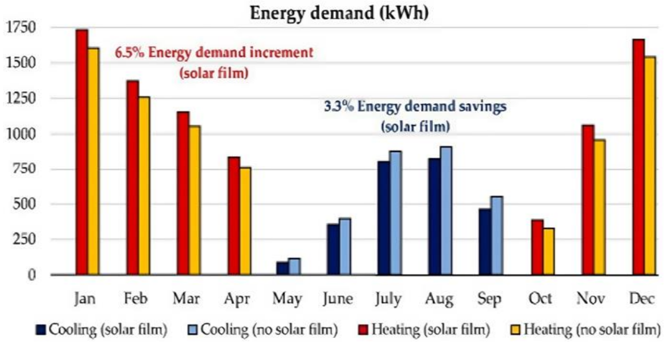


Figure 10. Monthly energy demand (kWh) ofe cooling & heating systems in rooms with & without solar protection films (Calama-González et al., 2019)

Daylight luminance levels and their spatial distribution are important design parameters to achieve indoor visual comfort and sustainability in buildings. While a proper day lighting scheme increases the efficiency of the building, the excessive use of glazed surfaces can contribute to thermal and visual discomfort. Pereira et al. (2020) analyzed the impact of single glazing with different SCFs on the indoor luminance and its distribution on horizontal plane and concluded that all SCFs reduced the indoor luminance. In another work, Pereira et al. (2022) presented a review of the performance of SCFs applied to glazing systems and identified and discussed interactions of glass-film systems, climatic conditions on energy savings and comfort.

Vacuum Glazing

Vacuum insulated glazing is an effective technology suitable for severe thermal performance requirements, enhanced thermal efficiency, sound insulation, and can achieve U-values as low as 0.7 W/m^2 K. **Table 5** shows comparison of vacuum-glazing windows commercially available (Aguilar-Santana et al., 2020).

Fang et al. (2006) developed a technique to determine the heat transfer coefficient of the evacuated gap and the comparison between the measured and predicted temperature profiles showed good agreement. Jelle et al. (2012) conducted a market review of the best performing fenestration products including electrochromic vacuum glazing and evacuated aerogel glazing as potential candidates for enhancing thermal and daylight performance of windows.

Ghosh et al. (2017) analyzed the variation of vacuum glazing transmittance with clearness index and showed that clearness index below 0.50 offers single value of transmittance. Alam et al. (2017) evaluated savings in space heating due to the installation of fumed silica and glass fiber and vacuum insulation panels (VIPs). The results show that VIP insulation reduced the annual space heating, energy

Table 5. Sample comparison of vacuum-glazing windows commercially available (Aguilar-Santana et al., 2020)

Name	Technology	Thickness (mm)	U-value (W/m^{2}K)	G-value
Pilkington Spacia™ (double glazing)	VDG with 0.2 mm pillars	6.2	1.4	0.66
Pilkington Spacia™ Shizuka (double g.)	VDG with laminated glass	9.2	1.4	0.61
Pilkington Spacia™ Shizuka cool (double g.)	VDG with interlayer single low-e coating	6.2	1.0	0.49
Pilkington Spacia™ 21 thermal control (triple g.)	VTG Kr interlayer double low-e coating	18.2	0.9	0.58
Pilkington Spacia™ 21 solar control (triple g.)	VTG Ar interlayer double low-e coating	18.2	0.7	0.46

Table 6. Comparison of interpane medium (Huang et al., 2021)

Medium	Advantages	Disadvantages
Airflow	Low density & transparent	Condensation problems, fans for ventilation, & low heat capacity
Flowing liquid	Transparent & high heat capacity	High density, heavy weight window, leakage risk, & piping system
Aerogel	High thermal insulation & low density	Durability & translucent
PCM	High thermal capacity	Translucent, heavy weight window, & leakage

demand and carbon dioxide (CO_2) emissions. Ascione et al. (2017) evaluated the effectiveness of VIP for application in the Mediterranean climate and the results confirmed the viability of the solution.

Kim et al. (2017) evaluated the performance of VIPs, and the effective U-value of building walls made with VIPs. Pont et al. (2019) reported on recent advances in the utilization of vacuum glass in contemporary window construction and highlighted the reduction of the weight of components, reduction of conduction and convection heat transfer are among the benefits of vacuum glazing. Aguilar-Santana et al. (2020) reviewed the performance of available window technologies with a special focus on the U-value. The authors concluded that further research is needed to develop window technologies with multiple functional attributions and characteristics such as high insulating properties, generation of energy, etc. Fang et al. (2020) analyzed the solar thermal performance of two configurations of air-vacuum layered triple glazed window and concluded that allocation of the vacuum gap near the indoor region reduces cooling load and enhances energy efficiency. Aguilar-Santana et al. (2020) experimentally determined the U-value of active insulated windows and compared them with other windows and concluded that vacuum glazing achieved a U-value 78.00% lower than traditional single glazing window units. Uddin et al. (2023) presented a review on PV combined with vacuum glazing, actual progress, and prospects for the design of energy-efficient buildings.

Double Glass Windows with Filling Materials

To reduce the heat gain or loss from double glazed windows and façades and improve the thermal performance adequate filling materials are inserted in the gap to provide the required effect. Varieties of gases and liquids were tried, tested, and evaluated such as stagnant inert gases, flowing air and flowing liquids, aerogels and PCM. **Table 6** provides a comparison of window gap fillers.

Windows with water flow

The use of the concept of fluid flow in the double glass window can enhance its thermal performance while the heat gained by the flowing liquid can be used in other applications. Triple and multiple glass panes windows may integrate with the liquid flow some additional functional component such as the air layer, or vacuum gap to enhance the system thermal performance. **Figure 11** shows the details of a water-flow double window.

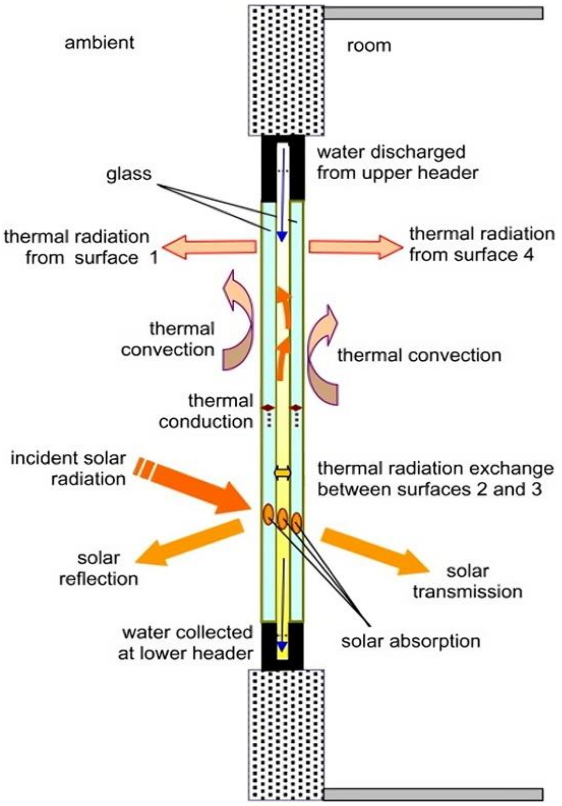


Figure 11. Details of a water-flow double glass window (Chow et al., 2011)

An experimental investigation of a glazed façade had been conducted by Qahtan et al. (2011) utilizing a water film and concluded that the flowing water film on the glazed façade lowered the glazing surface temperature by 7.2 to 14.0 ^{o}C and decreased the indoor temperature by 2.2 to 4.1 ^{o}C. Chow et al. (2011a, 2011b) connected the cavity of a double pane window to a water-flow circuit to absorb solar heat, reduce room heat gain, enhance thermal performance, and concluded that the proposed system is adequate for warm regions. Adu (2015) characterized the performance of water as gap-filler for double-glazing units and found that the thermal transmittance and SHGC were better than those of the traditional units, maintained lower indoor temperature swings, reduced the incident solar radiation, and maintained high visibility. Chow and Lyu (2017) investigated the effects of water layer thickness and glazing height-to-width ratio (GHTWR) and concluded that a water layer thickness of 15-20 mm and a GHTWR of 0.40 produced good results.

Romero and Hernández (2017) used a net energy balance radiation model to solve the spectral problem and determine the wavelength-averaged absorptances of the different layers of a multilayer water flow glazing system to be able to precisely simulate the performance of this type of windows. Lyu et al. (2019) proposed a triple glazing vacuum-water flow window and showed a heat reduction of about 44.00% due to the combined effects of vacuum gap and water flow. In another work Lyu et al. (2019) suggested using hot water flow to make the gap work as a heat radiator. The simulation results showed that the proposed system was viable. Li et al. (2019) investigated water-flow window for possible use in hospital patient wards with large demand of hot water. The numerical simulations showed reduction of penetrated solar energy, better thermal indoor conditions, and hot water for general use. The water inside fluid glaze façades creates a vertical hydrostatic pressure, which must be supported by the glazing. The simulations showed that pillars can solve this pressure problem (Escoto & Hernández,2019). Chow and Liu (2020) reported that the results of applying the dynamic simulation model of water-filled double-glazing indicated a thermal efficiency in the range 26.00-51.00%.

Double-circulation water-flow window is composed of four layers of glass panes and two layers of flowing water, which utilizes solar energy for domestic hot water and regulates heat gain through window (Li et al., 2020). Results showed that the annual solar collection efficiencies were 16.20% and 4.30% for the external and internal water circulation, respectively.

A literature review showed that fire safety and reduction of energy needs is a challenge in buildings with glass façades. Water wall system as a building façade is a possible solution that can allow achieving both objectives (Rathnayake et al., 2020). The transparency of the water wall allows daylight to enter the building and maintains good visual performance, while the water layer acts as a fire safety mechanism when needed.

In a review by Piffer et al. (2021) on windows filled with liquids with spectrally-selective and high thermal capacity properties to enhance optical and thermal performance and commented that these windows can transmit more light than when it is empty, promote solar heat gain or reduce cooling demand. Huang et al. (2021) provided a review on the application of fluids and other materials as fillers for multi-glazing windows to enhance thermal performance including airflow, flowing liquids, aerogels, and PCM. They included suggestions for future research and developments. Ghosh (2023) mentioned that diffuse transmission has several advantages like offering uniform daylight and reducing glare. Diffuse transmission windows prepared with aerogel, PCMs, and polymer dispersed liquid crystal had been reviewed and their potential for future buildings applications was discussed.

Window with phase change material

The use of PCMs as gap filler enhances the thermal inertia of windows, increases thermal resistance, and filters out unwanted radiation as UV and IR besides reducing window glare. A general arrangement for including PCM in double glass window is shown in **Figure 12** reproduced from (Khetib et al., 2021).

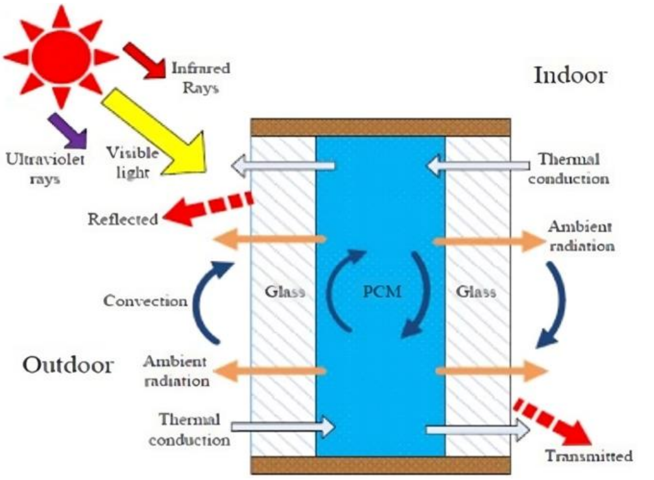


Figure 12. Double glass window with PCM (Khetib et al., 2021)

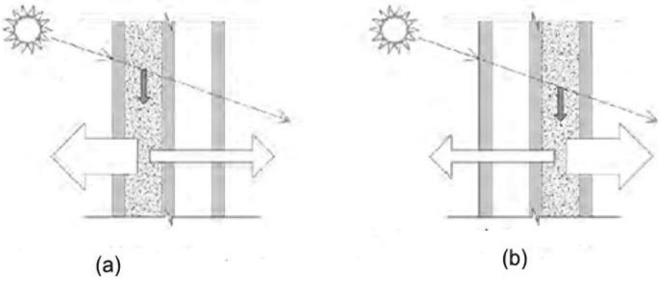


Figure 13. Two possible arrangements of PCM glazing: (a) PCM located from outside & (b) PCM located from inside (Wieprzkowicz & Heim, 2018)

A triple-glazed window can permit filling one of the window cavities with PCM to regulate indoor daylight, while the second provides the required thermal insulation. Two possible PCM-glazing arrangements are presented in **Figure13**. For summer conditions PCM should be placed near the exterior side, part a in **Figure 13**, while for winter PCM plays a role of dynamic insulation and should be located as in part b in **Figure 13**.

Ismail and Henriquez (2002) presented the results of a numerical and experimental study on thermally efficient windows. The results of transmittance and reflectance tests indicated large reductions in the infrared and UV while maintaining good visibility.

Goia et al. (2013) proposed a prototype of a simple PCM glazing system, compared the results with those of a reference conventional double glass window and showed improvement of thermal comfort. Zhong et al. (2014) investigated the effects of the inclusion of PCM in double glass window on the building thermal performance and reported good agreement between the experimental and numerical results. Li et al. (2016) investigated a configuration of triple-pane window, where PCM was placed in the cavity near the external side. The results showed a reduction of 5.5 °C of the internal surface temperature and a decrease of 28.00% of heat gains. Wieprzkowicz and Heim (2018) investigated the thermal performance of PCM glazed unit under real climatic conditions

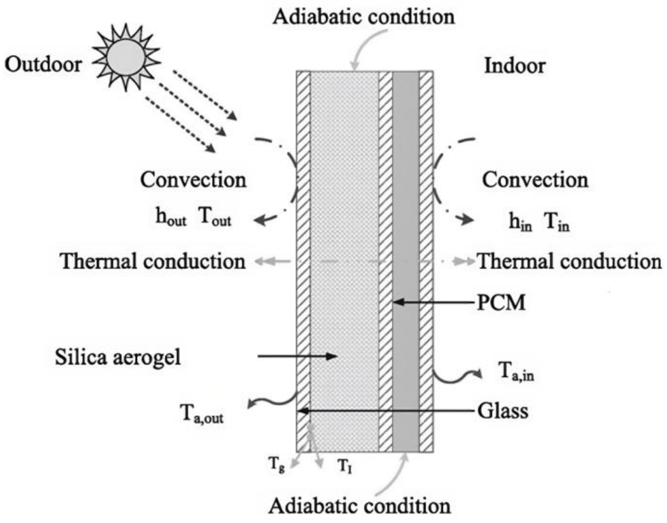


Figure 14. Double glass window with PCM & silica aerogel (Li et al., 2019)

and concluded that the insertion of PCM in the external cavity enhanced the thermal performance of the window and stabilized the temperature oscillation. Li et al. (2018) developed a model to evaluate the effect of different types of nanoparticles, volume fractions and size of nanoparticles on the thermal and optical performances of windows, compared the results with the case of pure PCM and reported significant improvements. Sun et al. (2018) reviewed the experimental and numerical methods used to predict the thermal and optical behavior of window including methods that permit the prediction of the combined effects on the thermal, daylight and energy behavior of buildings. Ehms et al. (2019) reviewed the numerical approaches used to formulate the solidification and melting processes and determine the heat exchange and transition velocity between the phases.

Li et al. (2019) evaluated the thermal performance of glass window with silica aerogels and PCM as in **Figure 14** and showed that the thermal conductivity and thickness of silica aerogel are important parameters and concluded that the concept is viable for cold climates. Yang et al. (2020) investigated two models to determine optical properties of PCM based nanofluids. The results showed that the large concentration of the nanoparticles produced big extinction and scattering coefficients of the paraffin nanofluid. Li et al. (2020) reviewed the optical and thermal performance of glazed units with PCM, presented and discussed the research methods, and indicated future works on PCM glazed units. Liu et al. (2019) developed a simplified method to analyze the thermal performance of multilayer glazing façades and showed good agreement between measurements and numerical predictions.

DSFs are considered as sustainable design elements for reducing energy consumption in buildings. However overheating problems in warm seasons have been reported in various studies (Li et al., 2019). The authors evaluated experimentally and numerically the thermal performance of an integrated PCM blind system for DSF buildings and reported that the system stabilized DSF indoor temperature. Uribe and Vera (2021) analyzed the impact of PCM glazing on buildings' energy performance and thermal and visual comfort and reported reduction of energy consumption and enhancement of the thermal and visual comfort. Khetib et al. (2021) simulated the three modes of heat transfer in an air-filled double-glazed window (DGW) and showed that the highest heat loss occurred for the vertical window.

Li et al. (2022) provided a review on optical transmittance, thermal resistance, and thermal inertia in glazed envelopes with PCMs and reported lack of information on acoustic data of glazed system with PCM. Li et al. (2022) investigated a roof based on silica aerogel and PCM glazed systems. The results showed improvement of the thermal performance. Kaushik et al. (2022) examined the heat transfer characteristics of a double-glazing window system having a nano-disbanded phase changing material and indicated a decrease of the indoor glass panel temperature by 8.5 °C and enhanced energy conservation by 4.61%. Liu et al. (2022) reviewed the different concepts related to PCMs and details of the different types of PCMs according to climate. Xu et al. (2022) prepared a phase-change gel with relatively high melting enthalpy, better leak proof characteristics, better thermal insulation, besides increasing time lag and lowering peak temperature. Arasteh et al. (2023) reviewed energy and thermal performance of PCM-incorporated glazing units combined with passive and active techniques including current passive smart glazing technologies, while Michael et al. (2023) provided a review on established and emerging glazing technologies and the inclusion of multiple functionalities to improve overall building performance.

Window with stagnant inert gas filling

Inert gases are used as fillers for double glass windows because of their thermal resistance. It is known that double glass windows filled with Argon can reduce the conductivity of the window by 67.00% in comparison with air-filled windows. Windows filled with Krypton can reduce the overall U-value by 17.20% compared to Argon filled windows, while Xenon-filled gap showed the lowest U-values of 0.28 W/m^2 K but is more expensive to manufacture. **Table 7** presents comparative values of triple-glazing heat transfer solar coefficient and transmittance for gas fillers (Aguilar-Santana et al., 2020).

Jelle et al. (2012) provided a review on actual fenestration technology at the time and possible future research and development to improve the fenestration products and make them not only efficient providing thermal and visual comfort but also affordable. The review covered U-values of commercially available glazed products such as aerogel, vacuum, low-emissivity coatings, and electro chromic vacuum windows. Arici and Kan (2015) evaluated the thermal performance of double, triple, and quadruple glass windows and presented correlations for predicting the glazing U-value for the cases of air and Argon as fillers. Aguilar et al. (2015) evaluated the thermal performance of a double pane window with three types of commercial glass and recommended the use of reflective film with double pane window in warm and cold climates. Lolli and Andresen (2016) conducted a study to evaluate emissions reduction due to substitution of triple-glazing units with double glass window with argon gas and monolithic or granular aerogel and concluded that the two options were viable.

Table 7. Comparative values of triple-glazing U-values & transmittance for gas fillers (Aguilar-Santana et al., 2020)

Manufacturer	Product	U-value (W/m^{2}K)	Visible transm. (T_v)	G-value (SHGC)
Modelling (Optitherm-Air)	4/12/4/12/4 air	0.90	0.58	0.34
Nippon Sheet Glass Co. Pilkington	6/12/4/12/4 Ar 90%	0.70	0.73	0.61
Nippon Sheet Glass Co. Pilkington	6/12/4/12/4 Kr 90%	0.60	0.73	0.61
Modelling (Optitherm-Xenon)	4/12/4/12/4 Xe 90%	0.53	0.58	0.34

Figure 15. Typical U-values of building elements (Cuce, 2014)

Sadooghi and Kherani (2018) presented a new methodology to evaluate the performance of glazing systems with partitioned radiant veil and reported that using internal partitioning veil can significantly enhance the U-values. Cuce (2018) analyzed argon filled double glazed windows in terms of U-*value*. The differences between experiments and numerical predictions were attributed to edge effects.

Windows are essential components of buildings, which provide vision, air ventilation, passive solar gain, and daylighting, but also contribute much to the thermal loads of buildings because of their high U-values, **Figure 15**, (Cuce, 2014). Hence, it is essential to reduce the U-value of windows and façades to improve thermal performance of components.

Baek and Kim (2019) developed a hybrid triple glazing that combines vacuum and carbon dioxide (CO_2) in gaps and concluded that the performance was comparable to that of the case with Argon gas. In another study Baek and Kim (2021) the authors analyzed the insulating effect and performance of double glazing with CO_2 as filler. From comparison with other gas fillers, they confirmed that glazing with CO_2 gas performance was like that of Argon gas. A review on thermal insulation materials, and factors that influence the choice for building applications was provided by Imhade et al. (2022).

Ventilated windows and façades

In VWs and façades part or total ventilation air is drawn through the gap separating the pair of glass sheets to be heated by solar radiation and inserted into the building, or alternatively to be induced from the indoor ambient by solar radiation action and removed to the exterior ambient. A dual airflow arrangement can allow preheating the fresh supply air or cooling it according to the season, and hence such window arrangement is suitable for different climates. Another possible solution is using reversible VWs, as shown in **Figure16** (Lago et al., 2020).

Figure 17 shows a sketch of VW integrated with PCM (Hu et al., 2020). The ventilated double glass arrangement acts as a passive heating system, where part of the heat loss is returned by the airflow, while part of the incident solar radiation heat is removed by the flowing air to the indoor ambience. Carlos et

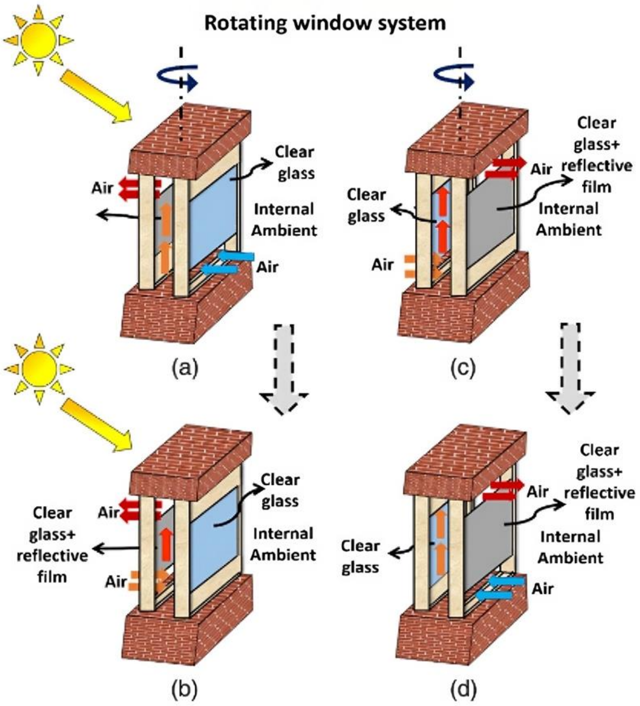


Figure 16. A reversible ventilated double glass window suitable for moderate climate regions (Lago et al., 2020)

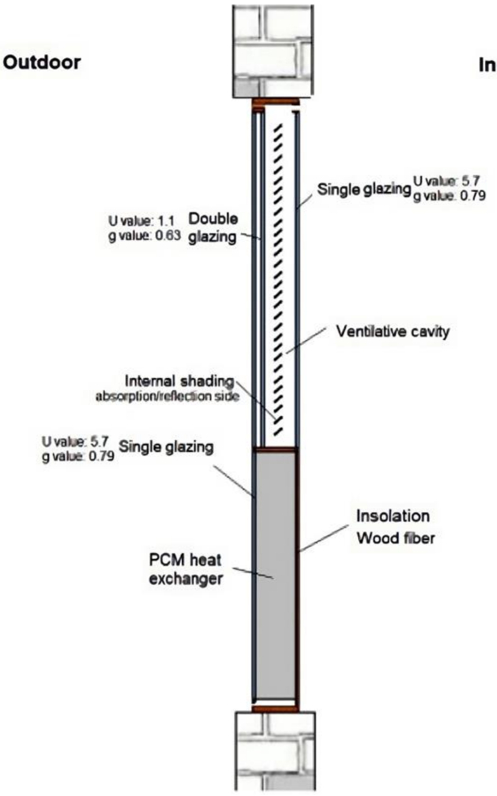


Figure 17. Ventilated window with PCM (Hu et al., 2020)

al. (2012) analyzed the two functions and concluded that the concept is applicable on any facade.

Carlos and Corvacho (2013) studied the performance of ventilated double window for the preheating of the ventilation air and concluded that the proposed system was viable. De Gracia et al. (2013) provided a review on DSFs modeling including analytical and lumped models, network models, control volume, and CFD and commented on their limitations and advantages. Barbosa and Ip (2014) reviewed application of DSFs technologies to provide guidelines to optimize designs in naturally ventilated buildings for improving indoor thermal comfort. Skaff and Gosselin (2014) investigated ventilated fenestration on energy performance and their benefits. They proposed a model to determine the total heat reduction provided by ventilated glazing.

Carlos and Corvacho (2015) studied numerically and experimentally the variation of SHGC of a ventilated double window with working conditions and types of glass and concluded that the results can be helpful for building energy analysis. Gloriant et al. (2015) proposed simplified models to be used in building simulation codes. Predictions from these simplified models were compared with those from CFD modeling and showed good agreement. Carlos (2017) commented that the double VW can preheat the incoming air, reduce thermal losses through windows and decrease the heating load of the building. Souza et al. (2018) investigated the efficiency of a naturally ventilated DSF and showed that DSF contributes to the decrease of the indoor temperature. Tukel et al. (2019) investigated the effect of air layer thickness, glass coating emissivity and number of panes on the thermal characteristics in glazed roof and showed that the U-value was reduced to 0.77 W/(m^2 K) and energy saving potential achieved about 71.00%. Lago et al. (2019) developed and validated a model for the ventilated double glass window with reflective solar film. The results showed that the solar reflective film can reduce the penetrating solar energy by about 64.70%. Zhang et al. (2019) investigated a triple glazed exhaust-air window (TGEW) and concluded that TGEW can reduce 25.30% and 50.10% of the annual cooling and heating loads, respectively. Choi et al. (2019) analyzed the cooling energy performance of a slim double-skin window and showed that the proposed system can reduce the cooling load and decrease the solar heat gains. Hu et al. (2020) proposed a PCMEVW system for ventilation preheating / precooling applications and showed a building energy saving increase of 62.30% and 9.40% for summer and winter, respectively.

Huang et al. (2021) provided review on fluid fillers for multi glass windows covering application technologies, performance analysis methods, and evaluation of different building applications. Khosravi and Mahdavi (2021) investigated the ability of VWs to preheat the incoming ventilation air and showed that taller cavities and a smaller cavity depth can enhance the incoming air temperature. Sadko and Piotrowski (2022) reviewed the investigations of the thermal properties of window systems and glazed buildings partitions.

Kumar et al. (2022) reviewed different building parameters to provide a conceptual framework for the building envelope. The proposed framework includes life cycle assessment, occupant's satisfaction, and social benefits. Preet et al. (2022) reviewed the studies on DSF systems and discussed the influence of geometric design parameters on heat transfer and fluid dynamics occurring in DSF system. **Figure 18** shows the schematic diagram of DSF system used by the authors.

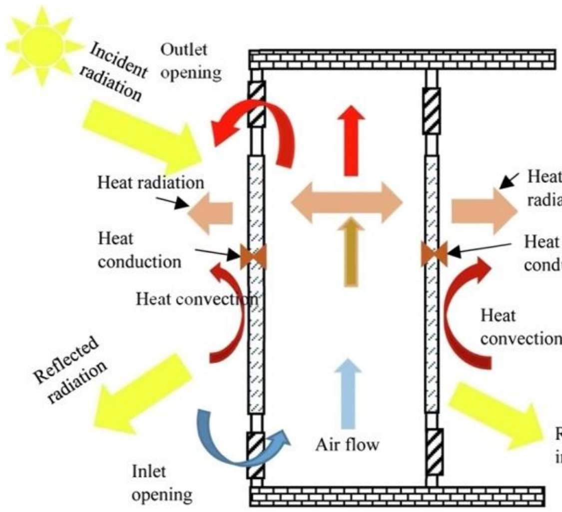


Figure 18. Schematic diagram of a ventilated cavity of DSF system (Preet et al., 2022)

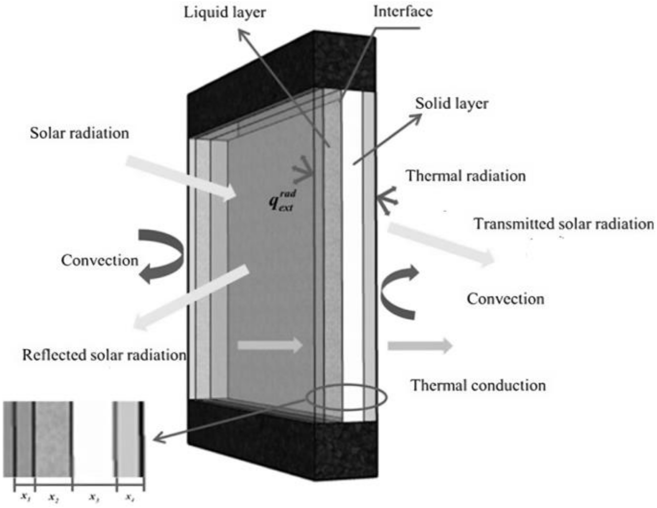


Figure 19. Model of double-glazed window filled with nano-PCM (Yang et al., 2023)

Tao et al. (2023) proposed a new theoretical model for a naturally ventilated double-skin façade to calculate the thermal and ventilation performance under varying environmental conditions.

Substantial performance improvements can be achieved by using hybrid nanoparticle-enhanced phase change material (NePCM) in DGWs but can cause local overheat and impacts negatively thermal comfort and natural lighting (Yang et al., 2023). **Figure19** shows the model of DGW filled with NePCM used by the authors.

Windows with Aerogel

Glass façades and windows are responsible for thermal comfort, daylighting, natural ventilation, and a big part of the energy demands due to thermal losses. Aerogel, due to its optical transparency and low thermal conductivity if inserted in windows and façades can significantly improve their performance and reduce discomfort and glare. **Figure 20**

Figure 20. Window with aerogel (Ding, 2020)

shows a window with aerogel insulation, while **Table 8** shows datum on aerogel glazing available in literature (Ding,2020).

Buratti et al. (2012) investigated innovative glazing systems with silica aerogel for energy saving. The monolithic aerogel glazing showed better performance in comparison with granular systems because of light transmittance, and thermal insulation. Experimental results from Gao et al. (2014) indicated that the optical and thermal properties of aerogel glazed units are dependent of the particle size of the granules and the results (for large granules) showed 58.00% reduction in heat losses and 38.00% reduction in light transmittance compared to a traditional DGW.

Cotana et al. (2014) assessed the effects of inserting aerogel in an innovative glazed system and concluded that aerogel reduced energy for heating by 50.00% in winter, increased the acoustic insulation index by three dB and reduced luminance by 10.00%. Ihara et al. (2015) evaluated the energy performance of aerogel granulate glazing systems from an office façade and indicated that the proposed façade can achieve a lower energy demand than a double glazed. In another work, Ihara et al. (2015) confirmed experimentally that convection in the granular cavity does not affect the thermal performance of aerogel granulate glazing systems.

Simulations and comparisons of aerogel window with traditional Argon-filled coated double-glazing showed that the aerogel window provided a low U-value of 0.30 W/m^2K, the daylight transmission of the aerogel window was lower than that of DGW (Garnier et al. 2015).

The different properties and energy performance of aerogel glazed units including durability can provoke architectural challenges and aesthetic problems (Gao et al., 2016). The authors highlighted the need for guidelines to regulate the use of aerogel glazing and presented suggestions and recommendations. In another work, Gao et al. (2016) analyzed the application perspective of aerogel glazing in energy efficient buildings by evaluating their energy efficiency, process economics, and environmental impact and concluded that it can reduce energy consumption by 21.00% and has a possible payback time of about 4.40 years. Buratti et al. (2017) investigated different glazing systems with different granular aerogel and different glass sheets and reported a reduction of 63.00% in the U-value and about 30.00% in light transmittance.

Moretti et al. (2018) compared the thermal performance of air and aerogel-filled PC systems and found that the impact of the aerogel was significant in reducing the U-value by 46.00-68.00%, light transmittance by 0.61 and 0.42 for 16 mm and 40 mm aerogel thickness, respectively. Also, the authors reported significant effect on reflectance while the solar factor was like that of the low-e glazing. Berardi (2019) provided review on the aerogel-enhanced opaque systems including cement-based products, aerogel-enhanced plasters, aerogel-enhanced blankets and commented future research and development challenges. Mujeebu (2019) presented a review of aerogel including glazing technologies, production, properties, manufacturing, aerogel windows and application in buildings besides challenges in research and developments. Leung et al. (2020) examined the application of aerogel glazing technology and concluded that it can significantly reduce the heat gains and cooling energy.

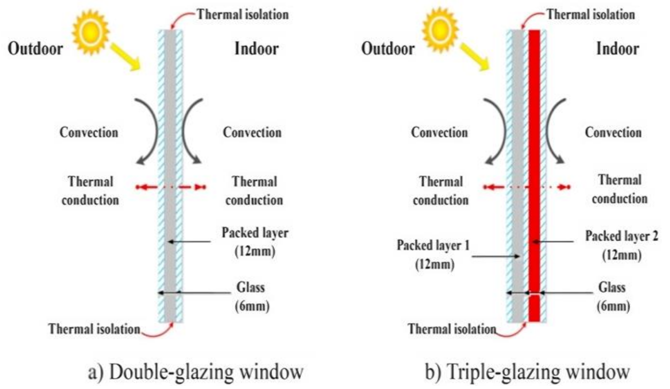
Almeida et al. (2020) reviewed the alumina-silica-based aerogels, including their fabrication processes and physical and thermal properties and commented that the insertion of the alumina phase makes the aerogels stable at high temperatures and maintain low thermal conductivity. Buratti et al. (2021) presented a review of aerogel glazing systems focusing on the main properties of interest in building applications including the material itself, the assembled glazing systems, thermal and optical properties, reliability, and durability of the aerogel glazed products.

Zhang et al. (2021) numerically investigated the energy performance of different glazing configurations including glass windows filled with silica aerogel or PCM and compared with traditional air-filled glass windows. **Figure 21** shows the schematic of double and triple glazing windows used in their study. Lamy-Mendes et al. (2021) provided a review on the production process of silica aerogels, and thermal and physical properties panels of blankets, cement, mortars, concrete, glazing systems, among others.

Meti et al. (2023) presented a review on the progress in the development of aerogels and their classification into three categories: inorganic, organic and organic-inorganic hybrid materials, **Figure 22**. Recent achievements in organic, inorganic, and hybrid materials and their outstanding physical properties were discussed focusing on adjusting the properties

Table 8. Literature data for aerogel glazing (Ding, 2020)

Type	Dimension	U-value (W/m^2K)	Transmission (%)	Thickness (mm)
Monolithic silica aerogel	55×55 cm^2	0.72	73-75	15±1.00% mm
Monolithic silica aerogel	58×58 cm^2	0.66	76-80	15 mm
Monolithic silica aerogel	55×55 cm^2	0.70	76	15 mm
Silica aerogel	7.5×25 cm^2	--	90	10 mm
Monolithic silica aerogel	(a) 0.5×0.5 m^2, (b)1.0×1.0, & (c) 1.5×1.5	0.40	--	--
Granular silica aerogels	NA	0.40	35	20 mm



a) Double-glazing window b) Triple-glazing window

Figure 21. Schematic of used glass system proposed by Zhang et al. (2021)

according to the application. Parale et al. (2017) gave a brief overview of reported flexible and transparent silica aerogels and their applications.

Abdelhafez et al. (2023) improved the building insulation using polycarbonate windows with nanogel. The incorporated nanogel layer reduced emissions and decreased the annual energy consumption by 29.00%.

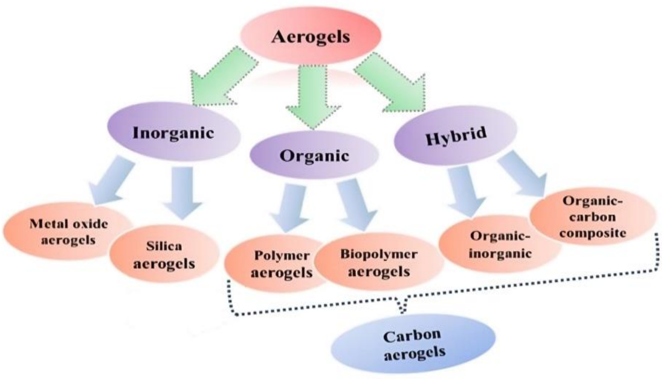


Figure 22. Classification of aerogels on precursor composition (Meti et al., 2023)

Jadhav and Sarawade (2023) provided a review that demonstrated the significant improvements in the mechanical and thermal properties of the nanocomposites.

Table 9 presents summary of results of some references on thermal enhancement of windows and façades.

Table 9. Summary of some reference results on thermal enhancement of windows & façades

Reference	Work nature	Climatic location	Window type	Main findings
Moretti and Belloni (2015)	Numerical	Moderate climate	Solar control films	Cooling energy demand decreased by about 29.00% due to solar control films, while energy demand for heating increased by about 15.00%.
Li et al. (2015)	Experimental & theoretical	Hong Kong	Solar window films	Thermal performance of film applications on clear glass is better than on tinted or laminated glass windows & that solar films have very good energy saving potential.
Xamán et al. (2017)	Numerical	Mexico	Double glazing window	For warm climate condition use of a SCF was able to reduce 62.00% of the energy gains, while for cold climate condition solar control film showed insignificant effect on average internal temperature.
Pereira et al. (2021)	Numerical	South area of Lisbon in Portugal	Solar control films	New window, which showed least performance indicated a life cycle energy of 1.5 times higher than average of three SCFs.
Pereira et al. (2020)	Experimental	Lisbon	Single glazing	All SCFs reduced indoor illuminance, which demonstrate their potential for glazing refurbishment when indoor visual discomfort occurs in buildings.
Ghosh et al. (2017)	Experimental	Dublin, Ireland	Vacuum glazing	Clearness index below 0.5 offer single value of transmittance, whereas above 0.5 clearness index glazing transmittance varies with clearness index.
Ascione et al. (2017)	Numerical & experimental	South Italy	Vacuum glazing	Effectiveness of solution with VIPs for mediterranean climate.
Fang et al. (2020)	Numerical	China	Air-vacuum layered triple glazed window	Setting vacuum gap at indoor side position provides lower cooling-load & higher energy-efficiency.
Aguilar-Santana et al. (2020)	Experimental		Single glass & double & vacuum glazing windows	Vacuum glazing achieving a U-value 78.00% lower when compared to traditional single glazing window units.
Chow et al. (2011b)	Numerical		Water flow window	Present innovative design is suitable for applications in warm & temperate climate regions.
Lyu et al. (2019)	Numerical	Various climates	Triple glazing vacuum-water flow window	Room heat gains through window can be reduced by 43.00%-44.00% during cooling operation.
Li et al. (2019)	Numerical	Shenzhen	Water-flow window	Year-round solar energy utilization rate can reach as high as 9.40%, & indoor thermal environment is better, compared with conventional window design.
Zhong et al. (2014)	Numerical & experimental	China	PCM-filled glass window	Annual energy consumption of air conditioning & heating system because of heat transferred though PCMW decreased 40.60%.
Wieprzkowicz and Heim (2018)	Numerical	Lodz, Poland	PCM-glazing unit	Application of a PCM in external cavity of triple-glazing window stabilizes diurnal temperature fluctuations.
Li et al. (2019)	Numerical	China	Glass window combining silica aerogels & PCM	Integrating silica aerogel insulation into PCM-glass window system is an effective technology in cold regions.

Table 9 (Continued). Summary of some reference results on thermal enhancement of windows & façades

Reference	Work nature	Climatic location	Window type	Main findings
Uribe et al. (2021)	Experimental	Santiago, Chile	PCM glazing	PCM glazing reduced energy consumption during summer & mid-seasons. An improvement in thermal comfort & visual comfort is achieved.
Khetib et al. (2021)	Numerical		Double-glazed window	Highest heat loss occurs for vertical window, & minimum one takes place for 60 °C window. Lowest PCM melting time occurs when window angle is 0 °C, & maximum one occurs for a window angle of 60 °C.
Aguilar et al. (2015)	Numerical	Mexico	Double pane window	Authors recommended use of reflective double pane window in Mexican warm and cold climates.
Lolli and Andresen (2016)	Numerical	Oslo, Norway	Double-glazing units	By increasing the share of aerogel glazing, savings in emissions increase from 5.00% to 9.00%.
Cuce (2018)	Numerical & experimental	The UK	Double-glazed windows	Thermal bridges & edge effects play a key role in actual U-value performance of glazing products.
Carlos and Corvacho (2015)	Experimental & analytical	Covilhã-Portugal	Ventilated double window	From an economic point of view single transparent glass is cheapest one & also one with higher SHGC values.
Carlos (2017)	Numerical	Bragança & Évora	Double ventilated window	Thermal balance was improved by 8.40% & 12.50% in Bragança & Évora, respectively.
Tukel et al. (2019)	Numerical	Winter season	Glazed roof	U-value can be reduced down to 0.77 W/(m^2 K) & energy saving potential of about 71.00%.
Zhang et al. (2019)	Numerical & experimental	Cooling & heating seasons	Triple glazed exhaust-air window	TGEW can reduce 25.30% & 50.10% of annual accumulated cooling and heating loads.
Choi et al. (2019)	Numerical & experimental	Korea	Double-skin window	Room with SDSW installed had 9.00% less total cooling energy for a week in summer. Total solar heat gain differed by up to 34.00%.
Buratti and Moretti (2012)	Experimental	Italy	Glazing systems with silica aerogel	Monolithic aerogel glazings showed best performance in comparison with granular systems because of light transmittance, thermal insulation, & solar factor of 0.74.
Gao et al. (2014)	Experimental	Norway	Aerogel glazing units	58.00% reduction in heat losses & a 38.00% reduction in light transmittance were achieved by AGUs with large aerogel granules.
Garnier et al. (2015)	Numerical	The UK	Aerogel window	Double-glazing showed that aerogel window provided an extremely low heat-loss index of 0.3 W/m^{2}K, latter offered a U-value of 1.4 W/m^{2}K.
Gao et al. (2016)	Experimental	Oslo, Norway	Aerogel glazings	Aerogel glazings can contribute to about 21.00% reduction in energy consumption related to heating, cooling, & lighting.
Buratti et al. (2017)	Experimental & numerical	Warm climates	Windows with granular silica aeroge	A 63.00% reduction in U-value was achieved, together with a significant reduction of about 30.00% in light transmittance.
Buratti et al. 2018)	Experimental & numerical	Rome, London, & Helsinki	Multiwall PC panels	Impact of aerogel was significant: Reduction in U-value is 46.00%-68.00%, depending on aerogel layer thickness. Light transmittance is 0.61 & 0.42.
Leung et al. (2020)	Experimental	Hong Kong	Aerogel glazing	Aerogel glazing could reduce 57.00% heat gain & save 8.50% cooling energy.
Zhang et al. (2021)	Numerical	Cold climate of China	PCM and aerogel-filled multiple glazing windows	Setting appropriate optical parameters of glass for radiation above 2.5 µm significantly enhances energy efficiency of glass window coupled with silica aerogel & PCM.

Smart Glazing

Functional thin films open new applications fields for smart glazed systems by adding other functionalities such as power generation. Power generation through window coatings is relatively new and can be achieved by using semi-transparent solar cells as windows.

Figure 23 shows a comparison of electric lighting energy and cooling energy of different glazing technologies (Granqvist et al., 2009), while **Table 10** presents a summary of electro chromic, photo chromic, thermos-chromic and gas chromic windows (Aguilar-Santana et al., 2020).

Selection of window glazing is complicated when energy saving and daylighting are required simultaneously, but optimization techniques can provide a balanced solution for this problem Hee et al. (2015). In their review, Anderson et al. (2016) discussed developments on low emissivity coatings to

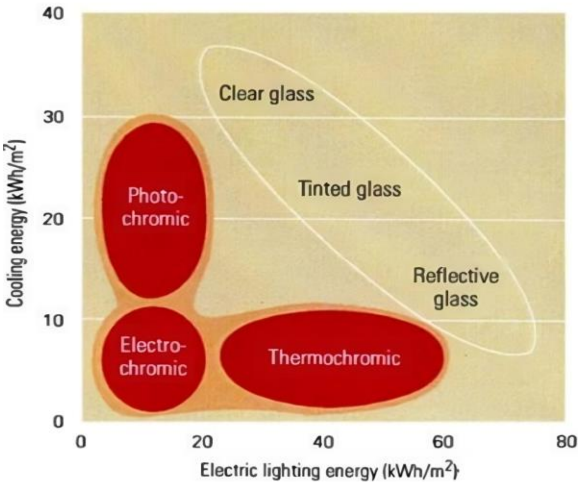


Figure 23. Comparison of electric lighting energy & cooling energy of different technologies (Granqvist et al., 2009)

Table 10. Summary of electro chromic, photo chromic, thermo chromic, & gas chromic windows (Aguilar-Santana et al., 2020)

Type	Behavior	U-value (W/m^{2}K)	Visible transmittance (V_t)	G-value (SHGC)	Comment
Electrochromic	Requires energy to maintain clear state	0.86	Reduces V_t I response to electic charges	Uese dynamic control	Requires energy to maintain clear state
Photochromic	Blocks sunlight in response to natural light incidence	5.30-1.58	Reduces Vt in response of light increase	Darkens when exposed to SHGC higher than 0.78	Blocks sunlight in response to the natural light incidence
Thermochromic	Polymer film	--	Reduces Vt when exposed to higher temperatures	--	Polymer film
Gasochromic	Regulates transparency in variations to temperature	--	Reduces 5.00-6.00% in visibletransmittance	--	Regulates transparency in variations to temperature

Table 11. Benefits & drawback of static & passive windows (Rezaei et al., 2017)

Glazing technology	Benefit	Drawback
Static		
Tinted glass	Decreases glare	Absorbs solar energy & releases heat into building & decreases visible transmittance
Reflective coating	Decreases glare & reflects NIR radiation	Decreases visible transmittance
Low-e & solar control coating	Reflects NIR or IR radiation & reduces heat reradiation by window	Decreases SHGC (should be high for cold climates)
Anti-reflective coating	Enhances visible transmittance	Increases SHGC (should be low for hot climates)
Self-cleaning coating	Visibility is maintained for longer time due to self-cleaning	--
Aerogel	Exceptionally low thermal conductivity & glare reduction	Translucent
Multiple-pane glazing	High insulating properties & can be used to combine various technologies for desired properties	Occupy considerable space & expensive
Passive		
PCM	Reduces building environment thermal fluctuation	Traslucent & needs a chamber since it turns liquid
Thermo chromic	Reduces glare, reflects NIR radiation, & reduces SHGC	Low visibility, solar modulation is not substantial, & activation temperature is high

replace indium and provided a perspective for future trends. Rezaei et al. (2017) reviewed glass coatings and glazing systems and showed possible applications in different climatic conditions. **Table 11** shows the benefits and drawbacks of static and passive windows Rezaei et al. (2017). Attia et al. (2018) investigated the current trends of adaptive façades, evaluation of their thermal and optical performance and provided current trends and future challenges.

Low heat loss through glazing systems can be achieved by suppression of convection by use of multiple glass panes with aerogels, inert gas, or vacuum between the panes to reduce convective heat transfer (Ghosh & Norton, 2018). Low emissivity coatings are also required to reduce the radiation heat transfer. Oh and Park (2019) analyzed building energy and daylight performance in an office building and concluded that cited parameters were improved in both cases.

Aoul et al. (2019) presented a review on electro chromic glazing and concluded that it can reduce electricity demand and provides energy savings for commercial and residential buildings.

Ke et al. (2019) reviewed recent progress in smart windows focused on multi-functionality and enhancement of design and performance.

Tällberget al. (2019) conducted a review on thermos-chromic, photo chromic and electro chromic smart windows and commented that the electro chromic window showed the best performance in all cases and highlighted the necessity of adequate operational control strategy.

Aburas et al. (2019) presented a review of the thermos-chromic films, coatings and glazing and commented that thermos-chromic windows reduce heating and cooling loads.

Attia et al. (2020) proposed a conceptual framework and technological classification for adaptive façades, where the multi-functionality and performance requirements of façade technologies can be inserted.

Chromogenic can be used in building façades to reduce the global energy consumption of the building energy consumption, improve the indoor visual comfort, and reduce the risks of glare and excessive artificial lighting Cannavale et al. (2020). In another work Cannavale et al. (2020) provided a review on smart electrochromic windows to enhance building energy efficiency and visual comfort from the available devices and concluded that electro chromic windows can enhance energy efficiency in the building sector. Tong et al. (2021) reviewed TRSG technologies, compared their key optical switch response, challenges and potential solutions and commented that TRSGs are key-elements for climate-adaptive envelopes. Yehia et al. (2021) reviewed different types of glazing including conventional and advanced technology. The main objective is identifying their potential to enhance thermal and lighting performance. Onubogu et al. (2021) presented a review on the existing technologies of daylighting systems including both passive and active daylighting systems equipped with sun tracking. The authors recommended further research and developments to make daylighting systems less expensive and relatively easy to install in buildings. Wang and Narayan (2021) provided a review focused on the recent advancement of thermos-chromic materials for smart windows including performance and commercialization and indicated possible challenges for future development.

Fathi and Kavoosi (2021) evaluated the influence of electro chromic widows, types of glazing and BIPVs on energy consumption of office buildings. The simulations showed a

Table 12. Summary of some reference results on smart glazing

Reference	Work nature	Climatic location	Window type	Main findings
Oh and Park (2019)	Experimental	South Korea	PDLC double glazing	Electrochromic double glazing could save 31.70% of energy & the PDLC double glazing 25.10% compared to conventional low-e double glazing.
Fathi and Kavoosi 2021	Numerical	Different climate regions of Iran	Electrochromic windows	Energy consumption of building reduced up to 35.57% using EC windows & other tools.
Rashidzadeh and Matin (2023)	Comparative study	Different climate zones	Seven types of smart windows	Limited studies on positive effects of photochromic windows in improving energy efficiency in buildings located in cold regions.

reduction of 35.57% in energy consumption by using these windows. Carlucci (2021) provided a review of smart and responsive building technologies focusing on building applications and envelopes, while Brzezicki (2021) reviewed the recent technological innovations in the field of smart windows and established functionalities for building applications. Ke et al. (2021) reviewed recent progress and performance improvement in smart windows technology, strategies, functional materials, and design and provided a perspective on the future developments. Wu et al. (2023) reviewed the advances achieved in materials and associated technologies, summarized experimental work and numerical simulations on buildings and proposed regulating the performance of smart windows by using a new concept. Navaratnam et al. (2023) reviewed the performance of existing façade systems including DSF, adaptive façades and photovoltaic façade systems and commented that to produce a sustainable building design, it is imperative to choose a façade system that has high energy efficiency, low cost, and thermal and visual comfort. Moghaddam et al. (2023) provided a review to assess different glazing solutions based on performance, comfort, cost, and environmental impacts and proposed a comprehensive approach to help choose the optimal glazing system. Rashidzadeh and Matin (2023) conducted a study to identify and propose efficient coatings to be used in smart windows. To achieve this, the authors reviewed all smart windows as well as the thermal properties and visual features of smart coatings and their impacts on energy efficiency and comfort. Mustafa et al. (2023) provided a review on smart window technology, limitations, commercialization, and potential materials for smart window technology. **Table12** presents summary of some reference results on smart glazing.

COMMERCIAL PROGRAMS & CODES

Many simulation codes and computer programs were developed for the calculation of thermal loads, evaluation of thermal comfort conditions and energy performance of buildings. Currently, there are several computational tools to analyze the thermal performance and energy consumption of buildings. According to DOE (2022), the US Department of Energy's Directory of Computer Simulation Tools has more than 408 simulation programs developed in several countries, such as: BLAST (1992), Comis (1990), EnergyPlus (2012, ,2016), DOE-2 (1993, 1985), Sunrel (1975), TRNSYS (2019, 2012, 2022), eQUEST (2010, 1994), Window (2015), and eQUEST and EnergyPlus (1989).

EnergyPlus (2012) is the most popular energy simulation program. The internationally known EnergyPlus program enables reliable simulations of various architectural typologies, building systems with windows and air conditioning. It is thermal load simulation and energy analysis software developed by the US Department of Energy, based on two other software, BLAST (1992) and DOE-2 (1993, 1985).

International Institute for Standardization and Technology developed AIRNET program. In 1990, researchers at Lawrence Berkeley National Laboratory developed COMIS program. Both programs analyze the model's air changes according to the temperatures of each node.

For accurate and flexible simulations, the Transient System Simulation (TRNSYS) and IDA Indoor Climate and Energy (ICE) have been widely used (TRANSSOLAR Energietechnic GmbH, 2012).

TRNbuild (2018) is an interface for the geometric, thermal, and optical definition of a specific building, while IDA ICE (Arasteh et al., 1994; Kalamees 2004) is a flexible whole-building performance simulation tool and is relatively easy to extend the existing modeling functionality.

DesignBuilder (2019) provides an easy-to-use interface to develop building designs from concept through to completion.

IES Virtual Environment (VE) (2011) is building performance analysis software that designers can use to test different window options, identify passive solutions, compare low carbon and renewable technologies, and draw conclusions about energy use, CO_2, and occupant comfort.

The LT Method (Baker & Steemers, 1996) is an energy design tool that responds to the parameters available at the beginning of the project development. This method provides an annual primary energy output for lighting, heating, cooling, and window ventilation.

ASHRAE Toolkit for Building Load Calculations (Pedersen et al., 2003) is written entirely in FORTRAN 90. The load toolkit components provide a valuable resource for making the thermal break-even load calculation procedure more readily available to ASHRAE members. This toolkit helps application developers incorporate the Load Calculations method, which is presented in the 2001 ASHRAE Handbook–Fundamentals (2001) as the preferred method. Over the years, Autodesk has developed software and devices that, using the same calculation mechanisms as EnergyPlus, provide the workflow and the possibility of energy efficiency simulations. The most recent software for this purpose is Autodesk Insight and its predecessor versions: Green Building Studio (2008) and Project Solon, all available in the cloud.

ESP-r (William & Arch, 2014) is open-source energy performance software used primarily in research and as a tool for consultants and teaching.

Capsol (2002) is a computer program to calculate conduction, convection, radiation, Ventilation heat flows through different zones in transient mode. SUNCODE-PC (De La Hunt, 1985), DEROB-LTH (Kvist, 1999), COMFEN (Hitchcock et al., 2008), IENUS (Gugliermetti et al., 2001), and iDbuild (Petersen & Svendsen, 2010) are also used by some researchers.

Finally, CFD tools (ANSYS, 2022) and (COMSOL, 2022) are also used to model the heat transfer in windows but, it is worth mentioning that these models are not integrated with the commercial programs. ANSYS is a general-purpose, finite-element modeling package for numerically solving a wide variety of mechanical problems including heat transfer, and fluid problems. COMSOL Metaphysics allows simulating acoustics, fluid flow, heat transfer, and chemical phenomena in one environment.

CONCLUSIONS, FUTURE TRENDS IN RESEARCH, & DEVELOPMENTS

Conclusions

A fair number of studies were dedicated to reducing energy and emissions of buildings by increasing thermal inertia of buildings structures and components and enhance their thermal performance.

Natural illumination and natural ventilation are important since they can reduce energy demands and improve thermal and visual comfort, which significantly impacts human comfort and efficiency in working areas like offices and classrooms.

The review shows tremendous progress in smart window technology and windows with internal insertions and reflective film, which when implemented can significantly improve the thermal performance of the buildings and residences. Additional efforts are needed to reduce the costs of these new products and facilitate their inclusion in old and new buildings.

The review did not show any publications on financial incentives, tax bonus and adequate public policies and awareness programs to enhance incorporation of new technologies on windows and façades in old and new buildings as well as in popular residences.

The review shows that a fair amount of research and development was done to improve the thermal and operational performance of windows and façades by using filling materials such as absorbing gases, PCM and water flow, vacuum, and aerogels. Smart windows and façades received a lot of attention, but their cost is still high and additional efforts are required to provide low-cost solutions for application in old and new buildings.

According to the bibliography consulted, the nature of the analyses is predominantly numerical, while experimental studies are less frequently addressed, **Figure 24**. Precisely the costs of the technologies, as well as the maturity of the concepts, are factors that condition this behavior.

In addition, the literature does not provide much information on optical and thermal properties, **Figure 25**. This, in general, limits the potential applications of the technologies under development. In fact, the state-of-the-art analyses showed a limited number of studies considering the combination of different technologies to take advantage of the benefits of each one in the same configuration.

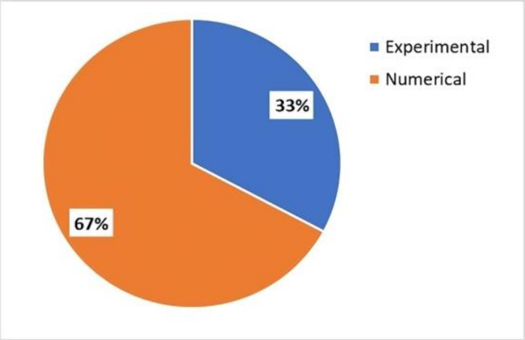


Figure 24. Consulted literature classification by work nature (Source: Authors' own elaboration)

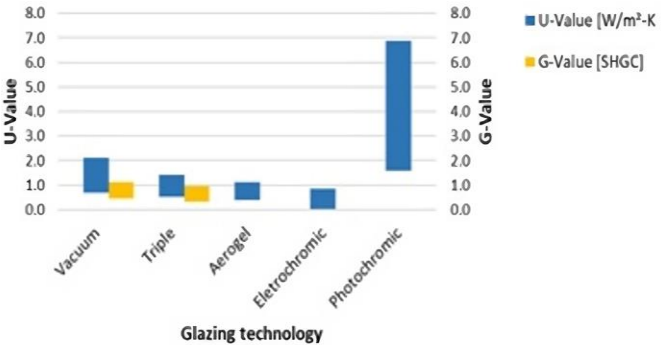


Figure 25. U- & G-value for some glazing technologies (Source: Authors' own elaboration)

Based on the U-value and G-value collected, it is possible to define the application range for each technology studied. In the case of vacuum glazing, it is possible to observe a reduction in the U-value parameter as the number of layers increases, from a range of 1.0-1.4 for double-glazing, to 0.7-0.9 for triple-glazing. This parameter shows the lowest values for aerogel-based technologies, from 0.4 to 0.72. However, of all the concepts, photochromic technology has the highest U-value range, from 0.53 to 1.58. Regarding the G-value parameter, used to measure the transmittance of solar gain through glazing, gas-filled technologies had the widest range, from 0.34 to 0.61.

A fair number of commercial simulation and calculations codes are available for local and global simulation of thermal performance of buildings. To improve energy thermal performance and increase the use of these tools there is a need to invest in the development of new codes and validate them in real buildings applications.

Considering the importance of reducing energy consumption of the building sector and reduce its emission contribution, it is hoped that this review can throw some light on the research and development opportunities and be of help for developers and young researchers, practicing engineers and general readers interested in the fascinating topic of windows and façades.

Future Trends in Research & Developments

1. Windows, façades, roofs, and walls are the major contributors to the buildings' heat losses and gains. To make buildings more sustainable and less energy consuming it is necessary to invest in thermally efficient materials and apply new technologies for windows, walls, and façades besides adopting energy efficiency strategies for heating and cooling.
2. Buildings should be designed to be self-sufficient as much as possible benefiting from natural energy resources as solar and wind and minimizing the needs for artificial lighting and ventilation, which leads eventually to having healthy internal ambient with adequate passive thermal and visual comfort.
3. Natural illumination is an important issue in commercial and office buildings, essential to promote well-being, visual comfort and reduces stress, besides reducing the cooling load and hence energy consumption. It is essential to promote the use of natural ventilation concept in buildings and residences when possible.
4. Strategies for natural ventilation systems must be encouraged in buildings to reduce the thermal load and consequently reduce the energy consumption in air conditioning systems.
5. Further research and development must be encouraged to reduce the cost of smart windows to help popularize their use in commercial buildings and residences.
6. Financial incentives, tax bonus and adequate public policies and awareness programs are required to enhance incorporation of new technologies on windows and façades in old and new buildings as well as in popular houses to reduce energy consumption and emissions.
7. More research work and development are required to provide cheap and effective performance enhancement equipment and strategies validated by extensive laboratory and infield tests.
8. Additional efforts should be directed towards characterizing the optical and thermal properties of the technologies under development, to broaden their range of applications.
9. It is also important to focus on analyzing new configurations that combine the advantages of the concepts, taking advantage of the properties of the different technologies.
10. Computers and simulation codes are handy tools for the development of new products and local and global simulation of thermal performance. There is a need to invest in the development of new codes and validate them in real applications.

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REFERENCES

Abdelhafez, M. H. H., Aldersoni, A. A., Gomaa, M. M., Noaime, E., Alnaim, M. M., & Ragab, M. A. A. (2023). Investigating the thermal and energy performance of advanced glazing systems in the context of Hail City, KSA. *Buildings, 13*(3), 752. https://doi.org/10.3390/buildings13030752

Abundiz-Cisneros, N., Sanginés, R., Rodríguez-López, R., Peralta-Arriola, M., Cruz, J., & Machorro, R. (2020). Novel low-e filter for architectural glass pane. *Energy and Buildings, 206*, 109558. https://doi.org/10.1016/j.enbuild.2019.109558

Aburas, M., Soebarto, V., Williamson, T., Liang, R., Ebendorff-Heidepriem, H., & Wu, Y. (2019). Thermochromic smart window technologies for building application: A review. *Applied Energy, 255*, 113522. https://doi.org/10.1016/j.apenergy.2019.113522

Acosta, I., Campano, M. A., & Molina, J. F. (2016). Window design in architecture: Analysis of energy savings for lighting and visual comfort in residential spaces. *Applied Energy, 168*(15), 493-506. https://doi.org/10.1016/j.apenergy.2016.02.005

Adu, B. (2015). *Characterizing water as gap fill for double glazing units* [Master's thesis, Western Kentucky University].

Aflaki, A., Mahyuddin, N., Awad, Z. A-C. M., & Baharum, M. R. (2014). Relevant indoor ventilation by windows and apertures in tropical climate: A review study. *E3S Web of Conferences, 3*, 01025. https://doi.org/10.1051/E3SCONF/20140301025

Aguilar, J.O., Xaman, J., Alvarez, G., Hernandez-Perez, I., & Lopez-Mata, C. (2015). Thermal performance of a double pane window using glazing available on the Mexican market. *Renewable Energy, 81*, 785-794. https://doi.org/10.1016/j.renene.2015.03.063

Aguilar-Santana, J. L., Jarimi, H., Velasco-Carrasco, M., & Riffat, S. (2020). Review on window-glazing technologies and future prospects. *International Journal of Low-Carbon Technologies, 15*, 112-120. https://doi.org/10.1093/ijlct/ctz032

Aguilar-Santana, J. L., Velasco-Carrasco, M., & Riffat, S. (2020). Thermal transmittance (U-value) evaluation of innovative window technologies. *Future Cities and Environment, 6*(1), 1-13. https://doi.org/10.5334/fce.99

Akram, M. W., Hasannuzaman, M., Cuce, E., & Cuce, P. M. (2023). Global technological advancement and challenges of glazed window, facade system and vertical greenery-based energy savings in buildings: A comprehensive review. *Energy Built Environment, 4*(2), 206-226. https://doi.org/10.1016/j.enbenv.2021.11.003

Alam, M., Singh, H., Suresh, S., & Redpath, D. A. G. (2017). Energy and economic analysis of vacuum insulation panels (VIPs) used in non-domestic buildings. *Applied Energy, 188*, 1-8. https://doi.org/10.1016/j.apenergy.2016.11.115

Allard, F., Dorer, V. B., Feustel, H. E., Garcia, E. R., Grosso, M., Herrlin, M. K., Mingsheng, L., Phaff, H. C., Ultsumi, Y., & Yoshino, H. (1990). *Fundamentals of the multizone air flow model*. https://www.aivc.org/sites/default/files/members area/medias/pdf/Technotes/tn29%20Fundamentals%20of%20comis.Pdf

Almeida, C. M. R., Ghica, M. E., & Durães, L. (2020). An overview on alumina-silica-based aerogels. *Advances in Colloid and Interface Science, 282*, 102189. https://doi.org/10.1016/j.cis.2020.102189

Alwetaishi, M. (2019). Impact of glazing to wall ratio in various climatic regions: A case study. *Journal of King Saud University–Engineering Sciences, 31*, 6-18. https://doi.org/10.1016/j.jksues.2017.03.001

Anderson, A.-L., Chen, S., Romero, L., Top, I., & Binions, R. (2016). Thin films for advanced glazing applications. *Buildings, 6*(3), 37. https://doi.org/10.3390/buildings6030037

ANSYS. (2022). *Engineering simulation software*. https://www.ansys.com/

Aoul, K. A. T., Attoye, D. E., & Ghatrif, L. A. (2019). Performance of electrochromic glazing: State of the art review. *IOP Conferences Series: Materials Science and Engineering, 603*, 022085. https://doi.org/10.1088/1757-899X/603/2/022085

Arasteh, D. K., Finlayson, E. U., & Huizenga, C. (1994). Window 4. I: Program description. *Lawrence Berkeley National Laboratory*. https://eta-publications.lbl.gov/sites/default/files/35298

Arasteh, H., Maref, W., & Saber, H. H. (2023). Energy and thermal performance analysis of PCM-incorporated glazing units combined with passive and active techniques: A review study. *Energies, 16*, 1058. https://doi.org/10.3390/en16031058

Arici, M., & Kan, M. (2014). An investigation of flow and conjugate heat transfer in multiple pane windows with respect to gap width, emissivity and gas filling. *Renewable Energy, 75*, 249-256. https://doi.org/10.1016/j.renene.2014.10.004

Ascione, F., De Masi, R. F., Mastrullo, R. M., Ruggiero, S., & Vanoli, G. P. (2017). Experimental investigation and numerical evaluation of adoption of multi-layered wall with vacuum insulation panel for typical mediterranean climate. *Energy and Buildings, 152*, 108-123. https://doi.org/10.1016/j.enbuild.2017.07.029

ASHRAE. (2001). *Fundamentals handbook*. American Society of Heating, Refrigerating and Air Conditioning Engineers.

ASHRAE. (2017). *ASHRAE handbook–Fundamentals*. American Society of Heating, Refrigerating and Air Conditioning Engineers.

Ashrafian, T., & Moazzen, N. (2019). The impact of glazing ratio and window configuration on occupants' comfort and energy demand: The case study of a school building in Eskisehir, Turkey. *Sustainable Cities and Society, 47*, 101483. https://doi.org/10.1016/j.scs.2019.101483

Attia, S., Bilir, S., Safy, T., Struck, C., Loonen, R., & Goia, F. (2018). Current trends and future challenges in the performance assessment of adaptive façade systems. *Energy and Buildings, 179*, 165-182. https://doi.org/10.1016/j.enbuild.2018.09.017

Attia, S., Lioure, R., & Declaude, Q. (2020). Future trends and main concepts of adaptive facade systems. *Energy Sciene Engineering, 8*, 3255-3272. https://doi.org/10.1002/ese3.725

Baek, S., & Kim, S. (2019). Optimum design and energy performance of hybrid triple glazing system with vacuum and carbon dioxide filled gap. *Sustainability, 11*, 5543. https://doi.org/10.3390/su11195543

Baek, S., & Kim, S. (2021). Analysis of the surface temperature and energy performance for the double paned glazing filled with carbon dioxide as an insulating gas. *Turkish Journal of Computer and Mathematics Education, 12*(6), 617-625. https://doi.org/10.17762/turcomat.v12i6.2056

Bahri, S. Y., Forment, M. A., Riera, A. S., Moghaddam, F. B., Guerrero, M. J. C., & Garcia, A. M. L. 2022). A literature review on thermal comfort performance of parametric façades. *Energy Reports, 8*, 120-128. https://doi.org/10.1016/j.egyr.2022.10.245

Baker, N., & Steemers, K. (1996). LT method 3.0–A strategic energy-design tool for Southern Europe. *Energy and Buildingss, 23*(3) 251-256. https://doi.org/10.1016/0378-7788(95)00950-7

Barbosa, S., & Ip, K. (2014). Perspectives of double skin façades for naturally ventilated buildings: A review. *Renewable and Sustainable Energy Reviews, 40*, 1019-1029. https://doi.org/10.1016/j.rser.2014.07.192

Berardi, U. (2019). Nanotechnology in eco-efficient construction, materials, processes and applications. In *Civil and structural engineering* (pp. 395-416). https://doi.org/10.1016/B978-0-08-102641-0.00017-7

Boutet, M. L., & Hernández, A. L. (2021). Generic proposal for the determination of optimal glazed areas for school buildings in the Northeast Region of Argentina. *Energy and Buildings, 243*, 110988. https://doi.org/10.1016/j.enbuild.2021.110988

Brzezicki, M. (2021). A systematic review of the most recent concepts in smart windows technologies with a focus on electrochromics. *Sustainability, 13*, 9604. https://doi.org/10.3390/su13179604

Buratti, C., & Moretti, E. (2012). Glazing systems with silica aerogel for energy savings in buildings. *Applied Energy, 98*, 396-403. https://doi.org/10.1016/j.apenergy.2012.03.062

Buratti, C., Belloni, E., Merli, F., & Zinzi, M. (2021). Aerogel glazing systems for building applications: A review. *Energy and Buildings, 231*, 110587. https://doi.org/10.1016/j.enbuild.2020.110587

Buratti, C., Moretti, E., & Zinzi, M. (2017). High energy-efficient windows with silica aerogel for building refurbishment: Experimental characterization and preliminary simulations in different climate conditions. *Buildings, 7*(8). https://doi.org/10.3390/buildings7010008

Calama-González, C. M., León-Rodríguez, Á. L., & Suárez, R. (2019). Day lighting performance of solar control films for hospital buildings in a Mediterranean climate. *Energies, 12*(3), 489. https://doi.org/10.3390/en12030489

Cannavale, A. (2020). Chromogenic technologies for energy saving. *Clean Technologies, 2*, 462-475. https://doi.org/10.3390/cleantechnol2040029

Cannavale, A., Ayr, U., Fiorito, F., & Martellotta, F. (2020). Smart electrochromic windows to enhance building energy efficiency and visual comfort. *Energies, 13*, 1449. https://doi.org/10.3390/en13061449

CAPSOL. (2014). Computer program to calculate multi-zonal transient heat transfer. *PHYSIBEL*. https://www.physibel.be/download/CapsolManual.pdf

Carlos, J. S. (2017). Optimizing the ventilated double window for solar collection. *Solar Energy, 150*, 454-462. https://doi.org/10.1016/j.solener.2017.04.063

Carlos, J. S., & Corvacho, H. (2013). Ventilated double window for the preheating of the ventilation air comparison of its performance in a northern and a southern European climate. *Journal of Renewable Energy, 2013*, 290865. https://doi.org/10.1155/2013/290865

Carlos, J. S., & Corvacho, H. (2015). Evaluation of the performance indices of a ventilated double window through experimental and analytical procedures: SHGC-values. *Energy and Buildings, 86*, 886-897. https://doi.org/10.1016/j.enbuild.2014.11.002

Carlos, J. S., & Corvacho, H. (2017). Assessing thermal comfort due to a ventilated double window. *IOP Conference Series: Material Science and Engineering, 245*, 042004. https://doi.org/10.1088/1757-899X/245/4/042004

Carlos, J. S., Corvacho, H., Silva, P. D., & Castro-Gomes, J.P. (2012). Heat recovery versus solar collection in a ventilated double window. *Applied Thermal Engineering, 37*, 258-266. https://doi.org/10.1016/j.applthermaleng.2011.11.027

Carlucci, F. (2021). A review of smart and responsive building technologies and their classifications. *Future Cities and Environment, 7*(1) 1-12. https://doi.org/10.5334/fce.123

Carlucci, S., Causone, F., De Rosa F., & Pagliano, L. (2015). A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. *Renewable and Sustainable Energy Reviews, 47*(7) 1016-1033. https://doi.org/10.1016/j.rser.2015.03.062

Casini, M. (2018). Active dynamic windows for buildings: A review. *Renewable Energy, 119*, 923-934. https://doi.org/10.1016/j.renene.2017.12.049

Chen, X., Zhang, X., & Du, J. (2019). Glazing type (colour and transmittance), day lighting, and human performances at a workspace: A full-scale experiment in Beijing. *Building and Environment, 153*(4), 168-185. https://doi.org/10.1016/j.buildenv.2019.02.034

Chen, Y., Tong, Z., Wu, W., Samuelson, H., Malkawi, A., & Norford, L. (2019). Achieving natural ventilation potential in practice: Control schemes and levels of automation. *Applied Energy, 235*, 1141-1152. https://doi.org/10.1016/j.apenergy.2018.11.016

Choi, H., An, Y., Kang, K., Yoon, S., & Kim, T. (2019). Cooling energy performance and thermal characteristics of a naturally ventilated slim double-skin window. *Applied Thermal Engineering, 160*, 114113. https://doi.org/10.1016/j.applthermaleng.2019.114113

Chow, T. T., & Lyu, Y. (2017). Effect of design configurations on water flow window performance. *Solar Energy, 155*, 354-362. https://doi.org/10.1016/j.solener.2017.06.050

Chow, T.-T., & Liu, W. (2020). Warm climate performance of water-filled double-glazing with submerged heat exchanger. *Sustainable Cities and Society, 58*, 102135. https://doi.org/10.1016/j.scs.2020.102135

Chow, T.-T., Li, C., & Lin, Z. (2011a). The function of solar absorbing window as water-heating device. *Building and Environment, 46*, 955-960. https://doi.org/10.1016/j.buildenv.2010.10.027

Chow, T.-T., Li, C., & Lin, Z. (2011b). Thermal characteristics of water-flow double-pane window. *International Journal of Thermal Sciences, 50*, 140-148. https://doi.org/10.1016/j.ijthermalsci.2010.10.006

Chow, T-t., Li, C., & Lin, Z. (2010). Innovative solar windows for cooling-demand climate. *Solar Energy Materials and Solar Cells, 94*(2), 212-220. https://doi.org/10.1016/j.solmat.2009.09.004

COMSOL. (2022). *Software for multiphysics simulation*. https://www.comsol.com/

Costanzo, V., Evola, G., & Marletta, L. (2016). Thermal and visual performance of real and theoretical thermochromic glazing solutions for office buildings. *Solar Energy Materials and Solar Cells, 149*, 110-120. https://doi.org/10.1016/j.solmat.2016.01.008

Cotana, F., Pisello, A. L., Moretti, E., & Buratti, C. (2014). Multipurpose characterization of glazing systems with silica aerogel: In-field experimental analysis of thermal-energy, lighting and acoustic performance. *Building and Environment, 81*, 92-102. https://doi.org/10.1016/j.buildenv.2014.06.014

Cuce, E. (2014). *Development of innovative window and fabric technologies for low-carbon buildings* [PhD thesis, The University of Nottingham].

Cuce, E. (2018). Accurate and reliable U-value assessment of argon-filled double glazed windows: A numerical and experimental investigation. *Energy and Buildings, 171*, 100-106. https://doi.org/10.1016/j.enbuild.2018.04.036

Cuce, E., Sher, F., Sadiq, H., Cuce, P. M., Guclu, T., & Besir, A. B. (2019). Sustainable ventilation strategies in buildings: CFD research. *Sustainable Energy Technologies and Assessments, 36*, 100540. https://doi.org/10.1016/j.seta.2019.100540

Day, J. K., Futrell, B., Cox, R., Ruiz, S. N., Amirazar, A., Zarrabi, A. H., & Azarbayjani, M. (2019). Blinded by the light: Occupant perceptions and visual comfort assessments of three dynamic daylight control systems and shading strategies. *Building and Environment, 154*(5) 107-121. https://doi.org/10.1016/j.buildenv.2019.02.037

De Gracia, A., Castell, A., Navarro, L., Oró, E., & Cabeza, L. F. (2013). Numerical modelling of ventilated facades: A review. *Renewable and Sustainable Energy Reviews, 22*, 539-549. https://doi.org/10.1016/j.rser.2013.02.029

DeLaHunt, M. J. E. I. (1958). *Suncode-PC, a program user's manual*. https://ecotope-publications-database.ecotope.com/1985_016_SUNCODE-PC.pdf

DesignBuilder. (2019). *Software Ltd. version 5.5.0*. https://designbuilder.co.uk

Ding, X. H. (2020). A brief analysis of energy conservation ways by building materials for ecological architecture. *Journal of Power and Energy Engineering, 8*, 13-22. https://doi.org/10.4236/jpee.2020.812002

DOE. (2012). EnergyPlus TM version 8.6 documentation, engineering reference. *U.S. Department of Energy*. https://energyplus.net/assets/nrelcustom/pdfs/pdfs_v22.1.0/ EngineeringReference.pdf

DOE. (2022). EnergyPlus TM 8.6. U.*S. Department of Energy*. https://www.energy.gov/eere/buildings/building-technologies-office

Dogan, T., & Park, Y. C. (2019). A critical review of day lighting metrics for residential architecture and a new metric for cold and temperate climates. *Lighting Research & Technology, 51*(2), 206-230. https://doi.org/10.1177/1477153518755561

Ehms, J. H. N., Oliveski, R. C., Rocha, L. A. O., Biserni, C., & Garai, M. (2019). Phase change materials (PCM) for building envelope applications: A review of numerical models. *AIP Conference Proceedings, 2191*, 020120. https://doi.org/10.1063/1.5138853

Eisazadeh, N., Allacker, K., & De Troyer, F. (2019). Impact of window systems on day lighting performance, visual comfort and energy efficiency in patient rooms. In *Proceedings of the 16th International Building Performance Simulation Association* (pp. 1207-1214). https://doi.org/10.26868/25222708.2019.211185

El-Eshmawy, A. W. Y. A., DessoqyFaggal, A. A. E., & Eissa, A. M. M. (2021). Conventional and advanced glazing technologies for enhancing thermal and lighting performance. *Engineering Research Journal, 171*, 1-15. https://doi.org/10.21608/ERJ.2021.193260

El-Rahman, S. M. A., Esmail, S. I., Khalil, H. B., & El-Razaz, Z. (2020). Sustainable optimization for thermal comfort and building energy efficiency in Cairo. *Engineering Research Journal, 166*, 18-34. https://doi.org/10.21608/ERJ.2020.135278

Elshafei, G., Negm, A., Bady, M., Suzuki, M., & Ibrahim, M. G. (2017). Numerical and experimental investigations of the impacts of window parameters on indoor natural ventilation in a residential building. *Energy and Buildings, 141*, 321-332. https://doi.org/10.1016/j.enbuild.2017.02.055

Equa Simulation AB. (2018). *IDA indoor climate and energy 4.8*. https://www.equa.se/en/

eQUEST. (2012). *The Quick energy simulation tool online*. http://www.doe2.com/download/equest/eQUESTv3-Overview.pdf

Escoto, F. J., & Hernández, J. A. (2019). Thickness dimensioning of water flow glazing facades. In *Proceeding 7th European Conference Renewable Energy System* (pp. 10-12).

Fahmy, M., Mahmoud, S. A., Olwy, I. M., & Abdelalim, M. (2020). Comparison of occupant thermal comfort with and without passive design for a naturally ventilated educational building: A case study in Cairo, Egypt. *IOP Conference Series: Material, Science and Engineering, 974*, 012027. https://doi.org/10.1088/1757-899X/974/1/012027

Fang, Y., & Cho, S. (2019). Design optimization of building geometry and fenestration for day lighting and energy performance. *Solar Energy, 191*, 7-18. https://doi.org/10.1016/j.solener.2019.08.039

Fang, Y., Eames, P. C., Norton, B., & Hyde, T. J. (2006). Experimental validation of a numerical model for heat transfer in vacuum glazing. *Solar Energy, 80*, 564-577. https://doi.org/10.1016/j.solener.2005.04.002

Fang, Y., Memon, S., Peng, J., Tyrer, M., & Ming, T. (2020). Solar thermal performance of two innovative configurations of air vacuum layered triple glazed windows. *Renewable Energy, 150*, 167-175. https://doi.org/10.1016/j.renene.2019.12.115

Fathi, S., & Kavoosi, A. (2021). Effect of electrochromic windows on energy consumption of high-rise office buildings in different climate regions of Iran. *Solar Energy, 223*, 132-149. https://doi.org/10.1016/j.solener.2021.05.021

Feng, F., Kunwar, N., Cetin, K., & O'Neill, Z. (2021). A critical review of fenestration/window system design methods for high performance buildings. *Energy and Buildings, 248*, 111184. https://doi.org/10.1016/j.enbuild.2021.111184

Foroughi, R., Asadi, S., & Khazaeli, S. (2021). On the optimization of energy efficient fenestration for small commercial buildings in the United States. *Journal of Cleaner Production. 283*, 124604. https://doi.org/10.1016/j.jclepro.2020.124604

G. B. Studio. (2008). *Autodesk Green Building Studio*. https://gbs.autodesk.com/gbs

Gao, T., Ihara, T., Grynning, S., Jelle, B. P., & Lien, A. G. (2016). Perspective of aerogel glazings in energy efficient buildings. *Building and Environment, 95*, 405-413. https://doi.org/10.1016/j.buildenv.2015.10.001

Gao, T., Jelle, B. P., & Gustavsen, A. (2016). Building integration of aerogel glazings. *Procedia Engineering, 145*, 723-728. https://doi.org/10.1016/j.proeng.2016.04.090

Gao, T., Jelle, B. P., Ihara, T., & Gustavsen, A. (2014). Insulating glazing units with silica aerogel granules: The impact of particle size. *Applied Energy, 128*, 27-34. https://doi.org/10.1016/j.apenergy.2014.04.037

Garnier, C., Muneer, T., & McCauley, L. (2015). Super insulated aerogel windows: Impact on day lighting and thermal performance. *Building and Environment, 94*, 231-238. https://doi.org/10.1016/j.buildenv.2015.08.009

Ghosh, A. (2023). Diffuse transmission dominant smart and advanced windows for less energy-hungry building: A review. *Journal of Building Engineering, 64*, 105604. https://doi.org/10.1016/j.jobe.2022.105604

Ghosh, A., & Norton, B. (2018). Advances in switchable and highly insulating autonomous (self powered) glazing systems for adaptive low Energy and Buildingss. *Renewable Energy, 126*, 1003-1031. https://doi.org/10.1016/j.renene.2018.04.038

Ghosh, A., Norton, B., & Duffy, A. (2017). Effect of sky clearness index on transmission of evacuated (vacuum) glazing. *Renewable Energy, 105*, 160-166. https://doi.org/10.1016/j.renene.2016.12.056

Gloriant, F., Tittelein, P., Joulin, A., & Lassue, S. (2015). Modeling a triple-glazed supply-air window. *Building and Environment, 84*, 1-9. https://doi.org/10.1016/j.buildenv.2014.10.017

Goia, F. (2016). Search for the optimal window-to-wall ratio in office buildings in different European climates and the implications on total energy saving potential. *Solar Energy, 132*, 467-492. https://doi.org/10.1016/j.solener.2016.03.031

Goia, F., Perino, M., & Serra, V. (2013). Improving thermal comfort conditions by means of PCM glazing systems. *Energy and Buildings, 60*, 442-452. https://doi.org/10.1016/j.enbuild.2013.01.029

Gosselin, J. R., & Chen, Q. (2008). A computational method for calculating heat transfer and airflow through a dual-airflow window. *Energy and Buildingss, 40*(4), 452-458. https://doi.org/10.1016/j.enbuild.2007.03.010

Granqvist, C. G., Lansåker, P. C., Mlyuka, N. R., Niklasson, G. A., & Avendaño, E. (2009). Progress in chromogenics: New results for electro chromic and thermo chromic materials and devices. *Solar Energy materials and Solar Cells, 93*(12), 2032-2039. https://doi.org/10.1016/j.solmat.2009.02.026

Gugliermetti, F., Santarpia, L., & Bisegna, F. (2001). Integrated energy use analysis in office spaces. In R. Lamberts, C. Negrao, & J. Hensen (Eds.), *Proceedings of the 7th International Conference Building Simulation* (pp. 991-998).

Guo, R., Gao, Y., Zhuang, C., Heiselberg, P., Levinson, R., Zhao, X., & Shi, D. (2020). Optimization of cool roof and night ventilation in office buildings: A case study in Xiamen, China. *Renewable Energy, 147*, 2279-2294. https://doi.org/10.1016/j.renene.2019.10.032

Guo, R., Hu, Y., Liu, M., & Heiselberg, P. (2019). Influence of design parameters on the night ventilation performance in office buildings based on sensitivity analysis. *Sustainable Cities and Society, 50*, 101661. https://doi.org/10.1016/j.scs.2019.101661

Gutiérrez, R. U., Du, J., Ferreira, N., Ferrero, A., & Sharples, S. (2019). Daylight control and performance in office buildings using a novel ceramic louvre system. *Building and Environment, 151*, 54-74. https://doi.org/10.1016/j.buildenv.2019.01.030

Hawila, A. Al-W., Merabtine, A., Troussier, N., & Bennacer, R. (2019). Combined use of dynamic building simulation and metamodeling to optimize glass facades for thermal comfort. *Building and Environment, 157*, 47-63. https://doi.org/10.1016/j.buildenv.2019.04.027

Hee, W. J., Alghoul, M. A., Bakhtyar, B., Elayeb, O., Shameri, M. A., Alrubaih, M. S., & Sopian, K. (2015). The role of window glazing on day lighting and energy saving in buildings. *Renewable and Sustainable Energy Reviews, 42*, 323-343. https://doi.org/10.1016/j.rser.2014.09.020

Hitchcock, R. J., Mitchell, R., Yazdanian, M., Lee, E., & Huizenga, C. (2008). COMFEN: A commercial fenestration/façade design tool. *Proceedings of SimBuild, 3*(1), 246-252.

Hoffmann, S., Lee, E. S., McNeil, A., Fernandes, L., Vidanovic, D., & Thanachareonkit, A. (2016). Balancing daylight, glare, and energy-efficiency goals: An evaluation of exterior coplanar shading systems using complex fenestration modeling tools. *Energy and Buildings, 112*(15), 279-298. https://doi.org/10.1016/j.enbuild.2015.12.009

Hu, Y., Guo, R., & Heiselberg, P. K. (2020). Performance and control strategy development of a PCM enhanced ventilated window system by a combined experimental and numerical study. *Renewable Energy, 155*, 134-152. https://doi.org/10.1016/j.renene.2020.03.137

Hu, Y., Heiselberg, P. K., & Guo, R. (2020). Ventilation cooling/heating performance of a PCM enhanced ventilated window–An experimental study. *Energy and Buildings, 214*, 109903. https://doi.org/10.1016/j.enbuild.2020.109903

Huang, Y., Mankibi, M. E., Cantin, R., & Coillot, M. (2021). Application of fluids and promising materials as advanced inter-pane media in multi-glazing windows for thermal and energy performance improvement: A review. *Energy and Buildings, 253*, 111458. https://doi.org/10.1016/j.enbuild.2021.111458

Ihara, T., Gao, T., Grynning, S., Jelle, B. P., & Gustavsen, A. (2015). Aerogel granulate glazing facades and their application potential from an energy saving perspective. *Applied Energy, 142*, 179-191. https://doi.org/10.1016/j.apenergy.2014.12.053

Ihara, T., Grynning, S., Gao, T., Gustavsen, A., & Jelle, B. P. (2015). Impact of convection on thermal performance of aerogel granulate glazing systems. *Energy and Buildings, 88*, 165-173. https://doi.org/10.1016/j.enbuild.2014.12.001

Ismail, K. A. R., & Henriquez, J. R. (2002). Parametric study on composite and PCM glass systems. *Energy Conversion Management, 43*(7), 973-993. https://doi.org/10.1016/S0196-8904(01)00083-8

Ismail, K. A. R., & Henriquez, J. R. (2005). Two-dimensional model for the double glass naturally ventilated window. *International Journal of Heat and Mass Transfer, 48*, 461-475. https://doi.org/10.1016/j.ijheatmasstransfer.2004.09.022

Ismail, K. A. R., Lago, T. G. S., Lino, F. A. M., Mondlane, M. V., & Teles, M. P. R. (2021). Experimental investigation on ventilated window with reflective film and development of correlations. *Solar Energy, 230*, 421-434. https://doi.org/10.1016/j.solener.2021.10.061

Jadhav, S. B., & Sarawade, P. B. (2024). Recent advances and prospective on the effect of processing parameters, additives, and applications of silica aerogel nanocomposites. *European Polymer Journal, 206*, 112776. https://doi.org/10.1016/j.eurpolymj.2024.112766

Jelle, B. P., Hynd, A., Gustavsen, A., Arasteh, D., Goudey, H., & Hart, R. (2012). Fenestration of today and tomorrow: A state-of-the-art review and future research opportunities. *Solar Energy Materials & Solar Cells, 96*, 1-28. https://doi.org/10.1016/j.solmat.2011.08.010

Jiang, Y., Li, N., Yongga, A., & Yan, W. (2022). Short-term effects of natural view and daylight from windows on thermal perception, health, and energy-saving potential. *Building and Environment, 208*, 108575. https://doi.org/10.1016/j.buildenv.2021.108575

Kaasalainen, T., Makinen, A., Lehtinen, T., Moisio, M., & Vinha, J. (2020). Architectural window design and energy efficiency: Impacts on heating, cooling and lighting needs in Finnish climates. *Journal of Building Engineering, 27*(1), 100996. https://doi.org/10.1016/j.jobe.2019.100996

Kalamees, T. (2004). IDA ICE: The simulation tool for making the whole building energy and HAM analysis. *Annex, 41*, 12-14.

Kasim, N. F. M., Zaki, S. A., Ali, M. S. M., Ikegaya, N., & Razak, A. A. (2016). Computational study on the influence of different opening position on wind-induced natural ventilation in urban building of cubical array. *Procedia Engineering, 169*, 256-263. https://doi.org/10.1016/j.proeng.2016.10.031

Kaushik, N., Saravanakumar, P., Dhanasekhar, S., Saminathan, R., Rinawa, M. L., Subbiah, R., Sharma, R., & Kumar, P. M. (2022). Thermal analysis of a double-glazing window using a nano-disbanded phase changing material (NDPCM). *Materials Today: Proceedings, 62*, 1702-1707. https://doi.org/10.1016/j.matpr.2021.11.537

Ke, Y., Chen, J., Lin, G., Wang, S., Zhou, Y., Yin, J., Lee, P. S., & Long, Y. (2019). Smart windows: Electro-, thermo-, mechano-, photochromics, and beyond. *Advanced Energy Materials, 9*, 1902066. https://doi.org/10.1002/aenm.201902066

Khaled, K., & Berardi, U. (2021). Current and future coating technologies for architectural glazing applications. *Energy and Buildings, 244*, 111022. https://doi.org/10.1016/j.enbuild.2021.111022

Khetib, Y., Alotaibi, A. A., Alshahri, A. H., Rawa, M., Cheraghian, G., & Sharifpur, M. (2021). Impact of phase change material on the amount of emission in the double-glazed window frame for different window angles. *Journal of Energy Storage, 44*, 103320. https://doi.org/10.1016/j.est.2021.103320

Khosravi, S. N., & Mahdavi, A. (2021). A CFD-based parametric thermal performance analysis of supply air ventilated windows. *Energies, 14*, 2420. https://doi.org/10.3390/en14092420

Kim, J.-H., Kim, S.-M., & Kim, J.-T. (2017). Simulation performance of building wall with vacuum insulation panel. *Procedia Engineering, 180*, 1247-1255. https://doi.org/10.1016/j.proeng.2017.04.286

Ko, W. H., Schiavon, S., Zhang, H., Graham, L. T., Brager, G., Mauss, I., & Lin, Y.-W. (2020). The impact of a view from a window on thermal comfort, emotion, and cognitive performance. *Building and Environment, 175*, 106779. https://doi:10.1016/j.buildenv.2020.106779

Krstic-Furundzic, A., Vujosevic, M., & Petrovski, A. (2019). Energy and environmental performance of the office building façade scenarios. *Energy, 183*, 437-447. https://doi.org/10.1016/j.energy.2019.05.231

Kumar, D., Alam, M., Memon, R. A., & Bhayo, B. A. (2022). A critical review for formulation and conceptualization of an ideal building envelope and novel sustainability framework for building applications. *Cleaner Engineering and Technology, 11*, 100555. https://doi.org/10.1016/j.clet.2022.100555

Kvist, H. (1999). DEROB-LTHfor windows. *Lund Institute of Technology*. https://scholar.google.com/scholar_lookup?title=DEROBLTH+for+MS+Windows&author=H.+Kvist&journal=User+Manual%2C+Department+of+Building+Science&publication_year=1999

Lago, T. G. S., Ismail, K. A. R., & Lino, F. A. M. (2019). Ventilated double glass window with reflective film: Modeling and assessment of performance. *Solar Energy, 185*, 72-88. https://doi.org/10.1016/j.solener.2019.04.047

Lago, T., Ismail, K. A. R., & Lino, F. A. M. (2020). Natural airflow in reversible double glass window with reflective film for building applications. *The Journal of Energy Engineering, 146*(4). https://doi.org/10.1061/(ASCE)EY.1943-7897.0000682

Lamy-Mendes, A., Pontinha, A. D. R., Alves, P., Santos, P., & Durães, L. (2021). Progress in silica aerogel-containing materials for buildings' thermal insulation. *Construction and Building Materials, 286*, 122815. https://doi.org/10.1016/j.conbuildmat.2021.122815

Lee, E. S., Matusiak, B. S., Geisler-Moroder, D., Selkowitz, S. E., & Heschong, L. (2022). Advocating for view and daylight in buildings: Next steps. *Energy and Buildings, 265*, 112079. https://doi.org/10.1016/j.enbuild.2022.112079

Lee, H., Baek, S., & Lee, H. (2022). A study on the application of solar modules to light shelves to improve generation and day lighting efficiency. *Energy and Buildings, 261*, 111976. https://doi.org/10.1016/j.enbuild.2022.111976

Leung, C. K., Lu, L., Liu, Y., Cheng, H. S., & Tse, J. H. (2020). Optical and thermal performance analysis of aerogel glazing technology in a commercial building of Hong Kong, *Energy and Built Environment, 1*(2), 215-223. https://doi.org/10.1016/j.enbenv.2020.02.001

Li, C., & Tang, H. (2024). Phase change material window for dynamic energy flow regulation: Review. *Renewable and Sustainable Energy Reviews, 189*, 113937. https://doi.org/10.1016/j.rser.2023.113937

Li, C., Li, C., Lyu, Y., & Qiu, Z. (2020). Performance of double-circulation water-flow window system as solar collector and indoor heating terminal. *Building Simulation, 13*, 575-584. https://doi.org/10.1007/s12273-019-0600-y

Li, C., Tan, J., Chow, T.-T., & Qiu, Z. (2015). Experimental and theoretical study on the effect of window films on building energy consumption. *Energy and Buildings, 102*, 129-138. https://doi.org/10.1016/j.enbuild.2015.04.025

Li, C., Tang, H., Ding, J., & Lyu, Y. (2019). Numerical research on thermal performance of water-flow window as hospital curtain-wall. *E3S Web of Conferences, 111*, 1059. https://doi.org/10.1051/e3sconf/201911101059

Li, D., Ma, Y., Zhang, S., Yang, R., Zhang, C., & Liu, C. (2022). Photothermal and energy performance of an innovative roof based on silica aerogel-PCM glazing systems. *Energy Conversion and Management, 262*, 115567. https://doi.org/10.1016/j.enconman.2022.115567

Li, D., Wu, Y., Liu, C., Zhang, G., & Arici, M. (2018). Numerical investigation of thermal and optical performance of window units filled with nanoparticle enhanced PCM. *International Journal Heat Mass Transfer, 125*, 1321-1332. https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.152

Li, D., Wu, Y., Wang, B., Liu, C., & Arici, M. (2020). Optical and thermal performance of glazing units containing PCM in buildings: A review. *Construction and Buildings Materials, 233*, 117327. https://doi.org/10.1016/j.conbuildmat.2019.117327

Li, D., Yang, R., Arici, M., Wang, B., Tunçbilek, E., Wu, Y., Liu, C., Ma, Z., & Ma, Y. (2022). Incorporating phase change materials into glazing units for building applications: Current progress and challenges. *Applied Thermal Engineering, 210*, 118374. https://doi.org/10.1016/j.applthermaleng.2022.118374

Li, D., Zhang, C., Li, Q., Liu, C., & Wu, Y. (2019). Thermal performance evaluation of glass window combining silica aerogels and phase change materials for cold climate of China. *Applied Thermal Engineering, 165*, 114547. https://doi.org/10.1016/j.applthermaleng.2019.114547

Li, S., Sun, G., Zou, K., & Zhang, X. (2016). Experimental research on the dynamic thermal performance of a novel triple-pane building window filled with PCM. *Sustainable Cities and Society, 27*, 15-22. https://doi.org/10.1016/j.scs.2016.08.014

Li, S., Zhong, K., Zhou, Y., & Zhang, X. (2014). Comparative study on the dynamic heat transfer characteristics of PCM-filled glass window and hollow glass window. *Energy and Buildingss, 85*, 483-492. https://doi.org/10.1016/j.enbuild.2014.09.054

Li, Y., Darkwa, J., & Su, W. (2019). Investigation on thermal performance of an integrated phase change material blind system for double skin façade buildings. *Energy Proceeding, 158*, 5116-5123. https://doi.org/10.1016/j.egypro.2019.01.688

Liu, C., Zhang, G., Arici, M., Bian, J., & Li, D. (2019). Thermal performance of non-ventilated multilayer glazing facades filled with phase change material. *Solar Energy, 177*, 464-470. https://doi.org/10.1016/j.solener.2018.11.044

Liu, L., Hammami, N., Trovalet, L., Bigot, D., Habas, J.-P., & Malet-Damour, B. (2022). Description of phase change materials (PCMs) used in buildings under various climates: A review. *Journal of Energy Storage, 56*, 105760. https://doi.org/10.1016/j.est.2022.105760

Lolli, N., & Andresen, I. (2016). Aerogel vs. argon insulation in windows: A greenhouse gas emissions analysis. *Building and Environment, 101*, 64-76. https://doi.org/10.1016/j.buildenv.2016.03.001

Lyu, Y., Wu, X., Li, C., Su, H., & He, L. (2019). Numerical analysis on the effectiveness of warm water supply in water flow window for room heating. *Solar Energy, 177*, 347-354. https://doi.org/10.1016/j.solener.2018.11.033

Lyu, Y.-L., Liu, W.-J., Su, H., & Wu, X. (2019). Numerical analysis on the advantages of evacuated gap insulation of vacuum-water flow window in building energy saving under various climates. *Energy, 175*, 353-364. https://doi.org/10.1016/j.energy.2019.03.101

Maghrabie, H. M., Abdelkareem, M. A., Elsaid, K., Sayed, E. T., Radwan, A., Rezk, H., Wilberforce, T., Abo-Khalil, A. G., & Olabi, A. G. (2022). A review of solar chimney for natural ventilation of residential and non-residential buildings. *Sustainable Energy Technologies and Assessments, 52*, 102082. https://doi.org/10.1016/j.seta.2022.102082

Makaremi, N., Schiavoni, S., Pisello, A. L., & Cotana, F. (2018). Effects of surface reflectance and lighting design strategies on energy consumption and visual comfort. *Indoor and Built Environment, 28*(4) 552-563. https://doi.org/10.1177/1420326X18793170

Mateus, R., Pereira, J. M. C., & Pinto, A. (2023). Natural ventilation of large air masses: Experimental and numerical techniques review. *Energy and Buildings, 291*, 13120. https://doi.org/10.1016/j.enbuild.2023.113120

Mazzeo, D., Matera, N., Cornaro, C., Oliveti, G., Romagnoni, P., & De Santoli, L. (2020). EnergyPlus, IDA ICE and TRNSYS predictive simulation accuracy for building thermal behaviour evaluation by using an experimental campaign in solar test boxes with and without a PCM module. *Energy and Buildingss, 212*. https://doi.org/10.1016/J.ENBUILD.2020.109812

Meti, P., Wang, Q., Mahadik, D. B., Lee, K.-Y., Gong, Y.-D., & Park, H.-H. (2023). Evolutionary progress of silica aerogels and their classification based on composition: An overview. *Nanomaterials, 13*(9), 1498. https://doi.org/10.3390/nano13091498

Michael, M., Favoino, F., Jin, Q., Luna-Navarro, A., & Overend, M. (2023). A systematic review and classification of glazing technologies for building façades. *Energies, 16*(14) 5357. https://doi.org/10.3390/en16145357

Moghaddam, S. A., Serra, C., Silva, M. G., & Simões, N. (2023). Comprehensive review and analysis of glazing systems towards nearly zero-Energy and Buildingss: Energy performance, thermal comfort, cost-effectiveness, and environmental impact perspectives. *Energies, 16*, 6283. https://doi.org/10.3390/en16176283

Mohammad, A. K., & Ghosh, A. (2023). Exploring energy consumption for less energy-hungry building in UK using advanced aerogel window. *Solar Energy, 253*(15) 389-400. https://doi.org/10.1016/j.solener.2023.02.049

Moretti, E., & Belloni, E. (2015). Evaluation of energy, thermal, and day lighting performance of solar control films for a case study in moderate climate. *Building and Environment, 94*, 183-195. https://doi.org/10.1016/j.buildenv.2015.07.031

Moretti, E., Zinzi, M., Merli, F., & Buratti, C. (2018). Optical, thermal, and energy performance of advanced polycarbonate systems with granular aerogel. *Energy and Buildings 166*, 407-417. https://doi.org/10.1016/j.enbuild.2018.01.057

Mujeebu, M. A. (2019). Nano aerogel windows and glazing units for buildings' energy efficiency. In *Nanotechnology in eco-efficient construction* (pp. 417-438). https://doi.org/10.1016/B978-0-08-102641-0.00018-9

Mustafa, M. N., Abdah, M. A. A. M., Arshid, N., Moreno-Rangel, A. A., Radwan, A., & Mohammad, K. (2023). Smart window technology and its potential for net-zero buildings: A review. *Renewable and Sustainable Energy Reviews, 181*, 113355. https://doi.org/10.1016/j.rser.2023.113355

Nasrollahi, N., & Shokri, E. (2016). Daylight illuminance in urban environments for visual comfort and energy performance. *Renewable and Sustainable Energy Reviews, 66*, 861-874. https://doi.org/10.1016/j.rser.2016.08.052

Navaratnam, S., Rajeev, P., & Sanjayan, J. (2023). Study of technological advancement and challenges of façade system for sustainable building: Current design practice. *Sustainability, 15*, 14319. https://doi.org/10.3390/su151914319

Nomura, M., & Hiyama, K. (2017). A review: Natural ventilation performance of office buildings in Japan. *Renewable and Sustainable Energy Reviews, 74*, 746-754. https://doi.org/10.1016/j.rser.2017.02.083

Oh, M., & Park, J. (2019). Evaluation of building energy and daylight performance according to applying electrochromic and pdcl (polymer dispersed liquid crystal) to office building in South Korea. *International Journal of Sustainable Building Technology and Urban Development, 10*(4), 227-240. https://doi.org/10.22712/susb.20190024

Okokpujie, I. P., Essien, V., Ikumapayi, O. M., Nnochiri, E. S., Okokpujie, K., & Akinlabi, E. T. (2022). An overview of thermal insulation material for sustainable engineering building application. *International Journal of Design & Nature and Ecodynamics, 17*(6), 831-841. https://doi.org/10.18280/ijdne.170603

Omrani, S., Garcia-Hansen, V., Capra, B. R., & Drogemuller, R. (2017). Effect of natural ventilation mode on thermal comfort and ventilation performance: Full-scale measurement. *Energy and Buildings, 156*, 1-16. https://doi.org/10.1016/j.enbuild.2017.09.061

Onubogu, N. O., Chong, K.-K., & Tan, M.-H. (2021). Review of active and passive technologies for sustainable building. *International Journal of Photoenergy, 2021*, 8802691. https://doi.org/10.1155/2021/8802691

Ozel, M., & Ozel, C. (2020). Effect of window-to-wall-area ratio on thermal performance of building wall materials in Elazig, Turkey. *PLoS ONE, 15*(9), e0237797. https://doi.org/10.1371/journal.pone.0237797

Palme, M., Carrasco, C., Ángel Gálvez, M., & Inostroza, L. (2017). Natural ventilation: A mitigation strategy to reduce overheating in buildings under urban heat island effect in South American cities. *IOP Conference Series: Materials Science and Engineering Open Access, 245*(7), 072046. https://doi.org/10.1088/1757-899X/245/7/072046

Parale, V. G., Lee, K.-Y., & Park, H.-H. (2017). Flexible and transparent silica aerogels: An overview. *Journal of the Korean Ceramic Society, 54*(3) 184-199. https://doi.org/10.4191/kcers.2017.54.3.12

Pedersen, C. O., Fisher, D. E., Liesen, R. J., & Strand, R. K. (2003). ASHRAE toolkit for building load calculations/discussion. *ASHRAE Transition, 109*, 583.

Pereira, J., Gomes, M. G., Rodrigues, A. M., Teixeira, H., & Almeida, M. (2020). Small-scale field study of window films' impact on daylight availability under clear sky conditions. *Journal of Facade Designer and Engineering, 8*, 65-84. https://doi.org/10.7480/jfde.2020.1.4785

Pereira, J., Rivero, C. C., Gomes, M. G., Rodrigues, A. M., & Marrero, M. (2021). Energy, environmental and economic analysis of windows' retrofit with solar control films: A case study in mediterranean climate. *Energy, 233*, 121083. https://doi.org/10.1016/j.energy.2021.121083

Pereira, J., Teixeira, H., Gomes, M. G., & Rodrigues, A. M. (2022). Performance of solar control films on building glazing: A literature review. *Applied Science, 12*, 5923. https://doi.org/10.3390/app12125923

Petersen, S., & Svendsen, S. (2010). Method and simulation program informed decisions in the early stages of building design. *Energy and Buildingss, 42*, 1113-1119. https://doi.org/10.1016/j.enbuild.2010.02.002

Phuong, N. T. K., Tamrazyan, A. G., Kien, N. T., & Luong, P. V. (2019). Window to floor ratio in the design stage in considering to visual-thermal comfort and safety in building. *IOP Conference Series: Materials Science and Engineering, 675*, 012010. https://doi.org/10.1088/1757-899X/675/1/012010

Piffer, Y., Lamberts, R., Mizgier, M. O., & Güths, S. (2021). A review on windows incorporating water-based liquids. *Solar Energy, 214*, 606-631. https://doi.org/10.1016/j.solener.2020.11.072

Piselli, C., Prabhakar, M., de Gracia, A., Saffari, M. Pisello, A. L., & Cabeza L. F. (2020). Optimal control of natural ventilation as passive cooling strategy for improving the energy performance of building envelope with PCM integration. *Renewable Energy, 162*, 171-181. https://doi.org/10.1016/j.renene.2020.07.043

Pont, U., Wölzl, M., Schober, P., Khosravi, S. N., Schuss, M., & Mahdavi, A. (2019). Recent progress in the development of windows with vacuum glass. *MATEC Web of Conferences, 282*, 02020. https://doi.org/10.1051/matecconf/201928202020

Preet, S., Mathur, J., & Mathur, S. (2022). Influence of geometric design parameters of double skin façade on its thermal and fluid dynamics behavior: A comprehensive review. *Solar Energy, 236*, 249-279. https://doi.org/10.1016/j.solener.2022.02.055

Prince, A. S. H. (2021). A comprehensive review of energy-efficiency of ventilation system using artificial intelligence. *Renewable and Sustainable Energy Reviews, 146*(2021), 111153. https://doi.org/10.1016/j.rser.2021.111153

Qahtan, A., Keumala, N., Rao, S. P., & Abdul-Samad, Z. (2011). Experimental determination of thermal performance of glazed façades with water film, under direct solar radiation in the tropics. *Building and Environment, 46*, 2238-2246. https://doi.org/10.1016/j.buildenv.2011.05.001

Rahnama, S., Sadeghian, P., Nielsen, P. V., Zhang, C., Sadrizadeh, S., & Afshari, A. (2020). Cooling capacity of diffuse ceiling ventilation system and the impact of heat load and diffuse panel distribution. *Building and Environment, 185*, 107290. https://doi.org/10.1016/j.buildenv.2020.107290

Rallapalli, H. S. (2010). A comparison of EnergyPlus and eQUEST whole building energy simulation results for a medium sized office building. *State University of Arizona*. https://keep.lib.asu.edu/items/149515

Rashidzadeh, & Matin, N. H. (2023). A comparative study on smart windows focusing on climate-based energy performance and users' comfort attributes. *Sustainability, 15*, 2294. https://doi.org/10.3390/su15032294

Rathnayake, U., Lau, D., & Chow, C. L. (2020). Review on energy and fire performance of water wall systems as a green building façade. *Sustainability, 12*, 8713. https://doi.org/10.3390/su12208713

Remion, G., Moujalled, B., Mankibi, M., Jobert, R., & Deleersnyder, L. (2018). Assessing the performance of natural ventilation systems: A review of existing methods. In *Proceedings of the 39th AIV Conference "Smart Ventilation for Buildings"*.

Rezaei, S. D., Shannigrahi, S., & Ramakrishn, S. (2017). A review of conventional, advanced, and smart glazing technologies and materials for improving indoor environment. *Solar Energy Materials & Solar Cells, 159*, 26-51. https://doi.org/10.1016/j.solmat.2016.08.026

Romero, X., & Hernández, J. A. (2017). Spectral problem for water flow glazings. *Energy and Buildings, 145*, 67-78. https://doi.org/10.1016/j.enbuild.2017.03.013

Saadatjoo, P., Mahdavinejad, M., & Armanshahr, A. Z. (2019). Porosity rendering in high-performance architecture: Wind-driven natural ventilation and porosity distribution patterns. *Architecture & Urban Development, 12*(26), 73-87. https://doi.org/10.22034/AAUD.2019.89057

Saber, A. (2021). Effects of window-to-wall ratio on energy consumption: Application of numerical and ANN approaches. *Journal of Soft Computing in Civil Engineering, 5*(4), 41-56. https://doi.org/10.22115/SCCE.2021.281977.1299

Sadeghian, P., Rahnama, S., Afshari, A., & Sadrizadeh, S, (2022). The role of design parameters on the performance of diffuse ceiling ventilation systems–Thermal comfort analyses for indoor environment. *Advances in Building Energy Research, 16*(6) 806-824. https://doi.org/10.1080/17512549.2022.2109211

Sadko, K., & Piotrowski, J. Z. (2022). Numerical investigations of the thermal properties of window systems: A review. *Structure and Environment, 14*(4), 126-141. https://doi.org/10.30540/sae-2022-015

Sadooghi, P., & Kherani, N. P. (2018). Thermal analysis of triple and quadruple windows using partitioning radiant energy veils with different physical and optical properties. *Solar Energy, 174*, 1163-1168. https://doi.org/10.1016/j.solener.2018.07.034

Salcido, J. C., Raheem, A. A., & Issa, R. R. A. (2016). From simulation to monitoring: Evaluating the potential of mixed-mode ventilation (MMV) systems for integrating natural ventilation in office buildings through a comprehensive literature review. *Energy and Buildings, 127*, 1008-1018. https://doi.org/10.1016/j.enbuild.2016.06.054

Sayadi, S., Hayati, A., & Salmanzadeh, M. (2021). Optimization of window-to-wall ratio for buildings located in different climates: An IDA-indoor climate and energy simulation study. *Energies, 14*, 1974. https://doi.org/10.3390/en14071974

Shahrzad, S., & Umberto, B. (2022). Parametric optimization of multifunctional integrated climate-responsive opaque and ventilated façades using CFD simulations. *Applied Thermal Engineering, 204*, 117923. https://doi.org/10.1016/j.applthermaleng.2021.117923

Shao, T., Jin, H., Zheng, W., & Wang, J. (2020). The influence of window-wall ratio on heating energy consumption of rural house in severe cold regions of China. *E3S Web of Conferences, 173*, 03008. https://doi.org/10.1051/e3sconf/202017303008

Shen, H., & Tzempelikos, A. (2017). Daylight-linked synchronized shading operation using simplified model-based control. *Energy and Buildings, 145*(15) 200-212. https://doi.org/10.1016/j.enbuild.2017.04.021

Silva, T., Vicente, R., & Rodrigues, F. (2016). Literature review on the use of phase change materials in glazing and shading solutions. *Renewable and Sustainable Energy Reviews, 53*(1) 515-535. https://doi.org/10.1016/j.rser.2015.07.201

Skaff, M. C., & Gosselin, L. (2014). Show more summer performance of ventilated windows with absorbing or smart glazings. *Solar Energy, 105*, 2-13. https://doi.org/10.1016/j.solener.2013.08.025

Solgi, E., Hamedani, Z., Fernando, R., Kari, B. M., & Skates, H. (2019). A parametric study of phase change material behaviour when used with night ventilation in different climatic zones. *Building Environment, 147*, 327-336. https://doi.org/10.1016/j.buildenv.2018.10.031

Solgi, E., Hamedani, Z., Fernando, R., Skates, H., & Orji, N. E. (2018). A literature review of night ventilation strategies in buildings. *Energy and Buildings, 173*, 337-352. https://doi.org/10.1016/j.enbuild.2018.05.052

Souza, L. C. O., Souza, H. A., & Rodrigues, E. F. (2018). Experimental and numerical analysis of a naturally ventilated double-skin façade. *Energy and Buildings, 165*, 328-339. https://doi.org/10.1016/j.enbuild.2018.01.048

Sun, Y., Wu, Y., & Wilson, R. (2018). A review of thermal and optical characterisation of complex window systems and their building performance prediction. *Applied Energy, 222*, 729-747. https://doi.org/10.1016/j.apenergy.2018.03.144

SUNREL. (2022). *National Renewable Energy Laboratory*. https://www.nrel.gov/docs/fy02osti/30193.pdf

Sureguard. (2023). *Sureguard window films*. https://www.sureguard.co.uk/window-film/solar-film/

Tällberg, R., Jelle, B. P., Loonen, R., Gao, T., & Hamdy, M. (2019). Comparison of the energy saving potential of adaptive and controllable smart windows. *Solar Energy Materials and Solar Cells, 200*, 109828. https://doi.org/10.1016/j.solmat.2019.02.041

Tao, Y., Yan, Y., Chew, M. Y. L., Tu, J., & Shi, L. (2023). A theoretical model of natural ventilation enhanced by solar thermal energy in double-skin façade. *Energy, 276*, 127534. https://doi.org/10.1016/j.energy.2023.127534

Teixeira, H., Gomes, M. G., Rodrigues, A. M., & Pereira, J. (2020). Thermal and visual comfort, energy use and environmental performance of glazing systems with solar control films. *Building and Environment, 168*, 106474. https://doi.org/10.1016/j.buildenv.2019.106474

Tong, S. W., Goh, W. P., Huang, X., & Jiang, C. (2021). A review of transparent-reflective switchable glass technologies for building facades. *Renewable and Sustainable Energy Reviews, 152*, 111615. https://doi.org/10.1016/j.rser.2021.111615

TRANSSOLAR Energietechnic GmbH. (2012). *TRNBuild 2.0*. https://transsolar.com/

Troup, L., Phillips, R., Eckelman, M. J., & Fannon, D. (2019). Effect of window-to-wall ratio on measured energy consumption in US office buildings. *Energy and Buildings, 203*, 109434. https://doi.org/10.1016/j.enbuild.2019.109434

Tukel, M., Mumcuoglu, K., Arici, M., & Karabay, H. (2019). Analysis of fluid flow and heat transfer characteristics in multiple glazing roofs with a special emphasis on the thermal performance. *Applied Thermal Engineering, 148*, 694-703. https://doi.org/10.1016/j.applthermaleng.2018.11.089

Uddin, M. M., Jie, J., Wang, C., Zhang, C., & Ke, W. (2023). A review on photovoltaic combined vacuum glazing: Recent advancement and prospects. *Energy and Buildings, 286*, 112939. https://doi.org/10.1016/j.enbuild.2023.112939

United States Department of Energy. (2022). *United States Department of Energy*. http://www.energy.gov/

University of Illinois. (1992). EnergyPlus: Energy simulation program. *LBNL*. https://simulationresearch.lbl.gov/dirpubs/46002.pdf

University of Wisconsin-Madison. (1975). A transient simulation program. *Solar Energy Laboratory*. https://search.library.wisc.edu/catalog/999800551102121

University of Wisconsin-Madison. (2012a). A transient system simulation program. *Solar Energy Laboratory*. http://www.trnsys.com/

University of Wisconsin-Madison. (2012b). Multi zone building modeling with type 56 and TRN-build. *Solar Energy Laboratory*. https://web.mit.edu/parmstr/Public/Documentation/06-MultizoneBuilding.pdf

Uribe, D., & Vera, S. (2021). Assessment of the effect of phase change material (PCM) glazing on the energy consumption and indoor comfort of an office in a semiarid climate. *Applied Science, 11*, 9597. https://doi.org/10.3390/app1120959

VE-Pro. (2011). *Integrated environmental solutions*. http://www.iesve.com/software/ve-proin

Vlachokostas, A., & Madamopoulos, N. (2017). Daylight and thermal harvesting performance evaluation of a liquid filled prismatic façade using the radiance five-phase method and EnergyPlus. *Building and Environment, 126*, 396-409. https://doi.org/10.1016/j.buildenv.2017.10.017

Walton, G. N. (1989). *AIRNET–A computer program for building airflow network modeling, NISTIR 89-4072*. National Institute of Standards and Technology. https://doi.org/10.6028/NIST.IR.89-4072

Wieprzkowicz, A., & Heim, D. (2018). Thermal performance of PCM-glazing unit under moderate climatic conditions. In *Proceedings of the 7th International Buildings Physics Conference*. https://doi.org/10.14305/ibpc.2018.be-10.06

William, J. (2018). *Strategies for deploying virtual representations of the built environment*. https://www.esru.strath.ac.uk/Courseware/ESP-r/tour/Downloads/strategiesmay2018.pdf

Winkelmann, F. C., & Selkowitz, S. E. (1985). Day lighting simulation in the DOE-2 building energy analysis program. *Energy and Buildings, 8*, 271-286. https://doi.org/10.1016/0378-7788(85)90033-7

Winkelmann, F., Birdsall, B., Buhl, W., Ellington, K., Erdem, A., Hirsch, J., & Gates, S. (1993). *DOE-2 supplement*. Lawrence Berkeley Laboraty.

Wu, S., Sun, H., Duan, M., Mao, H., Wu, Y., Zhao, H., & Lin, B. (2023). Applications of thermo chromic and electro chromic smart windows: Materials to buildings. *Cell Reports Physical Science, 4*, 101370. https://doi.org/10.1016/j.xcrp.2023.101370

Wu, W., Yoon, N., Tong, Z., Chen, Y., Lv, Y., Ærenlund, T., & Benner, J. (2019). Diffuse ceiling ventilation for buildings: A review of fundamental theories and research methodologies. *Journal Cleaner Production, 211*, e1619. https://doi.org/10.1016/j.jclepro.2018.11.148

Xamán, J., Olazo-Gómez, Y., Zavala-Guillén, I., Hernández-Pérez, I., Aguilar, J. O., & Hinojosa, J. F. (2017). Thermal evaluation of a room coupled with a double glazing window with/without a solar control film for Mexico. *Applied Thermal Engineering, 110*, 805-820. https://doi.org/10.1016/j.applthermaleng.2016.08.156

Xu, Z., Chen, Y., Lin, P., & Zhu, X. (2022). Leak proof phase-change glass window: Characteristics and performance. *Building and Environment, 218*, 109088. https://doi.org/10.1016/j.buildenv.2022.109088

Xuanjie, W., & Narayan, S. (2021). Thermochromic materials for smart windows: A state-of-art review. *Frontiers in Energy Research, 9*. https://doi.org/10.3389/fenrg.2021.800382

Yang, B., Melikov, A. K., Kabanshi, A., Zhang, C., Bauman, F. S., Cao, G., Awbi, H., Wigo, H., Niu, J., Cheong, K. W. D., Tham, K. W., Sandberg, M., Nielsen, P. V., Kosonen, R., Yao, R., Kato, S., Sekhar, S. C., Schiavon, S., Karimipanah, T., Li, X., & Lin, Z. (2019). A review of advanced air distribution methods–Theory, practice, limitations and solutions. *Energy and Buildings, 202*, 109359. https://doi.org/10.1016/j.enbuild.2019.109359

Yang, R., Li, D., Wei W., & Wang, F. (2020). A mie optimization model to determine optical properties of PCM based nanofluids for solar thermal applications of glazing window. *International Journal for Light and Electronic Optics, 212*, 164664. https://doi.org/10.1016/j.ijleo.2020.164664

Yang, S., Fiorito, F., Prasad, D., Sproul, A., & Cannavale, A. (2021). A sensitivity analysis of design parameters of BIPV/T-DSF in relation to building energy and thermal comfort performances. *Journal of Building Engineering, 41*, 102426. https://doi.org/10.1016/j.jobe.2021.102426

Yang, X., Li, D., Yang, R., Ma, Y., Tong, X., Wu, Y., & Arici, M. (2023). Comprehensive performance evaluation of double-glazed windows containing hybrid nanoparticle-enhanced phase change material. *Applied Thermal Engineering, 223*, 119976. https://doi.org/10.1016/j.applthermaleng.2023.119976

Yao, J. (2014). An investigation into the impact of movable solar shades on energy, indoor thermal and visual comfort improvements. *Building and Environment, 71*(1) 24-32. https://doi.org/10.1016/j.buildenv.2013.09.011

Yu, T., Heiselberg, P., Lei, B., Pomianowski, M., & Zhang, C. (2015). A novel system solution for cooling and ventilation in office buildings: A review of applied technologies and a case study. *Energy and Buildings, 90*(1) 142-155. https://doi.org/10.1016/j.enbuild.2014.12.057

Yu, X., & Su, Y. (2015). Daylight availability assessment and its potential energy saving estimation–A literature review. *Renewable and Sustainable Energy Reviews, 52*, 494-503. https://doi.org/10.1016/j.rser.2015.07.142

Zaniboni, L., & Rossano, A. (2022). Natural and mechanical ventilation concepts for indoor comfort and well-being with a sustainable design perspective: A systematic review. *Natural Buildings, 12*(11), 1983. https://doi.org/10.3390/buildings12111983

Zerroug, A., & Dzelzitis, E., (2015). Analysis of results of energy consumption simulation with eQUEST and energyplus. In *Proceedings of the 5th International Conference Civil Engineering*.

Zhang, C., Gang, W., Wang, J., Xu, X., & Du, Q. (2019). Numerical and experimental study on the thermal performance improvement of a triple glazed window by utilizing low-grade exhaust air. *Energy, 167*, 1132-1143. https://doi.org/10.1016/j.energy.2018.11.076

Zhang, C., Heiselberg, P., & Nielsen, P. V. (2014). Diffuse ceiling ventilation–A review. *International Journal of Ventilation, 13*(1), 49-64. https://doi.org/10.1080/14733315.2014.11684036

Zhang, H., Yang, D., Tam, V. W. Y., Ta, Y., Zhang, G., Setunge, S., & Shi, L. (2021). A critical review of combined natural ventilation techniques in sustainable buildings. *Renewable and Sustainable Energy Reviews, 141*, 110795. https://doi.org/10.1016/j.rser.2021.110795

Zhang, S., Hu, W., Li, D., Zhang, C., Arici, M., Yildiz, C., Zhang, X., & Ma, Y. (2021). Energy efficiency optimization of PCM and aerogel-filled multiple glazing windows. *Energy, 222*, 119916. https://doi.org/10.1016/j.energy.2021.119916

Zhong, H. Y., Sun, Y., Shang, J., Qian, F. P., Zhao, F. Y., Kikumoto, H., Bescos, C. J., & Liu, X. (2022). Single-sided natural ventilation in buildings: A critical literature review. *Building Environment, 212*, 108797. https://doi.org/10.1016/j. buildenv.2022.108797