Energy Consumption Assessment of Using Multi-Layer Electrochromic Windows in Buildings (A Case Study)

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This study explores the role of double-layer and electrochromic windows compared to simple single-layer windows in energy conservation within buildings. The study investigates the energy-saving potential of these advanced window technologies by analyzing their thermal performance, daylighting capabilities, and overall impact on building energy consumption. A comparative analysis evaluates each window type's benefits and limitations, considering factors such as insulation properties, solar heat gain control, and visual comfort. The findings suggest that double-layer and electrochromic windows offer significant advantages over traditional single-layer windows in reducing energy usage, enhancing occupant comfort, and promoting sustainable building practices. The building under study is modeled in DesignBuilder, and the impact of these three types of windows on the application is analyzed. On the hottest day of the year, the operative temperature is 1.3 degrees Celsius lower when utilizing double-layer windows compared to single-layer windows, and 0.2 degrees lower compared to electrochromic windows. On the coldest day of the year, using double-layers results in an operative temperature of 14.14 degrees Celsius, which is 1.3 degrees higher than single layers and 0.13 degrees lower than electrochromic windows.

Keywords: *Electrochromic window, Double-layer window, Design builder modeling*

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Nomenclature

h	convective heat transfer coefficient (W/m^2.K)
T_x	temprature (ºC)
Q_x	heat flux (W/m^2)
U	rate of heat transfer (W)
A_x	area of the surface (m^2)
conv	convection
cond	conduction
tot	total
eva	evaporation
up	upper
w	wall
amb	ambient
i	indoor
rad	radiation

1. Introduction

Building energy consumption accounts for a significant portion of global energy demand, with fenestration systems playing a critical role in determining both the energy efficiency and indoor environmental quality of a building. Windows are the most vulnerable components of the building envelope regarding heat transfer, daylighting, and solar heat gain. Consequently, the selection of an appropriate glazing type is a crucial decision in sustainable building design. Traditional single-layer windows offer minimal thermal resistance, leading to substantial conductive heat losses in winter and excessive solar heat gains in summer. To mitigate these issues, double-layer (insulating glass) windows, typically filled with inert gases like argon, have become the standard for improving the overall thermal transmittance (U-value) and thermal resistance (R-value) of the envelope.

Recently, dynamic glazing technologies, particularly Electrochromic Devices (ECDs), have emerged as advanced solutions for optimizing building energy performance. ECDs can dynamically modulate their tint in response to an applied voltage, thereby controlling the Solar Heat Gain Coefficient (SHGC) and visible light transmittance. The core components of high-performance ECDs include Transparent Conducting Oxides (TCOs) and specialized electrode architectures, such as Indium Tin Oxide/Silver/Indium Tin Oxide (IAI) multilayers, which ensure high optical transmittance and low sheet resistance. While ECDs offer unparalleled control over solar radiation and glare, their real-world energy-saving potential is highly dependent on the local climate, building orientation, and control strategies.

To compare the energy conservation potential of electrochromic, single-layer, and double-layer windows in a building, it is essential to consider the impact of these window technologies on energy savings.

Electrochromic (EC) windows have been identified as an emerging technology with the potential to control solar gain in buildings [1].

The use of EC windows has been studied using building energy simulation software, which compared several window solutions, including single and double-glazing, and their orientations. The results indicated potential energy savings resulting from the application of EC windows [2]. However, it is important to note that the performance of electrochromic smart windows has been progressively improved, but challenges such as low coloration efficiency, slow switching time, and poor durability still exist, which may impact their energy conservation potential [3]. In addition to electrochromic windows, single-layer and double-layer windows have also been studied for their impact on energy conservation. Infrared-regulating smart windows based on organic materials has been discussed in the context of their influence on temperature control and energy savings in the built environment [4].

Furthermore, a study on the performance of photovoltaic electrochromic window systems demonstrated that electrochromic glass windows controlled by the joint control of outdoor illumination and glare were more energy-saving than ordinary single-layer glass windows. It is evident that the integration of photovoltaic systems with electrochromic windows can contribute to energy conservation in buildings. Moreover, the thermal and optical properties of low-E storm windows and panels have been highlighted as important considerations for energy conservation, especially in existing buildings with older, inefficient windows [5]. This emphasizes the significance of window retrofit strategies for energy conservation. Additionally, transparent zinc-mesh electrodes for solar-charging electrochromic windows have been proposed as a potential solution for energy-efficient smart windows, addressing the drawbacks associated with external energy sources [6]. Furthermore, the potential of thermochromic smart windows for achieving optimal building energy conservation has been recognized due to their advantages, such as zero energy input, rational solar response, and low cost [7]. Similarly, the construction of liquid hybrid energy-saving windows with strong solar modulation capacity has been identified as a versatile strategy for building energy conservation [8] These references underscore the importance of exploring diverse window technologies to achieve energy efficiency in buildings.

In the context of energy-efficient window retrofit for existing buildings, it has been emphasized that windows play a significant role in transmitting heating and cooling between the indoor and outdoor environment, making them a crucial element for energy conservation [9]. Additionally, the establishment of passive energy conservation measures and economic evaluation of fenestration systems have been studied to determine the appropriate window types for heating energy conservation [10]. In conclusion, the comparison of energy conservation using electrochromic, single-layer, and double-layer windows in a building involves considering the energy savings potential of each technology. While electrochromic windows and their integration with photovoltaic systems show promise for energy conservation, challenges related to their performance and durability need to be addressed. Additionally, the role of window retrofit strategies and the exploration of thermochromic smart windows highlight the diverse approaches to achieving energy efficiency in buildings. By simulating a building model in DesignBuilder with different window configurations, we aim to evaluate the energy-saving potential, temperature distribution, U-value, and other thermophysical parameters associated with single-layer, double-layer, and electrochromic windows. Understanding the performance of these window types can inform building designers, engineers, and policymakers in making informed decisions to enhance building sustainability, energy efficiency, and occupant comfort.

Through this study, we seek to contribute to the knowledge base on the impact of window technologies on building performance and provide insights into optimizing window design for energy conservation and thermal comfort in buildings. The findings of this research can guide future building projects towards sustainable and energy-efficient design practices, fostering a more environmentally conscious built environment. Recent advancements in smart window technologies aim to address growing energy demands and climate concerns by reducing cooling loads in buildings and vehicles. One study introduced multilayer thin-film designs—both static and electro-tunable—that selectively filter solar radiation using insulator–metal–insulator structures. Electro-tunable models, equipped with electro-optic polymers, enable dynamic control of light transmission and show strong alignment between theoretical and simulated performance. In addition, research on electrochromic (EC) glazing highlights the importance of window-to-wall ratio (WWR) in energy efficiency. Simulations revealed that a 40% WWR on south-facing façades in humid subtropical climates offers optimal energy performance, suggesting that both material properties and architectural factors must be considered in window design for maximum energy savings [11].

Recent developments in electrochromic devices (ECDs) have explored the use of multilayer graphene (MLG) as a flexible and high-performance electrode material. In one study, MLG was synthesized via chemical vapor deposition (CVD) and transferred onto polyethylene substrates using a low-cost water bath technique. The resulting ECD demonstrated significant optical modulation, with transmittance increasing from a threshold of 2.8 V and reaching a 40% change at 5 V. Structural analysis using Raman spectroscopy revealed characteristic G peaks, with band shifts correlating to layer number, while XRD data indicated that p-type doping occurs more readily and at lower voltages than n-type doping. Additionally, switching time analysis showed slower intercalation compared to deintercalation, highlighting key kinetic aspects relevant to ECD performance optimization [12]. To enhance the durability and efficiency of electrochromic devices (ECDs), recent studies have focused on addressing structural degradation during prolonged ion intercalation cycles. A morphology-controlled multilayer design has been proposed to mitigate common issues such as surface cracking and peeling. This structure, incorporating smaller particles at the base and larger particles on the surface, facilitates improved electrolyte access and reduced ion diffusion length, resulting in faster switching and enhanced electrochromic performance. Moreover, the crack-free surface with minimized residual stress contributes to superior cycling stability. These findings offer promising strategies for optimizing metal oxide-based ECDs and advancing their practical application in energy-efficient systems [13].

Recent innovations in smart window technology have expanded their functionality beyond energy efficiency, aiming for multi-purpose applications. One study introduced a multi-functional tandem device using ionic gels, which serve simultaneously as electrolytes, ion storage media, and transparent electrodes. This simplified five-layered structure supports both DC-driven electrochromic and AC-driven electroluminescent functions. The device exhibits high tunable transparency (0–77%), selective infrared shielding, flexibility, and long-term stability over 3000 cycles. Its versatile design suggests broad applicability in dynamic display, decorative elements, and adaptive building components, pointing toward the next generation of smart window systems with integrated multifunctionality [14]. In recent decades, responsive technologies applied to transparent building envelopes have gained attention as an effective approach to reducing energy consumption. Electrochromic (EC) glazing stands out among these technologies due to its ability to dynamically modulate daylight and thermal radiation via externally applied voltage. One study proposed a methodological framework for optimizing EC glazing configurations in office buildings across different European climate zones. Using a genetic algorithm, five key parameters were optimized: solar heat gain coefficient and visible light transmittance in both bleached and colored states, and thermal transmittance (U-value). The findings offer tailored EC window designs controlled by daylight sensors, enhancing energy performance based on regional climatic demands [15].

While electrochromic smart windows hold strong potential for improving energy management in modern infrastructure, their widespread adoption has been limited by high material and processing costs. A recent study addressed this issue by developing a cost-effective electrochromic device using a chemically synthesized conducting polymer, poly(o-methoxyaniline) (PMOANI), deposited on a hybrid low-cost electrode (ITO 60 nm/Al-mesh). The resulting device demonstrated high optical contrast (57%), fast switching (∼5 s), excellent cycling stability (>500 cycles), and dual-functionality with integrated energy storage (areal capacitance ∼8 mF cm^{-2}), capable of powering a timer display in its dark state. This approach, which reduces ITO usage without performance loss, presents a viable pathway for producing affordable, high-performance electrochromic systems suitable for building and automotive applications [16]. Although electrochromic (EC) windows effectively reduce glare by modulating their tint, fully tinted glazing can compromise daylight availability and increase lighting energy consumption. To resolve this trade-off, one study proposed a novel design methodology for split-pane EC windows, aiming to minimize the tinted area hours (TAH) while maintaining visual comfort. Using a south-facing office building in Beijing as a case study, the simulation results demonstrated that the optimized split-pane configuration could prevent 95.3% of intolerable glare and achieve a daylight illumination index of 73.3%. Moreover, it resulted in a 29.8% reduction in lighting energy use compared to conventional full-window tinting. This approach underscores the potential of intelligent EC window partitioning in balancing daylight utilization and energy efficiency [17]. Recent advancements in high-performance electrochromic devices (ECDs) have focused on optimizing both transparent conducting oxide (TCO) electrodes and electrochromic (EC) layers. A notable approach involves the implementation of multilayer indium tin oxide/silver/indium tin oxide (IAI) electrodes, which exhibit superior optical transmittance (90.9%) and low sheet resistance (16.7 Ω/sq) due to a 15-nm-thick silver layer with a (111) preferential orientation and smooth morphology. Concurrently, tailoring the microstructure of the tungsten trioxide (WO_3) EC layer through controlled sputtering chamber pressure has been shown to influence film density and morphology. Specifically, deposition at higher chamber pressure (2.0 Pa) produces an open network WO_3 film with reduced mass density (5.72 g/cm^3) and rough surface characteristics. Experimental evaluations of half-cell ECDs comprising the IAI TCO and tailored WO_3 layer immersed in $LiClO_4$ electrolyte reveal significant enhancements in coloration efficiency compared to devices utilizing conventional ITO electrodes or dense WO_3 films. This improvement is attributed to facilitated charge carrier extraction and injection, as well as enhanced lithium ion transport, underscoring the critical role of electrode design and EC layer morphology in advancing electrochromic performance [18].

Electrochromic smart windows typically require lithium salt electrolytes that demand complex encapsulation to prevent moisture damage, limiting durability and repairability. Recent developments in lithium-salt-free, hydrophobic solid-state poly (ionic liquid) electrolytes with strong C─F bonds and low moisture absorption enable unencapsulated devices with excellent cycling stability and environmental resilience. In situ polymerization ensures strong electrolyte-electrode adhesion and efficient ion transport. This approach facilitates low-cost, removable, and customizable electrochromic window films, offering a promising route for scalable smart window applications [19]. Tungsten oxide (WO3) has garnered significant attention as an electrochromic material due to its fast response speed and low driving voltage. Recent studies have focused on the development of electrochromic laminated safety glass incorporating WO3, structured as glass/ITO/WO3/PVB electrolyte layer/NiO/ITO/glass. Electrochemical and optical performance evaluations, including cyclic voltammetry over 10,000 cycles, reveal that the amorphous WO3 nanofilm achieves an optical contrast of 71% at 550 nm and a maximum coloration efficiency of 140.06 cm^2/C. The fabricated electrochromic device (10 × 10 cm^2) demonstrates uniform color modulation at 3.0 V, underscoring its potential for applications in construction and smart window technologies [20].

Recent research highlights the critical role of fenestration in regulating indoor temperatures and enhancing building energy efficiency. Studies employing advanced simulation tools such as EnergyPlus and Radiance have evaluated the integration of static glazing with dynamic coatings, including thermochromic and electrochromic films, within lightweight structures in semi-arid climates. These investigations demonstrate that dynamic coatings significantly improve energy performance, thermal comfort (assessed via PMV and PPD indices), and visual comfort by optimizing daylighting and reducing glare. Among the glazing options, double glazing is identified as the most cost-effective and environmentally sustainable solution, achieving a CO2 emissions reduction of 1522.38 kg/year and a payback period of approximately 13 years. Moreover, the combination of dynamic coatings with optimized static glazing can reduce building energy consumption by up to 26%. These findings emphasize the importance of integrating smart glazing technologies in sustainable building design to balance energy savings, occupant comfort, and environmental impact [21]. Recent advances in net-zero energy buildings have focused on improving window efficiency through self-powered electrochromic smart windows. Simulations across 34 Chinese cities indicate a 17.25% reduction in HVAC energy consumption, highlighting the potential of self-powered smart windows for sustainable net-zero building design [22]. Recent developments in Low-emissivity (Low-e) smart windows focus on enhancing solar modulation and thermal regulation to reduce energy consumption. A novel amorphous SIZO/Ag/SIZO/NiO multilayer electrode fabricated via room-temperature sputtering exhibits high visible light modulation (78%) and superior near-infrared shielding (>80%), combined with fast switching speeds (1 s bleaching, 3 s coloration) and good cyclic stability. The electrode's high specific capacitance (220 F g^{-1}) and amorphous structure facilitate rapid ion intercalation, improving electrochromic efficiency and enabling energy storage functionality. These advancements contribute significantly to the development of Low-e electrochromic films for energy-efficient smart building applications [23].

Recent advances in stimuli-responsive polymeric materials, particularly thermochromic and electrochromic polymers reinforced with graphene nanocomposites, have attracted significant scientific attention due to their superior color-changing performance under heat or voltage stimuli. Key properties, including microstructure, thermal and mechanical stability, phase transition temperatures, optical transmittance, and stimuli sensitivity, have been extensively investigated [24]. Flexible electrochromic devices (FECDs) have attracted attention due to their applications in wearable electronics, camouflage, and smart windows; however, their patterned fabrication remains complex and costly [25]. In line with the present research, this study contributes to the advancement of adaptive and biocompatible optical technologies related to our work by introducing an electrochromic contact lens system with dynamic color-changing capability [26]. This study evaluates the thermal performance enhancement of a gray tintable electrochromic (EC) window in Singapore's tropical climate. Experimental comparisons were conducted between a double-glazed EC window and a conventional single-glazed window. Results under sunny conditions revealed that the EC window reduced interior surface temperatures by 4.4 °C in the tinted state and 3.0 °C in the clear state relative to the reference window. Thermal comfort, assessed via peak Predicted Mean Vote (PMV), improved by 37% in the bleached state and 50% in the fully tinted state. Additionally, the fully tinted EC window achieved up to 19% savings in air conditioning energy consumption. These findings demonstrate that EC windows can effectively enhance occupant comfort and reduce cooling energy demand in tropical environments [27]. This study presents a simple dual-band smart window capable of actively modulating visible (vis) light transmittance via an external electric field and passively controlling near-infrared (NIR) light transmittance through temperature changes. The device integrates polymer-dispersed liquid crystals, vanadium dioxide (VO2), and Al-doped ZnO, with VO2 serving both as a NIR modulator and conductive layer. Four distinct optical modes are achieved: simultaneous transmission or blocking of vis and NIR light in various combinations. Visible light transmittance (T_lum) reversibly varies between 0.38% and 39.93%, while solar irradiation transmittance (T_solar) passively changes between 42.32% and 9.95%. The response time significantly improves from 114.5 ms to 5.2 ms as VO2 transitions from monoclinic to rutile phase. Electro-optical characterization confirms fast switching, durability, and independent modulation of vis and NIR bands. Additionally, a prototype house model demonstrates indoor cooling of 7.7 °C, highlighting the potential of this straightforward, large-area fabrication approach for energy-efficient applications in buildings and vehicles [28]. This study presents a comparative analysis of static and electro-tunable smart window designs aimed at reducing energy consumption for air conditioning in buildings and vehicles. The windows consist of insulator–metal–insulator multilayer thin films on silica glass, selectively filtering visible and infrared solar radiation. Static windows are optimized for various climates by adjusting layer materials and thicknesses, while electro-tunable windows incorporate electro-optic polymers to dynamically control solar transmission within a voltage range of −12 to +12 V. The designs demonstrate robustness against fabrication imperfections, large-area scalability, and angle- and polarization-independence. Analytical and simulation results align closely, with theoretical figures of merit suggesting superior performance compared to commercial windows, indicating strong potential for energy-saving applications [29]. In line with the present research, this study demonstrates that the use of a single-layer core@VO_2 nanoparticle coating can provide multi-band modulation of sunlight and infrared radiation through a simpler fabrication process, enhancing the energy performance of thermochromic smart windows a concept that can inspire the development of tunable electrochromic contact lenses relevant to our work [30]. This review introduces smart photovoltaic windows (SPWs) as a key technology for energy-saving buildings (ESBs), combining dynamic solar modulation with electricity generation. The windows are categorized based on their working principles and components, with an emphasis on material and architectural innovations to enhance optical modulation, photovoltaic efficiency, durability, and operational flexibility. The study also discusses current challenges and future opportunities, aiming to advance multifunctional SPWs for sustainable and highly efficient buildings [31]. Occupancy patterns and occupants' behavioral parameters play a significant role in building energy consumption and can directly influence cooling and heating demands as well as the performance of components such as windows. Studies have shown that, in addition to the physical characteristics of buildings, factors such as user presence, comfort temperature settings, and managerial decisions are key determinants of energy efficiency. In this context, examining the impact of these variables on the thermal performance of different types of windows (including single-glazed, double-glazed, and electrochromic windows) can lead to a more accurate understanding of actual energy use behavior and contribute to the optimization of building design [32].

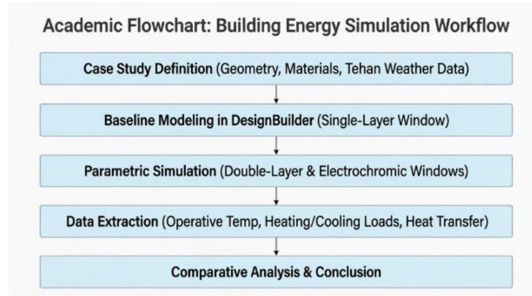

Fig. 1. Schematic flowchart of the building energy simulation methodology

Despite the promising material-level advancements in smart windows, there is a distinct gap in the literature regarding the comparative building-level performance of static (double-layer) versus dynamic (electrochromic) glazing in specific mixed climates. Most existing studies either focus on the material synthesis of ECDs or simulate their performance in extreme cooling-dominated (tropical) or heating-dominated climates. There is a lack of comprehensive, simulation-based comparative analyses evaluating these technologies in semi-arid, mixed climates such as Tehran, Iran where both winter heat loss and summer solar gain are significant drivers of energy consumption. Furthermore, the physical mechanisms dictating why a highly optimized static window might outperform a dynamic window in such specific climatic contexts remain underexplored. Therefore, this study aims to bridge this gap by conducting a comparative techno-thermal analysis of single-layer, double-layer (argon-filled), and electrochromic windows in a sports facility located in Tehran. The specific objectives are to: (1) quantify the impact of each window type on annual heating and cooling loads; (2) analyze the physical mechanisms (U-value vs. SHGC dynamics) driving the thermal performance differences; and (3) evaluate the practical implications of these findings for building design in mixed climates. By utilizing DesignBuilder simulation software, this research provides actionable insights for architects and engineers to optimize fenestration design for energy conservation and thermal comfort.

2. Methodology

2.1. Research Framework

The methodology of this study is structured into four sequential phases to ensure a systematic evaluation of the window technologies:

- Case Study Selection and Data Collection: Defining the geometric, thermophysical, and operational characteristics of the case study building in Tehran, including local weather data.

- Baseline Energy Modeling: Developing a validated 3D model of the building in DesignBuilder software and establishing the baseline energy performance using standard single-layer glazing.

- Parametric Simulation: Integrating the thermophysical properties of double-layer and electrochromic windows into the model and running annual dynamic energy simulations under identical boundary conditions.

- Comparative Techno-Thermal Analysis: Extracting and analyzing key performance indicators, including operative temperatures, heating/cooling loads, and heat transfer mechanisms, to compare the efficacy of the three window configurations.

To provide a clear overview of this process, the simulation methodology is summarized in the flowchart presented in Fig. 1.

2.2. Case of study Description

The location of study is a sports facility situated in Mehrabad, Tehran, Iran, at coordinates 35.6895° N, 51.3280° E. It covers a total area of 763.143 square meters and is specifically designed for martial arts. The dimensions of this building plot are 11.55 meters in width, 66.07 meters in length, and 7 meters in height. All the windows are 5 meters tall and collectively account for 30% of the total area of the walls. The plot is displayed in Fig. 2. The southern wall, covering approximately 462.51 square meters, receives the highest amount of solar radiation.

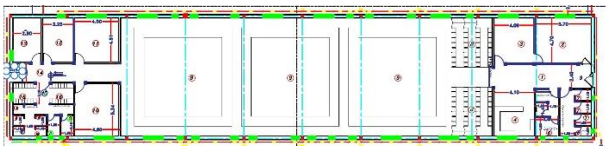

Fig. 2. Plot of the sports hall

The building, containing all its characteristics and conditions, is simulated in Design Builder. DesignBuilder is a sophisticated software tool that functions as a building simulation and energy modeling platform and is designed to be user-friendly. It serves diverse professionals in the architecture, engineering, and construction sectors, along with energy assessors and sustainability consultants. DesignBuilder's primary goal is to assist in developing intricate 3D building models and allowing users to simulate and analyze different aspects of building performance, particularly emphasizing energy efficiency and environmental impact.

DesignBuilder's energy modeling capabilities are one of its fundamental functions. Users can create complex building models in the software, including building geometry, construction materials, HVAC systems, lighting fixtures, and occupancy schedules. Users can use these parameters to conduct simulations for forecasting and assessing the building's energy consumption, heating and cooling loads, and indoor environmental conditions across various scenarios [33].

DesignBuilder provides capabilities for daylighting analysis in addition to energy modeling. Users can use this feature to evaluate the presence and spread of natural light in the building, helping them improve the design to increase daylight exposure and decrease the need for artificial lighting. By evaluating the effectiveness of natural lighting, individuals can enhance occupant well-being, reduce energy consumption, and boost the overall eco-friendliness of the structure.

DesignBuilder also facilitates the incorporation of renewable energy systems into building designs. Users can simulate and evaluate the efficiency of technologies like solar panels, wind turbines, and geothermal systems to analyze their influence on energy usage, carbon footprints, and the general sustainability of buildings. By integrating renewable energy solutions, users can improve the building's energy efficiency, decrease its environmental impact, and potentially attain energy self-sufficiency [34].

DesignBuilder enables the simulation of different HVAC systems and control strategies. Users can simulate various heating, cooling, and ventilation systems to assess their energy efficiency, thermal comfort features, and overall influence on building performance. Users can determine the best HVAC solutions that balance energy efficiency and occupant comfort by examining options available in the software [35].

DesignBuilder also assists in ensuring compliance with building regulations. The software allows users to evaluate building designs according to recognized energy codes and standards established by organizations such as ASHRAE, LEED, BREEAM, etc. By assessing designs for regulatory compliance at the beginning of the design process, users can guarantee that their buildings adhere to the required energy efficiency standards and sustainability goals [36].

DesignBuilder provides parametric analysis features that enable users to investigate various design alternatives and situations. Through parametric studies, users can evaluate the influence of various design variables on building performance, energy usage, and environmental results. Users can pinpoint the most energy-efficient, cost-effective, and sustainable solutions for their projects by iteratively exploring and comparing design alternatives [37].

DesignBuilder is a robust and flexible tool that enables architects, engineers, and sustainability professionals to create and enhance energy-efficient, environmentally sustainable buildings. Users can utilize advanced modeling and simulation capabilities to improve design decisions, enhance building performance, and support the development of sustainable built environments [38].

The material applied in the model's walls, ground, roof, and other external components possesses precise thermophysical characteristics. The solar radiation in that specific longitude and latitude is also applied, and the thermal conditions is monitored by the software.

2.3. Simulation Tool and Window Configurations

DesignBuilder was utilized as the primary building performance simulation tool due to its robust integration with the EnergyPlus engine, allowing for accurate dynamic thermal modeling, daylighting analysis, and HVAC load calculations.

This research's primary objective is to keep the temperature at the same level while simultaneously reducing its tolerance. In order to improve thermal conditions, the purpose of this study is to investigate the possibility of controlling heat transfer through the utilization of double-layer and electrochromic windows rather than single-layer windows.

The following are the different types of heat losses that can occur in an indoor sports hall: Radiation, convection, and conduction are the three ways that heat is lost from the walls of the swimming pool. Both convection and radiation are responsible for the majority of the heat transfer that occurs through these mechanisms, which results in a significant amount of heat being lost through the windows. For the purpose of calculating the total heating load of the sports hall as well as the specific convective heat loss, the following mathematical equations can be utilized [39]:

$$Q_{tot} = Q_{conv} + Q_{cond} + Q_{eva} + Q_{rad} + Q_{w.m} \quad (1)$$

$$Q_{conv} = A_{up} \times U \times (T_w - T_{amb}) \quad (2)$$

The variable Aup denotes the total area of the upper surface of the hall, including both the walls and the roof, measured in square meters (m^2). The thermal heat transfer factor symbolized as U, represents the rate of heat transfer from the upper surfaces of the hall to the surrounding environment, measured in watts per square meter per Kelvin ($W/m^2{\cdot}K$). Ti is the desired indoor temperature in the hall, while Tamb is the surrounding temperature. The unit for convection heat transfer coefficient is $W/m^2.K$, also known as h, and is determined using the following equation:

$$h = 0.22 \times (T_i - T_{amb})^{1/3} \quad (3)$$

2.4. Materials

The single layer window used in the first analysis has a single green glazing that is 6 millimeters thick, covers the entire window (100 percent fitted glazing), has a wooden frame with zero outside reveal depth, and is not shaded or divided.

The double-layer window in the second investigation consists of two layers of 3-millimeters green glazing separated by a 13-millimeter gap filled with argon gas. The glazing percentage, framing, shading, and divider configuration are consistent with the previous study.

The third type of window used in the building being studied is an electrochromic window. Electrochromic windows regulate the entry of light and heat into a building by altering the transparency or tint of the window glass. This technology uses an electrochromic material that can change its optical characteristics when an electric current is applied. Users can manipulate daylighting, solar heat gain, glare, and privacy in a building by adjusting the tint of the glass.

Daylighting control involves regulating the amount of natural light that enters a space to improve visual comfort, decrease reliance on artificial lighting, and promote a more efficient indoor environment. Controlling solar heat gain is an advantage of these windows, as they can adjust the amount of sunlight entering, which helps decrease the need for cooling and enhances energy efficiency. Enhancing energy efficiency by optimizing daylighting and solar heat gain results in decreased energy consumption and operational expenses. Electrochromic windows can be incorporated into intelligent building systems to improve energy efficiency and building performance. Privacy and glare control are essential features that allow users to modify the glass's opacity to enhance privacy and reduce glare.

3. Results and discussion

The main approach of the study involves applying these different types of windows to the building and extracting data, tables, and graphs from DesignBuilder to analyze the impact of these systems on energy consumption and heat transfer. Five different data exports will be offered for each window type to analyze and compare their impact. The initial key graph will display the operative temperature in a yearly examination of the sports hall. The first graph in Figure 3 illustrates the fluctuations in different thermal parameters over a year, utilizing the single-layer window mentioned earlier. In Table 1, In the data extracted from DesignBuilder, some negative values are observed, which indicate energy loss or removal from the building rather than calculation errors. For instance, in the External Infiltration column, negative values such as -132.75 kWh represent the amount of energy lost from the building due to air infiltration. Similarly, in the Zone Sensible Cooling column, negative values such as -394.91 kWh indicate the energy extracted from the indoor space by the cooling system to lower the temperature. In general, positive values represent energy entering the building or space, such as heating, lighting, or solar gains, while negative values represent energy leaving or being removed from the space. This convention is standard in energy simulation software like DesignBuilder and allows for precise analysis of energy flows and evaluation of the performance of heating and cooling systems.

Analysis of the graph reveals that the highest recorded temperature in a year occurs on July 20th at 33.29 degrees Celsius, while the lowest recorded temperature happens on December 25th at 12.84 degrees Celsius. The same analysis on double-layer windows yields results displayed in Fig. 4 and Table 2. Analysis of the graph reveals that the highest recorded temperature in a year occurs on July 20th at 31.96 degrees Celsius, while the lowest recorded temperature happens on December 25th at 14.35 degrees Celsius. The same analysis on electrochromic windows yields results displayed in Fig. 5 and Table 3. Analysis of the graph reveals that the highest recorded temperature in a year occurs on July 20th at 32.2 degrees Celsius, while the lowest recorded temperature happens on December 25th at 14.27 degrees Celsius. The cooling and heating design needed for thermal comfort in the building is another subject examined for the three kinds of windows. The results of the heating design analysis for the single-layer window utilization can be seen in Fig. 6 and Table 4.

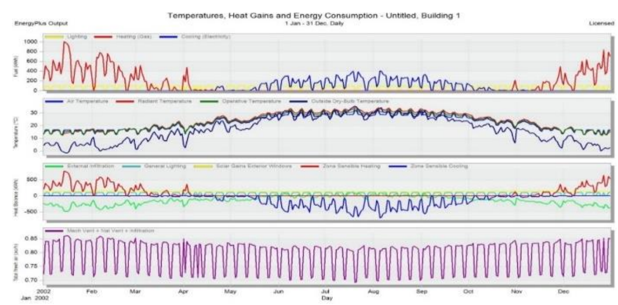

Fig. 3. Annual simulation of different thermal parameters using single-layer windows

Table 1. Different thermal parameters using single-layer windows

Parameters	Simulation Results									
Lightning (kWh)	0.00	86.15	86.15	0.00	86.15	86.15	86.15	0.00	86.15	86.15
Heating (Gas) (kWh)	0.00	114.92	10.58	0.00	0.00	0.00	0.00	0.00	1.32	82.34
Cooling (Electricity) (kWh)	0.00	0.00	0.00	0.00	193.90	253.36	218.24	1.83	10.22	0.00
Air Temperature	16.97	18.02	21.41	23.55	27.39	28.17	27.58	28.66	22.84	18.40
Radiant Temperature	18.46	19.02	22.46	25.03	29.71	30.62	30.48	29.56	24.63	19.92
Operative Temperature	17.72	18.52	21.94	24.29	28.55	29.40	29.03	29.11	23.74	19.16
Outside Dry-Bulb Temperature	10.83	9.75	16.35	17.78	29.51	32.94	28.21	25.31	15.46	8.56
External Infiltration (kWh)	-138.96	-188.58	-112.65	-128.25	43.70	99.16	11.48	-72.21	-165.3	-226.25
General Lightning (kWh)	0.00	86.15	86.15	0.00	86.15	86.15	86.15	0.00	86.15	86.15
Solar Gains Exterior Windows (kWh)	145.27	146.20	147.76	139.23	130.34	120.86	124.35	125.98	134.22	147.87
Zone Sensible Heating (kWh)	0.00	79.23	8.66	0.00	0.00	0.00	0.00	0.00	1.10	60.17
Zone Sensible cooling (kWh)	0.00	-14.72	-17.61	0.00	-323.43	-419.80	-371.56	-3.30	-40.42	-24.44

Table 2. Different thermal parameters using double-layer windows

Parameters	Simulation Results									
Lighting (kWh)	0.00	96.98	96.98	0.00	96.98	96.98	96.98	0.00	96.98	96.98
Heating (Gas) (kWh)	0.00	184.67	15.25	0.00	0.00	0.00	0.00	0.00	13.13	139.73
Cooling (Electricity) (kWh)	0.00	0.00	0.00	0.00	235.46	332.95	267.99	3.85	0.00	0.00
Air Temperature	16.04	17.57	21.19	22.57	27.94	28.84	28.33	29.31	22.01	17.68
Radiant Temperature	17.45	18.14	22.22	23.94	30.89	32.35	31.93	30.49	23.48	18.76
Operative Temperature	16.74	17.85	21.71	23.25	29.41	30.59	30.13	29.90	22.75	18.22
Outside Dry-Bulb Temperature	10.83	9.75	16.35	17.78	29.51	32.94	28.21	25.31	15.46	8.56
External Infiltration (kWh)	-132.75	-200.68	-121.37	-119.91	35.81	95.52	-5.07	-97.26	-165.37	-235.97
General Lightning (kWh)	0.00	96.98	96.98	0.00	96.98	96.98	96.98	0.00	96.98	96.98
Solar Gains Exterior Windows (kWh)	147.15	147.75	149.53	142.83	131.82	120.29	122.74	127.14	137.02	148.98
Zone Sensible Heating (kWh)	0.00	122.80	12.45	0.00	0.00	0.00	0.00	0.00	10.68	96.85
Zone Sensible cooling (kWh)	0.00	-3.40	-18.16	0.00	-394.91	-558.13	-458.18	-6.93	-21.08	-14.61

Table 2. Table of different thermal parameters using electrochromic windows

Parameters	Simulation Results									
Lighting (kWh)	0.00	61.02	61.02	0.00	61.02	61.02	61.02	0.00	61.02	61.02
Heating (Gas) (kWh)	0.00	135.91	4.21	0.00	0.00	0.00	0.00	0.00	0.00	77.63
Cooling (Electricity) (kWh)	0.00	0.00	0.00	0.00	161.55	214.43	201.01	10.63	0.85	0.00
Air Temperature	17.18	17.82	21.07	24.66	27.44	28.21	27.94	29.15	23.11	18.14
Radiant Temperature	18.28	17.96	21.77	25.91	29.57	30.54	30.76	30.07	24.35	19.01
Operative Temperature	17.73	17.89	21.42	25.28	28.51	29.38	29.35	29.61	23.73	18.57
Outside Dry-Bulb Temperature	10.83	9.75	16.35	17.78	29.51	32.94	28.21	25.31	15.46	8.56
External Infiltration (kWh)	-101.69	-130.30	-74.52	-108.20	30.13	69.61	2.75	-58.62	-121.50	-156.11
General Lightning (kWh)	0.00	61.02	61.02	0.00	61.02	61.02	61.02	0.00	61.02	61.02
Solar Gains Exterior Windows (kWh)	167.71	57.45	63.07	159.67	67.60	61.41	59.83	143.77	67.60	71.56
Zone Sensible Heating (kWh)	0.00	92.39	3.45	0.00	0.00	0.00	0.00	0.00	0.00	49.48
Zone Sensible cooling (kWh)	0.00	0.00	-9.83	0.00	-272.60	-360.13	-346.63	-19.14	-16.53	-5.53

Table 3. Heating design for single-layer utilization

Parameters	Amount
Air temperature(C°)	20.00
Radiant temperature(C°)	13.07
Operative Temperature(C°)	16.53
Outside Dry-Bulb Temperature(C°)	-3.60
Glazing (kWh)	-8.00
Walls (kWh)	-26.69
Ground floors (kWh)	0.73
Roofs (kWh)	-4.52
External infiltration (kWh)	-26.36
External Vent. (kWh)	-27.12
Zone sensible heating (kWh)	93.97

Table 5. Heating design for double-layer utilization

Parameters	Amount
Air temperature(C°)	20.00
Radiant temperature(C°)	16.81
Operative Temperature(C°)	18.41
Outside Dry-Bulb Temperature(C°)	-3.60
Glazing (kWh)	-8.69
Walls (kWh)	-1.03
Ground floors (kWh)	0.20
Roofs (kWh)	-5.09
External infiltration (kWh)	-23.41
External Vent. (kWh)	-24.09
Zone sensible heating (kWh)	62.12

Table 4. Heating design for electrochromic utilization

Parameters	Amount
Air temperature(C°)	20.00
Radiant temperature(C°)	16.72
Operative Temperature(C°)	18.36
Outside Dry-Bulb Temperature(C°)	-3.60
Glazing (kWh)	-9.19
Walls (kWh)	-0.33
Ground floors (kWh)	0.02
Roofs (kWh)	-5.08
External infiltration (kWh)	-16.58
External Vent. (kWh)	-17.07
Zone sensible heating (kWh)	48.22

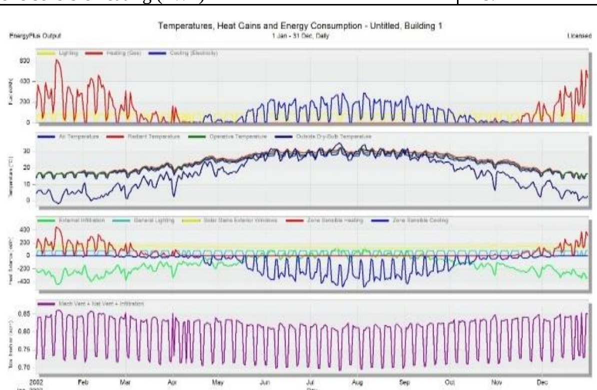

Fig. 4. Annual simulation of different thermal parameters using double-layer windows

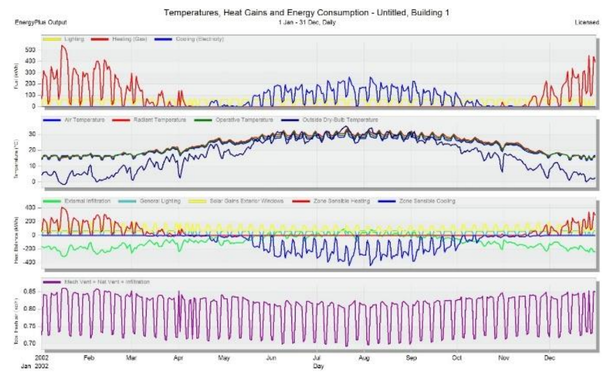

Fig. 5. Annual simulation of different thermal parameters using electrochromic windows

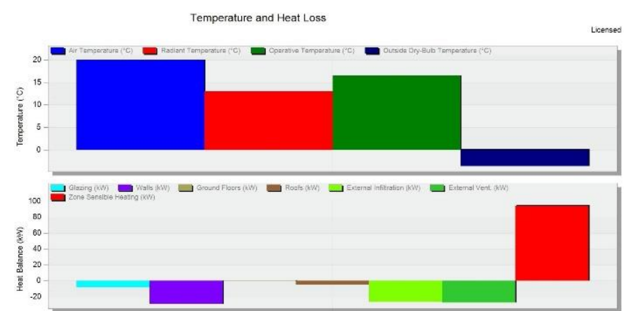

Fig. 6. Heating design for single-layer window utilization

Fig. 7. Heating design for double-layer window utilization

The results of the heating design analysis for the single-layer window utilization can be seen in Fig. 5 and Table 4. The results of the heating design analysis for the double-layer window utilization can be seen in Fig. 7 and Table 5. The results of the heating design analysis for the electrochromic window utilization can be seen in Fig. 8 and Table 6. The results of the cooling design analysis for the hottest day of the year (July 20th) for the single-layer window utilization can be seen in Fig. 9 and Table 7.

Table 5. Cooling design analysis on the hottest day of the year utilizing single-layer window

Time	2:00	4:30	7:00	9:30	11:00	13:30	16:00	18:30	21:00	23:30
Air Temperature(C°)	32.00	32.00	32.00	26.00	26.00	26.00	26.00	26.00	26.00	32.00
Radiant Temperature(C°)	32.92	32.70	33.03	31.63	32.22	32.73	32.95	32.77	32.65	33.03
Operative Temperature(C°)	32.46	32.35	32.51	28.81	29.11	29.37	29.48	29.39	29.32	32.51
Outside Dry-Bulb Temperature(C°)	30.20	29.52	29.52	32.21	36.24	39.04	40.50	39.83	37.81	34.90
Glazing (kWh)	-2.21	-2.36	1.22	4.39	8.77	11.64	11.47	8.50	7.28	-0.64
Walls (kWh)	10.13	9.65	5.94	19.02	10.20	7.62	7.66	10.31	13.07	525
Ground Floors (kWh)	-3.60	-3.17	-5.66	1.36	-2.18	-2.76	-2.69	-1.91	-1.89	-5.06
Roofs (kWh)	-0.96	-1.54	-2.20	-0.16	2.91	6.06	7.97	827	6.76	3.57
External Infiltration (kWh)	-1.80	·2.48	·2.48	6.11	9.96	12.57	13.91	13.29	11.43	2.82
Solar Gains Exterior Windows (kWh)	0.00	0.00	4.78	5.83	7.75	8.08	7.63	5.78	5.02	0.00
Zone Sensible cooling (kWh)	-1.61	-0.15	-0 34	-36.22	-47.16	-53.05	-55.89	-54.34	-51.87	-5.82
Total cooling (kWh)	-1.61	-0.15	-0 34	-36.22	-50.14	-60.63	-60.10	-62.38	-55.30	-5.82

Table 6. Cooling design analysis on the hottest day of the year utilizing electrochromic window

Time	2:00	4:30	7:00	9:30	11:00	13:30	16:00	18:30	21:00	23:30
Air Temperature(C°)	29.81	29.46	29.68	26.00	26.00	26.00	26.00	26.00	26.00	31.17
Radiant Temperature(C°)	29.63	29.43	30.04	29.72	30.03	30.43	30.58	30.41	30.15	30.35
Operative Temperature(C°)	29.72	29.45	29.86	27.86	28.02	28.21	28.29	28.21	28.08	30.76
Outside Dry-Bulb Temperature	30.20	29.52	29.52	32.21	36.24	39.04	40.50	39.83	37.81	34.90
Glazing (kWh)	-1.31	-1.46	2.40	5.06	9.64	11.44	11.76	9.78	8.92	0.11
Walls (kWh)	0.45	1.18	-1.64	3.95	1.84	0.02	-0.48	0.35	1.46	-3.79
Ground Floors (kWh)	0.47	0.75	-2.00	1.87	0.29	-0.62	-0.65	-0.03	0.57	-1.96
Roofs (kWh)	-0.26	-0.85	-1.62	0.04	3.36	6.51	8.43	8.73	7.25	4.21
External Infiltration (kWh)	0.23	0.03	-0.11	3.85	6.27	7.91	8.75	8.36	7.19	2.29
Solar Gains Exterior Windows (kWh)	0.00	0.00	5.22	6.47	3.03	3.47	3.18	2.22	0.94	0.00
Zone Sensible cooling (kWh)	0.00	0.00	0.00	-20.84	-30.54	-34.90	-37.27	-35.84	-32.90	0.00
Total cooling (kWh)	0.00	0.00	0.00	-20.84	-32.42	-39.67	-39.92	-40.90	-35.06	0.00

Table 7. Cooling design analysis on the hottest day of the year utilizing electrochromic window

Time	2:00	4:30	7:00	9:30	11:00	13:30	16:00	18:30	21:00	23:30
Air Temperature(C°)	29.89	29.55	29.79	26.00	26.00	26.00	26.00	26.00	26.00	31.29
Radiant Temperature(C°)	29.75	29.54	30.24	29.84	30.27	30.76	30.94	31.02	30.61	30.49
Operative Temperature(C°)	29.82	29.55	30.02	27.92	28.14	28.38	28.47	28 51	28.30	30.89
Outside Dry-Bulb Temperature	30.20	29.52	29.52	32.21	36.24	39.04	40.50	39.83	37.81	34.90
Glazing (kWh)	-1.35	-1.50	2.70	5.18	8.73	11.13	11.11	8.83	7.58	0.06
Walls (kWh)	0.48	1.22	-2.00	4.18	2.25	0.22	-0.46	-1.42	0.72	-3.81
Ground Floors (kWh)	0.55	0.83	-2.26	2.08	0.52	-0.57	-0.69	-1.26	0.18	-1.86
Roofs (kWh)	-0.27	-0.87	-1.68	0.10	3.43	6.54	8.44	8.55	7.22	4.23
External Infiltration (kWh)	0.18	-0.02	-0.18	3.85	6.27	7.91	8.75	8.36	7.19	2.22
Solar Gains Exterior Windows (kWh)	0.00	0.00	5.70	6.55	1.34	1.58	1.50	5.88	2.30	0.00
Zone Sensible cooling (kWh)	0.00	0.00	0.00	-21.32	-28.77	-33.08	-35.02	-35.03	-31.71	0.00
Total cooling (kWh)	0.00	0.00	0.00	-21.32	-30.65	-37.85	-37.67	-40.08	-33.87	0.00

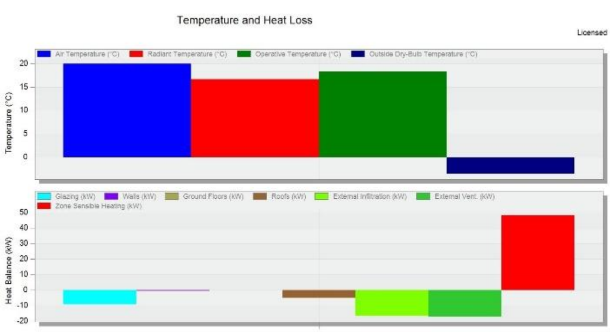

Fig. 8. Heating design for electrochromic window utilization

The results of the cooling design analysis for the hottest day of the year (July 20th) for the double-layer window utilization can be seen in Fig. 10 and Table 8. The results of cooling design analysis for the hottest day of the year (July 20th) for the electrochromic window utilization can be seen in Fig. 11 and Table 9.

3.1. Thermophysical Mechanisms Driving Window Performance

A critical observation from the simulation results is that the double-layer window marginally outperformed the electrochromic window in both peak summer and winter operative temperatures.

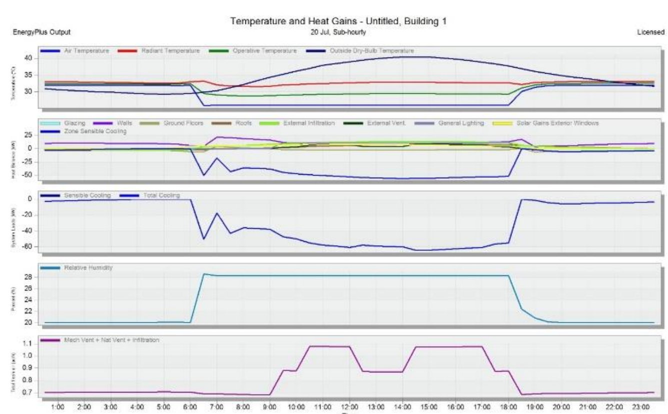

Fig. 9. Cooling design analysis on the hottest day of the year utilizing single-layer window

This counter-intuitive result given the dynamic capabilities of ECDs can be attributed to the specific physical mechanisms of heat transfer dominant in Tehran's semi-arid, mixed climate. In this climate, conductive heat transfer through the building envelope is a primary driver of energy loss during the cold winters and a significant factor during summer nights. The double-layer window, filled with 13mm of argon gas, provides a consistently high thermal resistance

(R-value) and a significantly lower baseline U-value compared to the electrochromic glazing. While the electrochromic window excels at dynamically reducing the Solar Heat Gain Coefficient (SHGC) to block shortwave solar radiation during hot summer days, its baseline U-value (particularly in the clear/bleached state during winter or at night) is inherently higher than that of an argon-filled double-glazed unit. Consequently, the superior baseline conductive insulation provided by the double-layer window effectively mitigates both winter heat loss and summer conductive heat gain, outweighing the dynamic solar control benefits of the electrochromic window in this specific architectural and climatic context.

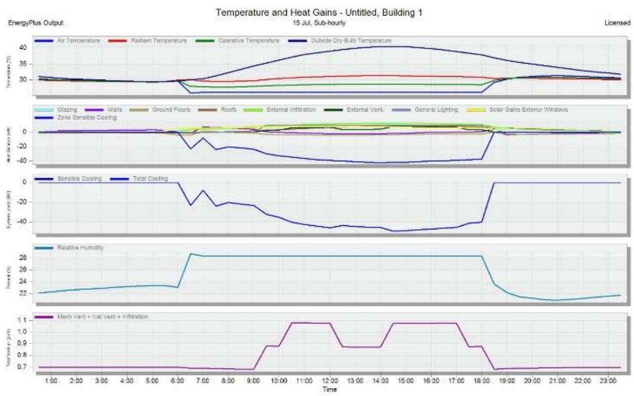

Fig. 10. Cooling design analysis on the hottest day of the year utilizing double-layer window

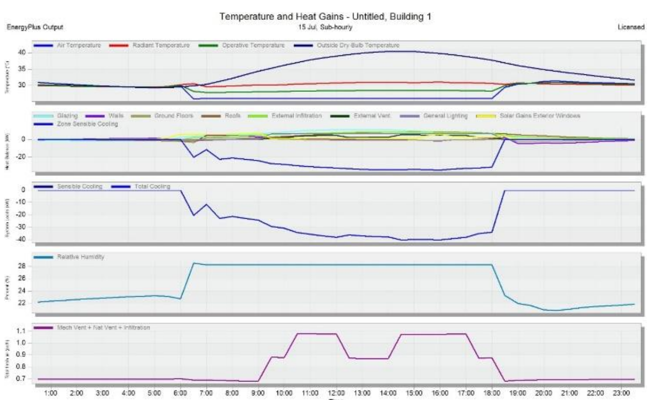

Fig. 1 Cooling design analysis on the hottest day of the year utilizing electrochromic window

Table 10. Summary of Key Thermal Performance Results for the Three Window Configurations

Window Type	Peak Summer Operative Temp. (July 20)	Peak Winter Operative Temp. (Dec 25)	Winter Heating Design Operative Temp.
Single-Layer	33.29 °C	12.84 °C	16.53 °C
Double-Layer	31.96 °C	14.14 °C	18.41 °C
Electrochromic	32.20 °C	14.27 °C	18.36 °C

3.2. Practical Challenges and Technological Advancements in ECDs

While the simulation highlights the theoretical thermal benefits of electrochromic windows, their widespread practical adoption in the construction industry faces several tangible challenges. The primary barriers include high initial manufacturing costs, long-term durability concerns (such as electrolyte degradation and delamination), and relatively slow switching speeds compared to other dynamic glazing. However, recent technological advancements are actively addressing these limitations. To combat durability issues related to moisture sensitivity, recent studies have developed lithium-salt-free, hydrophobic solid-state poly(ionic liquid) electrolytes, which enable unencapsulated devices with excellent cycling stability and environmental resilience. Furthermore, to reduce the high cost associated with traditional Transparent Conducting Oxides (TCOs), innovative low-cost hybrid electrodes, such as ITO/Al-mesh and ITO/Ag/ITO (IAI) multilayers, have been successfully fabricated, maintaining high optical transmittance while significantly lowering sheet resistance and material costs. Finally, morphology-controlled multilayer designs for the electrochromic layers (e.g., WO3 films) have been proposed to mitigate surface cracking and peeling during prolonged ion intercalation cycles, thereby enhancing the overall lifespan and switching kinetics of the devices. These material-level innovations suggest that the economic and durability barriers of ECDs are rapidly diminishing, paving the way for their broader integration into sustainable building envelopes.

3.3. Applicability to Different Climatic Zones

It is crucial to contextualize these findings within the specific climatic conditions of Tehran. The superior performance of the double-layer window in this study is primarily due to the significance of conductive heat transfer (U-value) in this mixed, semi-arid climate. However, the generalizability of these results to other climatic zones requires careful consideration. In cooling-dominated climates with high solar irradiance (e.g., tropical or hot-arid regions such as Singapore or Dubai), the physical mechanisms driving energy consumption shift heavily toward solar heat gain. In such contexts, the dynamic SHGC modulation of electrochromic windows would likely demonstrate superior performance and a faster return on investment, as the reduction in cooling loads would far outweigh the benefits of baseline conductive insulation. Therefore, while double-glazing remains the most cost-effective and thermally efficient solution for the current case study, electrochromic technologies hold immense, untapped potential for energy conservation in heavily solar-exposed, cooling-dominated urban environments.

4. Conclusions

This study conducted a comparative techno-thermal analysis of single-layer, double-layer, and electrochromic windows in a sports facility located in Tehran's mixed, semi-arid climate. By utilizing dynamic building energy simulation, the research quantified the impact of each glazing type on operative temperatures and heating/cooling loads. The key numerical findings for the three scenarios are summarized in Table 10. Based on the comprehensive analysis of the simulation results, the following main conclusions are drawn: Superiority of Static Insulation in Mixed Climates: The double-layer (argon-filled) window demonstrated the best overall thermal performance, achieving the lowest peak summer temperature (31.96 °C) and the highest winter temperature (14.14 °C). This indicates that in climates where conductive heat transfer is a dominant factor, baseline thermal resistance (R-value) outweighs dynamic solar control. Limitations of Electrochromic Windows in the Case Study: Although electrochromic windows effectively modulate solar heat gain, their performance was slightly outpaced by the double-layer window. This is attributed to the higher baseline U-value of the electrochromic glazing compared to the argon-filled double-glazed unit, highlighting a trade-off between dynamic SHGC control and static conductive insulation. Economic and Practical Implications: Given that double-layer windows are significantly more cost-effective in terms of initial investment and manufacturing compared to current electrochromic technologies, they represent the most practical and energy-efficient fenestration solution for the specific climatic context of Tehran. Future Outlook for Smart Glazing: While electrochromic windows did not outperform double-glazing in this specific study, their true potential is highly climate-dependent. In cooling-dominated, high-solar climates, dynamic glazing is expected to yield superior energy savings. Furthermore, ongoing advancements in solid-state electrolytes and low-cost hybrid electrodes are rapidly addressing the durability and cost barriers of ECDs, suggesting a highly promising future for smart windows in net-zero building designs.

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