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Advancing Sustainable Healthcare Facilities. Assessing the performance of Electrochromic Windows through Energy and Comfort KPIs. A case study

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Abstract

The current study, examines the case of a small-scale renovation of a hospital clinic, involving the replacement of the existing windows with advanced Smart Insulated Glass Units (IGUs), specifically Electrochromic (EC) glazing systems. A comparative assessment of the past and post-renovation condition is carried out in order to highlight the benefits of this intervention. This analysis is based on selected essential Key Performance Indicators (KPIs) addressing the needs of multiple stakeholder groups, with particular emphasis on patients and medical staff. In parallel, the study aligns with overall sustainability objectives by assessing the contribution of EC windows to energy savings, to optimize the renovation project.

A comparison of the performance over the entire year was performed, using the EnergyPlus software, and the results showed a reduction of the energy heating, cooling and lighting demands for the post installation state by ca. 10%. The simulation analysis of the indoor comfort KPIs, showed also an improvement in the thermal comfort conditions, due to the operation of the electrochromic windows that lead to a reduction of radiant temperature inside the patient rooms.

After the renovation, healthcare workers reported improved satisfaction with thermal comfort conditions, while they noted that interior shading was no longer necessary, due to reduced glare. This change also improved patients' psychological well-being and recovery, as access to natural light and continuous visual connection with the outside environment were maintained throughout the day.

Keywords: Electrochromic Windows; Key Performance indicators; Energy savings; Thermal Comfort; Visual comfort; patient well-being.

Highlights

- Installation of EC glazing reduced total energy demands by 9.5% in the hospital clinic renovation.
- Thermal comfort improvement with discomfort hours decreased by ca. 27%.
- EC windows eliminated need for interior shading while maintaining 500+ lux daylight

1 Introduction

Sustainable design of healthcare facilities is crucial for promoting patient well-being while addressing environmental and energy challenges. Hospitals, are among the most energy- intensive building types due to their continuous 24-hour operation and the critical demand for steady energy supply to support medical equipment, lighting, heating, cooling and ventilation systems. This sector represents about 7% of the electricity consumed in commercial buildings and releases 2.5 times more carbon emissions than typical commercial facilities (Billanes et al., 2018). The complexity and diversity of energy use in hospitals underscores the need for integrated energy-efficient measures.

Global climate commitments and increased awareness of environmental impacts have accelerated the shift to energy efficient and sustainable technologies in the design of healthcare facilities. Healthcare buildings are increasingly adopting green building standards, intelligent energy management systems, and renewable energy solutions to reduce operational costs and minimize carbon footprint, while maintaining high standards of medical care and indoor comfort (Karliner et al., 2019].

A critical component of sustainable healthcare facility design is to manage the daylight and energy ingress through building facades. The judicious integration of the daylight has been linked not only to reduced lighting demand, but also to improved physiological and psychological health outcome for occupants, including patients and healthcare professionals. Research indicates that access to daylight and views, often provided through optimally designed windows, can lead to reductions on blood pressure, enhanced mood, decreased sleepiness and greater satisfaction and productivity among staff and patients alike. (Zadeh et.al.,2014).

However, the extensive use of glazing presence challenges. Poorly controlled solar gains lead to increased thermal loads, glare, and higher heating and cooling requirements. Against this backdrop, the integration of advanced glazing technologies, particularly electrochromic (EC) windows are capable of dynamically modulating solar heat gain and daylight transmission in response to external conditions or user control, thereby contributing to reduced heating, cooling, and lighting energy demands. This adaptive behavior not only supports energy conservation goals but also helps to maintain optimal indoor comfort conditions conductive to patient recovery and personnel well-being.

Electrochromic (EC) glazing technologies have been widely studied in the context of energy-efficient building design, particularly for their ability to modulate solar radiation and control daylight admission. Numerous studies have highlighted the benefits of EC windows in reducing cooling loads, mitigating glare, and improving visual and thermal comfort in commercial buildings. (Wymelenberg, & Inanici, 2009), (Karlsson & Roos, 2001). However, the application of EC windows in healthcare environments, particularly in hospital settings, remains relatively underexplored despite the sector's high energy intensity and strict indoor environment requirements.

Lee et al (Lee et al, 2000) conducted early experimental studies demonstrating that EC glazing can significantly reduce peak cooling demand and improve lighting energy performance under variable sky conditions. Similarly, Tzemperlikos and Athienitis (Tzempelikos, & Athienitis, 2007) analyzed the integration of EC windows with daylighting controls and found combined effects in reducing overall energy consumption. More recent simulations by Baetens et al. (Baetens et al., 2010) assessed the performance of EC technologies in different climatic zones, confirming their effectiveness in modulating solar gain and maintaining thermal comfort across seasonal variations.

In healthcare environments, the need to balance energy performance with patient-centric considerations adds complexity to façade design. Research by Boubekri et al. (Boubekri et al., 1991) emphasized the importance of daylight and views in promoting patient recovery, suggesting that dynamic glazing systems like EC windows could contribute to both clinical and operational outcomes. A study of Reinhart and Ward (Reinhart & Ward, 2004), explored how EC windows could be adapted for use in spaces requiring precise control of lighting and indoor temperature, such as patient rooms and intensive care units.

Despite these findings, the literature reveals a gap in extensive reviews of EC window performance in hospital courtyards and common areas, where daylight access and glare control are critical but often overlooked. Furthermore, most existing research is based on more office environment occupancy profiles, which do not adequately reflect the continuous operation and specific functional need of healthcare environments. This study aims to address as possible these gaps by evaluating the thermal and visual performance of EC windows in a hospital yard, using dynamic simulation tools and performance-based metrics align with healthcare design standards.

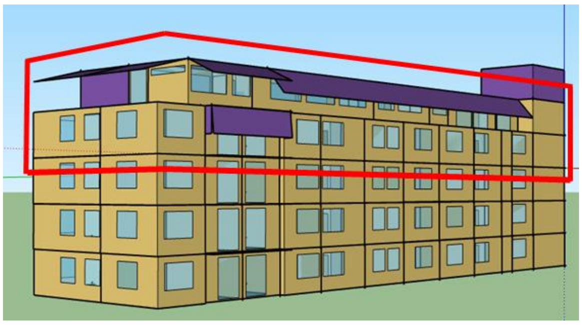
The concept of sustainable healthcare facilities, emphasizes the integration of technology and processes to create facilities that are safe, healthy, comfortable, and conductive to the well-being of occupants, with energy efficiency being the key feature. This paper explodes the potential impact of electrochromic windows on energy savings within a hospital yard, contributing to the broader understanding and implementation of bright green hospital principles. By adopting sustainable designs and intelligent technologies, hospitals can significantly reduce their environmental footprint while maintaining high service quality and occupant comfort.

2 Methodology

2.1 Building Model and Assumptions

To comprehensively assess the impact of electrochromic (EC) window installation on energy performance and occupant comfort in a hospital setting, a dynamic simulation was conducted using the EnergyPlus Software. The case study, focuses on the General State Hospital of Nikaia (NHOSP), one of the largest healthcare facilities in Greece and in whole Balkan Area. The simulated model includes the pediatric yard on the third floor (Clinic A) and the fourth floor (Clinic B) of the hospital Figure 1. 700m^2 of a total conditioned area on the simulated model are examined, divided into 22 thermal zones in Clinic A and adjacent spaces in Clinic B, as to capture shading and boundary effects The primary analysis is targeting to Clinic A, due to its high Window to Wall Ratio (WWR), 36.1% on the south and 21.7% on the West façade. 15 EC windows in total replace the existing ones on the South and the West facades on the Clinic A, corresponding to eight patient rooms and two administrative offices, enabling dynamic control of solar heat gains and visible light transmission. Prior to the renovation, in the existing state of the Clinic A, the building envelope featured double-glazed windows with an 12mm air gap with U-value of 2.74W/m^{2}K, contributing to significant energy and comfort issues.

Figure 1 Overview of the simulated building model



Four glazing configurations were compared in total. The existing state, a reference state with triple low-e glazing (U-value: 0.55W/m^{2}K), a theoretical upgrade of the reference state with 25% lower U-value (U-value: 0.41W/m^{2}K), and the renovation state with dynamic EC windows (U-value: 0.54W/m^{2}K). Main thermal and optical properties of the evaluated windows configurations are shown in Table 1. EC glazing properties are defined in both clear and dark states to account of dynamic switching behavior.

Table 1 Summary of Thermal and optical characteristics of evaluated windows types

Window Type	***U-value [W/m^{2}K]***	***g-value***	***τvis***
Existing State (Initial)	*2.74*	*0.76*	*0.81*
Reference	*0.55*	*0.56*	*0.77*
Reference 25%	*0.41*	*0.56*	*0.77*
Renovation State (EC)	*0.54*	*0.41/0.21*	*0.63/0.34*

Concerning ventilation rates, occupancy, internal loads, heating and cooling setpoints were assigned according to Greek national guidelines (KENAK) (Hellenic Republic, 2017) for hospital environments and ASHRAE 90.1 standards (ASHRAE, 2019). The simulation assumed continuous HVAC operation and zone-level control strategies to maintain thermal comfort within standard healthcare setpoints. The operative temperature during the heating and cooling period and the required values for fresh air, concerning ventilation, are presented in Table 2. Due to specific functional requirements of the hospital environment, the heating and cooling setpoints are specified according to standardized operational protocols to ensure consistent indoor environmental conditions. These operational characteristics of the hospital clinics are summarized in Table 3.

Table 2 Setpoint temperatures and ventilation requirements for Clinic A and Clinic B

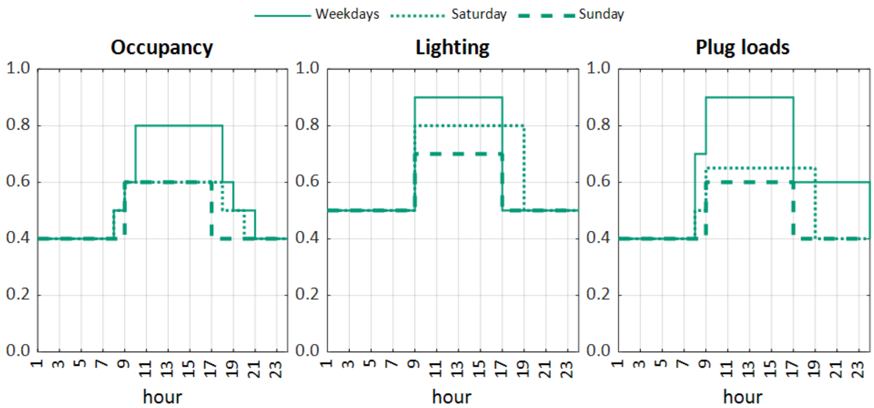
Hospital Units	Spaces	Temperature [°C]		Air intake/Air Discharge
		Heating	Cooling	[ACH]
Clinic A/B	Bed Units	22	25	10
	Other Occupied Spaces	22	26	5

Table 3 Operational characteristics of the hospital units

Operational characteristics	Spaces	
	Bed Units	Other Occupied spaces
Occupancy and Activity	22persons/100m^2	10persons/100m^2
Artificial lighting	500lux	200lux
Equipment	8W/m^2	15W/m^2

Figure 2 also presents the operational schedules applied for occupancy profiles and internal heat gains – lighting and equipment loads – as defined by ASHRAE Standard 90.1, to reflect realistic usage patterns within the hospital zones.

Figure 2 – Operational schedules for occupancy profiles and internal gains



2.2 KPI Categorization for Sustainable Healthcare Renovation

In the past, operational and financial metrics have primarily been used for the evaluation of building renovation projects. However, as a result of the increased global emphasis on the Sustainable Development Goals (SDGs) (United Nations, 2015), stakeholders are now adopting more comprehensive performance frameworks that integrate technical innovations, human well-being, and environmental resilience. Electrochromic (EC) glazing represents a transformative renovation solution, demanding multi-dimensional Key Performance Indicators (KPIs) to quantify its impact. Based on building sustainability standards, KPIs are categorized into two main pillars, concerning energy and comfort indicators The Energy Performance Indicator for EC glazing is evaluated through the energy demand indicator in [kWh/m^2]. The simulated Heating/Cooling requirements maintain ISO 18523-1 compliant thermal conditions, calculated using dynamic state-switching modeling of EC glazing (ISO, 2016). Concerning thermal comfort indicator, consistent with ASHRAE 55, thermal comfort into the examined pediatric renovated yard, is evaluated through Fanger's Predicted Mean Vote (PMV), accounting for six critical variables, air temperature, mean radiant temperature, air speed, relative humidity, metabolic rate and clothing insulation (ASHRAE, 2017). For visual comfort assessment, useful daylight illuminance (UDI) is served as the primary quantitative indicator for visual comfort, evaluated through hourly simulations across the occupied zones. Consistent with EN17038:2018, a target illuminance of 500lux was maintained for the bed units, at critical task planes e.g. at 0.75m height (CEN, 2018). EC glazing dynamically regulated illuminance through state-dependent visible transmittance. At clear state, the daylight harvesting is maximized under low-sun conditions, while tinted state prevents from high glare conditions during high-irradiance periods.

3 Simulation and Results

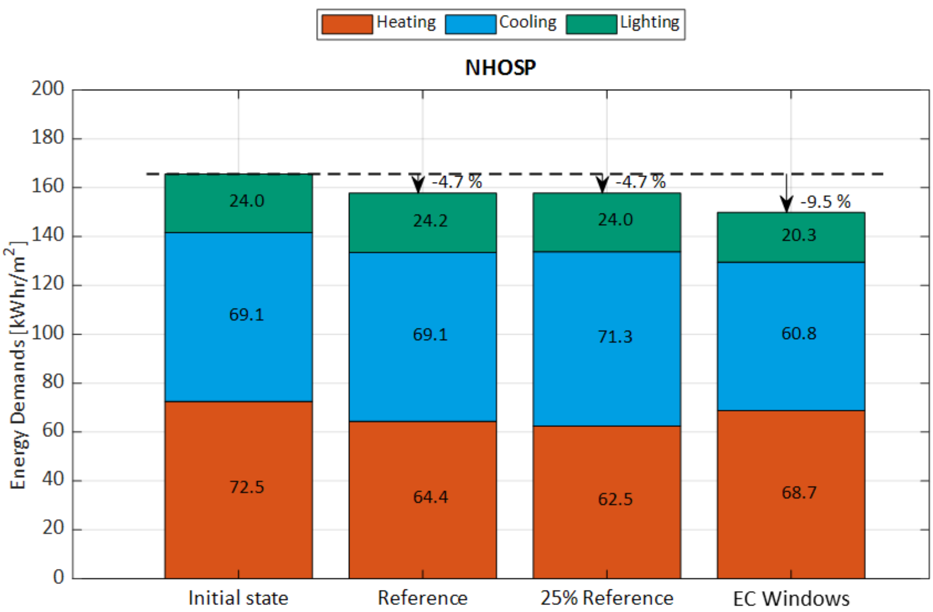
3.1 Energy Performance

The implementation of electrochromic (EC) windows in the south and west facades of Clinic A, resulted in a measurable improvement in building energy performance. Energy simulations conducted using EnergyPlus, revealed that the EC windows reduced the overall annual energy demand by 9.5%, compared to the pre-renovation state with double-glazed windows. The total energy demands by the installation of the EC windows leads to a yearly reduction from 166kWh/m^2 in the existing state, to 150kWh/m^2. This reduction was primarily driven to a 12.1% decrease of cooling energy consumption, demonstrating the effectiveness of EC glazing in modulating solar gains especially during peak irradiation periods. Additionally, heating demands were reduced by 5.2%, due to improved thermal insulation (U-value reduction from 2.74 to 0.54W/m^{2}K).

Compared with the reference case, using state-of-the -art triple-pane low emissivity glazing, the EC windows outperformed by nearly doubling the energy savings, indicating their added value in dynamic building envelope applications within healthcare settings. Moreover, the comparison between with the theoretical reference state of 25% reduced U-value reveals a 4.7% reduction in energy consumption highlighting the critical role of solar and visible light properties of EC configuration, in achieving energy savings. Unlike common glazing, EC glazing can dynamically adjust their tint based on the external conditions, effectively modulating solar heat gains and visible light transmission throughout the day. This adaptability allows EC windows to minimize the unwanted solar heat during peak sunlight, reducing cooling loads from 71.3kWh/m2 to 60.8kW/m2, while also maximizing daylight use when beneficial, thereby decreasing reliance on artificial lighting. This ability to optimize energy performance through real-time control of solar and visible properties prove to be a significant advantage over static glazing solutions, even when the latter offers a lower U-value.

Finally, unlike all the other examined cases, where the use of the internal shading requires the force of artificial lighting for longer periods during a day, EC windows autonomously maintain optimal internal illuminance by maximizing the natural daylight. This leads to a reduction in lighting energy demand by 15% due to the dynamic solar transmittance adaptation (τ_{vis}: 0.63 → 0.34).

Figure 3 – Total annual energy demands after the installation of EC windows, the pre-renovation, the reference and the improved reference glazing.



3.2 Thermal Comfort

Thermal comfort analysis was assessed through the Predicted Mean Vote (PMV) index, with target comfort Class C, defined by ISO 7730 thresholds, as lying with the range of -0.7 to +0.7. The PMV calculations incorporated standardized assumptions for the healthcare environments: air velocity of 0.2m/s, activity level of 120W/m^2, and clothing insulation values of 0.5clo for summer and 1.0clo for winter conditions. In the pre-renovation state, discomfort hours for patients totaled in 1422hr/year, whereas following EC windows installation, discomfort hours were reduced to 1044hr/year, indicating a 26.6% improvement, meaning 378 hours. This impact of this thermal buffering is critical in hospitals where patients require strict temperature stability. Figure 4 presents the annual PMV values of patients for the initial and renovation state, indicating the limits of PMV to achieve desired thermal comfort conditions.

Figure 5, illustrates the critical relationship between radiant temperature fluctuation and thermal comfort during peak summer conditions, from 1^{rst} to 10th of August. When the EC windows are transitioned to their fully dark state (g-value=0.21), during high-irradiance periods, the interior radiant temperature is decreased by up to 1°C, relative with the existing state with double glazed windows. This situation directly moderated PMV indices, maintaining them within the comfort boundaries of -0.7 ≤ PMV ≤ 0.7. In contrast, the double -glazed windows consistently allowed PMV values to exceed the upper hot discomfort limit, during midday hours due to uncontrolled solar gains. Critically, the installation of EC windows can also eliminate the on-demand thermostat adjustments, through manual interventions in Greek hospitals, especially during heatwaves.

Figure 4 – Annual PMV indexes for the initial and the renovated state

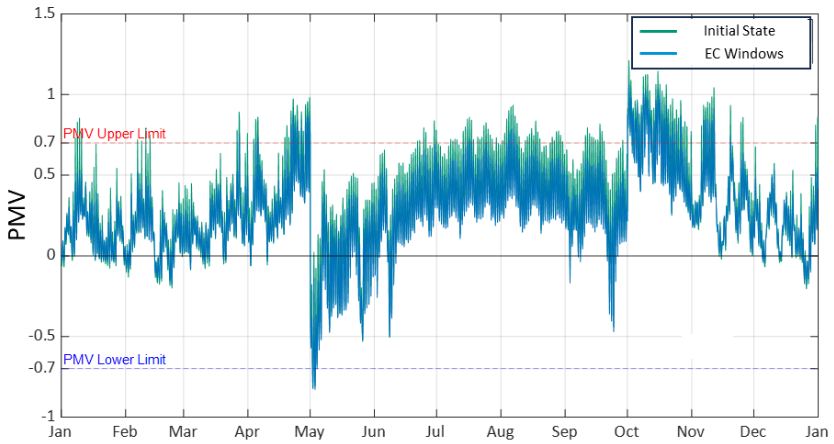
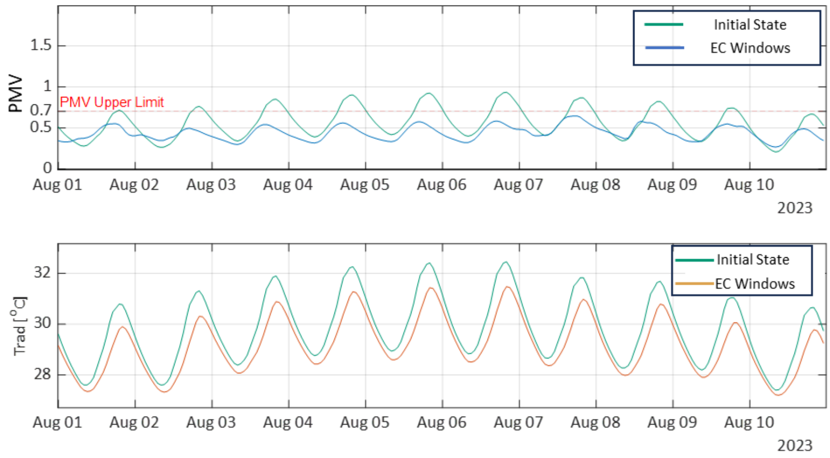


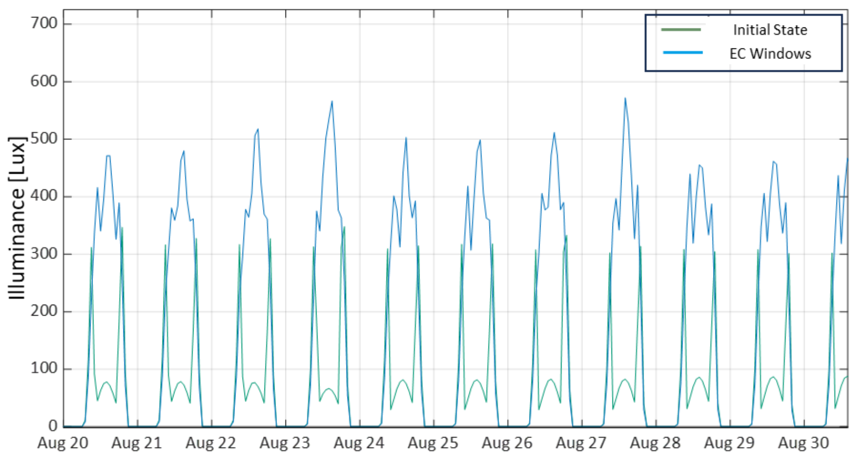
Figure 5 – PMV index and radiant Temperature (Trad) during a 10-day summer period.



3.3 Visual Comfort

The installation of EC glazing, also addressed visual comfort challenges in clinical spaces. In the pre-renovation state, internal shadings – curtains, were frequently used to mitigate glare, which significantly reduced daylight availability. Following the implementation of EC glazing, transformed visual conditions by eliminating glare without compromising daylight quality, thereby removing the need for interior shading devices. As illustrated in Figure 6, during a representative 10day summer period, daylight illuminance in patient rooms remained consistently above 500lux – recommended level for healthcare environments – avoiding glare and visual discomfort conditions. In contrast, during the pre-renovation state, double glazing with conventional blinds, reduced illuminance to sub functional levels (~70lux), necessitating artificial lighting even during peak daylight hours. In conclusion, the installation of EC windows, achieved dual benefits. Not only reduced reliance of artificial lighting, but also contributed positively to patient well-being by meaning a visual uninterrupted connection to the outdoors throughout the day.

Figure 6 – Daylight illuminance for a patient room during a 10-day summer period.



4 Conclusion

The current study assessed the performance of electrochromic (EC) windows installed in a high-occupancy pediatric clinic of a hospital through a dynamic energy simulation. Annual simulations results showed a 9.5% reduction in total energy demands, and 26.6% fewer thermal discomfort hours, compared to the existing state, exceeding also the performance of conventional triple-pane low-e glazing. Visual comfort also was improved significantly, as the EC windows eliminated the need for interior shading, preserved outdoor views and maintained daylight levels near 500lux throughout the day. Unlike static windows, EC's dynamic tinting can maintain consistent illuminance levels despite changing outdoor conditions. That's the unique angle to emphasize – how adaptive glazing solves a problem that even high-performance triple pane windows can't address effectively.

The findings support the viability of EC glazing as a dual-purpose strategy for enhancing occupant comfort and reducing operational energy costs in healthcare facilities. The results are particularly relevant in high-occupancy and high-sensitivity environments such as hospitals, where maintaining thermal and visual comfort without sacrificing energy efficiency, is a critical design challenge. The observed benefits also align with global healthcare design guidelines emphasizing patient – centered environments and sustainable targets. Overall, EC glazing presents a robust solution for enhancing building and patient-centered design in hospitals. Its integration supports both energy efficiency goals and improved healthcare outcomes, aligning with the broader sustainability agenda or modern medical infrastructure.

Acknowledgements

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Data Availability Statement

All simulation inputs/outputs e.g EnergyPlus IDF/EPW files, PMV outputs, analysis scripts, are available from the corresponding author upon reasonable request and institutional approval. Raw occupancy and staff feedback cannot be shared due to hospital privacy policies and patient confidentiality requirements.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study, in the analysis or interpretations of data, the writing of the manuscript, or in the decision to publish the results.

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