Journal of Engineering Research

Volume 7
Issue 4 *4*

Article 5

2023

The Impact of Using Smart Windows Technique in Reducing Energy Consumption and Improving Building Performance in the Office Building

Alaa Mohamed Khalifa, Walaa Noor, Rania Elghamry

Journal of Engineering Research (ERJ)
Vol. 7 – No. 4, 2023
©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

The Impact of Using Smart Windows Technique in Reducing Energy Consumption and Improving Building Performance in the Office Building

Alaa Mohamed Khalifa[1], Walaa Ahmed Nour[2], Rania Elghamry Ashmawy[3]

[1]Master Student; Department of Architecture; Faculty of Engineering, Tanta University, Tanta, Egypt – email: alaa147823@f-eng.tanta.edu.eg
[2]Professor, Department of Architecture; Faculty of Engineering, Tanta University, Tanta, Egypt – email: walaanour@f-eng.tanta.edu.eg
[3]Lecturer, Department of Architecture; Faculty of Engineering, Tanta University, Tanta, Egypt – email: rania.elghamry@ejust.edu.eg

***Abstract*- With the world's population increasing rapidly and industry modernization, building energy consumption is rising. Over 40% of the world's energy consumption is generated by buildings, and about 10% of this portion is consumed by office buildings through its uses of HVAC, office equipment, and lighting.**

***Research Problem*- In recent periods, Office buildings in Egypt have consumed a lot of energy to provide adequate lighting to occupants through windows, which is the reason for overheating and high thermal losses. It accounts for 60% of the building's energy loss.**

***Research Objective*- I am conducting this study to determine whether utilizing Smart windows techniques can help reduce energy consumption and improve the building performance of office buildings in Egypt.**

***Research Methodology*-**

- **The theoretical part used to review existing theoretical Studies to collect sufficient data on Windows and how they impact energy consumption, as well as Smart Windows techniques in buildings and the differences between them.**
- **The applied part used the Design Builder software to present the effect of Electrochromic Smart windows and window orientation for office buildings in Egypt. The analysis showed that the Smart application in Egypt has improved building performance and energy consumption significantly reduced by 14%, which is a great accomplishment.**

Results- showed that the annual energy was reduced by 14% due to using optimally designed and controlled Smart-glazed windows.

***Keywords:* Smart Materials, Smart Windows, Electrochromic Material.**

I. Introduction

As the world's population continues to rise and the industry becomes more modernized, experts predict a significant increase in energy consumption within buildings [1]. Buildings account for 30–40% of all consumed energy in developed countries, exceeding the necessary amounts for industrial and transport purposes [2]. Currently, office buildings in Egypt consume 20% in terms of total energy through the heating, ventilation, and cooling systems, in addition to lighting and air conditioning (HVAC) systems that consume a big percentage of energy consumption assigned for buildings, accounting for half of the total consumption [3]. One of the highest measures in solving this problem is that the energy efficiency of buildings should be improved.

A. Windows

The envelope of the building plays a crucial role in the heat transfer between outdoors and indoors because it behaves as a barrier between the indoor workspaces and the outside. The environmental performance of a building is typically determined by its construction and design features that consider the external climate factors and their impact on energy consumption [4]. Windows has a significant impact in controlling the amount of energy consumed as well as the indoor environment quality in the buildings they serve [5] and provides daylight and outdoor views to the building's occupants, which have been established to be significant for the comfort of humans. In addition, windows are weak for the building's energy performance due to their large thermal bridge, high thermal losses at the building envelope, undesired heat gains, and glare [6]. A suitable design of windows can provide various benefits, such as allowing enough solar energy and daylight to pass through for natural lighting and passive heating, reducing heat losses to save energy used for heating, preventing glare and overheating, and providing satisfactory views both from inside and outside of the building [7].

Notably, the characteristics of the windows themselves, including dimensions, orientation, and placement within the building facade, play a pivotal role in affecting the windows' performance and their effect on enhancing the performance of the internal environment and the amount of used energy in buildings, considering energy-efficient design decisions for the building is significant to keep in mind the impact of building orientation. By choosing the most optimal orientation, you can minimize direct sun radiation and improve the energy performance of the building envelope. This can be achieved using the precise placement of windows, building openings, and external opaque walls [8]. Traditional windows are typically a fixed component in a building, and the climate constantly shifts as temperatures and solar radiation change. Achieving a balance between Letting daylight, outdoor views, and solar heat while avoiding glare and overheating can be challenging. A valuable way to reduce energy consumption in the space can be by using accessory solar shading devices, like curtains or Blinds. However, advanced window technologies like dynamic windows are becoming more popular because of their ability to adjust to rapidly changing weather and user

Doi: 10.21608/ERJENG.2023.323547

Journal of Engineering Research (ERJ)
Vol. 7 – No. 4, 2023
©Tanta University, Faculty of Engineering
ISSN: 2356-9441
https://erjeng.journals.ekb.eg/
e ISSN: 2735-4873

needs [9]. The term "Smart Windows" is used for this type of window. In this context, Smart windows may be a more

Figure 1. Evolution of windows. [11]

B. Smart Windows

The emergence of Smart windows presents an excellent opportunity to reduce the total energy that ventilation, heating, and air conditioning systems consume and regulate the amount of sunlight entering a building [12]. The Smart window is a new adjustable window type that can effectively manage the amount of daylight that enters a space intelligently when exposed to external light, electricity, or heat stimulation [13]. Dynamic fenestration technologies, like switchable and controlled smart windows, can make a difference in terms of improving energy performance while improving occupant comfort when compared with static windows to increase occupant comfort. The main three chromic glazing categories of dynamic windows can be classified into thermal, chemical, and electrochromic [14]. In this respect, the Smart Windows technology development of multifunctional holds enormous promise in reducing building energy consumption [11] by about 10% when compared to conventional static windows [15]. Specifically, for building applications, various types of Smart glazing technologies have been created and shown to work [3].

Figure 2. Global Smart Glass Market (2018-2024) [11]

Innovative and efficient solution for building envelopes once compared to traditional static windows [10].

We can see how far windows have come since their rudimentary beginnings in the sixteenth century. Those early versions were made with unglazed openings made of stone mullions or wooden frames. However, as time has passed, windows have evolved dramatically in terms of design, purpose, size, pane quality, and overall function. [11], as shown in “Fig 1”

C. Chromic Materials

The so-called 'color-changing' material group includes the following Smart materials:

- Thermochromics: It’s a material whose color changes as changes in the temperature.

Architecture and furniture design use this phenomenon to display the person’s earlier presence at a specific position or on a piece of furniture as a new technique for expression. As an example, furniture and consumer goods products of Jurgen Mayer H.’s are sensitive to body heat and display a colorized imprint that fades with the time of someone who was sitting on the furniture.

Thermochromic materials used on the building’s exterior have similarly always aroused interest. Unfortunately, the main problem with using presently available thermochromic paints for facades is that they are exposed to infrared rays from the sun rays, which can cause the material to be damaged and lose its ability to change color [16].

Figure 3. Memories of touch via thermochromic material [16]

- Chemochromics: It’s the material that color changes due to exposure to specific chemical environments

This phenomenon is employed in developing double-pane windows with changing color when in contact with the hydrogen gas in the space between the two panes. With the assistance of a catalyst layer, the WO_3 coating changes from colorless to dark blue and reduces light transmissivity [17].

- Electrochromic: It changes color after applying a voltage to this material.

Doi: 10.21608/ERJENG.2023.323547

Journal of Engineering Research (ERJ)
Vol. 7 – No. 4, 2023
©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

The first significant technology that manufacturers of windows and facades have invested in was the Electrochromic material. The forming layers of the electrochromic component can be very thin and inserted easily between conventional glazing materials. Many companies have been developing products that integrate these characteristics into systems that range in size from a small residential window to a building's curtain wall. Electrochromic windows can have their relative transparency and color tint electrically controlled [16].

Figure 4. EC windows colors [18]

D. Smart Glazing Systems

For Smart glazing, many technologies have been suggested and even commercialized. These technologies are characterized by two principal categories: passive and active systems. [19]:

- Passive glazing systems automatically switch their tint level in response to changes in environmental factors (such as temperature or solar radiation). As opposed to that, by external signals based on widely used electrical flows, the active glazing systems may be controlled to switch from one tint state to another [3]. Passive glazing technologies include some materials such as thermochromic (TC) whose color change and their visual properties change automatically in response to temperature changes [20], in addition to gasochromic (GC) materials, whose transparency level changes through the integration of diluted hydrogen gas [21].
- Active glazing systems consist of materials such as electrochromic (EC) glazing whose optical properties change by using a direct current (DC) voltage [22]. Some active glazing systems aren't commonly used for windows, such as suspended particle devices (SPD) and liquid crystal devices (LCD) that work using alternative current (AC) [3]. Better solar and UV radiation protection is provided by EC glazing better than SPD and LCD glass. [23] Active dynamic windows, including electrochromic, are a significant tool for creating advanced, innovative building envelopes that enable better freedom in architectural design, improve energy efficiency, and improve visual and thermal comfort allows an entire building shell with climate Adaptation that can adjust to any weather condition or user preference [24].

The switchable Smart windows, like Thermochromic (TC) glazing, Electrochromic (EC) glazing, and Thermotropic (TT) glazing, give the ability to control solar and transmittance in a dynamic manner of daylight in rejoinder to the environmental variables [25]. Among them, the researchers have focused on electrochromic Smart windows due to their features, like active regulation, lower energy consumption, quick response time, and vibrant color [26]. Electrochromic windows have many studies that may be found, but limited ones are accessible on thermochromic and photochromic windows [6].

E. Electrochromic Glazing Material

The first one who used the electrochromic material to Fabricate Smart windows, Lampert and Granqvist et al. in the early 1980s (Energy-saving daylight system) for buildings. In the first half of the 1980s, Electrochromic received a great boost when it became generally acknowledged that this technology could be extremely important for energy-saving fenestration [27]. Electrochromic windows achieved a 54% energy reduction once compared to traditional single-glazed windows for over a 25-year life cycle [28]. Electrochromic windows have been the focus of intensive research and have been offered for purchase commercially for several years since they were released into the market because of their exceptional optical modulation, effective coloration, and exceptional strength [29]. Electrochromic (EC) Smart windows, which can actively control solar radiation transmission through electrochemical processes, can be used to improve energy efficiency in buildings [30]. Switchable Smart windows based on electrochromic (EC) technology are gaining popularity in the architectural sector due to their ability to save energy and improve visual comfort [31]. Five superimposed layers, which may be either on one transparent substrate or in combination with two transparent substrates, represent the general structure of an electrochromic device [32].

The structure's five layers consisted of a transparent conductive layer covered by an ion-storing film, another transparent conductive layer covered by an electrochromic layer, and a layer of electrolyte sandwiched in between each other [33]. There are bleaching and color properties in the electrochromic through redox reactions, whereas a crucial part is played by the ion storage layer in storing and providing the necessary ions needed by electrochromic material, the layer that ensures fat color switching and serves as an ion transport channel is the electrolyte layer. All constituent components must possess a high level of transparency to visible light and maintain electrochemical stability throughout the entire switching voltage range [34]. As shown in "Fig 4"

Doi: 10.21608/ERJENG.2023.323547

Journal of Engineering Research (ERJ)
Vol. 7 – No. 4, 2023
©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

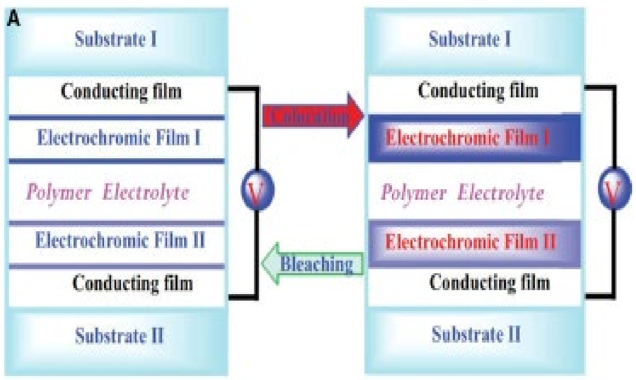

Figure 5. The general construction of EC devices [32]

To cause Li + ions to migrate from the layer of accumulation into an electrode, voltage is applied during operation. This determines the color change of the electrode layer as it transitions from a transparent to a darkened state (cathodic coloration) or the accumulation layer (anodic coloration). Depending on the kind of EC materials employed in the device, this change might also take place in both layers. By switching off the current, the transparency is restored. As a result, ions leave the electrode and return to the accumulation layer. [35]

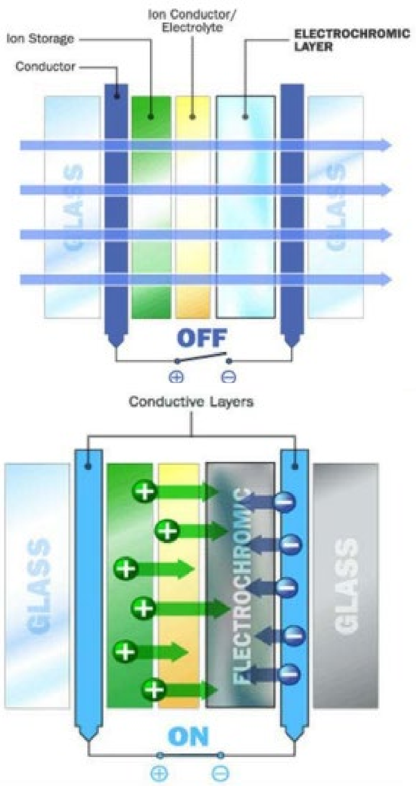

Figure 6. Electrochromic device's structure before and after switching [35]

According to "Fig 7" The important performance indicators in the field of ECWs are visible light transmission coloration efficiency (CE), switching time and cycles of electrochromic materials in bleaching or coloring states [36], the time necessary to finish 90% of the visual transformation between the bleached and colored stables is called the switching time, the window color will impact visual comfort [32].

Figure 7. Bleaching and coloring presence in EC devices [32]

F. Electrochromic Glazing Material Example

Saint Gobain HQ

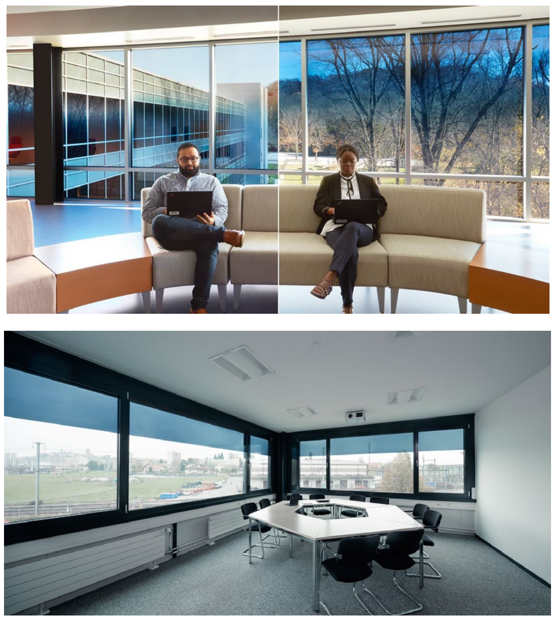

Figure 8. Electrochromic Smart windows in Saint Gobain HQ [37]

The Saint Gobain Corporate Headquarters, where hundreds of employees work for the progressive manufacturing company, is located in North America. Although natural light is a highly desirable feature of modern offices, solar gain or glare can cause problems due to overheating or undesirable glare on screens that can interfere with employees' productivity levels. The building makes the most of its use of glass, in contrast to the surroundings. Due to this, electrochromic glass was chosen for the extensive south-facing glazing elevations. In the warmer months, the electrochromic glass on the exterior façade produces a blue, nearly reflective surface resembling the sky's reflection. The electrochromic provides the occupants with a solar shading option that does not obstruct views or light transmission like other approaches. Using electrochromic glass allows architects to design highly glazed that can withstand intense solar glare without disrupting the occupants. [37]

Doi: 10.21608/ERJENG.2023.323547

Journal of Engineering Research (ERJ)
Vol. 7 – No. 4, 2023
©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

II. Case Study

A. The Site

There is now a large external glass surface in office buildings that makes it hard for natural ventilation, thereby affecting the air quality and heat comfort of the staff working in the offices, as well as their physical condition, productivity, or adaptability. In light of this, the chosen case is the National Bank of Egypt (NBE). The project is located on the eastern bank of the Nile River with a site area of 6200 m^2. The project consists of three floors covering the entire land area, containing a commercial center and showrooms. It has two towers with a total height of 36 floors, one of which is an office (southern tower), and the other is a residential (north tower).

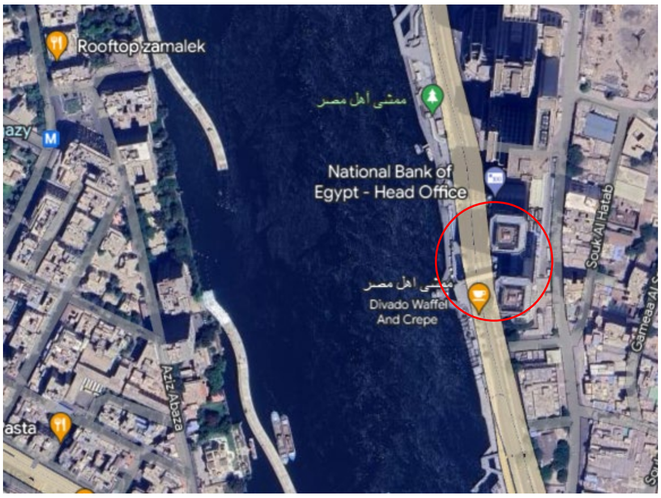

Figure 9. Site location of the case study (Google Earth)

B. The Weather

The office building location and climate, have a significant effect on Smart Glazing's energy performance. In this section, Cairo, the largest metropolis of northern Egypt and the country's capital, has been chosen as the location for the office room. The hot season lasts 4.6 months, from May 14 to October 2, with daily high temperatures averaging more than 32°C. August is the hottest month in Cairo, with typical highs of 35°C and lows of 24°C. The coldest season lasts 3.0 months, from December 3 to March 3, with a daily high temperature of less than 22°C. January is the coldest month in Cairo, with average lows of 10°C and highs of 19°C.

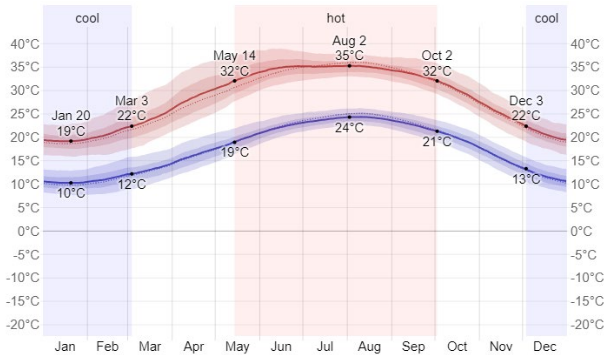

Figure 10. Weather [38]

C. Case Study Modeling

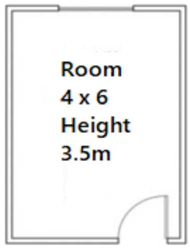

Figure 11. Office room plan

The model chosen is an office in a multi-story structural building with a double-skin façade. The room dimensions are 6 x 4 x 3.5 m (length x width x height respectively). The window opening is located in the middle.

Window wall area ratio (WWR) is set at 30%. All these parameters are integrated into four directions: north, east, south, and west, using the new glazing Smart material (Electrochromic Reflective Bleached 6mm-13mm Argon).

D. Software used for Simulation

Design Builder is the simulation tool used in this paper's case study. It is an easy-to-use environmental modeling program that allows us to work with digital models of buildings. The Energy Plus program is a ready-to-use software that interfaces with the Design-Builder environment and enables you to run complete simulations without leaving the interface. ASHRAE definitions form the basis of energy plus calculations with various data handling techniques. [39].

III. Results and Discussion

The most significant purpose of the world in this current period is the reduction of building energy consumption. The first energy consumer in the building is the building envelope, and buildings with walls that have a great surface area and wall-mounted windows have the highest energy-consuming element of the building. Structural characteristics of windows, like window position and material, influence the quantity of solar radiation that moves into the building and thus assume the amount of building energy used for thermal and lighting. As a result, the methodology is based on evaluating buildings' energy performance by incorporating architectural solutions for an opening design that reduces energy consumption and improves building performance.

A. Impact on Total Energy Consumption

The sum of all the different consumed energies the building uses makes up the annual energy consumption. (heating, lighting, and cooling), and it stands for the bell at the end of each year. This study case indicates that the total energy consumption is reduced after using the Smart window material by 14 %. The North direction represents the least amount of necessary energy consumption, and the west direction has the highest total requirement of energy use, as shown in "Fig 12".

Doi: 10.21608/ERJENG.2023.323547

Journal of Engineering Research (ERJ)
Vol. 7 – No. 4, 2023
©Tanta University, Faculty of Engineering
https://erjeng.journals.ekb.eg/
ISSN: 2356-9441
e ISSN: 2735-4873

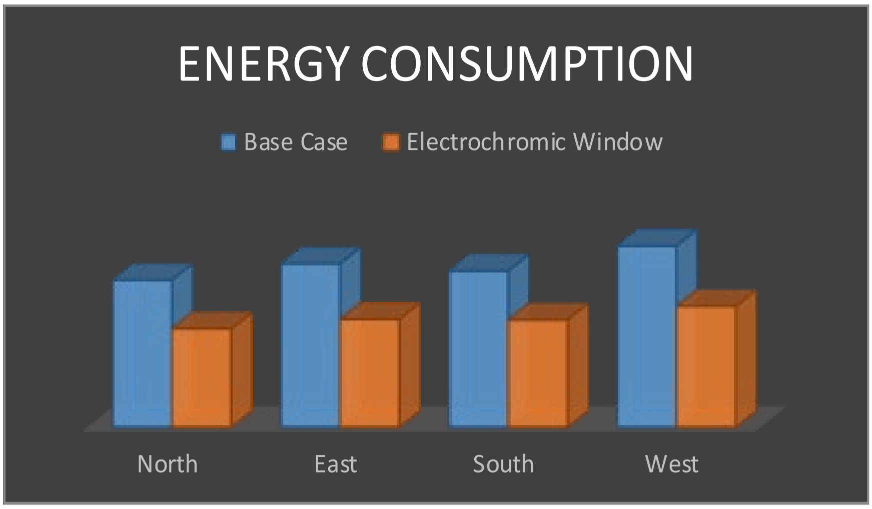

Figure 12. Comparison between the energy consumption before and after the smart window through the four orientation (Design Builder)

B. Impact on Interior Temperature

The monthly winter and summer temperatures indicate how well the air conditioning is working and how comfortable it is inside the building. The results show that The interior temperature in the north direction during summer (August) has been reduced after using the Smart window material, and during winter (January) has risen by about 1-1.5°C in the south direction, as shown in "Fig 13".

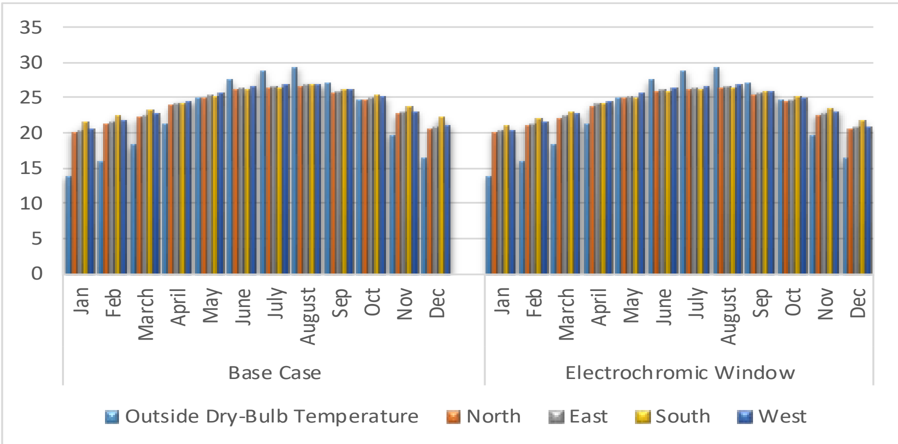

Figure 13. Interior Temperature (Design Builder)

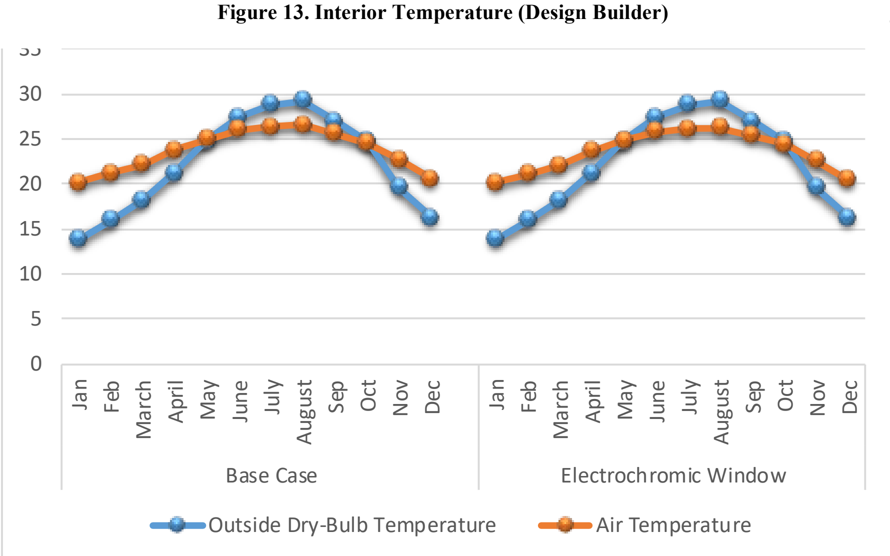

Figure 14. Interior Temperature in North Direction (Design Builder)

Doi: 10.21608/ERJENG.2023.323547

C. *Impact on Relative Humidity*

It is common knowledge that the ideal relative humidity for humans ranges from 38% to 59%. The results indicate That after adding the Smart window material, the average relative humidity in summer (August) is between 57% to 59%, and in winter (January) is between 44% to 46%.

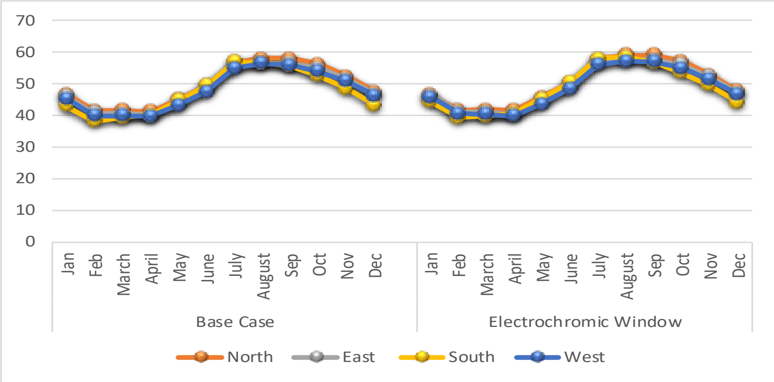

Figure 15. Relative Humidity (Design Builder)

D. *Impact on Lighting*

The energy consumption of lighting is regarded as one of the most significant features in determining window dimensions, as lighting is affected by opening position and direction. The quantity of inlet lighting in the building Changes when a window's orientation is changed, producing an alteration in the required lighting power. Figure 16 shows that after using the Smart window material, the north direction has the highest lighting loads, while the south and west have the lowest.

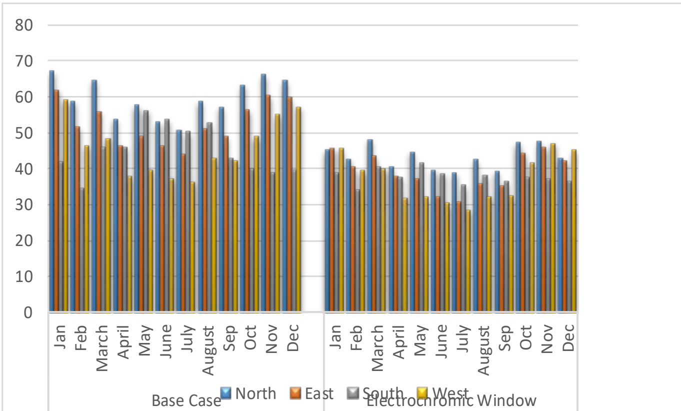

Figure 16. Lighting (Design Builder)

IV. CONCLUSION

This paper provides an overview of Smart glazing systems that are a contributing factor in developing the Smart building envelope, which addresses climate changes and improves building occupant's thermal comfort. Furthermore, it proves the viability of implementing these Smart solutions in Egypt. Information on the adjustable and controllable Smart window products that are commercially available has been collected for this work.

Furthermore, the analytical comparative simulations between the base case and case 1 that differed in the window orientation and the type of Smart glazing material showed how well replacing existing glass with Smart glass worked. The electrochromic windows have been simulated using electrochromic reflective bleached 6mm-13mm argon as glazing material and have been chosen to be simulated in

The design-builder software at Cairo has been contrasted With a typical static window. The results show that the building with electrochromic windows uses 14% less energy overall than the reference window, relying on the case and location. In addition to enhancing the efficiency of buildings without hurting energy performance, an Electrochromic glazing system proved useful in increasing this ratio, and their openings into the outside were improved.

Funding: The authors should mention if this research has received any type of funding.

Conflicts of Interest: The authors should explicitly declare if there is a conflict of interest.

REFERENCES

[1] Pallonetto, F., De Rosa, M., D'Ettorre, F., & Finn, D. P. (2020). On the assessment and control optimisation of demand response programs in residential buildings. Renewable and Sustainable Energy Reviews, 127 (July). https://doi.org/10.1016/j.rser.2020.109861

[2] Zhang, G., Li, X., Shi, W., Wang, B., & Cao, Y. (2019). Influence of occupant behavior on the energy performance of variable refrigerant flow systems for office buildings: A case study. Journal of Building Engineering, 22 (October 2018), 327–334. https://doi.org/10.1016/j.jobe.2018.12.020

[3] Krarti, M. (2022). Energy performance of control strategies for smart glazed windows applied to office buildings. Journal of Building Engineering, 45(August 2021), 103462. https://doi.org/10.1016/j.jobe.2021.103462

[4] Elghamry, R., & Hassan, H. (2020). Impact of window parameters on the building envelope on the thermal comfort, energy consumption and cost and environment. International Journal of Ventilation, 19(4), 233–259. https://doi.org/10.1080/14733315.2019.1665784

[5] Pereira, J., Glória Gomes, M., Moret Rodrigues, A., & Almeida, M. (2019). Thermal, luminous and energy performance of solar control films in single-glazed windows: Use of energy performance criteria to support decision making. Energy and Buildings, 198. https://doi.org/10.1016/j.enbuild.2019.06.003

[6] Tällberg, R., Jelle, B. P., Loonen, R., Gao, T., & Hamdy, M. (2019). Comparison of the energy saving potential of adaptive and controllable smart windows: A state-of-the-art review and simulation studies of thermochromic, photochromic and electrochromic technologies. Solar Energy Materials and Solar Cells, 200 (February), 109828. https://doi.org/10.1016/j.solmat.2019.02.041

[7] Konstantzos, I., Chan, Y. C., Seibold, J. C., Tzempelikos, A., Proctor, R. W., & Protzman, J. B. (2015). View clarity index: A new metric to evaluate clarity of view through window shades. Building and Environment, 90. https://doi.org/10.1016/j.buildenv.2015.04.005

[8] Fairuz Syed Fadzil, S., & Sia, S. J. (2004). Sunlight control and daylight distribution analysis: The KOMTAR case study. Building and Environment, 39(6), 713–717. https://doi.org/10.1016/j.buildenv.2003.12.009

[9] 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 (February 2019), 165–182. https://doi.org/10.1016/j.enbuild.2018.09.017

[10] De Masi, R. F., Festa, V., Gigante, A., Ruggiero, S., & Vanoli, G. P. (2022). The incidence of smart windows in building energy saving and future climate projections. Energy Reports, 8, 283–289. https://doi.org/10.1016/j.egyr.2022.10.222

[11] Mustafa, M. N., Mohd Abdah, M. A. A., Numan, A., Moreno-Rangel, A., Radwan, A., & Khalid, M. (2023). Smart window technology and its potential for net-zero buildings: A review. Renewable and Sustainable Energy Reviews, 181(May), 113355. https://doi.org/10.1016/j.rser.2023.113355

[12] Tarantini, M., Loprieno, A. D., & Porta, P. L. (2011). A life cycle approach to Green Public Procurement of building materials and elements: A case study on windows. Energy, 36(5). https://doi.org/10.1016/j.energy.2011.01.039

[13] Bai, T., Li, W., Fu, G., Zhang, Q., Zhou, K., & Wang, H. (2023). Dual-band electrochromic smart windows towards building energy conservation. Solar Energy Materials and Solar Cells, 256(February), 112320. https://doi.org/10.1016/j.solmat.2023.112320

[14] Lantonio, N. A., & Krarti, M. (2022). Simultaneous design and control optimization of smart glazed windows. Applied Energy, 328(September), 120239. https://doi.org/10.1016/j.apenergy.2022.120239

[15] Mann, D., Mann, D., Yeung, C., Yeung, C., Habets, R., Habets, R., Vroon, Z., Vroon, Z., Vroon, Z., Buskens, P., Buskens, P., Buskens, P., & Buskens, P. (2020). Comparative building energy simulation study of static and thermochromically adaptive energy-efficient glazing in various climate regions. Energies, 13(11). https://doi.org/10.3390/en13112842

[16] Addington, d. M., & L.shock, D. (2005). Smart Materials and New Technologies For the architecture and design professions. Elsevier, 1.

[17] Ferrara, M., & Bengisu, M. (2014). Intelligent design with chromogenic materials Materials that change colour : how they work , how they are applied and their multi-faceted nature. Journal of the International Colour Association, 13, 54–66.

[18] https://constrofacilitator.com/electrochromic-materials-devices-for-buildings/

[19] 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

[20] Granqvist, C. G., Bayrak Pehlivan, I., Ji, Y. X., Li, S. Y., & Niklasson, G. A. (2014). Electrochromics and thermochromics for energy efficient fenestration: Functionalities based on nanoparticles of In2O3:Sn and VO2. Thin Solid Films, 559. https://doi.org/10.1016/j.tsf.2013.10.033

[21] Feng, W., Zou, L., Gao, G., Wu, G., Shen, J., & Li, W. (2016). Gasochromic smart window: Optical and thermal properties, energy simulation and feasibility analysis. Solar Energy Materials and Solar Cells, 144(October 2019), 316–323. https://doi.org/10.1016/j.solmat.2015.09.029

[22] Tavares, P., Bernardo, H., Gaspar, A., & Martins, A. (2016). Control criteria of electrochromic glasses for energy savings in mediterranean buildings refurbishment. Solar Energy, 134, 236–250. https://doi.org/10.1016/j.solener.2016.04.022

[23] Taher, R., Abdelkader, W. A., & Fahim, A. A. M. A. (2022). Sustainable Building: To Achieve Thermal Comfort in Highly Glazed Buildings Using Smart Glass. IOP Conference Series: Earth and Environmental Science, 1113(1). https://doi.org/10.1088/1755-1315/1113/1/012021

[24] Sawyer, K. (2014). Windows and Building Envelope Research and Development Roadmap for Emerging Technologies. In US Department of Energy, Building Technologies Office.

[25] Ciampi, G., Scorpio, M., Spanodimitriou, Y., Rosato, A., & Sibilio, S. (2020). Thermal model validation of an electric-driven smart window through experimental data and evaluation of the impact on a case study. Building and Environment, 181. https://doi.org/10.1016/j.buildenv.2020.107134

[26] Bai, T., Li, W., Fu, G., Zhang, Q., Zhou, K., & Wang, H. (2023). Dual-band electrochromic smart windows towards building energy conservation. Solar Energy Materials and Solar Cells, 256(February), 112320. https://doi.org/10.1016/j.solmat.2023.112320

[27] Granqvist, C. G., Arvizu, M. A., Bayrak Pehlivan, Qu, H. Y., Wen, R. T., & Niklasson, G. A. (2018). Electrochromic materials and devices for energy efficiency and human comfort in buildings: A critical review. Electrochimica Acta, 259. https://doi.org/10.1016/j.electacta.2017.11.169

[28] Pacheco Torgal, F. (2016). Introduction to nano- and biotech-based materials for energy building efficiency. In Nano and Biotech Based Materials for Energy Building Efficiency. https://doi.org/10.1007/978-3-319-27505-5_1

[29] Cheng, W., Moreno-Gonzalez, M., Hu, K., Krzyszkowski, C., Dvorak, D. J., Weekes, D. M., Tam, B., & Berlinguette, C. P. (2018). Solution-Deposited Solid-State Electrochromic Windows. IScience, 10, 80–86. https://doi.org/10.1016/j.isci.2018.11.014

[30] Cai, G., Zhu, R., Liu, S., Wang, J., Wei, C., Griffith, K. J., Jia, Y., & Lee, P. S. (2022). Tunable Intracrystal Cavity in Tungsten Bronze-Like Bimetallic Oxides for Electrochromic Energy Storage. Advanced Energy Materials, 12(5). https://doi.org/10.1002/aenm.202103106

[31] Lee, E., & Laboratory, L. B. N. (2006). Advancement of Electrochromic Windows. Public Interest Energy Research, April, 1–101. http://www2.lbl.gov/Science-Articles/Archive/sabl/2007/Jan/Advance-EC-Windows.pdf

[32] Wu, S., Sun, H., Duan, M., Mao, H., Wu, Y., Zhao, H., & Lin, B. (2023). Applications of thermochromic and electrochromic smart windows: Materials to buildings. Cell Reports Physical Science, 4(5), 101370. https://doi.org/10.1016/j.xcrp.2023.101370

[33] Wang, B., Cui, M., Gao, Y., Jiang, F., Du, W., Gao, F., Kang, L., Zhi, C., & Luo, H. (2020). A Long-Life Battery-Type Electrochromic Window with Remarkable Energy Storage Ability. Solar RRL, 4(3). https://doi.org/10.1002/solr.201900425

[34] Wang, Y., Runnerstrom, E. L., & Milliron, D. J. (2016). Switchable Materials for Smart Windows. In Annual Review of Chemical and Biomolecular Engineering (Vol. 7). https://doi.org/10.1146/annurev-chembioeng-080615-034647

[35] Anissa Tabet Aoul, K., Efurosibina Attoye, D., & Al Ghatrif, L. (2019). Performance of Electrochromic Glazing: State of the Art Review. IOP Conference Series: Materials Science and Engineering, 603(2). https://doi.org/10.1088/1757-899X/603/2/022085

[36] Lin, S., Bai, X., Wang, H., Wang, H., Song, J., Huang, K., Wang, C., Wang, N., Li, B., Lei, M., & Wu, H. (2017). Roll-to-Roll Production of Transparent Silver-Nanofiber-Network Electrodes for Flexible Electrochromic Smart Windows. Advanced Materials, 29(41).

[37] https://www.iqprojectsuk.com/portfolio-posts/saint-gobain-hq-electrochromic-glass/

[38] https://weatherspark.com/y/96939/Average-Weather-in-Cairo-Egypt-Year-Round#google_vignette

[39] Design Builder Software 2009 Design Builder 2.1 User's Manual (© 2009 Design Builder Software)