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THE IMPACT OF USING ELECTROCHROMIC SENSITIVE SMART GLASS IN BUILDING FACADES TO REDUCE SOLAR HEAT GAIN IN HOT CLIMATE ZONES IN EGYPT

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ABSTRACT

Climate change is one of the most critical problems resulting from the emission of harmful gases, including chlorofluorocarbons, which result from the excessive demand for air conditioning to provide thermal comfort in architectural spaces. Approximately 60% of the energy consumed in buildings is through inefficient windows. So, this study aims to reduce heat gain through glass facades, consequently decreasing energy consumption in buildings by minimising air conditioner use. This is achieved by utilising sensitive reactive materials. When this material is applied between glass layers, they react to an external stimulus (electricity) and change colour from light to dark (tinted). This action reduces the solar heat gain coefficient (SHGC) within the spaces, improving internal temperature and reducing the need for cooling. Conversely, in the absence of the external stimulus (electricity), the glass returns to its natural colour (clear), allowing the entry of solar rays and reducing the need for heating. This, in turn, optimises energy consumption within the building. The research presents several global examples of buildings that use electrochromic reactive smart glass in different climatic regions, similar to Egypt's diverse climatic zones (North Coast Climate, Highlands Climate, and Desert Climate), and calculates the value of WWR for each building, then compares it with the required heat gain coefficient in the Egyptian code for energy efficiency in commercial buildings. The conclusion is that glass provides better efficiency and achieves the code requirements when applied in hot climatic zones.

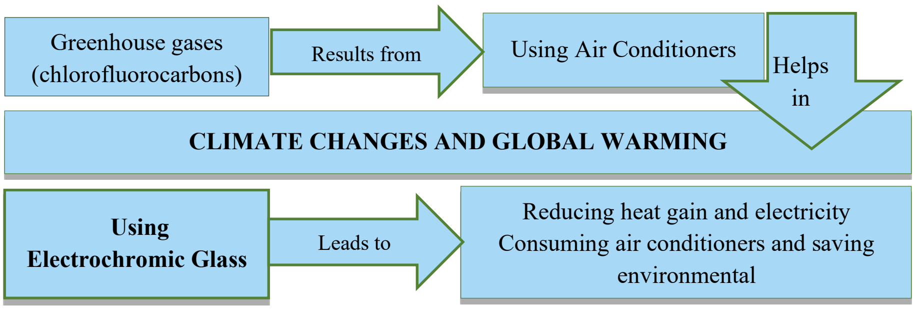

Fig. 1. The importance of using Electrochromic Glass in buildings.

KEYWORDS: Enhancing indoor air temprature, Energy conservation, Reactive sensetive glass, Color changing glass,Thermal comfort.

تأثير استخدام الزجاج الذكى الحساس للكهرباء بواجهات المبانى على تقليل الاكتساب الحرارى بالأقاليم المناخية الحارة بمصر

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الملخص

تعتبر التغيرات المناخية التى حدثت بكوكب الأرض من أهم المشكلات التي نتجت عن إنبعاث الغازات الضارة ومنها مركبات الكلوروفلوروكربون والتي تنتجت من فرط الطلب على مكيفات الهواء لتوفير الراحة الحرارية بالفراغات المعمارية ،حيث أنه يتم استخدام مايقرب من ٦٠٪ من الطاقة المستهلكة فى المبانى عن طريق النوافذ الغير فعالة، وعليه فإن الدراسة التالية تهدف إلى تقليل الاكتساب الحرارى للزجاج المستخدم بالواجهات وبالتالى تقليل استخدام المكيفات وتخفيض استهلاك الطاقة بالمبانى وذلك باستخدام الزجاج الكهربائى الذكى الذى يدخل في تكوينه مواد ذكية تتفاعل عند تعرضها لمؤثر خارجى (مجال كهربى)،فعند وضع هذه المواد الذكية بين طبقات الزجاج فإنها تتفاعل مع المؤثر الخارجى (الكهرباء) ونتيجة لذلك يتغير لونها من فاتح إلى داكن(Tinted) مما يعمل على تقليل اكتساب الآشعة الشمسية (SHGC) داخل الفراغات ،وذلك يحسن من درجة الحرارة الداخلية للفراغ ويقلل من استخدام المكيفات للتبريد وكذلك يقلل من استهلاك الطاقة ،وعند غياب المؤثر الخارجى (الكهرباء) يعود الزجاج إلى لونه الطبيعى(Clear) مما يسمح باكتساب الآشعة الشمسية ونفاذها داخل الفراغات مما يقلل من استخدام المكيفات للتدفئة، فمن خلال البحث سيتم عرض ثلاثة أمثلة لمبانى عالمية تم استخدام الزجاج الذكى المتفاعل بالكهرباء بواجهاتها بثلاثة أقاليم مناخية مختلفة الخصائص والتى تتشابة خصائصها بالأقاليم المناخية بمصر وهم(إقليم الساحل الشمالى-إقليم المرتفعات-الإقليم الصحراوى) وتم حساب نسبة الفتحات بالواجهة لكل مثال واستخدامها لمقارنة قيمة معامل الاكتساب الحرارى المطلوب بالكود المصرى لتحسين الطاقة بالمبانى التجارية لكل إقليم بقيمة معامل الاكتساب الحرارى للزجاج الذكى المستخدم ،وقد تم استنتاج أن الزجاج يعطى أفضل كفاءة وتحقيق لمتطلبات الكود وبالتالى ترشيد الطاقة عند تطبيقة فى الأقاليم المناخية ذات درجات الحرارة العالية بمصر .

الكلمات المفتاحية : تحسين درجة الحرارة الداخلية للفراغات، ترشيد الطاقة، الزجاج الحساس المتفاعل، الزجاج متغيراللون ، الراحة الحرارية.

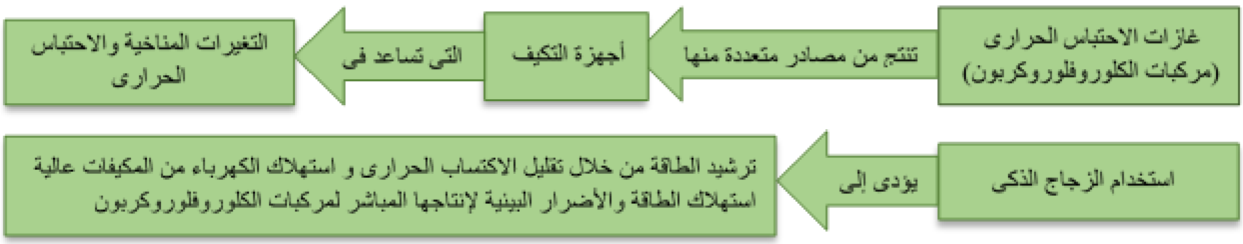


Fig. 1.The importance of using electrochromic glass in buildings.

1. INTRODUCTION.

Glass is an indispensable element in building facades; it is the transparent component that connects indoor and outdoor environments, facilitating natural ventilation within spaces. Over time, the use of clear glass allows solar radiation to penetrate spaces, resulting in increasing indoor temperatures. This necessitates the use of air conditioners to regulate temperatures for occupants, and that's increased the emissions of greenhouse gases, which contribute to global warming and climate change.

According to Egypt's Vision 2030, aimed at achieving sustainable development goals, including the establishment of sustainable local communities and cities by optimising energy consumption in buildings, it became imperative to consider treating glass to minimise heat gain, conserve energy, and preserve the environment. This led to a rethinking of glass components and trying to find solutions to decrease solar radiation from passing through glass to enter spaces.

The use of sensitive smart material between glass layers transforms it into responsive smart glass that interacts with external environmental factors. This glass can be controlled through tinting and clearing mechanisms,and the user can control it with a remote control or smart phone, providing the ability to regulate heat gain within spaces, which provides thermal comfort while also decreasing energy consumption.

Sustainable Development Goals Targeted in the Research

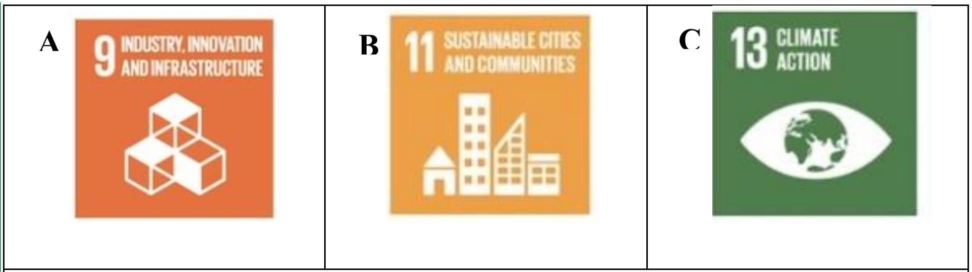


Fig. 2. Sustainable development goals targeted in the research : (A) showing goal 9 can be achieved through creating new smart materials in building elements; (B) showing goal 11 can be achieved by using sustainable materials in buildings; and (C) showing goal 13 can be achieved through reducing the use of air conditioners and thus reducing the production of harmful gases.

2.Materials and Methods

2.1 Elements of buliding facades.

The main elements of an external envelope for any building are divided into two main parts:

First: the solid part, which is the external walls of the building.

Second: the void part, which is windows and openings in the external walls.

There may also be some elements added to the facade of the building as architectural formations or as treatments such as mashrabiyas and sunshades.[1]

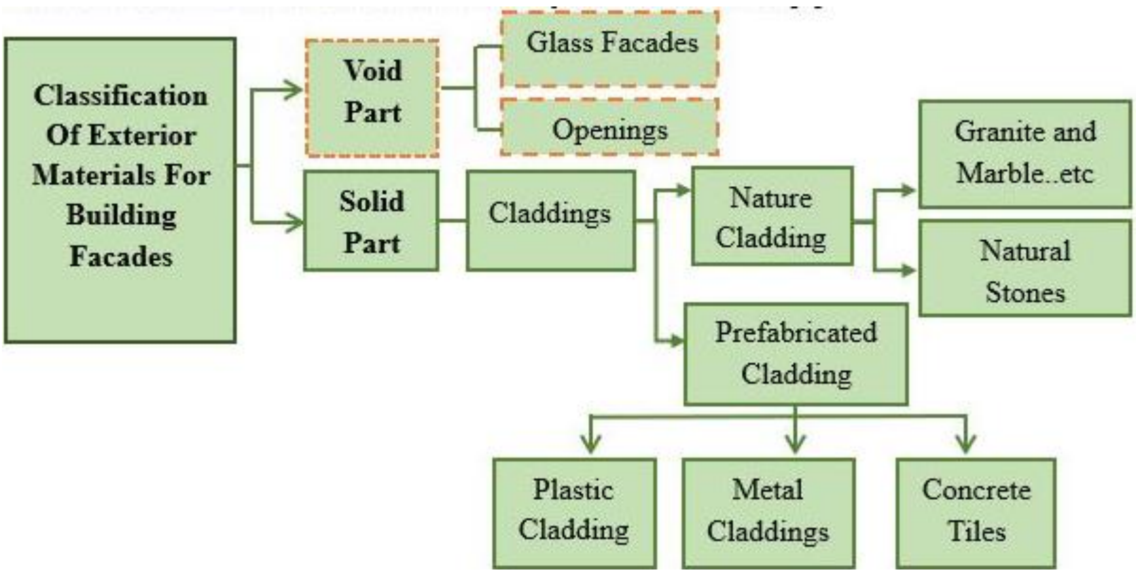


Fig. 3. Main types of exterior finishes for building facades [1].

The research will focus on researching the development of void part finishes (glass), and the solar heat gain coefficient (SHGC), shading coefficient (SC), and U-value are considered important factors that demonstrate the efficiency of glass and its ability to reduce solar radiation into spaces. Here are the definitions for each of these factors.

2.1.1. **Solar Heat Gain Coefficient (SHGC):** the ratio between the amount of solar radiation transmitted through the glass added to the heat lost from the glass's inner surface by the heat load and the amount of solar radiation incident on the glass's surface, and it has a ratio between 0-1.

2.1.2. **Shading Coefficient (SC):** The ratio between the amount of solar radiation passing through the glass and the amount passing through a single clear glass with a thickness of 3mm. SC = SHGC/0.87.

2.1.3. **Window-to-Wall Ratio (WWR):** The ratio between the area of openings in the external facades and the total area of the external facades.

2.1.4. **Thermal conductivity (U-value):** The amount of heat passing vertically through a unit of thickness of a structural element when there is a temperature difference of one degree Celsius between its surfaces [W/(m^2 .^{O}C][2].

2.2. Types of Solar Radiation.

The solar radiation consists of two main types of radiation:

2.2.1. Visible light solar radiation.

2.2.2. Invisible light solar radiation,which consists of two types of radiation,

2.2.2.1. Infrared Rays.

٢.2.2.2. Ultraviolent Rays .

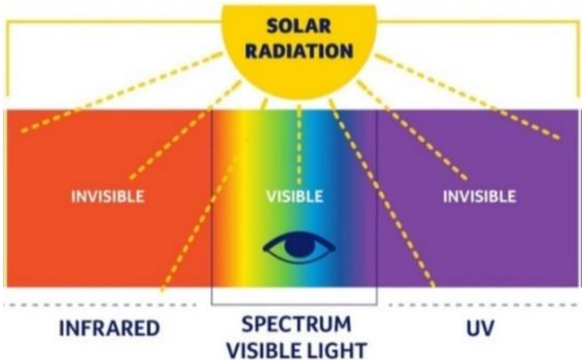


Fig. 4. Types of Solar radiation [3].

٢,٣.Types of radiation falling on glass.

There are three main types of radiation falling on glass openings**:**

2.3.1**. Direct radiation**: The radiation that comes directly from the sun.

2.3.2.**Diffuse radiation:** The radiation that is re-emitted from components of the atmosphere.

2.3.3**. Reflected radiation**: The radiation that is reflected from the surfaces surrounding the building, such as plants, asphalt, concrete, or water.[4]

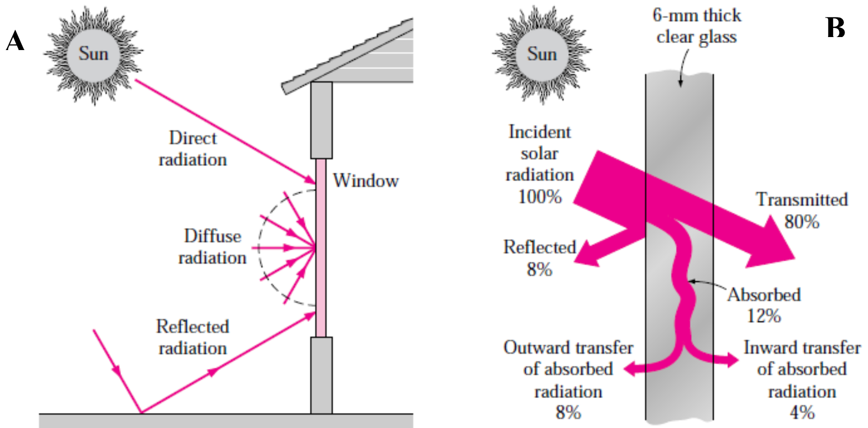


Fig. 5. Types of radiation falling on glass facades: (A) showing Types of radiation falling on glass (B) Types of solar radiation falling on glass [4].

2.4. Historical development of glass.

Glass is one of the oldest materials made by humans, continuously used since its invention until today.The exact period of glass invention is unknown, but the earliest discovered history dates back to 7000 BC in the modern Stone Age. It was first used in Egypt for decorative purposes around 3000 BC, adding colored glass to stones, pottery, and beads. Romans began using it in windows, and the emergence of glass in windows and architectural engineering in the 17th century AD. The development of leaded glass was a significant step forward in manufacturing large window panes. Stained glass was used in churches and cathedrals during the Gothic and Baroque periods from the 11th to the 18th century[5] .

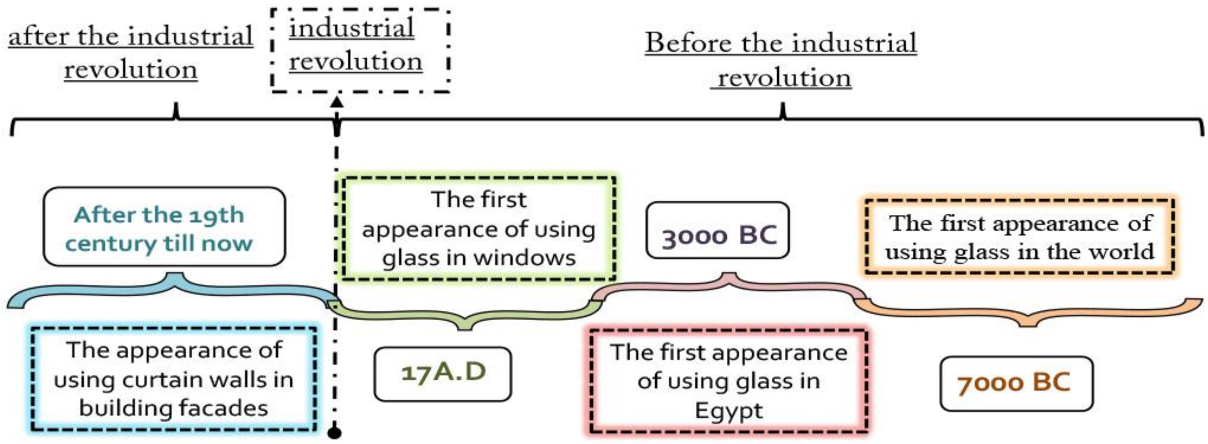


Fig. 6. Historical development of glass.

The development of the glass used in openings and facades can be divided into four main eras, which are in order:

Arab architecture, which is the period from the 13th century to the 17th century,

Traditional architecture, which is the period from the 17th century to the 19th century, Modern architecture, which is the period from the 19th century to the 20th century,

Smart Architecture, which is the period from the 20th century to the present.

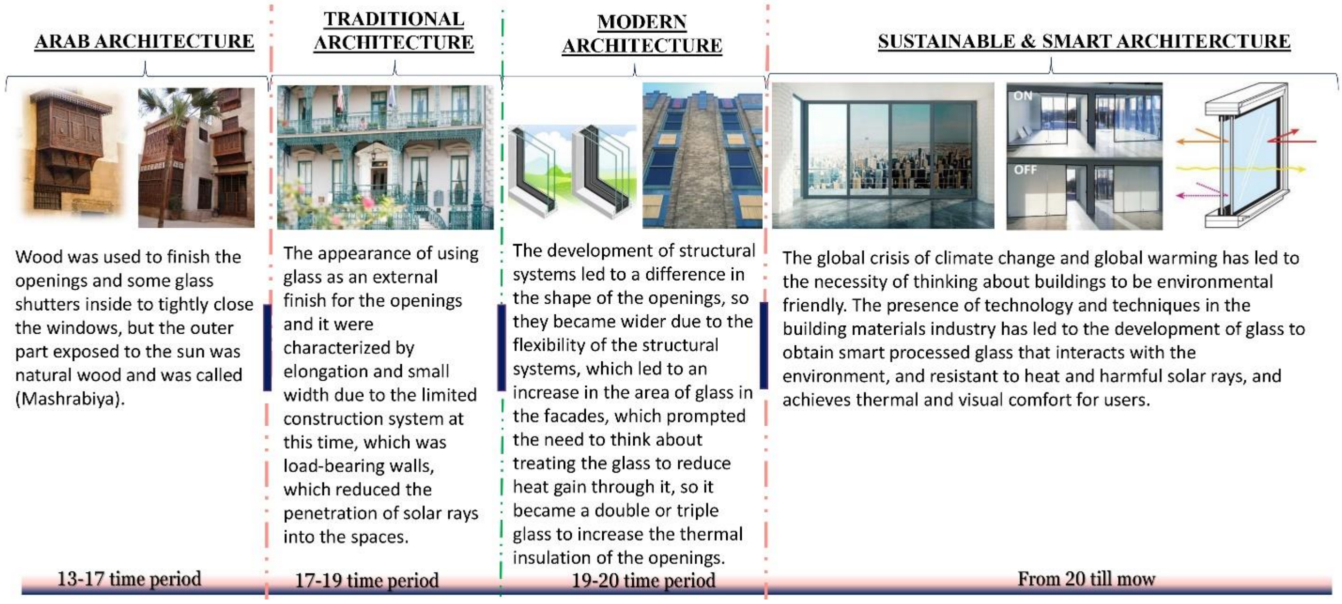
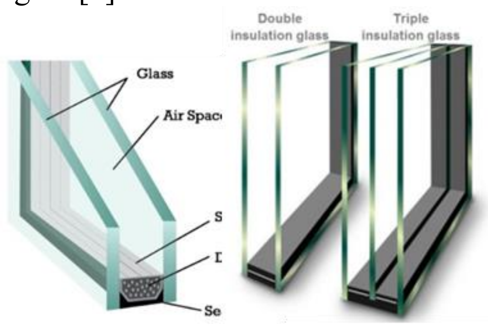
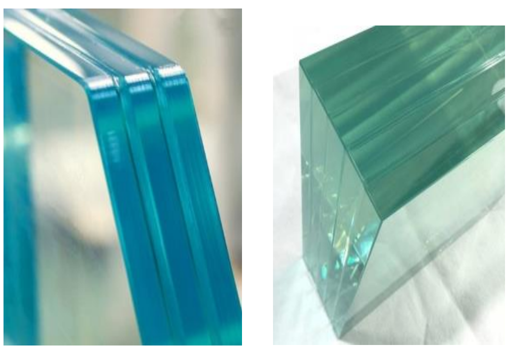


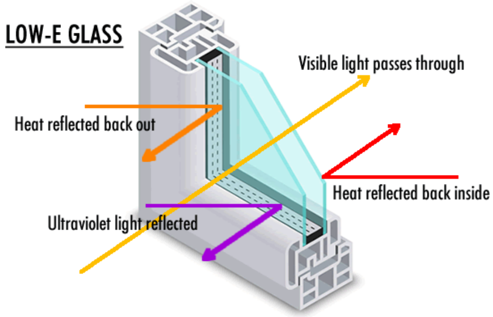
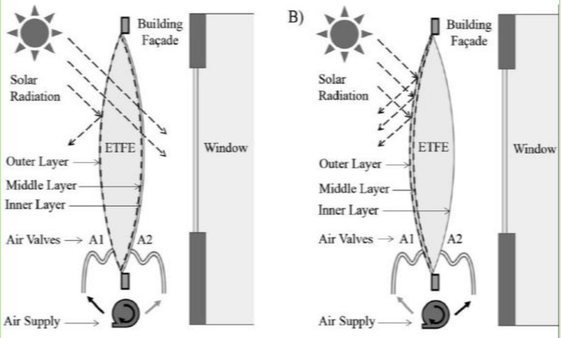
Fig. 7. The development of glass in architecture eras .

2.5. A list of glass trearments and the development which occurred in traditional and modern architecture.

Table 1. Traditional And Modern Glass Treatments.

Material		Insulated Glass	Laminated Glass
Improving The Properties Of Glass In Traditional Architecture	Description	Two layers of glass are between them. 1) 4-6 mm air vacuum. 2) **or** a 7–12 mm air vacuum. 3) **Or** 4-6 mm of vacuum filled with argon. 4) **Or** a 7–12 mm vacuum filled with argon. [2]  **Fig. 8.** The Components of double glazing[8].	Two or more layers of glass and transparent plastic film made of an adhesive such as polyvinyl chloride. It is known as safety-soundproof glass. It is commonly used to provide safety because it does not break but remains stuck, forming a shape resembling a spider's nest.  **Fig. 9.** Multilayer glass[7].

<table>
<tr><th colspan="2">Material</th><th colspan="2">Insulated Glass</th><th>Laminated Glass</th></tr>
<tr><td rowspan="9">Improving The Properties Of Glass In Traditional Architecture</td><td>Gap thickness</td><td colspan="2">3-6 mm air vacuum.
7–12mm air vacuum.
3-6 mm of vacuum filled with argon.
7–12 mm of vacuum filled with argon [2].</td><td>Nothing</td></tr>
<tr><td>Glass thickness</td><td colspan="2">5mm, 6mm, 8mm</td><td>3mm, 4mm, 5mm, 6mm, 8mm, 10mm,12mm, 15, 19mm [7].</td></tr>
<tr><td>Color</td><td colspan="2">Transparent or opaque (light and dark blue, light grey, blue-grey, light green, brown) [8].</td><td>Transparent and opaque (blue, green, red, bronze, grey) [7].</td></tr>
<tr><td>position</td><td colspan="2">Openings and Facades.</td><td>Openings and Facades.</td></tr>
<tr><td rowspan="2">U-Value</td><td>Air gap 3-6 mm
Air gap 7-12 mm</td><td>U value = 3.12 w/(m2.c)
U value = 2.73 w/(m2.c)</td><td rowspan="2">The value of thermal conductivity varies depending on the type of material used between the layers of glass,but it has an average value of 4.09 w/(m2.c) [7].</td></tr>
<tr><td>Argon gap 3-6 mm.
Argon gap 7-12 mm.</td><td>U value = 2.90 w/(m2. c)
U value = 2.56 w/(m2. c) [2].</td></tr>
<tr><td>SHGC</td><td colspan="2">0.70 [2].</td><td>0.69 [7].</td></tr>
<tr><td>Case Study</td><td colspan="2">
Fig. 10. Straits Meadow Student Residence in London[9].</td><td>
Fig. 11. Abu Dhabi International Airport in Abu Dhabi[10].</td></tr>
</table>

Material		Low Emissivity Glass (Low- E)	(Ethylene Tetra Fluoro Ethylene) Etfe
Improving The Properties Of Glass In Modern Architecture	Description	Single. Double. Triple glass panels with a silver coating with a diameter of 150 nanometers Gas such as argon or krypton between the glass panels, while it prevents sunlight from entering the space and prevents the heat of internal space from gaining access to the outside.  **Fig. 12.** The components of low-e glass[12].	The material (ethylene tetrafluoroethylene) is a membrane of molten extruded polymer [4]. It is a transparent air-compressed cushion, which can be of one, two, three, or four layers. It forms the building envelope and is surrounded by a metal frame [13].  **Fig. 13.**Shows ethylene tetrafluoroethylen[14].
	Gap thickness	gap filled with 12 mm of argon gas. Thickness of Low E: 150 nm [11].	It does not have fixed sizes, as it is calculated according to the requirements of each building.
	Glass thickness	4mm, 5mm, 6mm, 8mm ,10mm [11]	
	Color	Colored.	Transparent, printed, or coloured varieties.
	position	Openings and Facades.	Douple Skin Facades, Cladding, and Roofs.
	U-Value	٥W/m^2.^{o}C [11].	One Layer ٥,٦W/m^2.^{o}C Two Layer ٢,٩W/m^2.^{o}C Three Layers ١,٨W/m^2.^{o}C Four Layers ١,٤W/m^2.^{o}C[15].
	SHGC	0.26-0.24-0.76 According to glass type [11].	Two Layer. 0.48. Three Layers . 0.35 [15].

	Case Study	 **Fig. 14.** Kande International Hotel, China[17].	 **Fig. 15**. The Shed Building in New York, United States [16].

2.6. Smart architecture.

2.6.1. Definition of smart material.

Materials that change their properties based on an external stimulus producing an output. They are capable of being replicated, and the effect can be either specific wavelengths of light, changes in temperature,motion, deformation, pressure, chemical concentration, or electrical or magnetic fields. while the output can be changes in colour, light, temperature, deformation, stress, hardness, or viscosity.

Smart materials have common properties:

1. **Immediacy**: immediate response upon exposure to an external stimulus.
2. **Transiency**: reacting to multiple environmental influences and possessing different properties based on varying environmental factors.
3. **Self-actuation**: Material properties are intrinsic and not solely produced by external influences on the materials.
4. **Directness**: precision in the material's response, generating outputs precisely at the point where inputs are applied.
5. **Selectivity**: anticipating the response properties of the external stimulus, allowing the prediction that a single environmental condition can lead to a unique and consistent response in the material [18].

Fig. 16. Behaviour of smart materials.

2.7. Development of electrochromic smart materials.

Materials that change their colour when an electric field is applied to them. Electrochromic materials became known in 1953 when Crowas worked on tungsten trioxide, which he found changed its colour to a dark blue upon the application of an electric field.

In 1969 and 1973, Dep published research on thin films of molybdenum and tungsten trioxide, laying the principles of modern electronics. In the 1970s, Nick Cheriden developed a research paper for the European market, introducing the first commercial electrochromic glass under the trademark name 'Prive Lite' in 1991. This system, relying on liquid crystals, transitions from transparent to opaque. This system is still available today. It is based on liquid crystals and shifts from transparent to opaque [19].

The initial applications for electrochromic-responsive materials were anti-glare mirrors, reducing glare for car drivers, thus ensuring their safety while driving, and electric-sensitive materials are considered one of the most flexible types of chromogenic materials, as they can be controlled through external control (active material) [20].

Fig. 17.EC glass applications: (A) using EC glass in cars mirrors and (B) EC glass in windows applications[18,23].

2.7.1. Electrochromic glass components.

Electric smart sensitive glass consists of five layers: two layers act as electrodes (such as the positive and negative poles of the battery), and an inner electrolyte layer contains ions.

When the electric current is turned on, positively charged ions are pushed to one layer while the electrons move to the other, activating the dye, changing its colour, and making it opaque, which works to block some of the visible light [22].

1. Ion conductor helps to colour through redox reactions, while the ion storage layer stores and provides the required ions for the material (this layer is polyvinyl butyral (PVB)).
2. Conducting Film.
3. 2 mm thick electrochromic layer (tungsten oxide (WO3) and prussian blue) [23].
4. Vacuum 12 mm, 90% Krypton Gas.
5. 4 mm Low-E Coating (not an essential layer; it is just added to increase glass efficiency).
6. Two layers of glass.

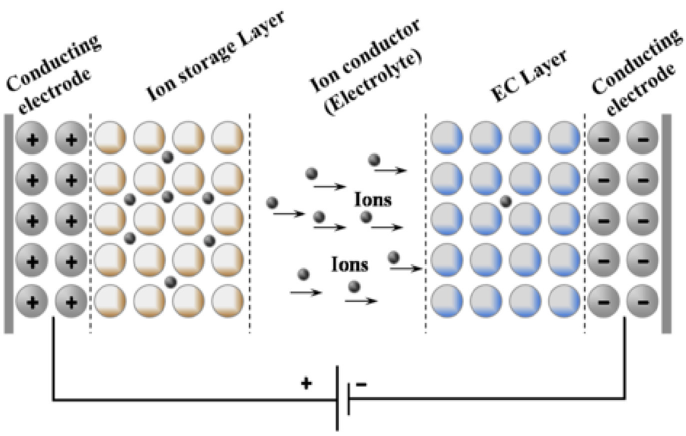
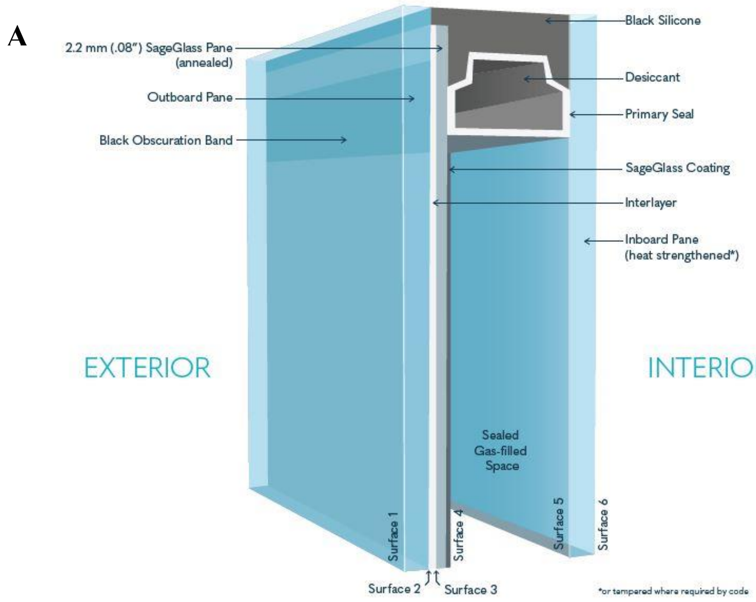


Fig. 18. Electrochromic Glass Components[24].

2.7.2. Properties of electrochromic sensitive glass.

Table 2. Properties of electrochromic sensitive glass.

Thermal Conductivity Coefficient **(U-value)**	Double Glass 1.1 W/m^2.ºC	
	Triple Glass 0.6 W/m^2.ºC [25]	
Heat Gain Coefficient **(SHGC)**	Clear Glass	0.41
	Intermediate State 1	0.15
	Intermediate State 2	0.10
	Fully Tinted	0.09 [٢6]
Shading coefficient **(SC)**	Clear	0.48
	Tinted	0.12
Visual Light Transmittance	Clear glass	0.4 (60%)
	Intermediate State 1	0.12 (17%)
	Intermediate State 2	0.07 (5%)
	Fully Tinted	0.05 (1%) [26]
Electric current	1.5V to 3V (DC)./ 1.2 Am to 3.75 Am Power consumption/sqm: 2.5 Watts, Average: 0.4 Watt; when the electric current is connected(on),the glass becomes tinted and when the power supply is disconnected(OFF),it returns to its normal state [26].	
The Time It Takes To Do Switching	5-15mins To reach 90% of tinting [26]	
The life span	Almost 20 years [25].	
Energy Conservation	Energy conservation depends on the climate zones and window wall ratio (WWR); the ratio ranges from 5% to 50%. A study by a glass manufacturer showed a decrease in energy consumption of 5% in Copenhagen (a warm, humid climate). to 18% in Madrid (warm, dry climate).with an average daily consumption of glass w/m2 of 0.05 [25].	
(Thermal Comfort & Productivit)	Eliminate 91% of heat gain which enhances employees wellness, satisfaction and productivity.	
Noise Reduction (Rw)	31 (-3;-6) dB (double glazing). 32 (-1;-5) dB (triple glazing) .[26]	
Thickness	20mm [25].	
Sizes	Minimum sizes 457mm x 457mm. Max Sizes 1520mm*3050mm [25].	

<table>
<tr><td>Double Glass</td><td>


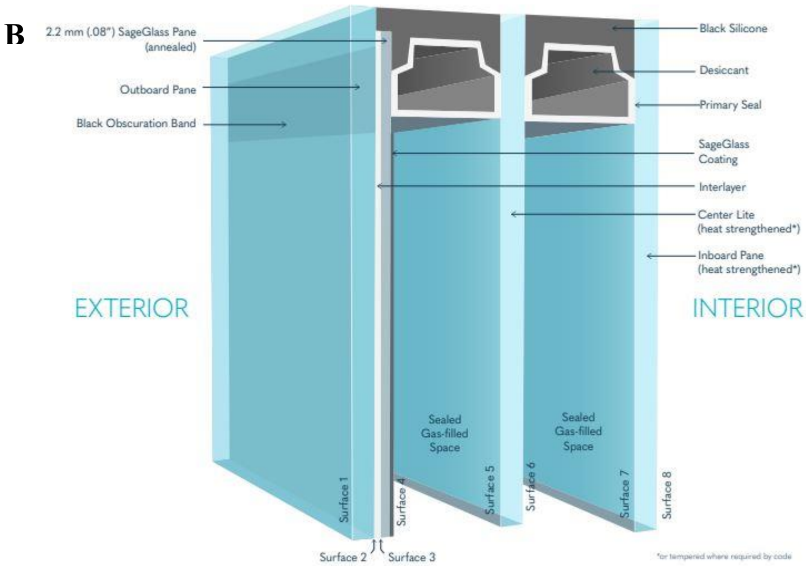
</td></tr>
<tr><td>Triple Glass</td><td>


Fig. 19. Different sections of electrochromic glass: (A) EC glass double section and (B) EC glass triple section [27].
</td></tr>
<tr><td>Sustainability</td><td>The glass is self cleaning(based on a predictive algorithm and weather data) , and can also be recycled.</td></tr>
<tr><td>Certificates</td><td>LEED Certified</td></tr>
</table>

2.7.3. Controlling electrochromic sensitive glass.

Electrochromic Sensitive Glass is controlled using a remote or smart phone, as well as linked to the BMS system, which is the main control system that connects all the mechanical, electrical, information technology, and security systems of the building and unites them in one system, so they can share information and work together easily for better control. It also contains a smart control system that self-cleans the glass [26].

Fig. 20. Controlling Electrochromic-Sensitive Glass[27].

2.7.4 Changing of glass color according to solar radiation intinisity.

The glass can change its colour between clear and tinted, which controls solar radiation entering architectural spaces, as shown in **Fig.21.**

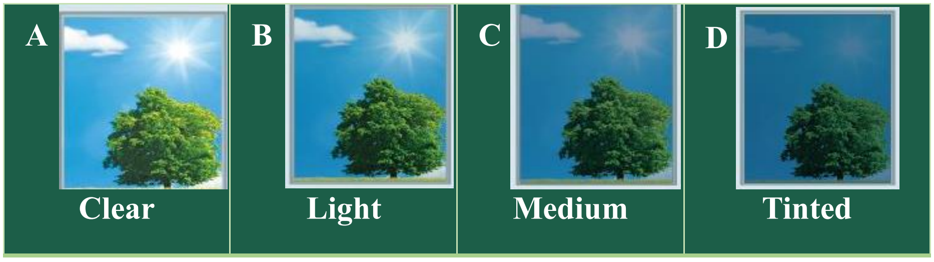


Fig. 21. Changing Of Electrochromic Sensitive glass color: (A) glass clear state and (B) glass light state; (C) glass medium state and (D) glass tinted state [27].

Sunrise:

When the sun shines, the glass facing the sun is tinted to reduce glare inside the spaces, which works to create a visually and thermally comfortable indoor environment.

Noon:

When the sun moves at noon and is perpendicular to the building, the glass facing the sun is darkened to reduce the penetration of solar rays into the spaces until the sun disappears.

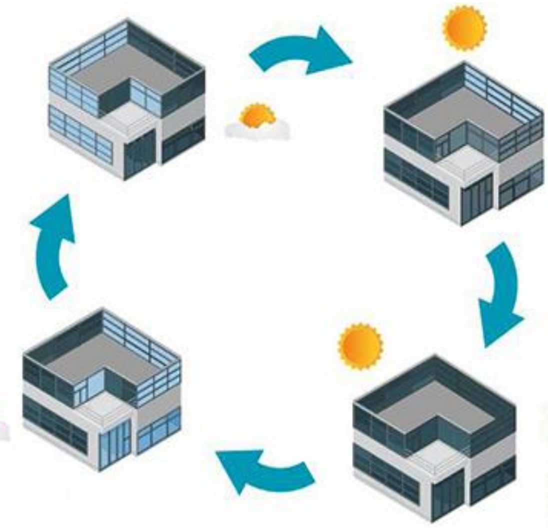


Fig. 22. The glass interacts with the sun's movement throughout the day[27].

Sunset:

The western façade is exposed to solar radiation when the sun starts to set, and the users who sit near the windows feel it is completely tinted to prevent glare and solar rays from entering the spaces.

Late afternoon:

In the afternoon, sun heat increases, which creates a need to maintain thermal comfort, so the glass changes to a tinted colour to achieve maximum comfort for users and save energy.

2.8. Egypt's main climate zones.

2.8.1. Climate Zone Definition: It is an area of the earth that has climatic characteristics that distinguish it from others.

Egypt has a significant difference in climatic conditions and is divided by the Egyptian Organisation for Energy Conservation and Planning (EOECP) into seven different climatic zones based on the analysis of climate data from 45 meteorological stations nationwide. These seven climatic zones are: Mediterranean coastal zone, Red Sea coastal zone, semi-temperate zone, semi-desert zone, desert region, very dry desert region, and mountainous region. These areas vary greatly in climatic conditions.

Another additional climate classification has been developed by the Housing and Building Research Centre (HBRC), and this classification divides Egypt into eight climatic zones, namely: North Coast Region, Delta and Cairo Region, North Upper Egypt Region, South Upper Egypt Region, East Coast Region, Highlands Region, Desert Region, and South Egypt Region. This classification is based on operating temperature and humidity, precipitation, wind speed, altitude, and solar radiation,as well as the natural topography of the country. [28]

In this research, the climatic division of the HBRC will be used, and it will also be guided by the Egyptian code to improve energy efficiency in commercial buildings as a ruler to measure the solar heat gain coefficient (SHGC) required to achieve with the glass used in different zones to achieve energy conservation in this building.

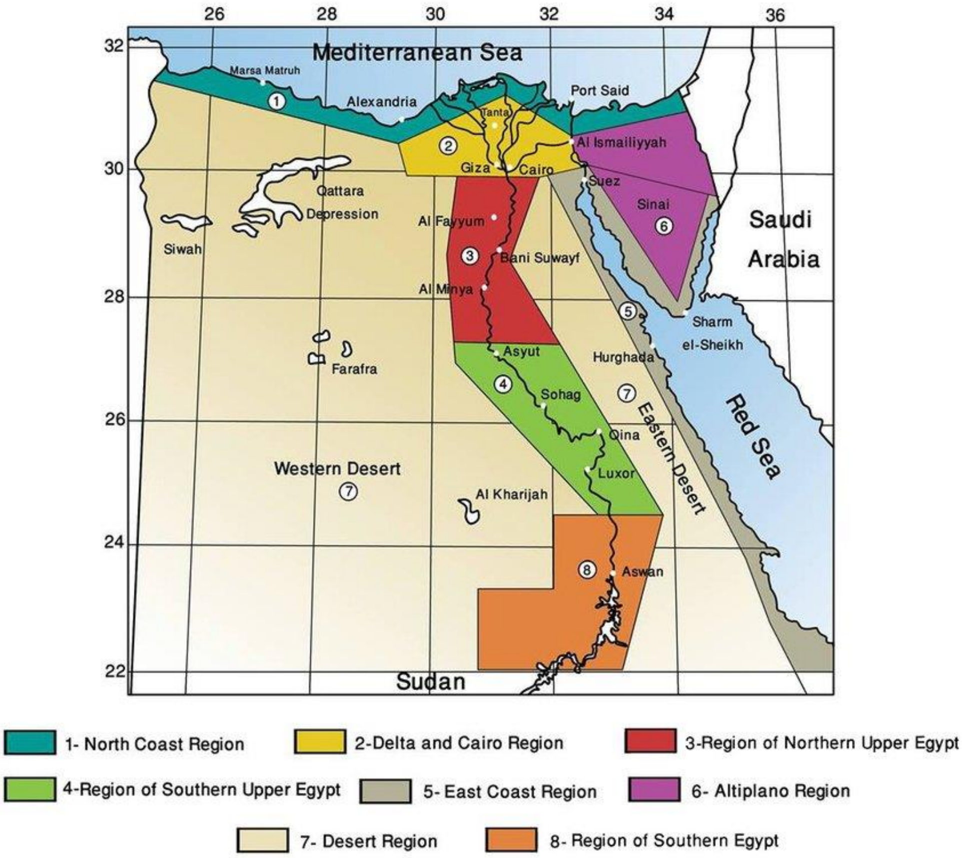


Fig. 23. Classification of climatic regions in Egypt according to (HBRC)[28].

2.8.2. Requirements of the egyptian code for improving energy efficiency in commercial buildings for exterior facades.

Table 3. The Requirements Of The Egyptian Code To Improve Energy Efficiency In Commercial Buildings For The Outer skin (Egyptian Code To Improve Energy Efficiency In Commercial Buildings).

Climate Zone	Element Type	Color	Solid Parts: Required Thermal Resistance m^2.^{O}C/W		Void Parts: Window to wall ratio(WWR)				
			Heavy constr-uction	Light constr-uction	10< O< 20%	20< O< 30%	30< O< 40%	40< O <50%	O > 50%
					Maximum Solar Heat Gain Coefficient (SHGC)				
	Surface Walls	Dark	2.2	2.7					
North Coast Zone	E/W	Dark	0.9	2.0	0.7	0.4	0.3	0.3	0.2
		Light	0.6	1.6					
	S	Dark	0.6	0.7	N.R	0.8	0.6	0.4	0.3
		Light	0.5	0.83					
Highlands Zone	Surface Walls	Dark	2.4	2.9					
	E/W	Dark	1.3	1.8	N.R	0.5	N.R	N.R	N.R
		Light	1.1	1.5					
	S	Dark	1.4	1.9	N.R	0.7	0.6	0.5	N.R
		Light	1.0	1.5					
Desert Zone	Surface Walls	Dark	3.3	3.8					
	N	Dark	1.3	1.8	N.R	0.8	0.5	0.4	0.4
		Light	1.2	1.7					
	E/W	Dark	1.6	2.1	0.6	0.3	0.3	0.2	0.2
		Light	1.4	1.9					

2.9.Smart glass and electricity bills.

The smart glass is composed of smart materials, which are highly efficient and require accurate manufacturing and extensive research and development, making it costly. The owner, seeking low prices, considers purchasing these materials a financial loss without considering their short- and long-term benefits, as they will save on building electrical bills by reducing air conditioner usage. Studies have shown that smart glass can reduce building energy consumption by 5–50%, depending on the climatic region, with an assumed lifespan reaching up to 20 years.

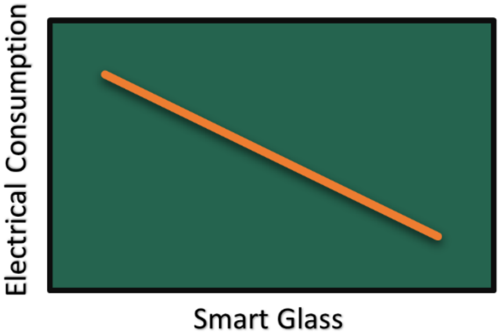
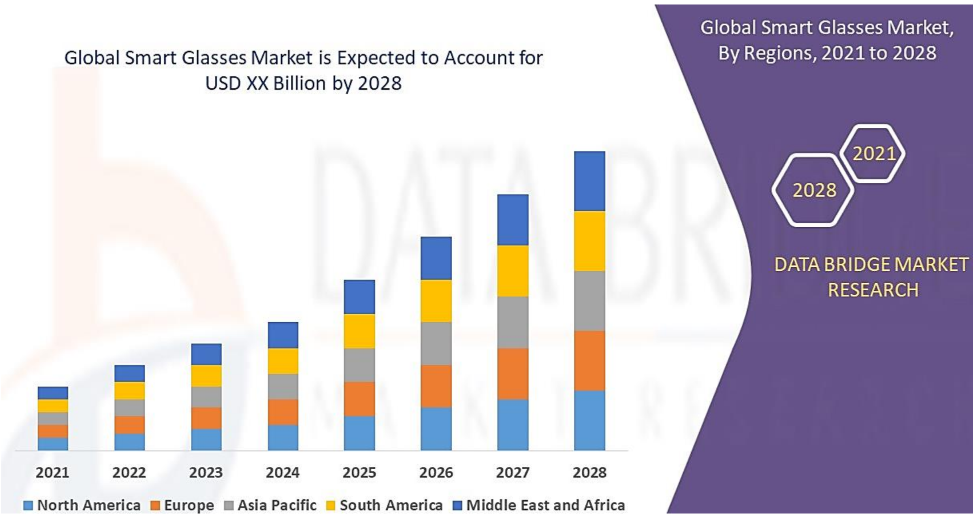


Fig. 24. The chart illustrates the relationship between smart electrochromic glass and electrical bills in buildings..

On the other hand, it self-cleans and can be recycled, making it a sustainable and environmentally friendly material. The demand for smart glass in manufacturing countries such as Germany, the United States, China,etc. has been increasing in recent years. It has become evident that when applied to suitable facades, it effectively affects energy consumption and helps the building obtain LEED certification. However, in Egypt, there is still a need for greater awareness and promotion so that the owner can realise the importance of this glass when used in buildings. Simply put, to use it efficiently, you have to calculate the cost of using glass with energy efficiency through simulation programmes, and then the designer and the owner can make the right decision.



.

Fig. 25. The increase in the global smart glass market (2021-2023), then the expected increase ratio till 2028. [29]

2.10. Analytical study.

Three examples were chosen in three different climatic regions whose characteristics are similar to the following three climatic regions in Egypt: the north coast climate, which is a hot humid climate; the highland climate, which is a cold humid climate; and the desert climate, which is a hot dry climate.

Measuring the value of the WWR of glass used in different facades and comparing the values of the solar heat gain coefficient (SHGC) for the openings in the facades in which the glass is used with the solar heat gain coefficient (SHGC) required to be achieved in the Egyptian code.

2.10.1. A case study of a building in a region similar to the climatic characteristics of the North Coast region.

The city of Brownsville is located according to the American code ASHAREA in the climatic zone (2A), which is similar to the north coast region of Egypt, and it is characterised by a hot, humid climate.

Brownsville Airport is one of the largest and most modern airports that have been established in Brownsville. It was designed by architect Corgan and established in 2020 [30].

Table 4. Brownsville South Padre Island International Airport case study**.**

Brownsville South Padre Island International Airport	Electrochromic sensitive glass was used on the main (western) façade as well as the southern façade, as they are almost the two most exposed facades to solar radiation throughout the daytime.The area of the glass was 1.223 m^2 .[30]  **Fig. 26.** Brownsville South Padre Island Airport: (A) and (B)different perspectines foe the airport [31].

Brownsville South Padre Island International Airpot Analysis

Analysis of climatic conditions.

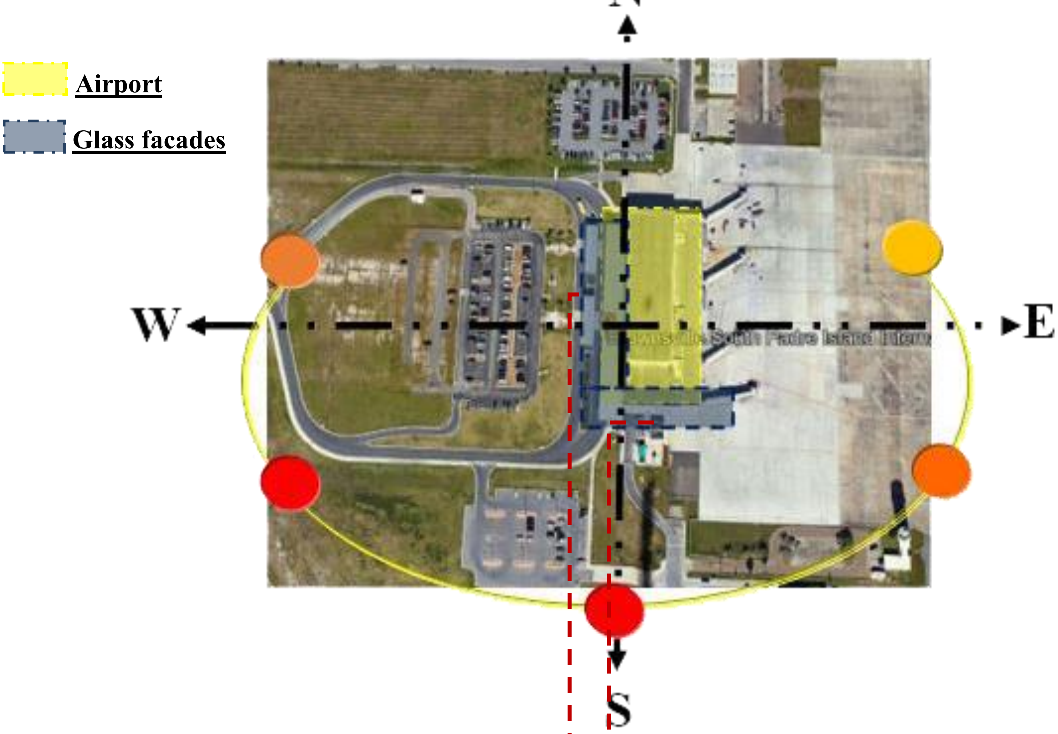


Fig. 27. Brownsville South Padre layout[32].

Fig. 28. Electeochromic sensitive glass was used on the western façade, where there is the entrance to the airport, which is a gathering area for passengers and must be suitable for waiting. [30].

Fig. 29. Electrochromic-sensitive glass was used on the southern façade. as it contains the passenger waiting area for the plane. [30] .

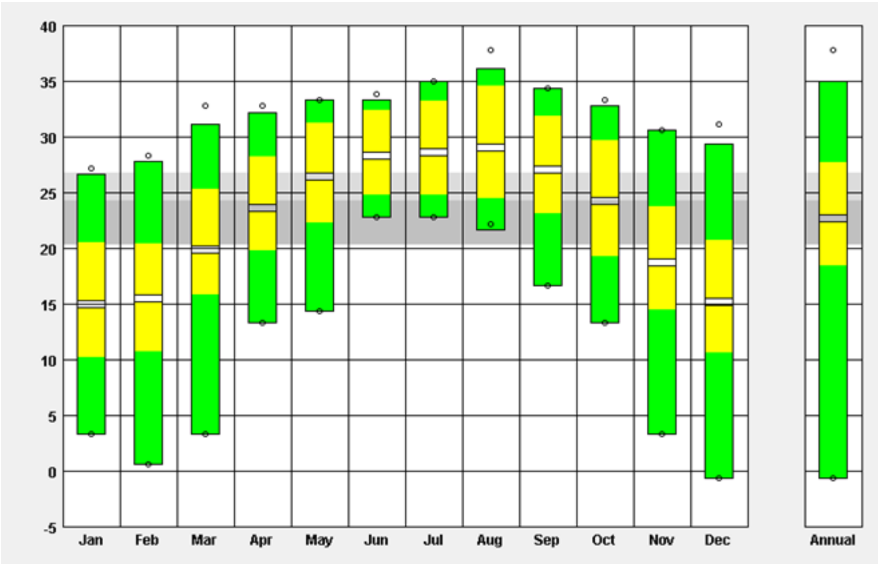
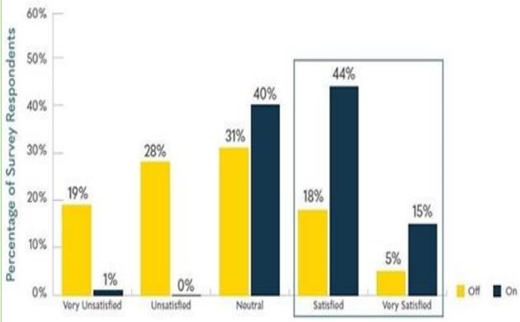


Fig. 30. The graph shows the lowest temperature reaches approximately -1 degree Celsius in December, and the highest temperature is in August, where it reaches 38◦C**[**33].

A survey was made for 160 people from users as well as airport employees from July 11, 2022, to July 25, 2022, and a comparison was made between the results of the glass, which is in the closed state (OFF), and the results of the glass, which is in the open state (ON), and the results were as follows [30] :

	Closed glass (OFF)	**Opened glass (ON)**	**Results**
Thermal comfort surveying	1.Passengers expressed their discomfort at the airport, especially when sitting near windows. 2. Users expressed a more negative experience when using glass while closed during daylight hours when the glass is exposed to sunlight, including sweating, and employees use the industrial ventilation system and fans throughout the day.	1. Tripling of thermal comfort in internal spaces. 2. One user saw that he felt thermal comfort even though he was sitting near the window.	59% satisfied with sensitive glass & 23% satisfied with the normal condition of the glass.  **Fig. 31.** The survey of usrer of brownsville airport on thermal comfort[30].

Day	18/7/2022	19/7/2022	20/7/2022	21/7/2022	22/7/2022	23/7/2022	240/7/2022

Glass OFF	36◦C	38◦C	36◦C	37◦C	37◦C	36◦C	37◦C
Glass ON	35◦C	36◦C	34◦C	35◦C	35◦C	34◦C	35◦C

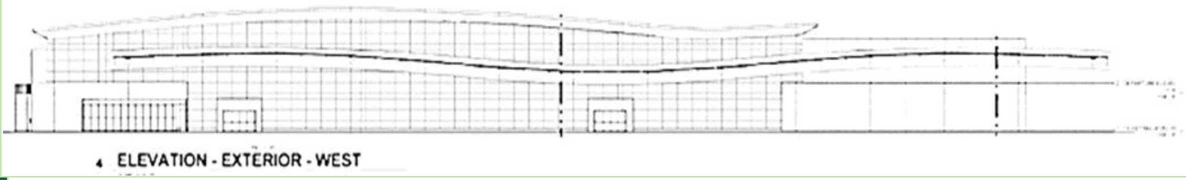
Table 5.Showing the decreasing in inner spaces temprature.

From above, we conclude that Electeochromic Sensitive Glass can lower the temperature of spaces by 2-3 degrees, and this value depends on the climate zone of the project and W.W.R.

Energy saving ratio	26.8% when comparing electricity bills for 7/2021 to 7/2022[30].

Glass facades — **Glass facades .**

A



Glass facades — **B**

Fig. 32. Brownsville South Padre Island Airport facades: (A) The South Facade (B) The West Façade of the Airport[34].

Comparing The Heat Gain Coefficient.

window to wall ratio (WWR)		West Façade 81%. South Facade 43.6%.		
Comparingthe Value Of The Heat Gain Coefficient		**The Required Value In The Egyptian Code**	Glass Solae Heat Gain Coefficent(SHGC)	
	West Façade	**0.2**	Clear glass Intermediate State 1	0.41 0.15
	South Façade	**0.3**	Intermediate State 2 Fully Tinted	0.10 0.09

Result	Glass can be applied in the North Coast climate, where it achieves the values of the heat gain coefficient required by the Egyptian code to improve energy efficiency in commercial buildings while also decreasing energy consumption.

2.10.2. A case study of a building in a region similar to climatic characteristics of (the highlands region).

Retrofitting the headquarters of Saint-Gobain, the world's largest building materials company, and transforming it into a LEED-certified building. The project is located in Malvern, Pennsylvania, in the in the United States.

Pennsylvania is located according to the American code ASHAREA in zone (5A), which is a cold, humid climate similar to the climate of the highland region of Egypt.

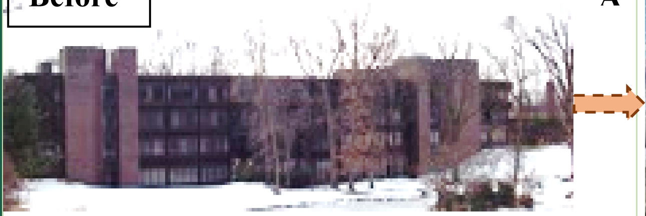
Table 6. Saint-Gobain And CertainTeed North American case study.

Saint-Gobain and CertainTeed building Analysis

The project consists of the company's headquarters, which is an office building,and the only building in the state that has an interior and exterior design approved by LEED Platinum and designed by architect Neil Liebman. The aim of the project was to create a second-generation workplace that increases employees comfort, daylight, and air quality through the use of innovative building materials from the Saint-Gobain Group, where the area of smart glass used in facades is 17,000 ft² / 1579 m² The development was completed in 2015 [35].

Fig. 33. Saint-Gobain and CertainTeed building[35].

Before **A**



A **After**

After

Fig. 34. Saint-Gobain facades before retrofitting:(A) the southern and (B) the western façade [36].

Fig. 35. Saint-Gobain facades after retrofitting :(A) the southern and (B) the western facade [35].

The western facade before retrofitting was made of clear glass with sun louvres.

The southern façade after retrofitting using electrochromic glass to exploit the view and provide thermal comfort.

Saint-Gobain and CertainTeed building Analysis

Analysis of Climate Conditions .

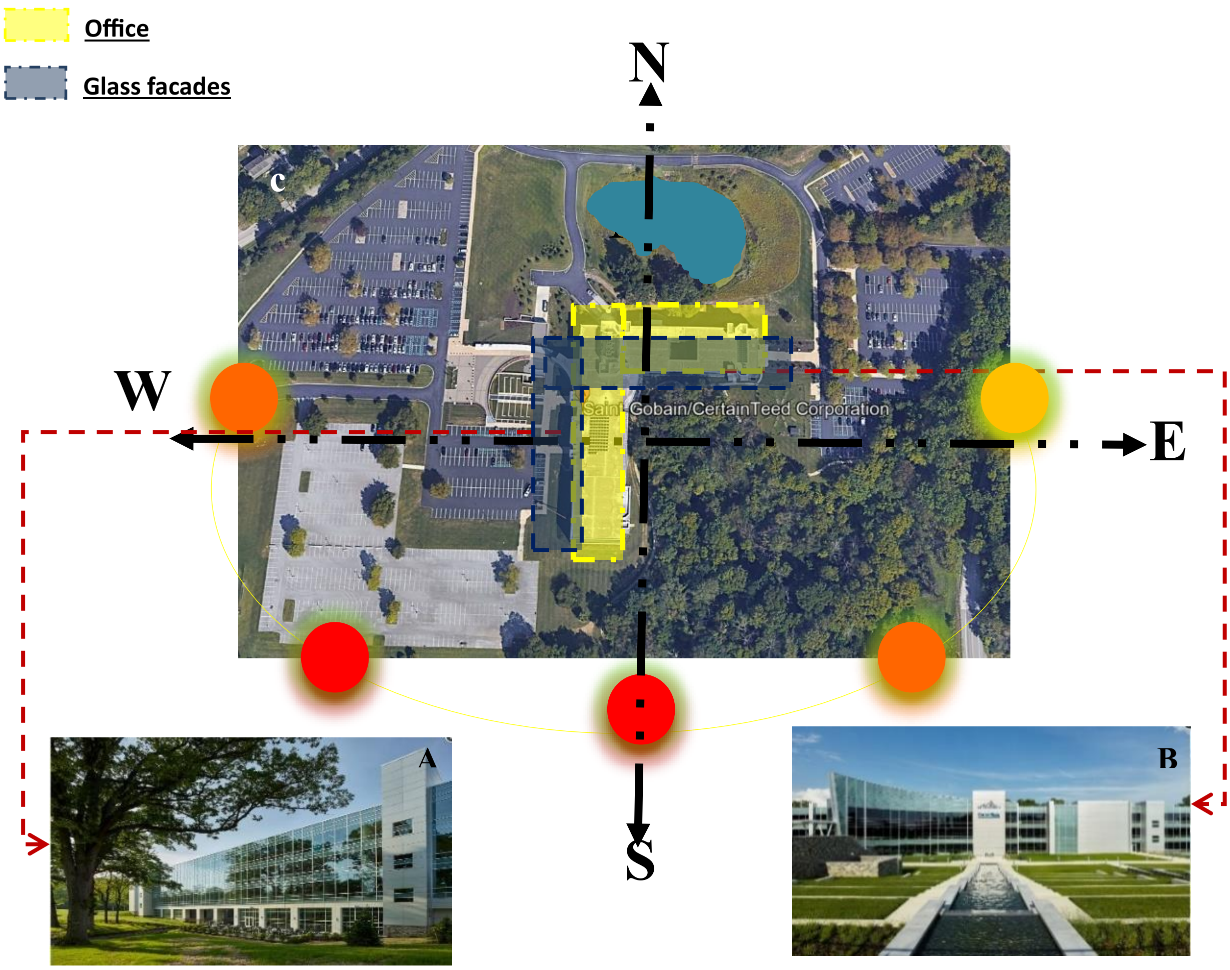


Fig. 36. Building climate conditions analysis:(A)the west ;(B) the south façade and (C) illustrating Saint-Gobain and CertainTeed building layout[32,35].

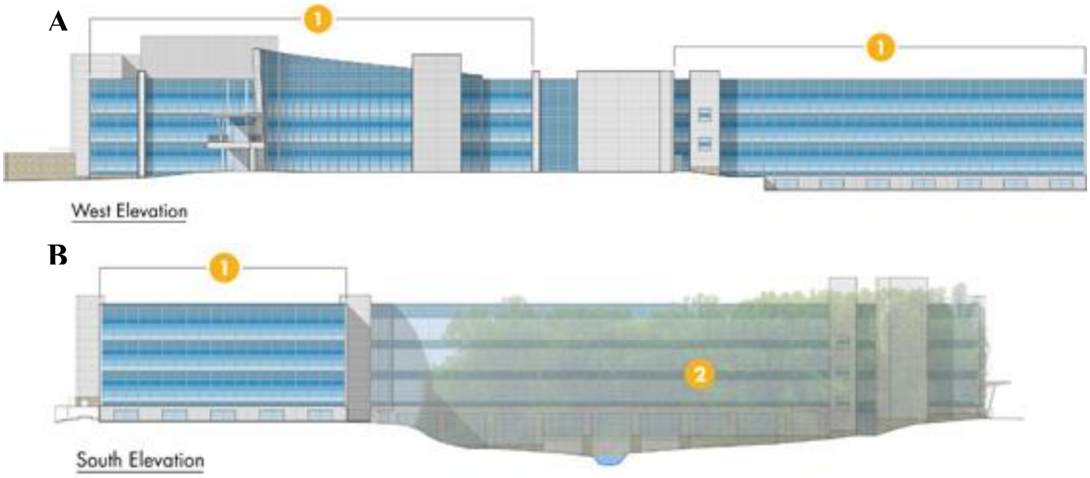
<table>
<tr><td rowspan="7">Saint-Gobain and CertainTeed building SHGC.</td><td colspan="5">Glass facades.
A


Fig. 37. Saint-Gobain and CertainTeed facades:(A)The west facade and (B) south façade [36].</td></tr>
<tr><td colspan="5">Comparing The Heat Gain Coefficient.</td></tr>
<tr><td colspan="2">window to wall ratio (WWR)</td><td colspan="3">Western façade:70%
Southern façade:68.8%</td></tr>
<tr><td rowspan="3">Comparingthe Value Of The Heat Gain Coefficient</td><td></td><td>The Required Value In The Egyptian Code</td><td colspan="2">Glass Solae Heat Gain Coefficent(SHGC)</td></tr>
<tr><td>West Façade</td><td>Not Required</td><td rowspan="2">Clear glass
Intermediate State 1
Intermediate State 2
Fully Tinted</td><td rowspan="2">0.41
0.15
0.10
0.09</td></tr>
<tr><td>South Façade</td><td>Not Required</td></tr>
<tr><td colspan="2">Result</td><td colspan="3">There is no need to use electrochromic glass in the Highlands region, where temperatures are low and times of sunshine are not great. Glass was used in this example to get the most of natural light and enter spaces without needing artificial lighting, and this also reduces the building's energy.</td></tr>
</table>

2.10.3. Case study of a building in a region similar to climatic characteristics of (the desert region).

The Swiss International Scientific School in Dubai (SISD) is a leading international school, owned by Al Ahmadiah Contracting (D&B) and designed by DSA Architects. It is educating more than 2,000 students. The project was completed in 2015 and is the first building in the Middle East to receive the Swiss Minergie Environmental Standards Mark [37].

The Emirate of Dubai has a hot, dry climate, which is the same climatic zone in which the desert climate is located in Egypt.

Table 7. Swiss International Scientific School case study.

<table>
<tr>
<td rowspan="2">Swiss International Scientific School Analysis</td>
<td>Electrochromic-Sensitive Glass was used, where electrochromic-tinted glass is dimmed to prevent sunlight and heat from entering the building, a function that can significantly reduce energy consumption and the need for heating, ventilation, and air conditioning. Glare reduction is also one of the main features of high-quality educational spaces where school students remain in touch with their surroundings as visual barriers such as curtains or shades are unnecessary [38].

Fig. 38. The Swiss International Scientific School in Dubai[38].</td>
</tr>
<tr>
<td>Analysis of the climatic conditions .


Electrochromic smart glass was used on the northern and western facades of the educational building to provide thermal comfort inside the spaces in addition to energy conservation.</td>
</tr>
</table>

B

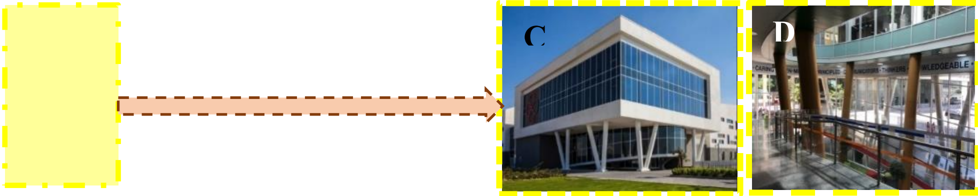


Fig. 39. Building climate conditions analysis:(A) and(B) showing The Swiss International Scientific layout;(C) perspective for EC glazing and (D)interior shot for glass in swiss international school[32,38,39].

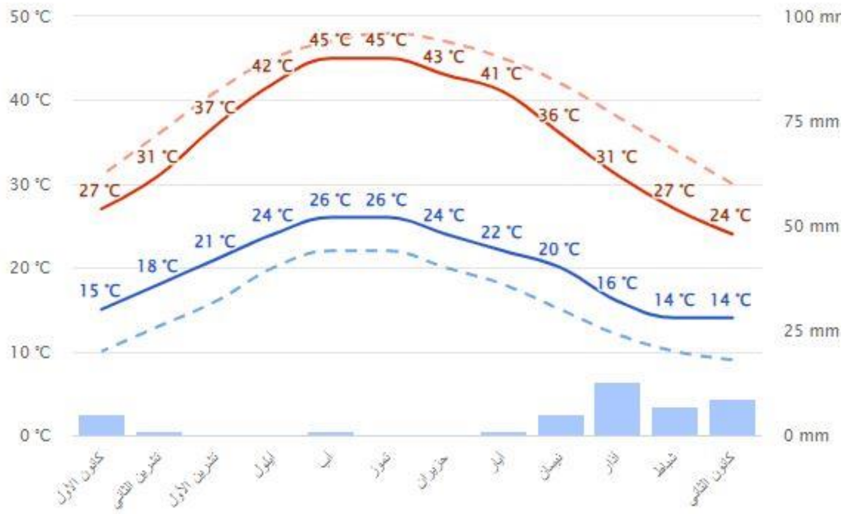


Fig. 40. The average temperature in Dubai, UAE [40] .The graph shows the average temperatures in the Emirate of Dubai, where the highest temperatures in the summer reach 45°C and the lowest temperatures in the winter season reach 10°C.

Glass Facades.

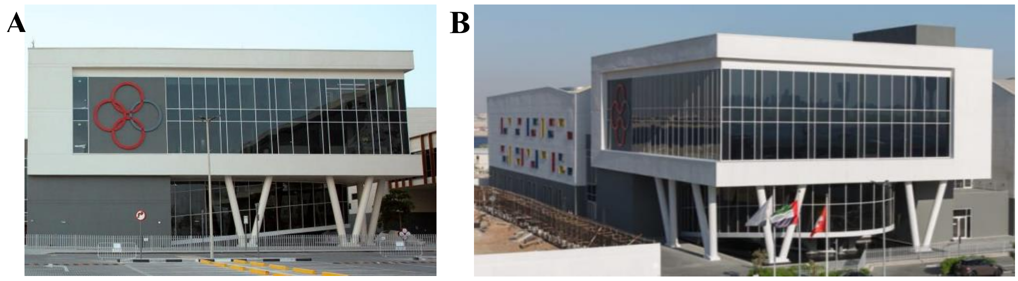


Fig. 41. Swiss International Scientific School: (A) The Northern Facade and (B) Perspective showing the northern and western facades that use smart glass to provide thermal comfort as well as natural lighting for students inside educational spaces [41].

Energy saving Ratio	An experimental study titled "The Energy-Saving Potential and Visual Comfort of Electrochromic Smart Windows Office Buildings: A Case Study in Dhahran, Saudi Arabia" was conducted using the simulation programme DesignBuilder to assess the energy consumption percentage of the building. The study simulated an office building in the city of Dhahran,Saudi Arabia,located in the desert climate, and it consists of 11 floors,with floor areas ranging from 300 to 800 square

<table>
<tr><td colspan="2"></td><td colspan="3">meters. And the results indicated a decrease in energy consumption by 23% compared to the previous year [42].</td></tr>
<tr><td colspan="5">Comparing The Heat Gain Coefficient.</td></tr>
<tr><td colspan="2">window to wall ratio (WWR)</td><td colspan="3">West Façade 62%.
North Facade 65% .</td></tr>
<tr><td rowspan="3">Comparingthe Value Of The Heat Gain Coefficient</td><td></td><td>The Required Value In The Egyptian Code</td><td colspan="2">Glass Solae Heat Gain Coefficent(SHGC)</td></tr>
<tr><td>West Façade</td><td>٠,٢</td><td rowspan="2">Clear glass
Intermediate State 1
Intermediate State 2
Fully Tinted</td><td rowspan="2">0.41
0.15
0.10
0.09</td></tr>
<tr><td>South Façade</td><td>0.4</td></tr>
<tr><td colspan="2">Result</td><td colspan="3">Glass can be applied in the climate of the desert region, where it achieves the values of the heat gain coefficient required by the Egyptian code to improve the energy efficiency of commercial buildings and lead to energy consumption.</td></tr>
</table>

3. RESULTS AND DISCUSSION.

The research reached a set of general and specific results related to the subject of the study, which can be summarised in the following points:

3.1.Results

The analytical study was made on various examples in different climatic regions (hot dry region, hot humid region, cold humid region) to try to cover the different climates in Egypt regardless of the small differences between the similar regions to draw conclusions and clarify which of the climatic regions in Egypt gives glass the best efficiency. The study showed that glass has the best efficiency in terms of reducing heat gain and achieving thermal comfort inside spaces in hot climates, and this material is more likely to be used in zones with hot climates in Egypt.

The study demonstrated a reduction in electricity bills when using glass in sun-exposed glass facades. As mentioned In Brownsville South Padre Island Airport in the coastal climate (hot-humid), there was a 26.8% decrease in energy consumption, and in Dubai, the Swiss International Scientific School building in the desert climate (hot-dry), there was a 23% decrease annually,which helps cover the high cost of glass in the short and long run. It only requires careful study to properly use glass in the correct facades to maximise its efficiency, and the owner gets the highest benefit from its advantages.

3.2.Discusion

Smart architecture is one of the most modern trends, a concept that emphasises the interaction of buildings with the surrounding climatic conditions and gives the user the ability to control the provision of a thermally comfortable climate inside the spaces in easy, simple, and fast ways, which works to provide a better life for humans**.**

Use of vast areas of glass is necessary in public buildings such as commercial, office, and recreational buildings for the desire to take advantage of external views and link the building with the external environment, but glass is also one of the factors in increasing the rate of thermal transfer due to the small thickness of the glass panel, so it was necessary to develop glass to provide these considerations with an aesthetic form and not consume large amounts of energy or not provide thermal comfort for users.

Many previous studies have been interested in doing experimental studies to measure the extent to which thermal comfort is achieved through the use of smart glass in facades, but a tiny number of previous studies are interested in mentioning real, realistic examples of projects in different zones of the world and analysing these examples, which was a reason to study this subject from a new point of view and provide sufficient information about some projects already existing in different climatic zones.

A necessary glass development happened as a result of the high temperatures and the global climate crisis, which is an emergency reason to rethink glass as not only a transparent element in the façade but also as an important façade element that must achieve the requirements of the Egyptian code for energy rationalisation as well as providing a comfortable environment for users**.**

Recommendations

There is a need to emphasise the importance of considering environmental data when designing and determining the final finishes of facades, as it is one of the most important elements in the building responsible for thermal transfer from the outside to the inside.

Through the previous results, there is a set of recommendations at the level of architects and researchers as well as the state.

First: Architects

The importance of using smart glass and taking it into consideration as an influential element in the thermal performance of the building from the first steps of the project.

Second: Researchers

Attention to the work of analytical studies for projects that have implemented smart changing colour glass facades to clarify its importance and availability as a product in the markets and to demonstrate its usefulness in rationalising energy and achieving the quality of the internal environment by reducing heat gain or providing the necessary natural lighting, as well as its usefulness in achieving a better quality of life for users by reducing glare resulting from the use of glass.

Third: The State

Due to the advantages provided by smart glass interacting with the external environment, using smart electrochtomic glass and manufacturing it in the Egyptian market will certainly be a strong addition to buildings, the environment, and the user.

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