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Bio-based Adaptive Skins: Investigating the Impact of Using Shape-morphing Skins on the Energy Consumption of Administrative Buildings

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Abstract: Recent research indicates that by employing adaptive architectural skins, energy consumption can be significantly reduced, as building skins are regarded as a boundary line between external and internal conditions and play the primary role in regulating energy consumption in buildings and preserving internal comfort. In architecture, smart materials with intrinsic properties that vary in response to different material-specific inputs or operating conditions are becoming widely researched. As they accumulate sensors and actuators that allow them to detect a stimulus, respond to it in a controlled manner, and return to their initial condition when the stimulus is removed . Accordingly, the main aim of this research is to investigate the viability of using smart materials in building skins in Egypt and how this will affect the energy consumption of buildings using a biomimetic approach. This approach suggests a compact, silent, lightweight dynamic building panel with simple actuation components. A performance comparison between the proposed shape morphing skin and a base case meeting room indicates that energy consumption can be reduced by 43%. These substantial results indicate that adaptive façades have the potential to improve building energy efficiency.

Keywords: Biomimicry, Smart materials, Shape-Morphing facades, Energy consumption, Nitinol wires.

ABBREVIATIONS:

NZEB	Net Zero Energy Buildings
SMA	Shape memory alloy
Ni-Ti	Nickel Titanium
MS	Martinsite start
MF	Martinsite finish
AS	Austenite start
AF	Austenite finish
OWSME	One way shape memory alloy
TWSME	Two way shape memory alloy

1. Introduction

Egyptian Electricity Holding Company yearly report stated that, in 2021 almost 60% of the energy generated in Egypt is consumed by the building sector only[1].Internationally, according to the International Energy Agency, buildings accounted for 27% of all energy sector emissions and 30% of global energy consumption, generating 8% of those emissions directly and 19% indirectly through the generation of the heat and electricity those structures consumed[2]. COVID-19 regulations led to a reduction in energy consumption and emissions in 2020, but by 2021 they had risen to even higher levels than in 2019[2].respectively. A large portion of a building's total energy consumption occurs during its operational phase, which includes tasks like lighting, heating, and cooling[3],[4]. Reducing the amount of energy needed for buildings to operate is crucial to achieving the Net Zero Energy Buildings (NZEB) goal.[5].As shown in fig 1, the energy consumption in Egypt by sector demonstrates that the building sector uses a significant amount of energy for all its services[1].

In high performance building design, adaptive facades are essential[6]. Smart materials with changing properties that adapt to environmental changes have the potential to significantly impact the built environment and the look of the building [7]. The publication by Addington and Schodek [8], has emerged as a ground-breaking resource for an academic approach to smart materials for architects. Internationally, numerous academic research teams have been advancing the study of smart materials and showcasing a variety of applications, including those at MIT, IAAC, Stuttgart University, and TU Eindhoven[7]. By incorporating the ability of biological transformation patterns to sense environmental changes and trigger inherent responses in man-made structures., Sung, Decker, Sabin, and Menges demonstrated a new understanding of particular material reactions[9]–[11].

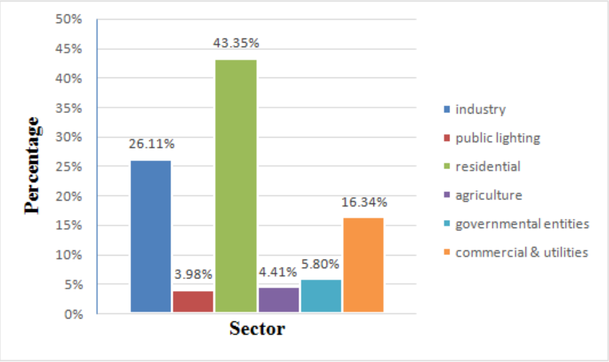


Fig 1. energy consumption in Egypt[1].

2. AIM OF THE PAPER

Accordingly, the aim of the research is to investigate the effectiveness of using smart materials in administrative building skins in Egypt and their impact on the building's energy consumption while using a biomimetic approach. Moreover,the long-term goal is to establish paths for widespread usage of thermo-responsive smart materials in energy-efficient, climate-adaptive facades and to develop more innovative prototypes to improve the dynamic and functional aspects of building skin material and system development.

3. METHODOLOGY

The methodology of this paper began with a brief introduction to bio-based design, followed by the selection of the biological model from which the skin will be inspired, the investigation of shape memory alloy (SMA) properties to determine how to use its intrinsic sensors as an actuator, and the determination of its form and dimensions in which it will be used. After presenting the design and mechanism of the shape morphing skin model, an energy simulation was done on a meeting room in office building in Cairo, Egypt, as a base case, compared to another energy simulation done on the same space after adding the new bio-based, nitinol actuated skin to evaluate the efficiency of using smart materials on increasing the energy efficiency of administrative buildings in Egypt.

4. BIO-BASED DESIGN

Bio-baseddesign,also known as biomimicry, is the study of imitation and imitating nature; designers have utilized it to assist in the solution of human problems. Architects and designers have looked to nature as a vital source of inspiration for millennia[12]. Biomimicry says that nature is the best, most influential, and most reliable source of innovation for designers due to nature's 3.85 billion years of evolution, which provides it with a vast amount of expertise in solving environmental problems[13], [14].Typically, biomimicry as a design process is employed using one of two approaches shown in fig. 2: Defining a human need or design problem and investigating how other organisms or ecosystems solve it is referred to as design looking to biology (top-down approach), whereas identifying a particular trait, behavior, or function in an organism or ecosystem and translating it into human designs is referred to as biology influencing design (Bottom-up approach)[15].

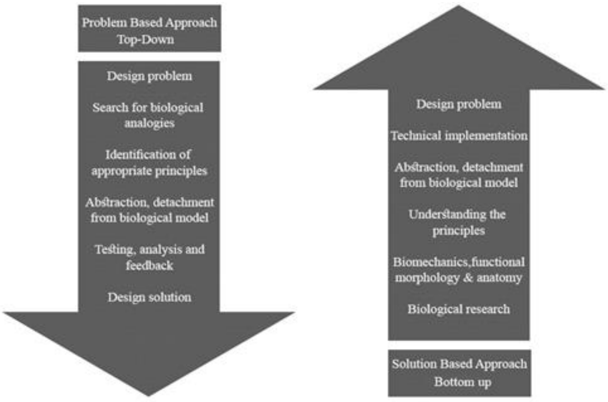


Fig 2. Biomimicry top-down and bottom-up approaches[15].

The organism, behavior, and ecosystem are the three levels of biomimicry in architecture[15]. On the level of organism, architecture takes inspiration from the organism and adapts its form, shape, or structure to a building. On the behavioral level, biomimicry is imitating how an organism reacts to, blends in, and integrates with its environment. On the eco system level, biomimicry entails imitating how different elements of an environment interact with one another at the urban level. These levels serve as a framework for designers who are interested in employing biomimicry to improve the sustainability and performance of buildings[16].

4.1 SELECTING BIOLOGICAL MODEL

There are two types of adaptation in plants, and they are defined as dynamic mechanisms and static strategies. In this research we will be focusing on dynamicmechanisms only. Nastic movement describes the motion of a plant component in response to an external stimulus where the direction of movement does not follow the direction of the stimulus. Light, heat, touch, contact, and changes to the water environment are all examples of stimulus[17].

Rhododendron leaves, shown in fig. 3, which exhibit thermos-nastic movements, will serve as a biological model for the design of the shape-morphing bio-based skin panels.The rhododendron and azalea are two of the most essential garden plants. Most naturally existing species are indigenous to the regions of southeast Asia stretching from the northwestern Himalayas, Tibet, and western and central China to Malaysia and the Philippines[18]. Members of the genus Rhododendron, whose species and hybrids are known as azaleas and rhododendrons, are ancient members of the Ericaceae plant family. According to fossil evidence, rhododendrons have existed for at least 50 million years and their flower shape and behavior have altered relatively little. There are around 1,000 known terrestrial and epiphytic species. They range from little ground cover plants to trees over 60 feet in height[19].

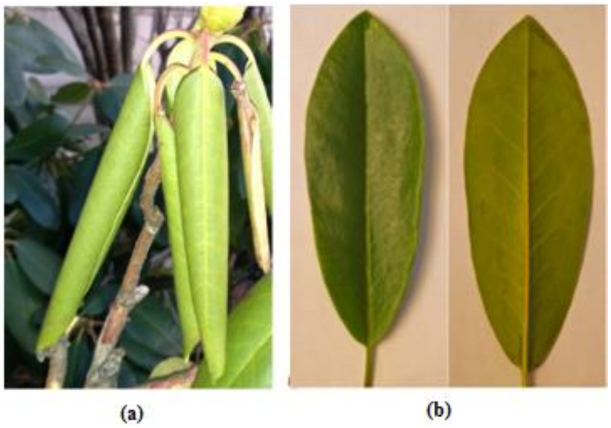


Fig 3.(a) Pendant and curled leaves at sub-zero air temperatures. (b) adaxial and abaxial surfaces of a freshly excised leaf at room temperature. [19].

Curling and rolling leaves are symptoms of low temperatures in rhododendrons. They spread more when the temperature increases[19], This is why rhododendrons are often called the thermometers of nature, As shown in fig 4.

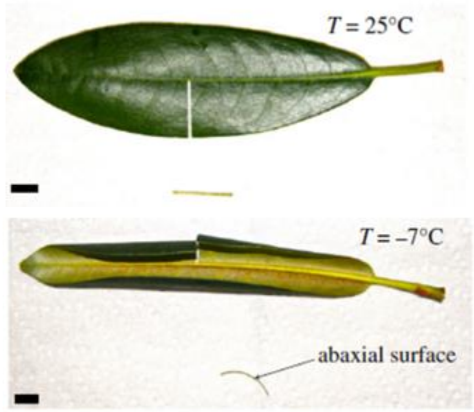


Fig 4.abaxial view of the unrolling of a frozen leaf after being exposed to room temperature [19].

Figure 5 shows, The unusual collection of reversible leaf movements provides the plant with a considerable advantage for survival throughout the harsh cold winter since the leaves can operate despite challenges like snowfall, freeze-thaw cycles, and drying winds. The thermo-nastic characteristics of a Rhododendron leaf are utilized to design a simple adaptive module panel. This module is then duplicated to create a shape-morphing building [19].

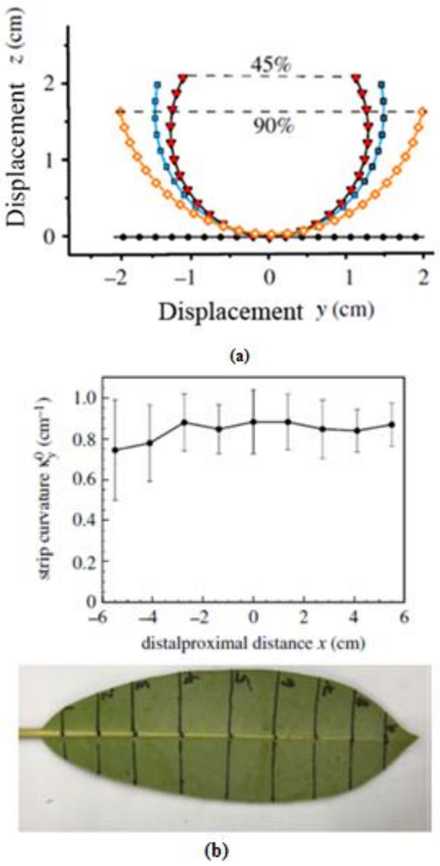


Fig 5. (a) cross-sectional profiles of the rolled morphologies for varying spontaneous curvatures and midrib moduli. (b) variation of the curvature of transverse strips cut along the midrib[19].

Based on the Leaf-dissection tests conducted by Wang, Nilsen, and Upmanyu, strips from the leaf lamina were cut with varying thicknesses and orientations based on the rolling experiment being conducted. The experiment revealed that the strip bends non-uniformly, with a greater curvature around the midrib, and the twist is minimal[19].

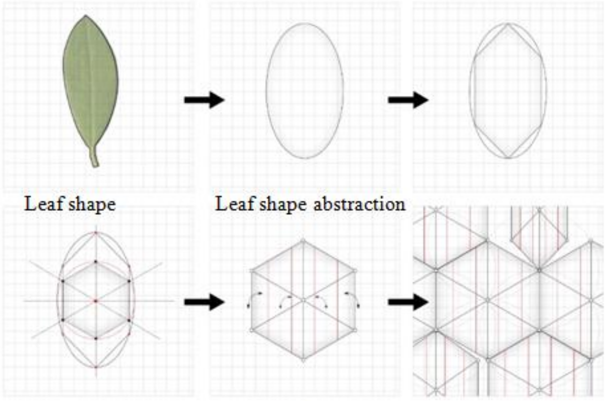
4.2 PRESENTING THE DESIGN OF THE SHAPE-MORPHING MODULE PANEL.

The proposed shape-morphing module panel incorporates biomimicry at both the organism and behavior levels. The basic form of the panel was developed from the physical look of the leaf, while its function was generated from the behavior of the leaf (Table 1).

Accordingly, the shape-morphing module panel that is being proposed will be designed to be able to be curled and rolled on its symmetry axis in low temperatures, which can be set at temperatures below 30 degree Celsius, and it will return to its fully flat extended posture when the temperature surpasses 30 degree Celsius, thereby providing the required shading to the window surfaces or curtain wall that is located behind it, as shown in figure 6.

TABLE 1.application of biomimicry levels in the design of the shape-morphing module panel.

Biomimicry level	Application
Organism level	-The form of the shape-morphing module panel is derived from abstracting the shape of the leaf.
Behavior level	-Sensing the outdoor temperature. -Curling and rolling of the leaf according to itstemperature.



(a)

Module panel design

(b)

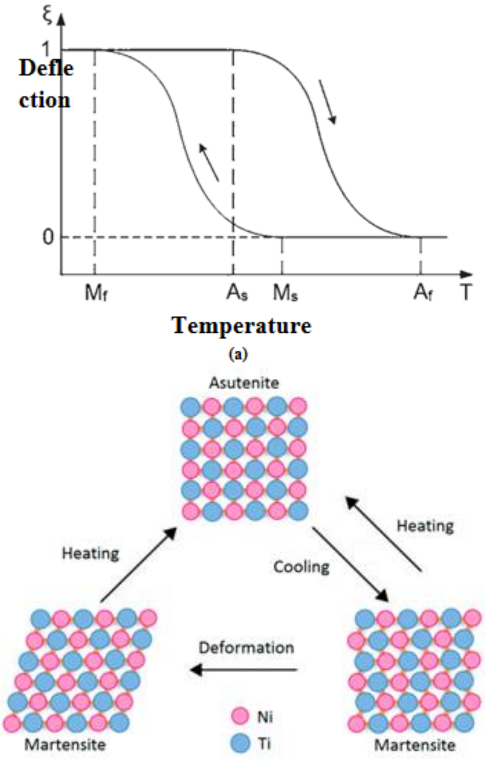
Fig 6.(a) abstraction process from the leaf shape to the module panel. (b) the module panel morphing between curled and opened phases.

5. SHAPE MEMORY ALLOY AND THE PANEL MECHANISM DESIGN

Shape-memory alloy (SMA), commonly referred to smart metal, is an alloy that can be deformed easily at a low temperature and regain its memorized shape when temperature increases[20]. SMAs are lightweight and chemically resistant in addition to having shape memory[21]. Certain SMAs have the properties of super elasticity, damping capacity, and biological compatibility, hence they are extensively utilized in the aerospace, robotics, and biomedical industries. Real-world SMA products include self-adjustable dental braces, eyeglass glasses, vascular stents, etc. SMAs can efficiently reduce the expense of repeated shape adjustment and lengthen the lifetime of a product[21].

In the 1960s, the Shape Memory Effect on Ni-Ti alloy was discovered[20]. Nitinol is the name of the alloy that Buchler and Wiley created at the Naval Ordnance Laboratory (NOL). Materials with shape memory are a significant and expanding class of intelligent materials. These are alloys whose crystalline structure and shape change at the phase transition temperature (or transformation temperature). Above the transition temperature, the alloy reaches a cubic structure and reverts to its original shape. A body is said to have shape memory[22].

Whereas alloys are made up of diverse metal atoms, pure metals are made up of the same type of atoms that are densely packed. Martensite and austenite shown in fig.7 are the two main phases of shape memory alloys[20]. The former is present at lower temperatures, whilst the latter is present at higher temperatures. When pure metals are distorted beyond their elastic range by an external force, they cannot restore their original shape by heating. In contrast, when SMA is in the martensite phase and plastically bent to a limited extent, it can be changed into the austenite phase by heating to the transition temperature, at which point it will regain its previous shape. The SMA will maintain its shape even if the temperature drops below normal once more. Several intelligent goods can be created using the shape memory property. SMAs fall under the category of intelligent materials as a result[20], [21].



(a)

(b)

Fig 7. (a) Curve of heating and cooling SMA alloys. (b) Transformation between the martensite and the austenite phases[21].

The Ni-Ti alloy is composed of approximately 50% Ni and 50% Ti, and the percentage can be modified according to the needs of various applications, such as the transition temperature range and mechanical qualities[20]. In general, a larger Ni concentration reduces the transition temperature. For instance, the alloy containing 50% Ni and 50% Ti has a transition temperature of 40 °C, whereas the alloy containing 55% Ni and 45% Ti is capable of form memory at room temperature. If Ni is less abundant than Ti, the transition temperature of the alloy can approach 120 °C[21].

5.1 SHAPE MEMORY ALLOY PROGRAMMING

Generally, the shape memory effects of SMA can be separated into two categories:

- One-way shape memory effect:

Deforming a SMA while it is in the martensite phase will result in the material keeping its new shape until its temperature is elevated above the transition temperature. The SMA reforms into its original form when heated, into austenite phase structure. After the SMA has cooled, it will maintain its current shape until it is once again distorted[21].

- Two-way shape memory effect:

When the SMA is bent with or without an external force and heated beyond the transition temperature, it enters the austenite phase and returns to its former shape. As the temperature falls below the transition temperature, the SMA will automatically revert to the martensite phase form that was previously memorized. The effect is known as the intrinsic two-way effect. This effect will be the core actuator mechanism of our research paper[21].

In order to get the shape memory alloy formedinto specific shapes at specific temperatures, it has to be programmed and trained in one of the following methods:

- Training by Over deformation.

The alloy is cooled below Mf and repeatedly bent to well beyond the stain limit while it is in the martensite stage for fully recoverable shape memory. The alloy won't change back to its original shape when heated to the parent phase. A partial loss of shape memory happens when the shape memory strain limit is exceeded. The alloy will spontaneously revert to the over-deformed shape if the SMA is cooled to the martensitic stage once more[20].

- Training by Shape Memory Cycling.

This process entails performing shape memory cycles repeatedly until the two-way behavior starts. The component is typically cooled to below Mf, deformed up to the shape memory strain limit, and then heated to restore the component's original, high temperature undeformed shape. After performing five to ten of these cycles, the component will start to spontaneously change shape after cooling, travelling in the direction that it consistently deformed over the training cycles. Much less spontaneous shape change will occur during cooling than was necessary to cause the shape memory deformation[20].

- Training by Pseudo elastic (PE) Cycling.

By repeatedly loading and unloading the parent phase above theaustenite finish temperature (Af) but below the Mf where pseudo elastic (or super elastic) behavior is anticipated, stress is repeatedly induced in Martensite. The approach typically requires 5 to 10 training cycles[20].

- Training by Combined SME/PE Training.

In order to stress induce some stress biased Martensite, the specimen must first be deformed in the parent phase state. It is then cooled to below Mf while maintaining the induced strain in the component, and finally heated to restore its original undeformed shape. After several iterations of this procedure, Two way shape memory alloy(TWSME)behavior will be seen during subsequent heating and chilling[20].

- Training by Constrained Temperature Cycling of Deformed Martensite.

Given that it is a little bit simpler to execute in terms of temperature management, this training method is probably the most popular at the moment. This mechanism results in a stress-biased martensitic microstructure by deforming the specimen below Mf. The sample is then kept in its distorted state and heated to a temperature above Af. To finish the training procedure, the sample is typically repeatedly cycled from below Mf to above Af while being restrained in its original distorted shape. This training approach shows to be quite successful and is rather simple to implement[20], as shown in fig. 8.

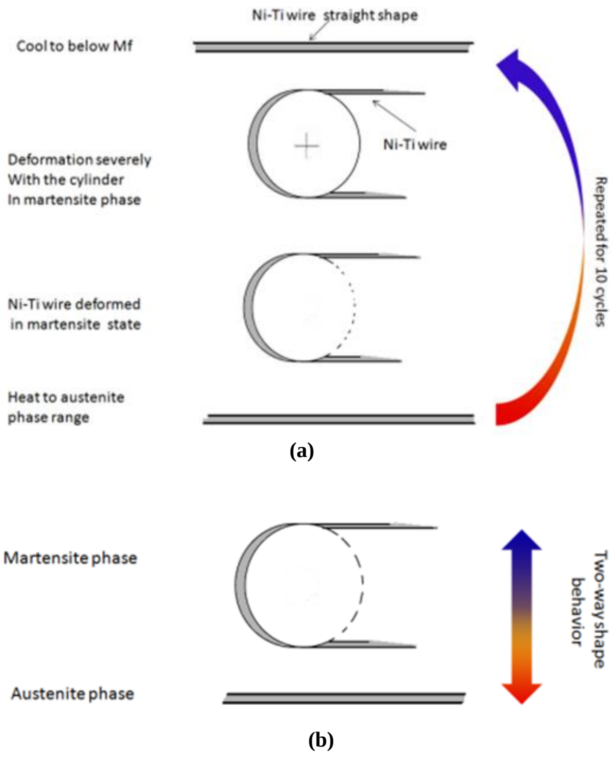


Fig 8.(a) Schematization of procedure made to achieve TWSME.(b) two shape memory behavior: curvilinear rolled shape in martensite state, straight shape in austenite phase [20].

5.2 SHAPE MORPHING PANEL MECHANISM DESIGN

Figure 9,10. show the design of the shape morphing module panel. The actuator for the shape-morphing module panels will be a two-way shape memory alloy wire with a width of 2 mm. The panel will be curled and rolled on its symmetry axis (martensite phase shape) when the temperature is below thirty degrees Celsius because the wire will have a transition temperature of that level. It will have a completely flat shape once the temperature exceeds 30 degrees. (austinite phase shape), Table 2 presents the components of the module panel.

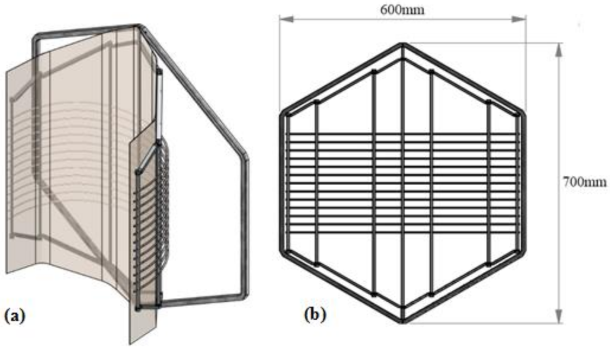


Fig 9. (a) axonometry showing the design of the shape-morphing module panel. **(b)** front view of the module panel and it’s dimensions.

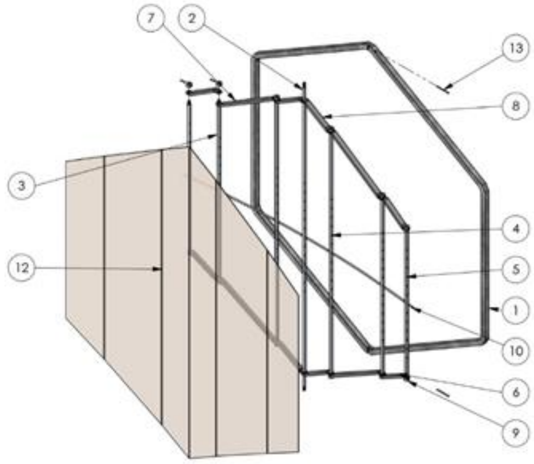


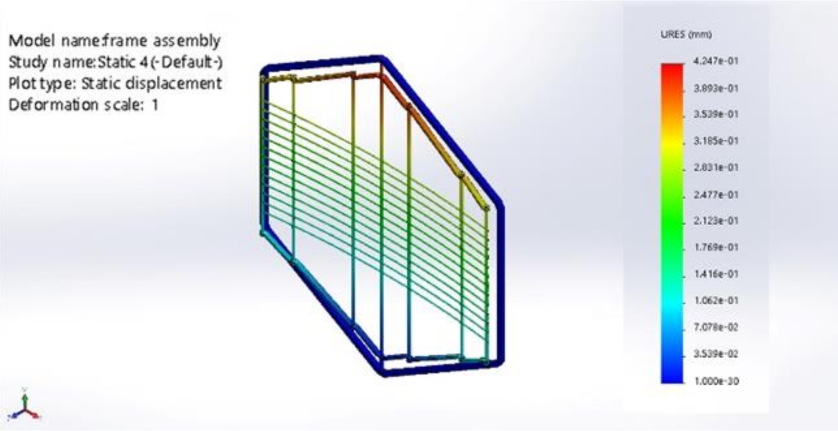
Fig 10. exploded diagram of the module panel showing all its components.

TABLE 2. components of the module panel.

Item no.	Description	Quantity
1	Frame	1
2	Support	1
3	Vertical support no.1	2
4	Vertical support no.2	2
5	Vertical support no.3	2
6	Arm no.1	6
7	Arm no.2	4
8	Arm no.3	2
9	Hinge	12
10	Nitinol wire	13
11	Hinge pin	12
12	Frame pin	2
13	Textile fabric	1

finite element analysis (FEA) with the material properties (tensile yield strength, and density of (2.4 GPa, and 6.45 g/cc) was carried out to ensure structural stability of the design. Fig. 11 shows the results of FEA simulation using Solid works software. The simulation shows that the system is stable as displacement and strain are very minimal and can be ignored.

To block the sun's rays, the suggested shape-changing shade facade is installed in front of the existing building's glass front. The assembled construction is a hexagonal grid of metal bars upon which the shape-shifting shading is placed. Textiles covering the module panel are chosen to allow some transparency so as not to interfere with the building's daylighting performance and to prevent blocking the sun's heat from heating the SMA wires.



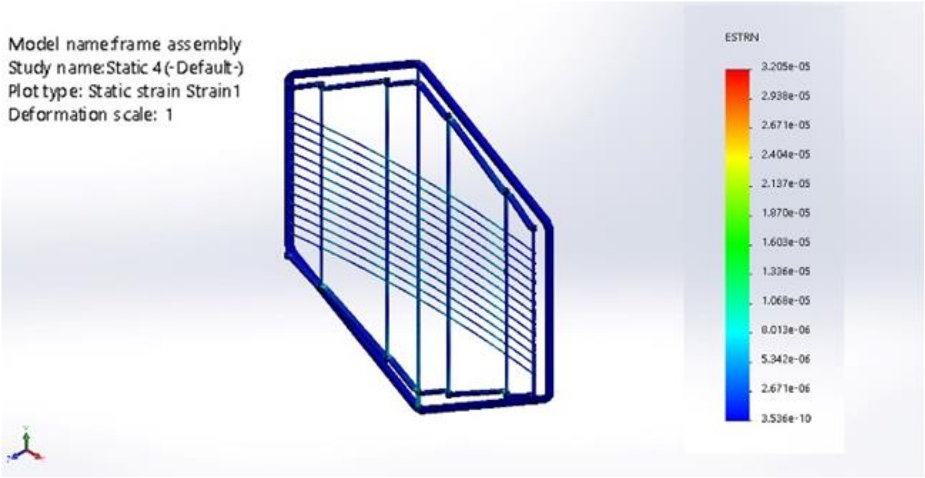


Fig 11. results of finite element analysis.

6. CASE STUDY

The research case study was carried out on a meeting room in New Cairo, Egypt. The meeting room is 6 meters in length, 10 meters in width and 2.8 meters height with an area of 60 square meters. the meeting room windows only on the southern façade with an area of 27 m2. accordingly, the window wall ratio is 90% (Fig.12).

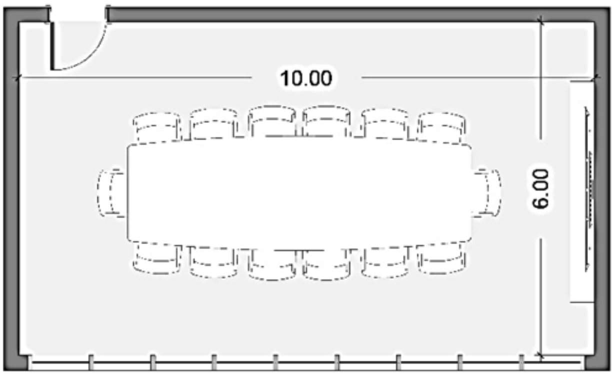


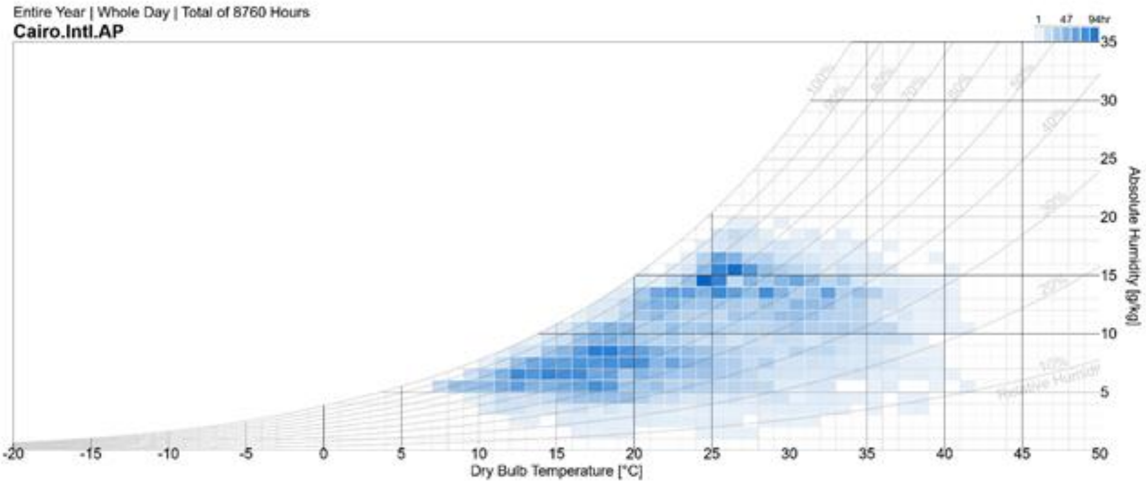
Fig 12. Case study meeting room floor plan.

6.1 Cairo climate

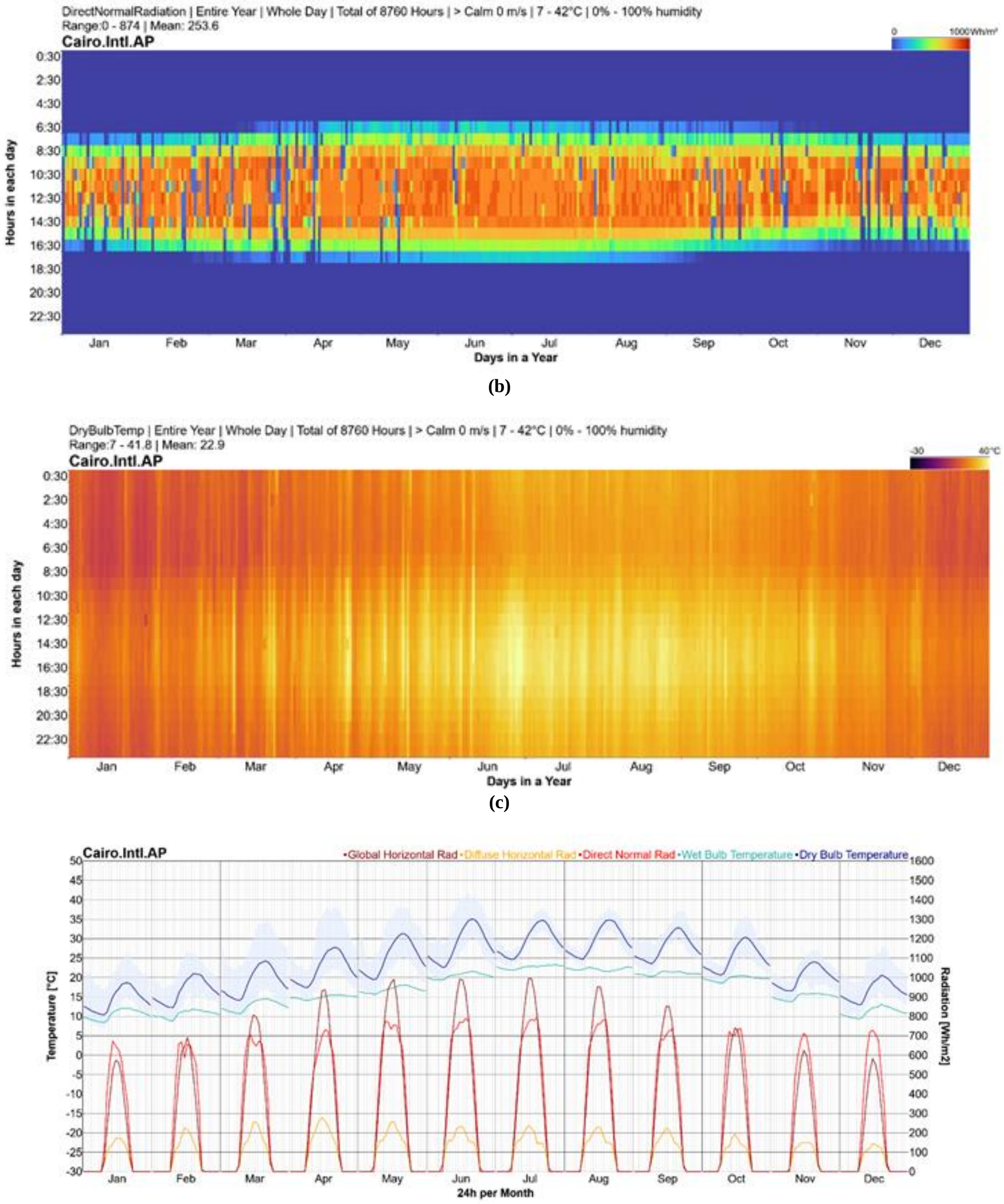
The elevation of Cairo is 29 meters above sea level. It has a desert climate and receives no precipitation throughout the year except for a small quantity during the winter months. This climate is classified as Hot Desert Climate by the Köppen-Geiger climatic classification system, as shown in fig.13.

6.2 Energy simulation

The energy simulation methodology is initiated by modeling the meeting room, using Rhino software. After having the geometry model of the room, an energy model was created using energy simulation software Climate Studio by Solemma, it's the updated version of Diva for Rhino and Grasshopper, The energy modeling of the building incorporates all of the Information related to the space's construction, envelope (fenestration, glazing walls, roof), HVAC system, activities, finishing materials, lighting fixtures, and equipment (fig. 14).



(a)



(b)

(c)

(d)

Fig 13. **(a**) psychrometric chart. **(b)** hourly radiation. **(c)** hourly heat map **(d**) Diurnal Averages. All generated from Climate Studio software.

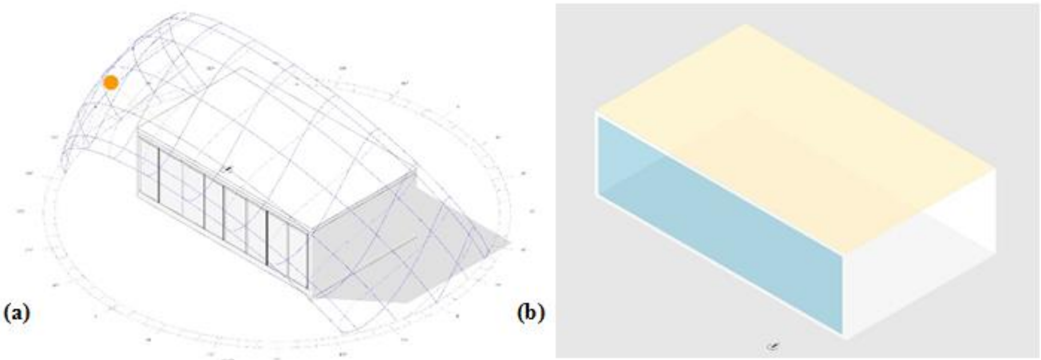
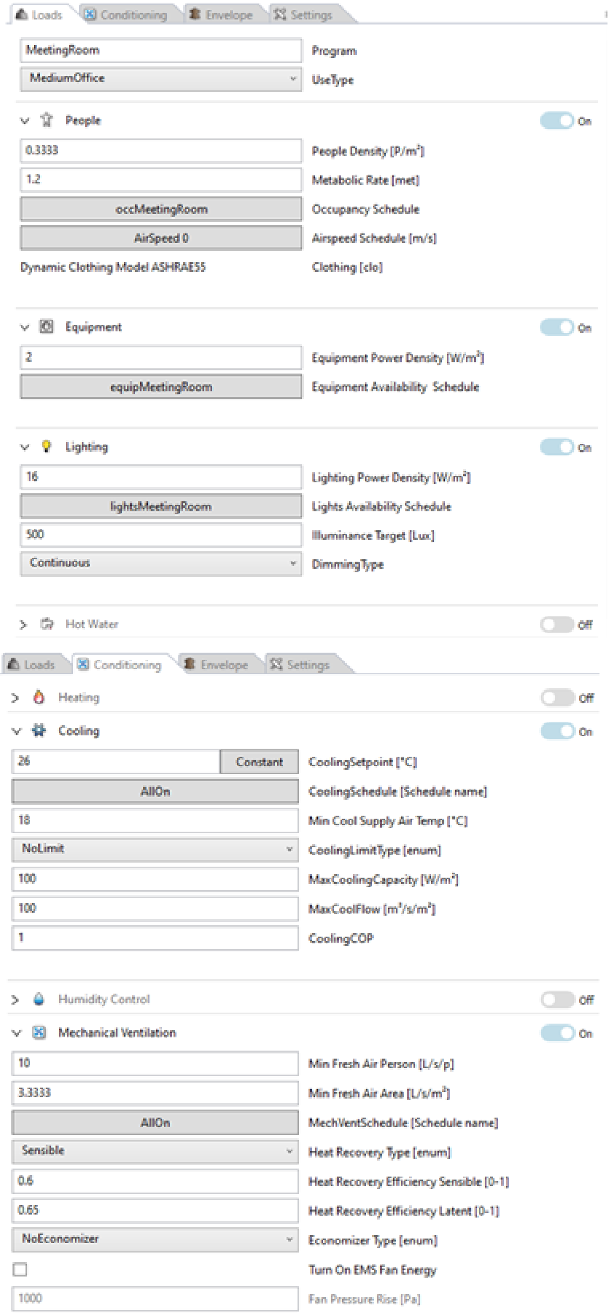


Fig 14. (a) case study meeting room modeled in Rhino software. **(b)** energy model of the meeting room modeled using Climate Studio software.

6.2.1 Stage 1 (Base case)

Before initiating the simulation of the base model to determine the annual energy consumption of the building. the building data was inserted as shown in table 3,4, including zone function type, building envelope materials, glazing type, people activity, equipment and its availability schedule, lighting and its availability schedule, and HVAC system and its availability schedule, as depicted in fig. 15.



MeetingRoom	Program
MediumOffice	UseType
People	On
0.3333	People Density [P/m²]
1.2	Metabolic Rate [met]
occMeetingRoom	Occupancy Schedule
AirSpeed 0	Airspeed Schedule [m/s]
Dynamic Clothing Model ASHRAE55	Clothing [clo]
Equipment	On
2	Equipment Power Density [W/m²]
equipMeetingRoom	Equipment Availability Schedule
Lighting	On
16	Lighting Power Density [W/m²]
lightsMeetingRoom	Lights Availability Schedule
500	Illuminance Target [Lux]
Continuous	DimmingType
Hot Water	Off

Heating	Off
Cooling	On
26 Constant	CoolingSetpoint [°C]
AllOn	CoolingSchedule [Schedule name]
18	Min Cool Supply Air Temp [°C]
NoLimit	CoolingLimitType [enum]
100	MaxCoolingCapacity [W/m²]
100	MaxCoolFlow [m³/s/m²]
1	CoolingCOP
Humidity Control	Off
Mechanical Ventilation	On
10	Min Fresh Air Person [L/s/p]
3.3333	Min Fresh Air Area [L/s/m²]
AllOn	MechVentSchedule [Schedule name]
Sensible	Heat Recovery Type [enum]
0.6	Heat Recovery Efficiency Sensible [0-1]
0.65	Heat Recovery Efficiency Latent [0-1]
NoEconomizer	Economizer Type [enum]
☐	Turn On EMS Fan Energy
1000	Fan Pressure Rise [Pa]

Fig 15. energy model loads and conditioning settings of the space by SIA merkblatt 2024.

HVAC, lighting and equipment schedule all are set to meeting room_medium office by Swiss Association of Engineers and Architects (SIA) merkblatt 2024. Room usage data for energy and building technology.

TABLE 3. windows glass properties.

Glass type	U-Value (Thermal Transmittance)	SHGC (Solar heat gain coefficient)	LT (light transmission)
Single glass 6 mm	6.17 W/m^2.K	0.88	0.82

TABLE 4. wall section properties.

Wall section	U-Value (Thermal Transmittance)	R-Value	Thermal Capacitance
Stucco paint 0.025 m	2.738 W/m^2.K	0.195	5.16.595 KJ/K/M^2
Red Bricks 0.25 m			
Interior Paint 0.01 m			

6.2.2 Stage 2 (Adding the shape-morphing skin)

The shape morphing skin panels will be installed on the 27 m2 windows on the southern façade of the case study room, as shown in figure 16,17, as full glass facades account for about 45 percent of the cooling demand of buildings [23].

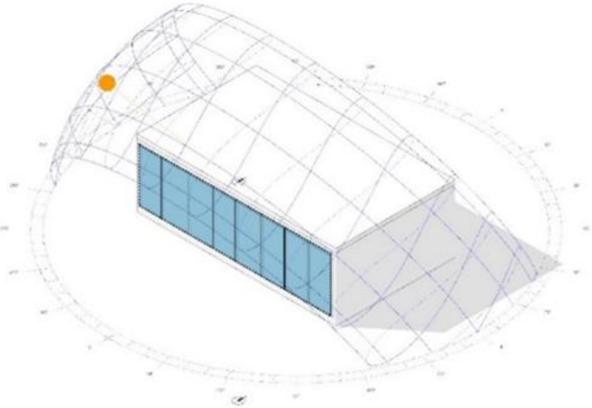


Fig 16. selecting the southern façade windows highlighted in blue color to implement the shape-morphing skin.

For each season, four variants of the shape-morphing skin were modeled based on the incident radiation and temperature data, by using Grasshopper and Ladybug software. Then, energy consumption simulation of the meeting room is performed separately for each season, and the sum of each season's energy consumption simulation is compared to the energy consumption of the base case (fig. 18).

6.3 Results

6.3.1 Stage 1 (Base case)

Figure 19 shows that, The simulation of base case model reveals an annual energy consumption rate of 5139.76 kWh.

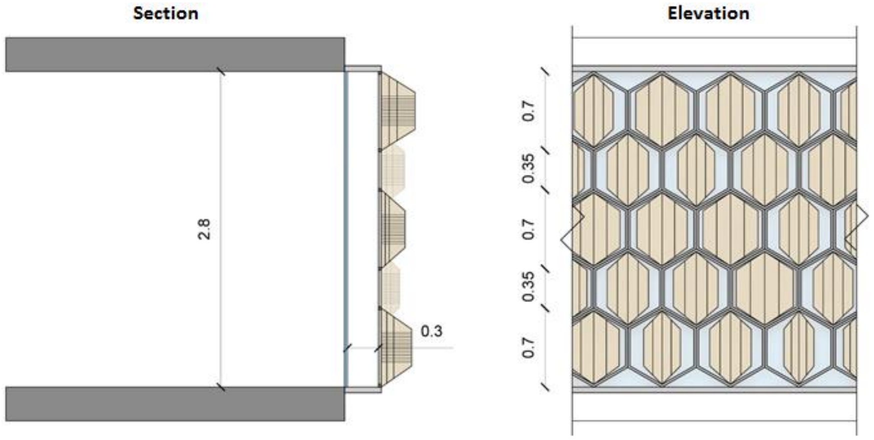


Fig 17. Details of proposed shape morphing skin installation in front of the building glass façade.

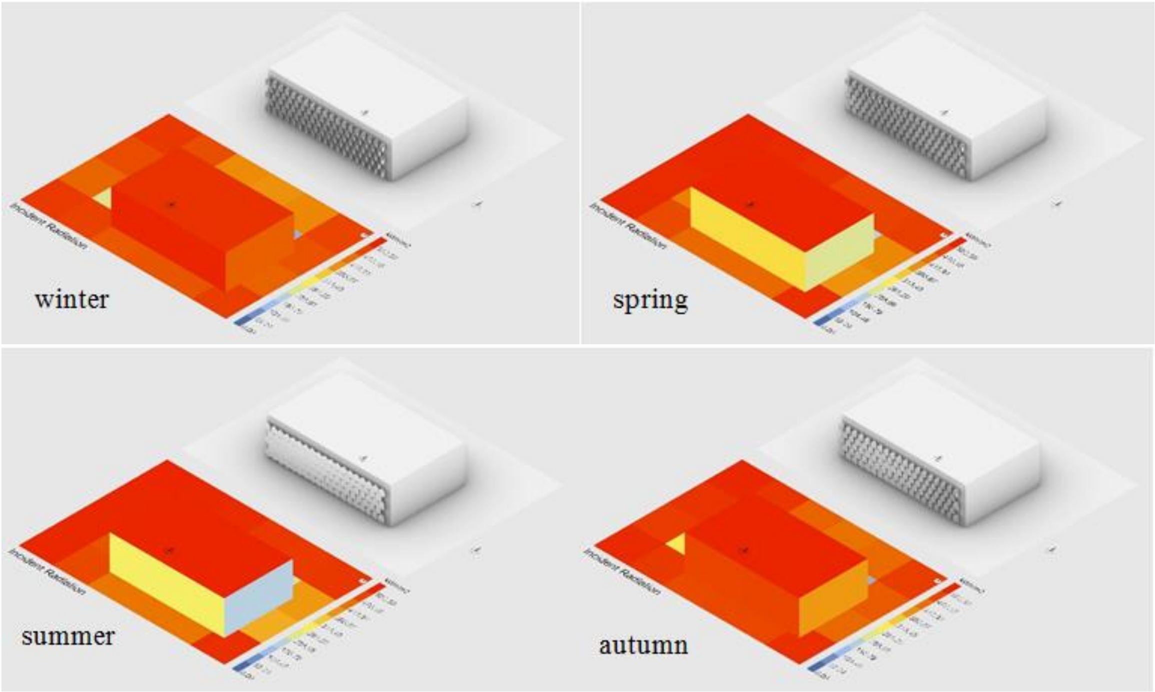


Fig 18. incident radiation in each season and the corresponding shape-morphing skin to it.

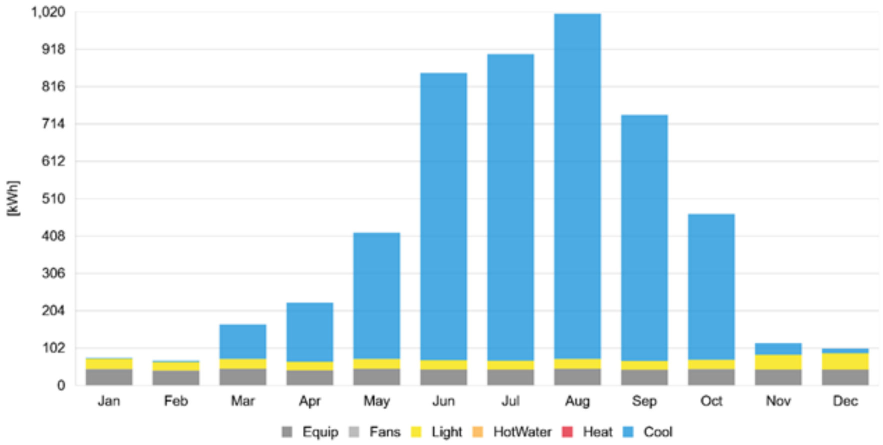


Fig 19. stage 1 base case annual energy consumption.

6.3.2 Stage 2 (Adding the shape-morphing skin)

The simulation of the shape-morphing skin added model reveals an annual energy consumption rate of 3582.97 kWh, as depicted in fig. 20,21.

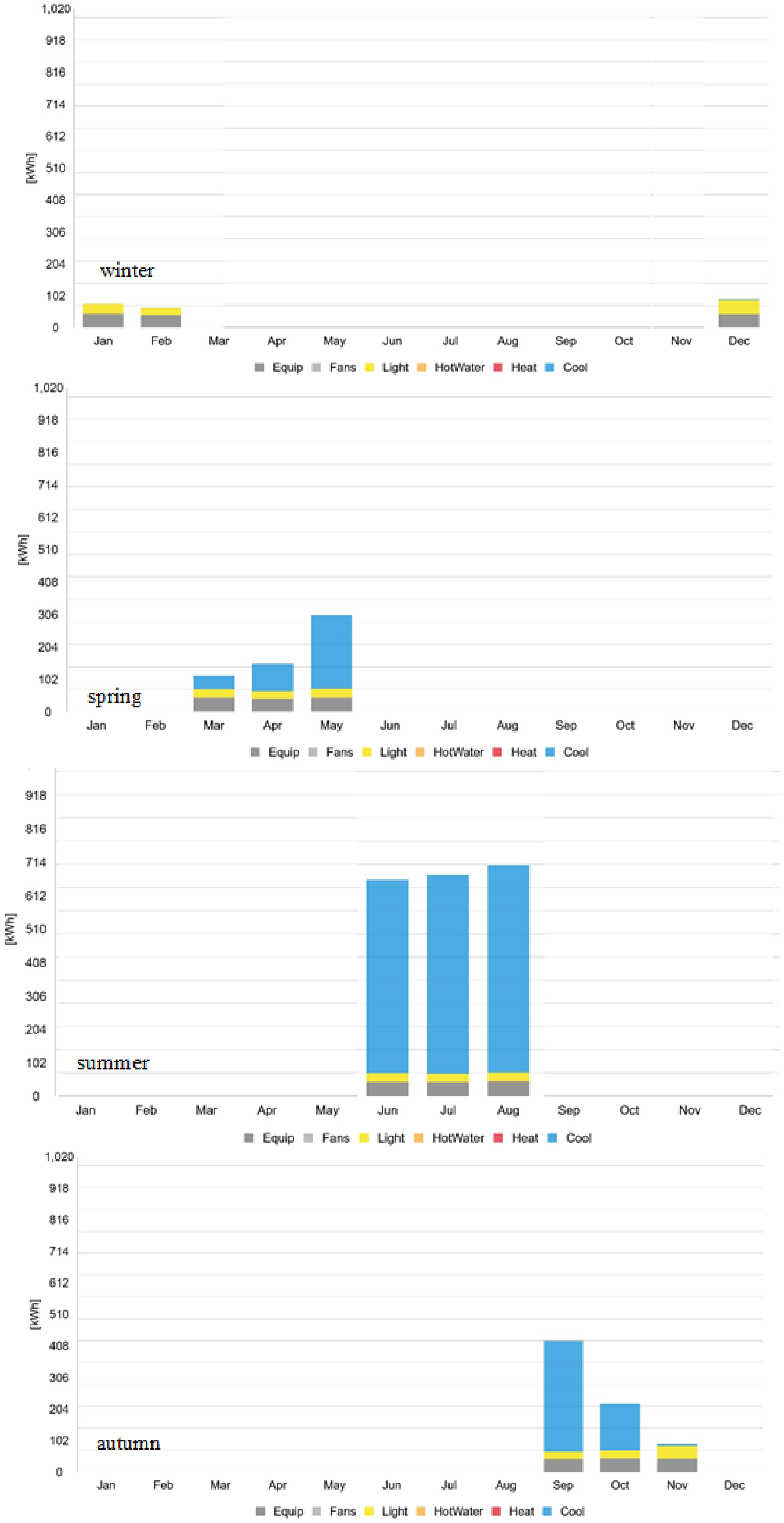


Fig 20. energy consumption of the meeting room per season.

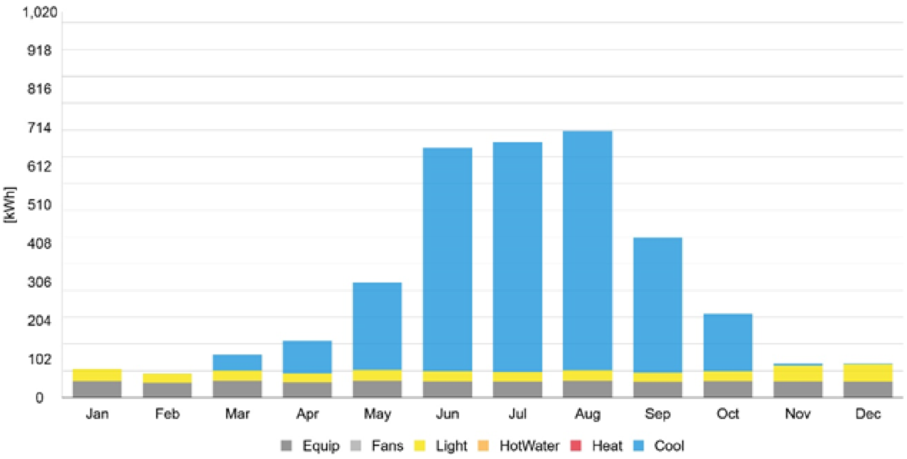
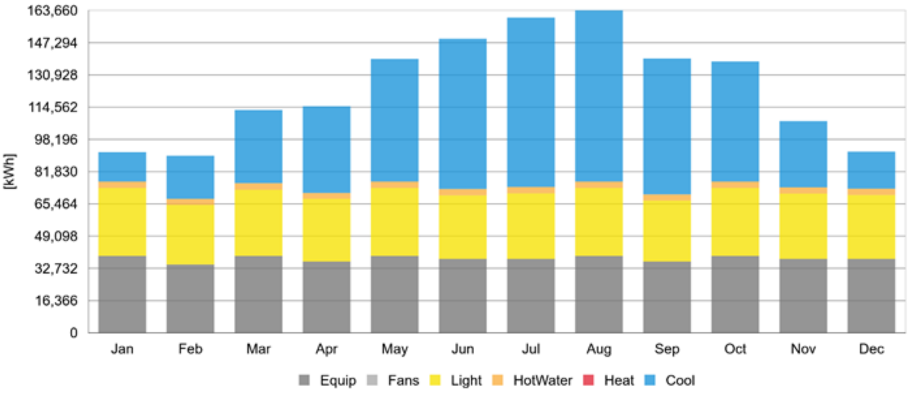


Fig 21. stage 2 adding the shape morphing skin annual energy consumption.



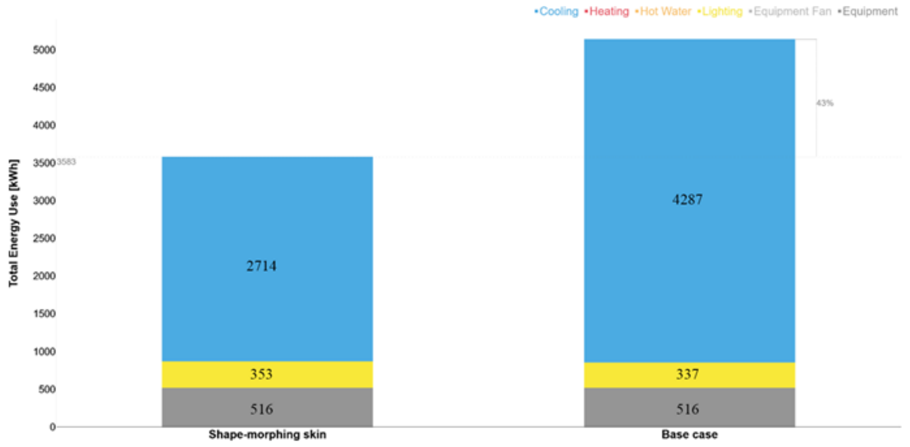


Fig 22. comparison between annual energy consumption of the meeting room before and after adding the proposed shape-morphing skin.

As shown in fig. 22, The comparison reveals a 43% annual decrease in the meeting room energy consumption and a 37% annual decrease in its total cooling loads with the installation of the shape-morphing skin.

Conclusions

This paper investigates the effectiveness of employing smart materials in administrative building skins in Egypt and their effect on the building's energy consumption using a bio-based strategy. In this paper, we propose a lightweight adaptive shape-morphing skin. The two-way Nitinol wires with a transition temperature of 30 degrees Celsius have the potential to be utilized as an actuator to move shape-morphing skin panels based on their intrinsic properties, hence eliminating the need for high complex systems and motors that consume additional energy. A comparative study was then conducted to compare the energy consumption rates between the base case of meeting room in office building in Cairo, Egypt, and the same space after adding the new proposed skin. The results showed a 43% reduction in total energy consumption rates, a 37% reduction in annual cooling loads. This performance of the suggested skin demonstrates a high potential for energy savings.

Other aspects needs to be disscuesed while addressing the application of the proposed shape-morphing skin which is applicability, cost, building shape and effect on natural lighting. Scaled-down model by Yoon [7], and findings from literature proved the applicability of using shape memory alloys as actuators for adaptive skins. Egypt is not a producer of the shape memory metal. This is a drawback because we can't predict how much it will cost to produce the shape-changing skin we're proposing without first importing the necessary materials from the companies who manufacture them in the United States or China.

This paper limitations were to evaluate the proposed shape-morphing on small-scale of a meeting room in an office building in Cairo, Egypt. Further work and research needs to be done on large scale office buildings with different shapes in order to evaluate the impact of the building shape on the effectivness of using the proposed shape-morphing skin. The paper primarily focused on the aspect of energy consumption, and did not fully address the impact of the proposed skin on natural lighting. Future research should further investigate this aspect and provide precise figures based on daylighting simulations conducted using software such as Climate Studio. Even if the proposed shape-morphing skin were to increase dependency on artificial lighting to achieve the required indoor Illumination Levels of 500 Lux for office spaces, LED lighting systems are becoming increasingly affordable and efficient and could potentially reduce energy consumption.

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