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Building Energy Performance Assessment Based on a Bio-Inspired Kinetic Shading Devices

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Abstract

As part of the energy transition and climate change adaptation, buildings are increasingly required to interact dynamically with their environment to reduce energy consumption and mitigate environmental impacts. In this context, kinetic shading systems represent a promising solution, particularly those inspired by the adaptive mechanisms of plants responding to environmental stimuli, within a biomimetic design framework. This study follows such an approach by evaluating the performance of a proposed biomimetic kinetic shading system applied to a residential building located in Guelma, Algeria. A dual methodological framework was adopted, combining a problem-driven biomimetic approach with parametric simulation techniques. Three building orientations were assessed across five configurations of the shading system. The findings reveal that the biomimetic kinetic system effectively mitigates solar gains, reducing them by up to 73% during the summer, which results in a 46.6% decrease in cooling energy demand. In the winter, the system enhances solar gains by 16%, leading to a 31.9% reduction in heating requirements. These results underscore the potential of this approach to improve building energy performance while advancing innovative and sustainable passive design strategies.

KEYWORDS

Biomimicry, energy consumption, optimization, parametric simulation, smart materials, solar gains

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1. Introduction

The world is currently facing major environmental challenges, notably climate change and the increase in greenhouse gas emissions. The building sector plays a central position in this context, accounting for over 30% of global energy consumption and approximately 26% of total greenhouse gas emissions (U.S. Energy Information Administration, 2023). Given the growing urgency of the energy transition and the objective of reaching net-zero carbon emissions by 2050, reducing energy demand in buildings has become an essential priority (Sommese *et al.*, 2022). The building envelope, as the essential interface between outdoor conditions and interior spaces, is pivotal to a building's energy performance (Djedouani *et al.*, 2021; Khelil *et al.*, 2022). Among its components, windows represent a particularly sensitive element: While they provide daylighting and contribute to passive solar gains, they are also a major source of thermal losses and gains (Ashraf and Abdin, 2024; Badeche, 2022); According to Sozer (2010), windows alone can account for nearly 30% of a building's total energy consumption. In response to these challenges, dynamic façade systems have emerged as a promising technological advancement. These systems are designed to adjust their physical characteristics in real time according to climatic conditions, solar radiation, or seasonal variations (Hosseini *et al.*, 2021). By doing so, they dynamically enhance both occupant well-being and energy performance (Wang *et al.*, 2024). Through the modulation of thermal, optical, and morphological properties, these façades offer a responsive solution that reconciles environmental performance with interior well-being (Brzezicki, 2024; Sommese *et al.*, 2024). These adaptive systems typically incorporate geometric configurations or elements capable of autonomously or semi-autonomously responding to external and internal stimuli. In the field of dynamic shading devices, two main categories of systems are identified. Active shading devices consist of mechanical movable devices that require an external energy source to operate. They are further divided according to Al-Masrani *et al.,* (2018) into two subcategories: motorized personally controlled systems, where users directly or remotely activate electric motors to adjust shading elements, thereby enhancing comfort and achieving energy savings despite relatively simple movement mechanisms, and automatically controlled systems, which autonomously adapt to variations in light and heat through the interaction of sensors, controllers, and mechanical actuators. In parallel, hybrid shading systems leverage smart materials capable of deformation to produce spatial movements, thus combining passive and active mechanisms (Al-Masrani *et al.*, 2018). Their design is based on the principles of biomimetics, an approach that draws inspiration from natural systems and models to develop innovative and high-performance technical solutions (Bijari *et al.*, 2025). Recent breakthroughs in digital design and fabrication technologies have greatly facilitated the application of biomimetic principles in the conception of dynamic shading systems. Parametric modeling tools now enable the simulation and optimization of complex adaptive behaviors, thereby facilitating their incorporation into high-performance architectural systems (Toutou *et al.*, 2018). Simultaneously, the emergence of smart materials, engineered to respond to environmental stimuli such as light, temperature, and humidity, has greatly expanded the potential for implementing responsive and low-energy architectural solutions (Brzezicki, 2024; Sommese *et al.*, 2024). This interdisciplinary convergence of biology, computational design, and material science has given rise to a new generation of bio-kinetic solar shading systems that unite technological innovation, functional resilience, and energy efficiency. These systems demonstrate a strong capacity to enhance building energy performance while maintaining a high level of indoor environmental quality through adaptive responses to fluctuating external conditions (Soliman and Bo, 2023). Within this context, a growing body of research has focused on the integration of bio-inspired solar shading strategies aimed at optimizing building energy efficiency, particularly in hot and arid climates. In Egypt, Ashraf and Abdin (2024) developed a saguaro cactus-inspired façade that reduced cooling loads by 36.5% and total

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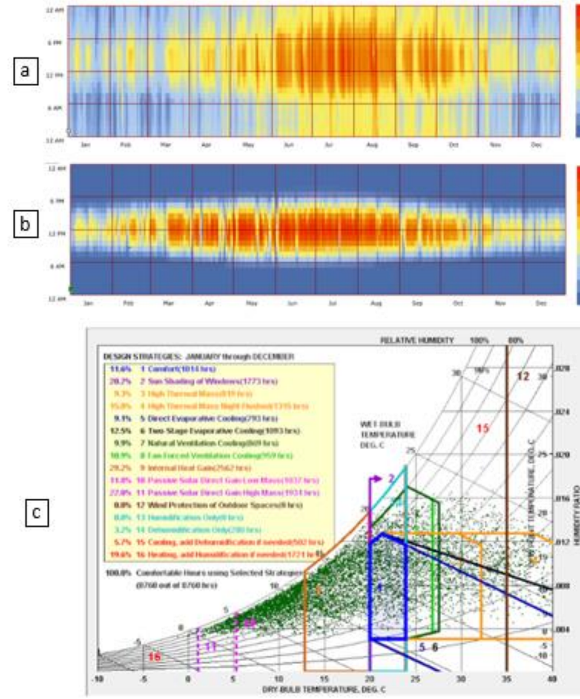
energy consumption by 20%. Similarly, Shahin *et al.,* (2023) used shape memory alloys in a rhododendron-mimicking dynamic envelope, achieving a 43% reduction in annual energy consumption. Mohamed *et al.,* (2020) designed a PTFE membrane inspired by various plant species (mangrove, sunflower, cactus, *Ipomoea*), leading to a 39% decrease in cooling demand, while Abdel-Rahman (2021) optimized thermal transfers with a barrel cactus-inspired façade, achieving a 12.65% energy reduction. In Algeria, Khelil (2021) created an adaptive façade based on Ipomoea purpurea, yielding daily energy savings of up to 13% during hot periods and 9% in colder months. Similarly, Hadbaoui (2018) translated the thermonastic behavior of the crocus flower into a passive bimetallic shading system, reducing summer energy consumption by up to 11.29%. Meanwhile, in a hot and humid climate, developed a light-responsive façade inspired by *Oxalis oregana*, achieving a 32% overall energy reduction. In a temperate climate, Kuru *et al.,* (2018) applied a barrel cactus concept to a building in Atlanta, reducing heating demand by 51.5% and cooling needs by 67.5%. The existing literature thus reveals a growing interest in bio-inspired shading systems across diverse climatic contexts. These studies demonstrate that replicating the adaptive mechanisms of flora can achieve significant energy savings, primarily through the reduction of cooling loads. Such strategies, which integrate smart materials with morphological and functional principles derived from nature, have shown particular relevance in regions facing severe thermal stress, notably arid and semiarid climates. Nevertheless, two major research gaps persist. Firstly, the majority of studies have focused on tertiary sector buildings (e.g., offices, educational establishments). However, the residential sector, despite accounting for a substantial share of global energy consumption, remains largely underexplored in bio-inspired architectural applications. Secondly, the geographical scope of existing research predominantly focuses on arid and tropical climates. Warm Mediterranean climates, characterized by marked seasonal variability, are significantly underrepresented. This research addresses these two critical gaps by focusing on a residential building located in Guelma, a city in northeastern Algeria characterized by a hot Mediterranean climate (Csa). This climate is marked by two highly contrasting seasons (Harbi *et al.*, 2024): dry summers with intense solar radiation and cold winters with limited solar irradiance. According to a psychometric analysis based on the 2013 California Energy Code thermal comfort model (Figure 1), the region falls outside thermal comfort conditions for approximately 88% of the year. To address this issue, both passive and active strategies are needed: effective solar protection for 1,773 hours during the summer (20.2% of the year) and direct passive heat gains combined with high thermal mass for 1,931 hours during the winter (22%). The central challenge lies in balancing summer overheating prevention with the optimization of solar heat gains during the winter (Sahnoune, 2022). To meet this challenge, the study proposes the development and implementation of a bio-kinetic shading system for a residential building. The system is designed to respond to daily and seasonal solar variations through biologically inspired morphological adaptability. To meet this challenge, the study proposes the development and implementation of a bio-kinetic shading system for a residential building. The system is designed to respond to daily and seasonal solar variations through biologically inspired morphological adaptability. This research aims to design, model, and evaluate a biomimetic kinetic shading system using a parametric approach. By assessing different aperture configurations based on orientation and seasonal variations, the study seeks to evaluate the system's effectiveness in mitigating excessive solar gains during the summer while enhancing passive thermal gains during the winter. This approach aspires to contribute to the improvement of energy efficiency in residential buildings, aligning architectural design with the imperatives of the energy transition and the broader goals of sustainable development.

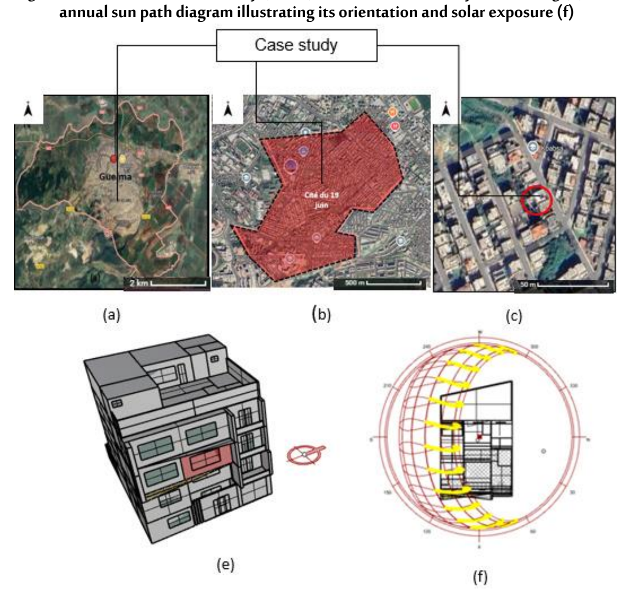
Figure 1: (a) Dry bulb temperature, (b) global solar radiation, and (c) psychometric chart of Guelma



2. Case Study Description

Based on the typological analysis, a reference building was selected: a multifamily villa located at latitude 36°45'18.67" N and longitude 7°42'74.09" E, within the "19 Juin" individual housing subdivision in the southeastern part of Guelma (Figure 2). This building consists of four floors, plus an accessible terrace, and houses three apartments. The first apartment occupies the first two floors, while the others occupy the third and fourth floors, respectively. Each apartment benefits from dual orientations: east and west. The room under study is a living room located on an intermediate floor (the third level) to avoid the direct influence of heat gains from the roof. It has a rectangular shape, measuring 5.20 m by 5.75 m, with a ceiling height of 3.06 m. This room accounts for approximately two-thirds of the total apartment area. It features an east-facing window measuring 3.00 m by 1.60 m, resulting in a window-to-wall ratio of 30%.

Figure 2: Location of the case study (a, b, c), 3D model of the analyzed building (e), and annual sun path diagram illustrating its orientation and solar exposure (f)



3. Materials and Methods

A three-phase methodology was applied to assess the environmental performance of the biomimetic kinetic shading system: in situ measurements, biomimetic design, and validation via numerical energy simulations.

3.1. Field Measurements:

On-site measurements established the building's thermal baseline without shading, ensuring accurate simulation calibration and impact assessment under the real climate. Critical periods were identified from Guelma's 15-year dataset (2009–2023) from the Climate. One Building database, processed in Grasshopper using the "Ladybug Open EPW," "Stat Weather File," and "Import Stat" modules. The hottest week (July 20–26; design day: July 21) and coldest week (January 20–26; design day: January 21) were selected. Measurements on January 23 and July 25 (8 a.m.–6 p.m., every 2 hours) used a thermo-hygrometer (Hanna HI9565) to record ambient temperature and relative humidity at a height of 1 m, following ASHRAE (2010). HVAC, appliances, and lighting remained off; openings were closed; shading devices were fully opened to neutralize external effects.

3.2. Bio-Kinetic Shading Design Process:

A problem-driven top-down biomimetic approach was applied, following the three-step framework of Sommese *et al.*, (2022): problem framing, biological research, and implementation. This systematic process translates a context-specific architectural issue into a nature-inspired technical solution through abstraction, functional transposition, and validation.

3.2.1. Scoping Phase: Defining the Architectural Problem

The first step involves identifying the key environmental issue relevant to Guelma's local climate (Csa), marked by significant daily and seasonal variations in solar radiation and ambient temperature. This climatic context results in two major challenges: (1) overheating during the summer, which necessitates solar protection strategies to limit unwanted heat gain, and (2) winter heat losses, requiring improved solar heat collection to reduce heating demand.

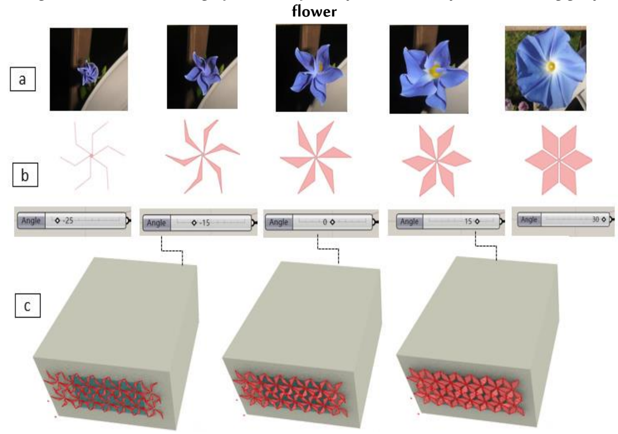
3.2.2. Biological Research Phase: Observation, Selection, Abstraction

This phase examined the thermonastic behavior of certain plants to identify adaptive mechanisms applicable at the architectural scale. The "Heavenly Blue" morning glory (Ipomoea tricolor) was selected as the biological model for its capacity to modulate its petal aperture in response to temperature changes from solar radiation. Morphologically, its petals spiral around a central axis, forming a compact cone when closed and a deployed polygonal geometry when open, thus optimizing light capture. Behaviorally, its petals open during sunny daytime and close at night, under clouds, or at low temperatures. The motion follows a progressive helical rotation driven by differential cell growth between the adaxial (inner) and abaxial (outer) petal surfaces. Time-lapse video analysis (Figure 3a) revealed two key adaptive mechanisms: (1) helical uncoiling around the central axis, creating radial opening, and (2) subtle longitudinal torsion from asymmetric growth, enhancing control of the surface area exposed to sunlight.

3.2.3. Implementation Phase: Translating Natural Strategies Into a Technical System

In this phase, functional principles observed in nature were abstracted and translated into a kinetic architectural system. The process began with the geometric simplification of a single petal, which, when closed, forms a spiral tightly coiled around a central axis and, when thermally activated, unfolds into an elongated, slightly twisted form, generating a radial opening. This transformation was abstracted into an elongated diamond-shaped module—retaining vertical extension and opening via controlled rotation around its axis—replicating the flower's helical mechanism. The asymmetry between adaxial and abaxial surfaces was modeled as a variable angular torsion, enabling rotation from −30° (closed) to +30° (fully open) (Figure 3b). Parametric modeling in Grasshopper (Rhinoceros 3D) defined each module as six elongated diamond-shaped surfaces arranged radially to form a dynamic cell reproducing natural opening/closing sequences. The system adapts in real time to thermal and solar variations: In the summer, partial opening reduces direct solar gains and cooling loads; in the winter, closing maximizes passive heat gains (Figure 3c).

Figure 3: Biomimetic design process inspired by the "Heavenly Blue" morning glory flower



The adaptive behavior is enabled by shape-memory polymers (SMPs), smart materials that recover their original form upon heating (Brzezicki, 2024). At low temperatures, SMPs have reduced elastic modulus, allowing deformation into a martensitic phase; reheating triggers return to the austenitic (stable) phase (Chayaamor-Heil and Laracuente, 2020). SMPs combine durability, mechanical strength, flexibility, precise actuation, and corrosion resistance, making them suitable for kinetic façades requiring repeated or load-bearing motion with low energy consumption (Naeem *et al.*, 2024). As they can be activated solely by temperature changes, SMPs enable autonomous, closed-loop, self-reactive behaviors analogous to biological systems (Brzezicki, 2024).

3.3. Energy Simulation:

The performance of the biomimetic kinetic shading system, in terms of solar gain control and energy demand reduction, was evaluated through simulations in the Grasshopper parametric environment, integrating Ladybug, Honeybee, and EnergyPlus for environmental modeling and thermal analysis (Sadeghipour *et al.*, 2013). The geometries of the test space and shading device were modeled in Rhinoceros 3D, then imported into Grasshopper. Thermal zones were defined via Ladybug with site-specific weather data (Lahmar *et al.*, 2022), and construction materials were assigned according to Algerian thermal regulations for residential buildings (Jaber and Ajib, 2011) (Table 1). Internal loads were based on occupancy profiles, equipment loads, and HVAC specifications, including COP values (Table 2).

Table 1: Thermal properties of construction materials used in the simulation model (Jaber and Ajib, 2011; Khadraoui and Sriti, 2018)

Material	Thickness (m)	Thermal conductivity, λ (W/m.K)	Specific heat, S (kJ/kg.K)	Density, D (kg/m^3)
Cement mortar	0.02	1.4	1,080	2,200
Hollow brick	0.10–0.15	0.48	1,080	900
Air gap	0.05	0.047	1,000	1
Plaster coating	0.02	0.35	936	1,150
Hourdi	0.16	1.2	1,000	1,300
Reinforced concrete	0.04	1.75	1,080	2,500
Single glazing	Solar Heat Gain Coefficient (SHGC)	Visible Transmittance (VT)		Thermal Transmittance (U-values)
	0.74	0.86		5.70

Table 2: Boundary conditions for model simulation

Parameter	Criteria	Value
Occupancy	Number of people per m²	0.05 ppl/m²
	Schedules	12 p.m.–12 a.m.
Loads	Equipment thermal loads per m²	5 W/m²
	Lighting density	3 W/m²
	Ventilation rate per person	0.0075 m^3/s
	Infiltration rate	0.0003 m^3/s-m²
Temperature/ lighting	Set point temperature for heating cooling	20°C 26°C
	Limit for lighting	300 lux
HVAC system	Type	Ideal load air system
	COP	2.7

All variables remained constant relative to the baseline, except for orientation, analyzed at 0° (south), 90° (west), and 270° (east) in 90° increments; north (180°) was excluded due to minimal solar exposure. Five blade tilt configurations were tested: −30° (fully open, 100% opening ratio), −15° (75%), 0° (50%), 15° (25%), and 30° (fully closed, 0%). Simulations covered January 21 (heating design day) and July 21 (cooling design day), identified via climatic analysis. Performance was assessed through solar gain reduction and heating/cooling energy consumption, comparing reference (no shading) and shaded cases to quantify energy performance improvements.

4. Results and Discussion

The energy simulation results are presented in three parts: (1) model validation, ensuring data reliability; (2) solar gain analysis, first by examining monthly averages by façade orientation, then by assessing the impact of different shading configurations; and (3) hourly energy consumption evaluation, focusing on cooling loads on the hottest day and heating loads on the coldest day.

4.1. Model Validation:

Since Sonelgaz's electricity bills report only total dwelling consumption without detail by end-use or room, this study validated the energy model using in situ temperature measurements and thermal simulations, following the approach of Chaturvedi *et al.,* (2024) and Lakhdari *et al.,* (2021). This method treats the room as an independent unit, enabling precise definition of occupancy, temperature setpoints, and internal gains, and allowing accurate indoor temperature assessment. Simulated and measured indoor temperatures (Table 3) were compared using mean bias error (MBE) and the coefficient of variation of the root mean square error [CV(RMSE)], calculated as per ASHRAE, (2010) Guideline 14 (eqs. 1–2).

$$\text{MBE} = \frac{\sum_{i=1}^{n} (Xm - Xs)}{\sum_{i=1}^{n} Xm} \quad (1)$$

$$\text{CV(RMSE)} == \frac{1}{\bar{y}} \sqrt{\frac{\sum_{i=1}^{n} (Mi - Si)^2}{n}} \quad (2)$$

where Mi is the measured value, Si is the simulated value, n is the total number of values considered in the calculation, and $\bar{y}$ is the mean of the measured values.

The results showed excellent agreement: MBE = 0.1% and CV(RMSE) = 1.1% in the summer; MBE = –1.32% and CV(RMSE) = 2.92% in the winter, well within ASHRAE's (2010) limits (|MBE| ≤ 10%, CV(RMSE) ≤ 30%). This confirms the model's reliability for assessing heating and cooling performance.

4.2. Base Case Performance Evaluation:

4.2.1. Solar Gain Estimation

Figure 4 (b, c, d) presents the average hourly monthly solar gains for the base case without shading, considering east, south, and west orientations.

- East (E): Gains concentrate between 6 a.m. and 12 p.m., peaking in the summer above 3.4 kWh/h, causing overheating; in the winter, low solar altitude reduces gains, increasing heating needs.
- South (S): Gains occur from 10 a.m. to 4 p.m., peaking in transitional seasons at 3.6 kWh; this is favorable for passive winter heating but may cause summer overheating without shading.
- West (W): Gains peak from 12 p.m. to 6 p.m. between May and September (up to 2.9 kWh/h), leading to end-of-day heat accumulation and high summer overheating risk; modest winter gains still support late-day heating.

Introducing biomimetic, kinetic shading significantly reduces summer solar gains versus glazing-only scenarios. With a −15° opening, the reductions are 41% (S), 36% (E), and 40% (W). At 0°, the reductions increase to 58.8% (S), 56.25% (E), and 50% (W). At 15°, they reach 73.07% (S), 72% (E), and 71.42% (W). In the winter, compared to fully closed shading, activating the system increases gains as follows: at −15°: +5% (S), +4% (E, W); at 0°: +10% (S), +9% (E), +8% (W); at 15°: +16% (S), +18% (E), +15% (W) (Table 3).

These findings highlight the adaptive capacity of biomimetic shading to mitigate summer overheating while enhancing passive winter gains, thereby improving seasonal building energy performance.

Figure 4: Solar gains for east (a), west (b), and south (c) orientations

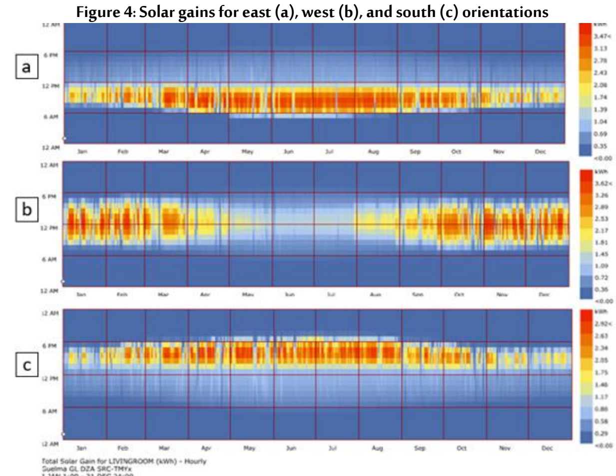


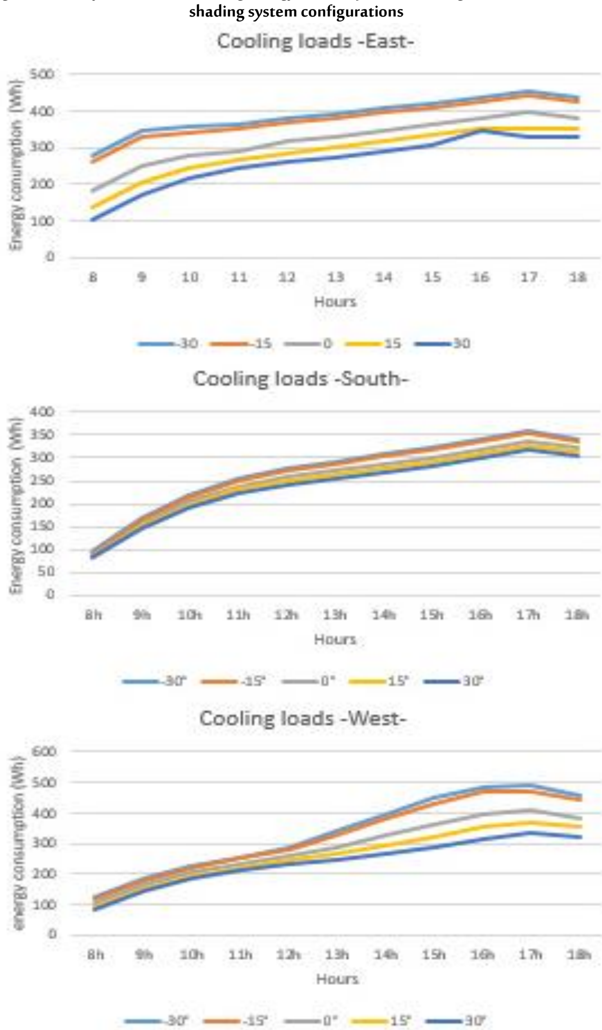
Table 3: Solar gains and losses according to orientation and shading system configuration.

Angle of shading panel	Solar losses (kWh)			Solar gains (kWh)		
	East	South	West	East	South	West
−30°	3.42	3.62	2.92	1.39	1.45	1.17
−15°	3.25	3.25	2.74	1.34	1.40	1.12
0°	2.07	2.07	1.75	0.86	0.91	0.74
15°	1.4	1.42	1.19	0.59	0.64	0.53
30°	0.81	0.86	0.67	0.37	0.38	0.32

4.2.2. Cooling Loads

For the east-facing façade, cooling demand rises sharply from 8 a.m. due to morning solar exposure, peaking around 5 p.m. The glazing-only case (−30°) records the highest daily energy use, exceeding 470 Wh. Shading at 15° or 30° limits direct gains between 8 a.m. and 1 p.m., with the 15° configuration reducing cooling loads by 46.4%, showing the benefit of early-day active shading.

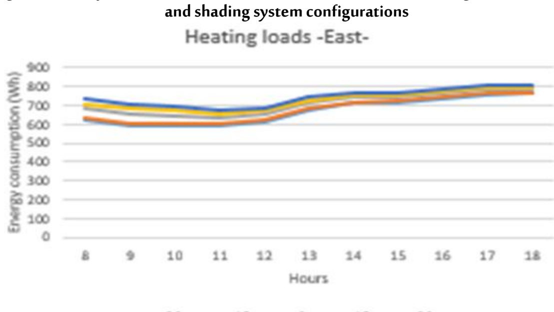
Figure 5: Hourly evolution of cooling energy consumption according to orientations and shading system configurations

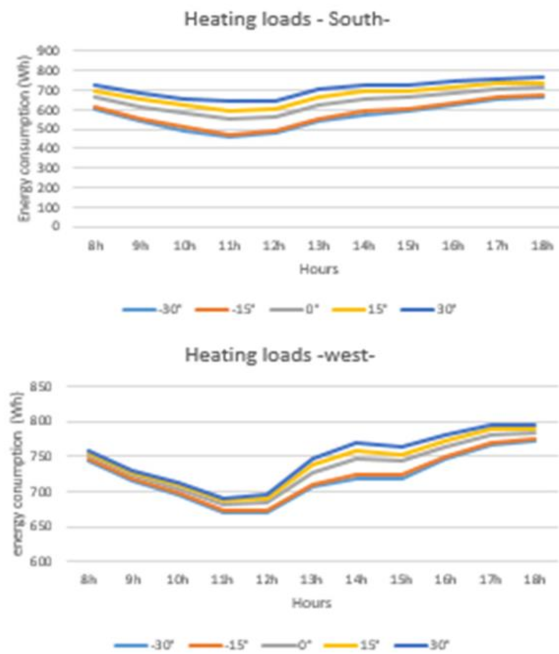


For the south-facing façade, loads increase steadily from 8 a.m. to 5 p.m., with generally lower values than other orientations. Dynamic shading effects appear from late morning, with 15° providing a 10.7% reduction starting at 11 a.m. as solar gains intensify. While differences are less marked than for the east-facing façade, dynamic shading still moderates midday peaks and improves comfort.

For the west-facing façade, cooling loads rise from noon and peak between 3 and 5 p.m. under the intense afternoon sun. Shading effectiveness is most apparent after 1 p.m.; the 15° opening achieves up to a 33% reduction. Orientation- and time-specific control, especially partial openings around 15°, effectively limits critical solar gains, enhances comfort, and reduces active cooling demand, particularly valuable for the east and west orientations, where solar management is most challenging.

Figure 6: Hourly evolution of heating energy consumption according to orientations and shading system configurations





4.2.3. Heating Loads

The heating loads for the east, south, and west façades follow a concave daily pattern, with a notable drop between 11 a.m. and 1 p.m., coinciding with peak solar radiation and reduced reliance on active heating. Demand rises in the early morning and late afternoon due to limited solar gains.

For the east façade, heating peaks between 8 and 10 a.m., when solar input is minimal. Partial shading at −15° reduces loads by 13% compared to full closure (+30°), demonstrating the value of adaptive modulation in the morning. The south façade benefits from extended direct solar exposure (9 a.m.–1 p.m.), yielding the lowest heating needs. Partial opening at −15° maximizes solar capture while limiting losses, cutting heating loads by up to 31.9% between 10 a.m. and 2 p.m., confirming the winter advantage of this orientation. On the west façade, heating decreases slightly from 8 a.m. to 12 p.m., then rises in the afternoon due to solar path geometry. Partial opening at −15° between 11 a.m. and 2 p.m. reduces heating by 6.11%. Cross-analysis with cooling loads highlights the bimodal functionality of the biomimetic kinetic shading system: reducing cooling needs—particularly on the east and west façades in the summer—while enhancing passive solar gains on the south façade in the winter. This adaptive capacity enables fine-tuned seasonal performance, offering a strategic tool for high-performance, climate-responsive building design. This study's results align with prior research regarding the influence of kinetic shading systems on buildings' energy performance. For instance, the observed improvements in solar gains align with the conclusions drawn by Hadbaoui (2018), Khelil (2021), and Salah and Kayili (2022), who demonstrated the importance of dynamic shading devices during extreme climatic periods. Regarding the reduction in heating demands, the results correspond to the work of Kuru *et al.,* (2018), who highlighted the significant contribution of adaptive façades to lowering winter energy requirements. Moreover, the analysis of energy consumption related to air conditioning is consistent with previous observations (Ashraf and Abdin, 2024; Mohamed *et al.*, 2020; Shahin *et al.*, 2023; Sheikh and Asghar, 2019). This highlights how biomimetic adaptive envelopes contribute not only to reducing energy consumption but also to improving thermal comfort for building occupants. These points of convergence underscore the value of the biomimetic kinetic approach as a credible and innovative strategy for advancing sustainable, energy-efficient architectural design.

5. Conclusion

This study proposes a biomimetic kinetic shading system inspired by the morphological and behavioral dynamics of the morning glory (*Ipomoea tricolor*) flower to address the challenge of improving energy efficiency in warm Mediterranean climates. Following a problem-driven biomimetic methodology combined with parametric simulations, the research evaluated the impact of different opening configurations on solar gains and energy consumption in a residential building. The findings indicate that the system adaptively regulates solar heat gains according to orientation, seasonal changes, and time of day. This adaptability reduces cooling demand in the summer while maintaining passive solar benefits in the winter, thereby enhancing both building energy performance and indoor thermal comfort. To ensure practical applicability, future research should focus on developing and testing physical prototypes to assess mechanical behavior, functional efficiency, and architectural integration. An in situ validation phase will be essential to evaluate performance under real climatic conditions, including effects on thermal comfort, daylight quality, energy use, and user interaction, as well as to confirm or refine simulation results. A comprehensive life cycle assessment of the materials covering extraction, manufacturing, transport, installation, operation, maintenance, and disposal will guide the selection of smart, durable, recyclable materials with low environmental impact. Moreover, applying multi-objective optimization algorithms will help refine the system's design parameters to achieve an optimal balance between environmental efficiency, economic viability, architectural expression, and user acceptance. Overall, this research demonstrates the potential of biomimicry as a design strategy for creating adaptive, high-performance, and sustainable building envelopes that support the goals of energy transition and climate-responsive architecture.

Data Availability Statement

The data that supports the findings of this study are available from the corresponding author, upon reasonable request.

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Conflict of Interest

The authors declare no conflict of interest.

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