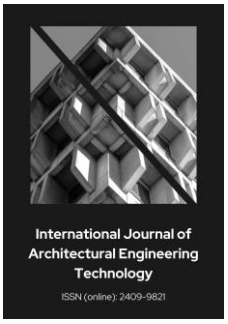
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Achieving Net-zero Operational Energy in High-rise Residential Buildings: A Deep Bioclimatic Design Case Study of the PHANTOM Eco-tower in Miami

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ABSTRACT

This study presents an integrated design process for achieving high-performance sustainable skyscrapers through *Deep Bioclimatic Design*. In this study, *Deep Bioclimatic Design* is defined as an architectural approach capable of enabling buildings to maintain adequate indoor thermal conditions through passive and climate-responsive strategies, without relying on conventional heating or air-conditioning systems. Furthermore, the additional construction cost of a Deep Bioclimatic Design building is, at most, equivalent to the cost of the conventional heating and air-conditioning systems that it is designed to eliminate. Under appropriate climatic conditions, its application has the potential to substantially reduce operational energy demand, while avoiding substantial additional construction costs. To maximize overall sustainability performance, the study incorporates CEDES, a *Green Building Rating System* (GBRS) specifically developed to provide a comprehensive assessment of environmental, energy, economic, and occupant-related performance. Previous comparative analyses indicate that CEDES can provide a more effective assessment than currently established GBRSs. The proposed design methodology is applied to the *PHANTOM Eco-tower*, a skyscraper project developed for Miami, USA. The analysis estimates that the proposed design could reduce operational energy consumption by approximately 57% relative to the selected high-performance multifamily residential benchmark, while eliminating the need for conventional air-conditioning. The case study illustrates how the systematic integration of deep bioclimatic strategies, energy-efficiency measures, and comprehensive sustainability assessment can substantially improve the projected environmental performance of high-rise buildings. These results support the potential of *Deep Bioclimatic Design* as an effective approach for developing next-generation sustainable skyscrapers while maintaining economic feasibility.

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1. Introduction

The oil crises of the 1970s prompted the development of bioclimatic building design, initially driven by the need to minimize building energy consumption, particularly that associated with heating and air conditioning [1, 2]. In some cases, bioclimatic strategies were capable of achieving thermal self-regulation, thereby eliminating the need for mechanical heating and air conditioning and maximizing energy savings [3-7].

However, effective bioclimatic design requires architects to possess extensive technical knowledge and considerable project experience. Its performance depends fundamentally on the ability to understand and manipulate the thermodynamic behavior of buildings through architectural strategies. Consequently, the actual performance of bioclimatic buildings may sometimes fall short of initial predictions.

At the same time, manufacturers rapidly identified an opportunity to develop and commercialize increasingly energy-efficient building equipment. As a result, bioclimatic design progressively assumed a secondary role, while a different conception of sustainable and highly energy-efficient buildings became dominant: conventional buildings supplemented with additional insulation and increasingly efficient heating and air-conditioning systems. Commercial interests associated with these technologies contributed to the marginalization of architectural bioclimatic strategies and promoted the concept of "*passive design*". This shift reflects a broader tendency to relegate bioclimatic design to a secondary role while prioritizing the widespread incorporation of technological systems into buildings. Consequently, many standards, regulations, and *green building rating systems* (GBRS) place considerable emphasis on the integration of high-energy-efficiency equipment, while assigning limited value—or no value at all—to the energy performance achieved through bioclimatic design itself [8].

Nevertheless, *effective bioclimatic design* can substantially improve building energy efficiency and sustainability by reducing, and in some cases eliminating, the need for heating and air-conditioning equipment. This remains a critical objective because current building design practice continues to exhibit substantial limitations in this respect. Moreover, the additional cost associated with the design and construction of bioclimatic buildings can be comparable to the cost of the heating and air-conditioning equipment that would otherwise be required. For this reason, some architects continue to develop bioclimatic buildings despite the constraints imposed by current regulatory frameworks [9].

The energy performance achievable through bioclimatic design, however, depends largely on the architects' knowledge of building thermodynamics and, above all, on their professional expertise and design capabilities. Depending on the quality and effectiveness of the architectural strategies employed, bioclimatic design may result in a relatively modest reduction in energy consumption or, at the other extreme, completely eliminate the need for heating and air-conditioning systems.

Within this context, *deep bioclimatic design* is defined as an architectural approach capable of enabling buildings to thermally self-regulate and maintain comfortable indoor temperatures without the use of heating or air-conditioning devices [8]. This approach therefore represents a more demanding form of bioclimatic design, in which the building itself, through its architectural configuration and passive environmental strategies, becomes the primary mechanism for achieving thermal comfort.

Deep bioclimatic design requires architects to possess in-depth knowledge of the thermodynamic behavior of buildings and substantial practical experience, allowing them to continuously evaluate, refine, and combine architectural strategies capable of achieving effective environmental performance. Although the complete elimination of heating and air-conditioning systems may not be feasible in all climatic contexts, minimizing their required power and operating time can provide substantial energy savings while simultaneously improving thermal comfort [10-12].

The environmental implications of this approach extend beyond the reduction of operational energy consumption. Deep bioclimatic architecture can reduce energy demand [13, 14], while also contributing to reductions in waste generation and emissions [15]. It can further maximize the overall sustainability of buildings [16], improve health and well-being [8], reduce the construction, operational, and maintenance costs of social

housing, and facilitate building self-sufficiency [8]. Thus, deep bioclimatic design can be understood not merely as a strategy for reducing energy consumption, but as a comprehensive architectural approach in which environmental performance is achieved primarily through the building's own design rather than through the addition of energy-consuming technological systems.

2. Method: *Deep Bioclimatic Design Process*

A carefully conceived and context-specific bioclimatic design can reduce building energy consumption to varying degrees, regardless of the climatic context in which the building is located. However, achieving *deep bioclimatic design* represents a substantially more demanding objective and may not always be technically or economically feasible without a significant increase in design and construction costs. Its successful implementation requires a specific and rigorous project methodology capable of translating climatic, thermodynamic, and energy requirements into coherent architectural configurations.

The complexity of this process lies in converting quantitative and mathematical requirements into tangible architectural solutions while maintaining functional, spatial, structural, and aesthetic coherence. Consequently, substantial projectual expertise and professional experience are essential for effectively integrating and testing the architectural strategies involved. Furthermore, because the same environmental and thermodynamic requirements can often be satisfied through different combinations of architectural strategies, the design process may generate multiple architectural configurations that are technically equivalent and equally valid from a bioclimatic perspective.

In this study, and in a definition that can be generalised to other contexts, *Deep Bioclimatic Design* is defined as the set of architectural strategies that result in a building capable of thermally self-regulating and maintaining a comfortable indoor temperature without the need for heating or air-conditioning equipment. This type of design is technically possible in any climatic environment on Earth; however, in extreme climates, the associated construction costs may be prohibitively high.

For example, in cold climates, it may be necessary to construct large greenhouses with high internal thermal mass and multiple layers of glazing to ensure adequate solar heat gain, effective thermal insulation, and sufficient thermal inertia. In such cases, installing efficient mechanical systems powered by conventional fuels or alternative energy sources may be a more economical solution. The same principle applies to climates characterised by extremely high temperatures, where underground cooling systems could be prohibitively expensive, making a conventional approach more cost-effective.

Nevertheless, most cities, towns, and human settlements in general are located in regions without extreme temperatures, partly to ensure favourable living conditions. In these moderate climates, *Deep Bioclimatic Design* can generally be achieved without additional construction costs or with an acceptable and economically manageable increase.

By definition, buildings incorporating *Deep Bioclimatic Design* do not entail additional construction costs, since their thermal self-regulation can be achieved through the architect's or engineer's experience, intelligence, expertise, and creativity, rather than through the incorporation of mechanical equipment. Consequently, these buildings can have lower initial construction costs because they avoid the need for high-tech heating, air-conditioning, and artificial lighting systems.

By contrast, conventional bioclimatic buildings may involve two types of additional costs. The first arises from the incorporation of low-tech equipment, such as fans, dampers, external shading devices, dynamic shading systems, and similar components. The second results from the inclusion of supplementary architectural features, such as solar protection elements, increased thermal mass, more robust structures, underground galleries, and internal courtyards. In moderate climates, the costs associated with these bioclimatic strategies are generally comparable to those of the mechanical systems they are intended to replace. Consequently, the overall economic balance may be approximately neutral. However, bioclimatic buildings offer the significant additional advantages

of reduced maintenance requirements and the absence of lifelong dependence on energy-consuming mechanical systems for heating and cooling.

Accordingly, this study defines *Deep Bioclimatic Design* as "the design of bioclimatic buildings capable of thermally self-regulating and maintaining a comfortable indoor temperature without heating or air-conditioning equipment, with any additional initial construction cost being no greater than the cost of the mechanical equipment that the design eliminates". Where the additional construction cost exceeds this threshold, the buildings will instead be classified as *high-performance bioclimatic buildings*, which may achieve substantial thermal self-regulation but still require the partial use of mechanical equipment.

2.1. Methodology for Deep Bioclimatic Design

Achieving a building capable of thermal self-regulation—that is, maintaining indoor temperatures within a comfortable range throughout the year without relying on conventional mechanical heating or air-conditioning systems—requires a rigorous, iterative, and comprehensive design methodology [17, 18].

Unlike conventional bioclimatic approaches, in which passive strategies may be incorporated as complementary measures, *deep bioclimatic design* seeks to establish the building itself as the primary mechanism for regulating its thermal environment. Consequently, climatic conditions, solar radiation, building geometry, envelope characteristics, glazing, shading, construction systems, and internal spatial organization must be considered as mutually interdependent variables rather than as isolated design decisions.

The methodology is therefore conceived as a *progressive design and optimization process*, beginning with the characterization of the environmental conditions of the site and continuing through increasingly detailed architectural, energetic, and constructive decisions [8]. Each stage provides information required by subsequent stages, while the results obtained during later calculations may require previous decisions to be reconsidered and refined. The process is consequently iterative rather than strictly linear. The general methodology comprises, at a minimum, the following stages:

1. Collection of General Data

As in any project, the design process begins by gathering as much information as possible on the client's requirements, mandatory regulations, site analysis, visual impact, environmental impact, cultural and social context, economic context, historical evolution, and so forth. In the case of skyscraper design, it is essential to gather information on the cultural, social, and symbolic contribution the building will make, not only to its immediate surroundings but also to the city in which it is to be built.

2. Collection and Analysis of Environmental and Climatic Data

The process begins with the systematic collection of the principal environmental and climatic parameters characterizing the building site. These data constitute the fundamental boundary conditions for the subsequent design process and should include, where available, information concerning air temperature, relative humidity, solar radiation, wind conditions, precipitation, and seasonal climatic variations.

The objective is not merely to describe the climate, but to establish the environmental conditions that the building must respond to passively. Particular attention should be paid to the temporal variation of climatic parameters because thermal strategies that are beneficial during one period may become undesirable during another.

3. Determination of Solar Geometry

The second stage consists of determining the geometry of solar radiation at the site. The solar position and the corresponding radiation angles are calculated for the principal characteristic dates of the year, particularly the summer and winter solstices and the equinoxes (Fig. **1**).

This analysis establishes the relationship between the building's geometry and the seasonal trajectory of the sun. It provides the basis for determining the orientation of the building, the potential exposure of different façades, the periods during which solar radiation can contribute positively to indoor thermal conditions, and the periods during which solar gains must be restricted.

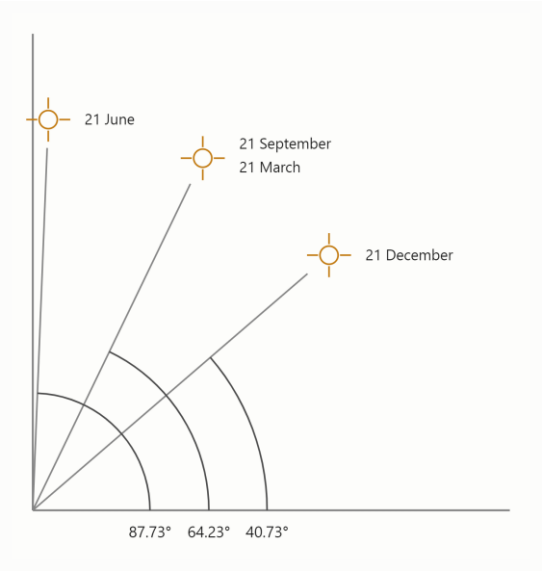


Figure 1: Sun position at solar noon on the solstices and equinoxes in Miami (latitude: 25.77° N). Equinoxes: 90°−25.77° = 64.23°; Summer solstice: 64.23°+23.5° = 87.73°; Winter solstice: 64.23°−23.5° = 40.73°.

4. Preparation of the Psychrometric Charts

The variations in air temperature and relative humidity are subsequently analyzed, particularly through psychrometric charts. This stage makes it possible to identify the periods in which indoor comfort may potentially be achieved through passive environmental strategies and to determine which combinations of temperature and humidity require specific architectural responses.

The psychrometric analysis therefore constitutes an important link between climatic data and architectural design. Rather than selecting bioclimatic strategies independently of the climate, the strategies are derived from the environmental conditions identified at the specific location.

5. Preliminary Estimation of Energy Losses and Solar Gains

Once the principal climatic and solar conditions have been established, a preliminary estimation of the building's potential thermal energy losses and solar energy gains is undertaken. Heat losses associated with the building envelope and openings are considered alongside potential passive solar gains.

At this stage, the objective is not yet to produce a final energy model, but to establish the approximate energetic behavior of alternative design configurations. This preliminary balance provides an initial indication of whether the proposed architectural configuration can potentially approach thermal self-regulation.

6. Preliminary Sizing and Positioning of Glazed Surfaces

The area, orientation, distribution, and position of glazed surfaces are then preliminarily determined according to the climatic and solar conditions identified in the previous stages. Glazing represents a particularly sensitive component because it can simultaneously provide useful daylight and solar heat gains while also becoming a significant source of unwanted thermal gains or losses.

Consequently, glazed surfaces should not be defined exclusively according to aesthetic, functional, or daylighting criteria. Their dimensions and location must be evaluated in relation to seasonal solar radiation, orientation, thermal losses, and the overall energy balance of the building.

7. Determination of the General Building Parameters

The information obtained from the environmental, solar, psychrometric, and preliminary energetic analyses is subsequently translated into a set of general architectural and environmental parameters. These parameters establish the principal conditions that the building configuration should satisfy.

They may include, among others, requirements concerning orientation, compactness, solar exposure, thermal protection, glazing, ventilation, shading, internal organization, and the relationship between exposed and protected surfaces. At this point, the climatic analysis begins to directly influence the architectural configuration.

8. Development of Preliminary Architectural Sketches

The established parameters are incorporated into a series of preliminary architectural sketches. These initial proposals should simultaneously address functional, spatial, formal, structural, and bioclimatic requirements (Figs. **2, 3**).

The objective is not to produce a definitive architectural solution at this stage, but to generate alternative configurations that can subsequently be compared according to their environmental and energetic performance. Architectural creativity is therefore integrated from the beginning with quantitative environmental analysis.

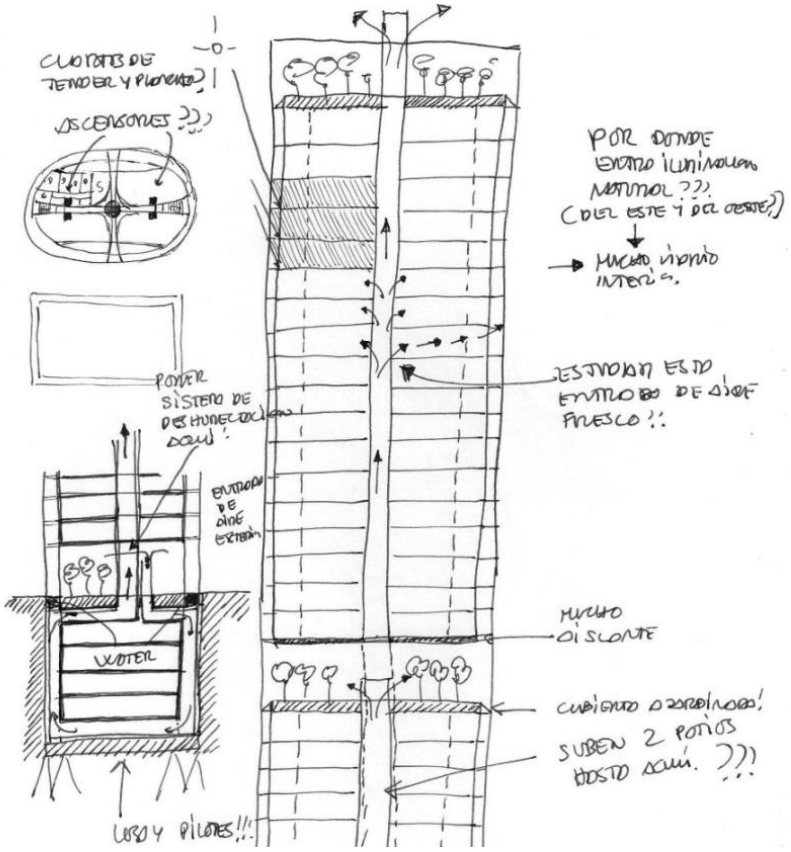


Figure 2: Sketches for the design of the PHANTOM Eco-tower (made by Luis de Garrido).

9. Selection of the Most Appropriate Architectural Typology

The alternative preliminary configurations are evaluated in order to identify the architectural typology most suitable for achieving the required bioclimatic performance. The selected typology should provide favorable conditions for passive solar utilization, thermal protection, natural ventilation, daylighting, and the minimization of unwanted thermal exchanges.

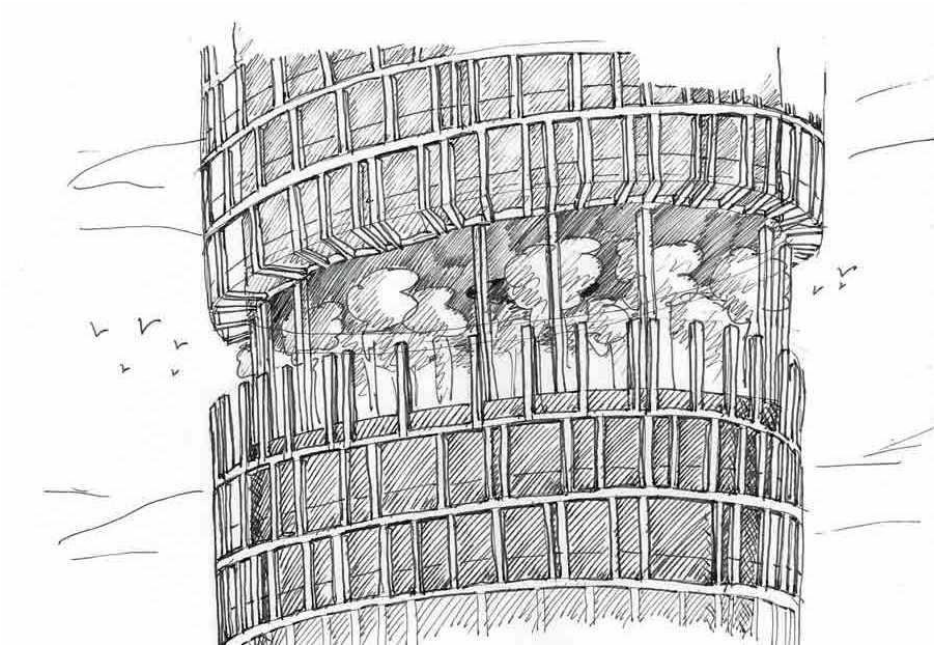


Figure 3: Sketches for the design of the PHANTOM Eco-tower (made by Luis de Garrido).

This decision is particularly important because the fundamental geometry of a building can substantially condition its subsequent environmental performance. Consequently, the typology should be selected before the design becomes excessively constrained by secondary architectural or constructional decisions.

10. Geometric Definition of the Typology

Once the most appropriate architectural typology has been selected, its geometric definition begins with the preliminary total floor area and the geometry of the principal elements of the proposed solution. The initial configuration should establish the main dimensions, proportions, spatial relationships, and compositional alignments of the building and its components. Particular attention should be given to the compositional guidelines governing the dimensions and proportions of the different elements, so that they integrate into a coherent and balanced whole. This process should follow the principle of concinnitas, understood as the harmonious organization of relationships among the individual elements and between those elements and the architectural whole. The aim is a geometrically coherent configuration in which dimensions, proportions, and relationships contribute to the compositional balance and aesthetic unity of the skyscraper.

11. Progressive Refinement and Optimization of the Architectural Design

Once the most appropriate typology has been identified, its geometry and organization are progressively refined (Fig. **4**). This stage constitutes an essential iterative component of the methodology. Dimensions, proportions, orientation, internal distribution, openings, exposed surfaces, and other relevant characteristics are modified and recalculated in response to their predicted environmental performance.

The objective is to progressively converge toward an architectural configuration capable of achieving the desired thermal conditions with the minimum possible dependence on active energy systems.

12. Definition and Integration of the Principal Bioclimatic Strategies

The principal passive strategies required by the climatic conditions are subsequently defined and integrated into the architectural configuration. These strategies may include the controlled use of solar radiation, thermal protection, natural ventilation, passive cooling, thermal inertia, appropriate orientation, daylighting, solar shading, and other architectural mechanisms derived from the previous analyses.

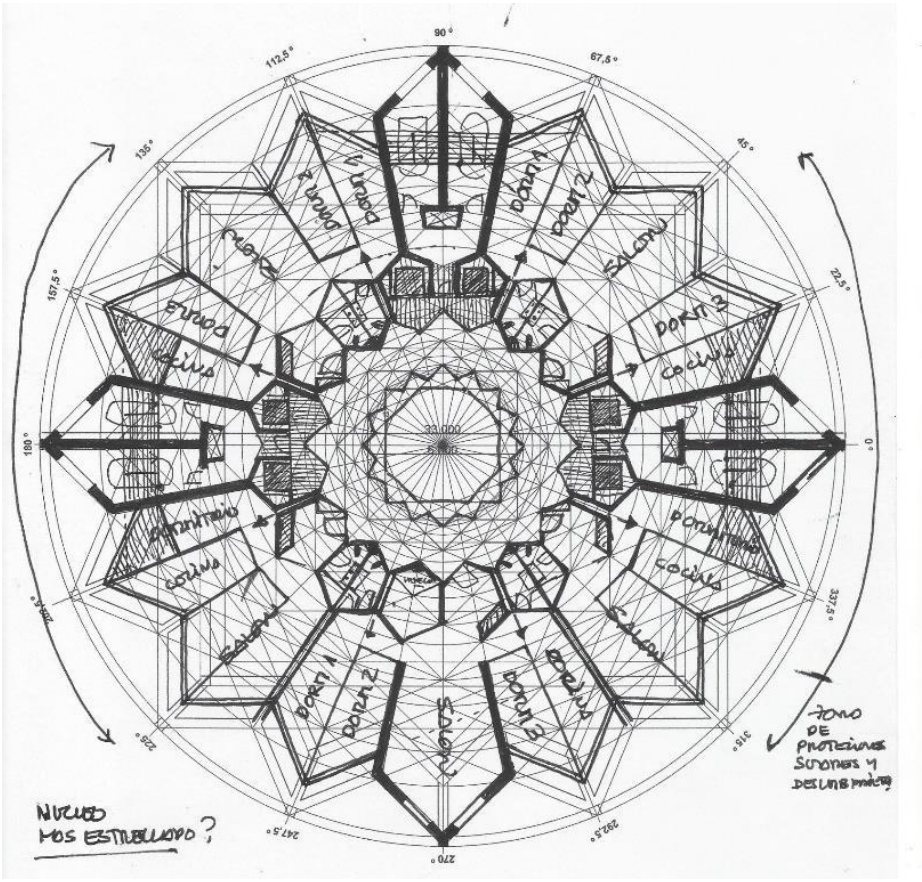


Figure 4: Progressive refinement and optimization of the architectural typology of the *PHANTOM Eco-tower (made by Luis de Garrido).*

A central principle of the methodology is that these strategies should not be considered as independent technological additions. They must operate as components of a coherent environmental system, in which the interaction between different architectural elements contributes to the overall thermal performance of the building.

13. Optimization of the Energy Balance

The different passive gains and thermal losses are then progressively balanced. The objective is to achieve an appropriate equilibrium between useful passive energy gains and unwanted thermal losses or gains throughout the year.

This stage requires iterative adjustment because improving one component of the energy balance may adversely affect another. For example, increasing solar exposure may provide beneficial winter gains while simultaneously increasing summer thermal loads. Consequently, the final configuration must emerge from the optimization of the annual and seasonal energy balance, rather than from maximizing any individual passive strategy.

14. Design and Calculation of Solar-shading Systems

Solar-shading elements are subsequently designed and dimensioned according to the previously established solar geometry. Their configuration should permit the controlled admission of desirable solar radiation while restricting excessive solar gains during periods of overheating risk.

The geometry and dimensions of overhangs, terraces, horizontal and vertical shading elements, recessed façades, and other architectural protection systems are therefore determined according to the actual solar

trajectory at the site. In this way, solar control becomes an intrinsic component of the architecture rather than an independently added technical system.

15. Selection of Appropriate Construction Solutions

The final stage consists of defining the construction systems, materials, envelope characteristics, thermal properties, and other technical solutions required to achieve the intended environmental performance. At this point, the architectural configuration developed during the preceding stages is translated into a technically viable construction system.

The selection of construction solutions must be consistent with the previously established thermal strategy. The envelope, insulation, thermal mass, surface characteristics, glazing systems, joints, and other constructional components must collectively contribute to reducing unwanted heat transfer and supporting the building's passive thermal regulation.

The thirteen stages should not be interpreted as a rigid sequence in which each decision is made only once. Rather, *deep bioclimatic design* is conceived as an *iterative feedback process* in which environmental analysis, architectural design, energetic assessment, and constructional definition continuously inform one another. Results obtained at advanced stages may reveal the need to modify decisions established during earlier stages, requiring the design to return to previous stages and be progressively refined.

The final objective is therefore not simply to reduce energy consumption, but to develop an architectural system in which the geometry, orientation, envelope, solar control, ventilation, thermal behavior, construction systems, and renewable energy generation operate synergistically. Through this integrated approach, the building itself becomes an active component of environmental regulation, substantially reducing or potentially eliminating the need for conventional mechanical heating and cooling.

This methodology has been successfully applied to the design of *deep bioclimatic buildings* capable of thermally self-regulating their indoor environments and maintaining comfortable temperatures without the need for conventional heating or air-conditioning systems [8].

2.1.1. South Orientation. Distribution of Solar Radiation

The first guiding principle to be settled when designing a deep bioclimatic building is its solar orientation [8, 17, 19].

Here, a south-facing building is not merely one whose façade happens to point roughly toward geographic south. It denotes a deliberate architectural arrangement in which the main occupied façade and its largest glazed areas face the equator, that is, due south in the Northern Hemisphere and due north in the Southern Hemisphere. The purpose of this arrangement is to make the greatest possible use of regulated solar gains in winter, while allowing those gains to be effectively blocked in summer. Meeting this requirement depends on the combined coordination of the building’s form, internal functional layout, façade design, glazing, and shading devices [8].

1. East–West Building Alignment and Equator-Facing Orientation

The building’s principal longitudinal axis should preferably follow an east–west direction, thereby allowing its main façade to face the equator. In the Northern Hemisphere, this configuration corresponds to a predominantly south-facing principal façade, whereas in the Southern Hemisphere, the preferred orientation is north-facing. This arrangement facilitates the controlled exploitation of seasonal solar radiation and supports the implementation of horizontal shading devices designed to admit useful solar gains during winter while limiting excessive exposure during summer.

2. Solar-Responsive Functional Zoning

The internal spatial organization should be coordinated with the building’s orientation and the distribution of solar exposure [8, 17, 19].

Primary occupied spaces should preferentially be positioned along the equator-facing façade, where access to natural daylight and the potential for useful solar heat gains can be optimized. Conversely, service areas, circulation zones, storage spaces, and other functions with lower occupancy requirements should generally be concentrated toward the pole-facing side. Accordingly, primary spaces would predominantly occupy the southern side in the Northern Hemisphere and the northern side in the Southern Hemisphere, with the arrangement reversed in the opposite hemisphere. When appropriately coordinated with the building's overall environmental design, this functional distribution may also support natural ventilation by facilitating airflow between zones exposed to different levels of solar radiation and thermal loading. Its effectiveness, however, depends on the availability of suitable openings, pressure differences, and an appropriate ventilation configuration.

3. Geometric Continuity of the Equator-Facing Façade

The architectural configuration should preserve a clear solar relationship between the principal façade and the sun's seasonal trajectory. An approximately east–west longitudinal axis facilitates the design of solar-control systems that respond to the changing altitude and direction of solar radiation throughout the year. This approach makes it possible to regulate the admission of beneficial winter radiation while restricting excessive summer exposure. Unnecessary projections, deep recesses, setbacks, and other geometric irregularities should therefore be assessed according to their potential effects on solar access. In particular, architectural elements that obstruct useful winter radiation from reaching the principal glazed surfaces should be avoided unless they serve a demonstrable functional, structural, or environmental purpose. The objective is not to eliminate architectural complexity, but to ensure that the building's geometry remains compatible with its intended seasonal solar performance.

4. Orientation-Based Allocation of Glazed Areas

The distribution of glazed surfaces should be determined by their orientation, their contribution to daylight provision, and their implications for the building's annual thermal balance. Glazing should generally be concentrated on the equator-facing façade, where solar gains can be regulated through carefully designed shading systems. This corresponds predominantly to the south-facing façade in the Northern Hemisphere and the north-facing façade in the Southern Hemisphere.

The area of glazing on the opposite façade should normally be reduced. East- and west-facing glazed surfaces should also be carefully controlled and, where appropriate, minimized. These orientations are particularly exposed to low-angle solar radiation during the morning and afternoon, which can be difficult to intercept using conventional horizontal overhangs. Excessive glazing in these locations may consequently increase unwanted solar heat gains and the risk of indoor overheating. The optimal configuration must therefore be established through the coordinated assessment of orientation, glazing area, daylight requirements, envelope thermal properties, and shading performance. Building orientation should not be treated as an isolated geometric decision, but as part of an integrated architectural strategy in which spatial organization, façade design, and solar protection operate in combination. This coordination establishes the initial framework for the subsequent stages of Deep Bioclimatic Design.

2.1.2. Seasonal Solar Exposure of Building Envelope Surfaces During Winter

During winter, the sun follows a comparatively low trajectory across the sky. Consequently, a south-facing building in the Northern Hemisphere can receive substantial direct solar radiation on its south façade, whereas the east and west façades are generally exposed for shorter periods, primarily during the morning and afternoon, respectively. The roof also receives solar radiation throughout daylight hours; however, the intensity incident on a horizontal surface relative to that received by a vertical façade depends on the solar altitude, the time of day, and the geographic location [8, 17, 19].

These seasonal conditions make the south-facing façade particularly relevant to passive solar heating in the Northern Hemisphere. The corresponding orientation in the Southern Hemisphere is the north-facing façade. The extent to which each surface contributes to the building's thermal balance must nevertheless be established from location-specific solar geometry and climatic data (Fig. **5**).

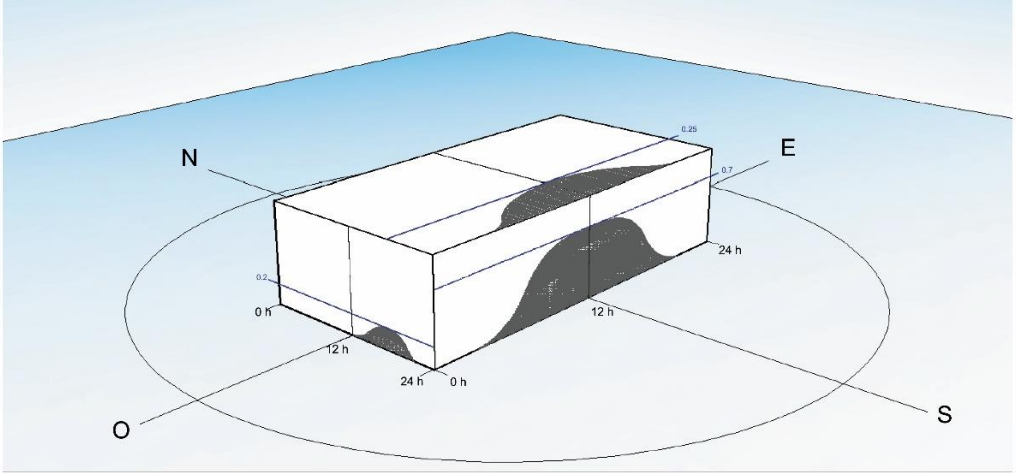


Figure 5: Wintertime solar exposure of the principal envelope surfaces of a south-facing building in the Northern Hemisphere. Drawing by Luis de Garrido.

The diagram illustrates the approximate duration of solar exposure and the relative maximum intensity of incident solar radiation on the different building surfaces. The solar indices are expressed in relation to the maximum solar radiation intensity incident on the roof during summer. The relative proportions represented in the central and upper and lower parts of the diagram are illustrative averages rather than universal values; actual relationships vary according to latitude, solar geometry, and local environmental conditions.

2.1.3. Seasonal Solar Exposure of Building Envelope Surfaces During Summer

During summer, the sun reaches substantially higher elevations in the sky, increasing the potential for intense solar exposure on horizontal and near-horizontal surfaces. The roof may therefore receive strong solar radiation over an extended period, from sunrise to sunset, depending on atmospheric conditions and the building's location. By comparison, the intensity of radiation incident on a south-facing vertical façade in the Northern Hemisphere is influenced by the sun's high elevation and its changing azimuth throughout the day [8, 17, 19].

The east-facing façade is predominantly exposed during the morning, whereas the west-facing façade receives radiation mainly during the afternoon. Both orientations may experience significant solar gains when the sun is at a low angle, which can complicate the use of fixed shading devices. The north-facing façade may also receive direct sunlight during parts of the day, particularly at higher latitudes in summer, although the duration and intensity of this exposure depend on the geographic location and the sun's trajectory (Fig. **6**).

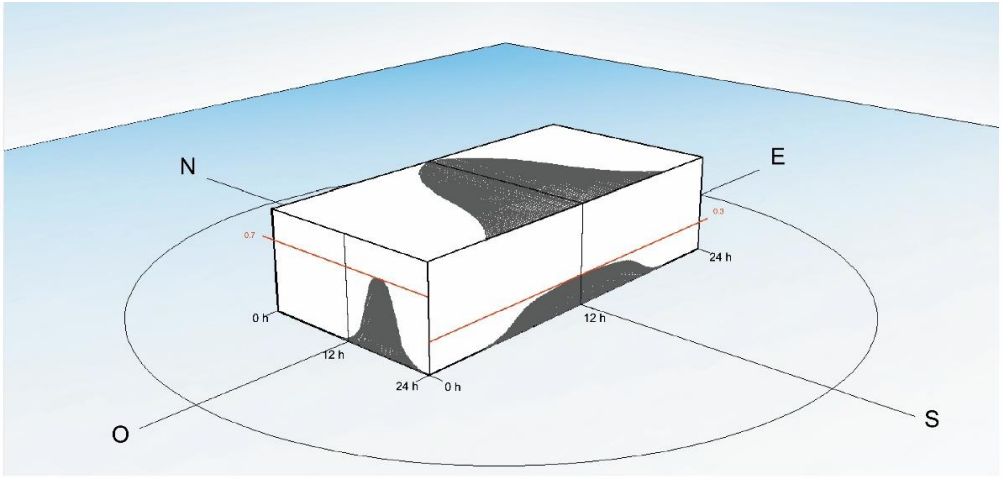


Figure 6: Summertime solar exposure of the principal envelope surfaces of a south-facing building in the Northern Hemisphere. Drawing by Luis de Garrido.

The diagram represents the approximate duration of solar exposure and the maximum intensity of radiation incident on each principal building surface, relative to the maximum solar radiation intensity received by the roof during summer. The relative solar indices shown in the central and upper and lower portions of the diagram are intended for illustrative comparison only. Their actual values depend on latitude, local solar geometry, atmospheric conditions, and the specific orientation of the building.

2.1.4. Solar-Responsive Envelope Design Guidelines for Deep Bioclimatic Buildings

The analysis of solar radiation across the principal surfaces of a *Deep Bioclimatic Building* provides a fundamental basis for formulating architectural strategies intended to improve thermal performance and reduce dependence on conventional heating and cooling systems [8 17, 19]. These strategies should be considered from the earliest conceptual sketches and progressively integrated into the subsequent stages of architectural development. The principal recommendations are outlined below.

1. Restriction of Roof Glazing

Horizontal roof glazing should generally be avoided or used only when justified by specific daylighting or functional requirements. In many configurations, it provides limited opportunities for useful winter solar heating while exposing the building to substantial solar gains during summer, when the sun is high in the sky. These gains may increase cooling loads and make it more difficult to maintain comfortable indoor temperatures through passive means. Roof glazing should therefore be evaluated in relation to local climatic conditions, solar exposure, thermal performance, and the availability of alternative daylighting strategies.

2. Optimization of Glazing on the Equator-Facing Façade

The equator-facing façade should generally accommodate the principal proportion of the building's solar-responsive glazing. In the Northern Hemisphere, this is typically the south-facing façade; in the Southern Hemisphere, it is the north-facing façade. With appropriate sizing and orientation, these glazed areas can contribute to passive heating during colder periods while allowing seasonal solar exposure to be controlled through carefully designed shading systems.

Horizontal overhangs and, where necessary, vertical or adjustable shading elements should be dimensioned according to the sun's seasonal trajectory, façade orientation, and local climatic conditions. The objective is to admit useful solar radiation when heating is beneficial while limiting excessive direct radiation and associated overheating during warmer periods. Diffuse and reflected radiation should also be considered when assessing the overall performance of the façade.

3. Control of East- and West-Facing Glazing

Glazing on east- and west-facing façades should generally be limited and carefully designed, particularly in climates with significant summer overheating risks. During winter, the period in which these façades receive direct sunlight may be relatively short, restricting their contribution to useful passive heating. During summer, however, low-angle morning and afternoon sunlight can produce substantial heat gains that are difficult to control using fixed horizontal overhangs alone.

Reducing the glazed area on these façades can therefore help limit unwanted thermal gains. Where windows are required for daylight, views, or functional reasons, their dimensions and solar protection should be designed in conjunction with the building's orientation, internal layout, and ventilation strategy.

4. Reduction of Unnecessary Pole-Facing Glazing

Glazing on the pole-facing façade should generally be minimized to the extent compatible with daylighting, views, and functional requirements. In the Northern Hemisphere, this typically refers to the north-facing façade, while in the Southern Hemisphere it refers to the south-facing façade. Compared with a well-insulated opaque envelope, glazed assemblies may exhibit higher thermal transmittance, potentially increasing heat losses during cold periods. Their thermal performance depends, however, on the glazing specification, frame design, installation quality, and overall envelope construction.

The appropriate strategy is therefore to limit unnecessary glazing while retaining openings that provide demonstrable functional or environmental benefits. This approach can reduce avoidable heat transfer and contribute to the building's overall energy performance.

5. Integration of Elevated Glazing and High-Level Ventilation Openings

Elevated vertical glazing may be incorporated where it serves daylighting, passive solar heating, or architectural objectives, provided that its thermal implications are addressed through appropriate orientation and solar protection. During winter, such openings may contribute to useful solar gains when suitably positioned. During summer, shading and ventilation measures should prevent excessive solar heat accumulation.

Where the building's configuration supports buoyancy-driven airflow, high-level openings can also facilitate the discharge of warm indoor air through the stack effect. Their effectiveness depends on the availability of lower-level air inlets, sufficient vertical separation between openings, appropriate airflow paths, and suitable indoor–outdoor temperature differences. Elevated glazing should consequently be coordinated with the building's overall ventilation strategy rather than treated as an independent passive-cooling measure.

Taken together, these recommendations establish the principal solar-responsive envelope principles to be incorporated into the initial stages of *Deep Bioclimatic Design*. They provide a basis for estimating thermal losses and solar gains, determining the dimensions and placement of glazed surfaces, defining the building's principal bioclimatic parameters, developing preliminary architectural configurations, and progressively refining the selected architectural typology.

2.2. Thermodynamic Balance and Minimization of Building Thermal Loads

2.2.1. Reducing Heat Transfer Through the Building Envelope

The thermal energy exchanged between a building and its external environment is strongly influenced by the thermal properties and surface areas of its envelope components, together with the temperature difference between indoor and outdoor conditions. Under simplified steady-state conditions, the heat-transfer rate through the building envelope can be expressed as follows [8, 20]:

$$Q_l = \sum_n (K_n * S_n * (t_{int} - t_{ext}))$$

Where Q_l denotes the net conductive heat-transfer rate through the envelope, with n envelope components with distinct thermal properties; K_n is the thermal transmission coefficient of each differentiating element of the architectural envelope; Sn is the surface area of each differentiating element of the envelope; and (t_{int} - t_{ext}) is the difference between the interior and outdoor air temperatures.

The resulting heat-transfer rate is positive when indoor temperatures exceed outdoor temperatures, indicating outward heat loss, and negative when outdoor temperatures exceed indoor temperatures, indicating inward heat gain. For clarity, this expression describes conductive transfer through the envelope under a simplified steady-state approximation; a comprehensive building energy balance must also account for ventilation and infiltration, solar radiation, internal heat gains, thermal storage, and other relevant processes.

The equation identifies three principal variables that can be addressed through architectural design: envelope thermal transmittance, exposed surface area, and the indoor–outdoor temperature difference. Heat transfer can therefore be reduced by specifying highly insulating envelope assemblies, adopting a compact building configuration where appropriate, and avoiding unnecessarily high indoor temperature setpoints in winter or excessively low setpoints in summer. These measures reduce the thermal loads that would otherwise need to be offset by mechanical heating or cooling equipment.

In a conventional building, heating or cooling systems must compensate for the net thermal imbalance to maintain the required indoor conditions. Under a simplified steady-state balance, the thermal output supplied by

a heating system must offset the building's net heat losses, whereas a cooling system must remove the net excess heat entering or being generated within the building. In actual operation, however, the relationship between system output and envelope heat transfer also depends on internal gains, ventilation, thermal mass, system efficiency, and transient conditions.

For *Deep Bioclimatic Design*, the priority is to minimize these thermal loads before introducing additional means of heat generation or removal. Because the objective is to maintain acceptable indoor thermal conditions primarily through architectural and environmental mechanisms, the building envelope, geometry, orientation, and thermal properties must be coordinated to reduce unwanted heat transfer throughout the year. This reduction constitutes a prerequisite for the effective integration of passive heating, cooling, and thermal-storage strategies [8, 20].

2.2.2. Passive Thermal Regulation Through Natural Energy Flows

In conventional buildings, thermal imbalances are commonly corrected by mechanical systems that supply heat during cold periods or extract heat during warm periods. Although these systems can maintain indoor comfort, they require energy inputs and introduce additional equipment, operational costs, and environmental impacts.

An alternative approach is to configure the building so that naturally available energy flows contribute directly to its thermal regulation.

- During winter, solar radiation can be captured through appropriately oriented and proportioned glazed surfaces. When the resulting solar gains exceed immediate thermal losses, part of the heat can be stored in the building's internal thermal mass and subsequently released as indoor temperatures decline. The effectiveness of this strategy depends on the intensity and duration of solar exposure, glazing properties, envelope insulation, thermal storage capacity, and the timing of heat gains and losses.

- During summer, passive cooling can be achieved by reducing solar heat gains and using cooler outdoor air to remove heat accumulated within the building. Nighttime ventilation is particularly useful when outdoor temperatures fall sufficiently below indoor temperatures. Where the external air remains too warm to provide effective cooling, additional architectural measures, such as earth-coupled air passages, may reduce the temperature of the incoming air before it enters occupied spaces. The performance of these systems depends on local climatic conditions, airflow rates, ground temperatures, duct geometry, and the management of moisture and indoor air quality.

The underlying principle is to coordinate the building's capacity to capture, reject, and store heat with the temporal availability of natural energy resources. During winter, solar gains and thermal storage can reduce heating requirements; during summer, shading, controlled ventilation, and the dissipation of accumulated heat can reduce cooling requirements. When these strategies are appropriately integrated, the building may maintain acceptable indoor conditions with substantially reduced reliance on conventional mechanical systems. Achieving complete thermal self-regulation without mechanical heating or cooling, however, requires verification under the specific climatic, architectural, and occupancy conditions of each project [8].

2.3. Architectural Configurations for Passive Heating and Cooling

Deep Bioclimatic Design seeks to exploit naturally available environmental resources by integrating climate-responsive architectural strategies into the building's geometry, envelope, spatial organization, and construction systems. Rather than relying primarily on mechanical equipment to compensate for excessive heat losses or gains, this approach aims to prevent unwanted thermal exchanges and facilitate the selective capture, storage, and removal of heat [6, 8, 20, 21].

- During winter, the design should maximize the useful solar radiation available at the building's location. In the Northern Hemisphere, this generally involves orienting the principal solar-collecting façade toward the south; in the Southern Hemisphere, the corresponding orientation is generally north. Appropriately sized

glazed surfaces can admit solar radiation, allowing short-wave energy to enter the building and contribute to the warming of internal surfaces and spaces. The resulting heat should be stored in suitable thermal-mass elements so that it can be released gradually after sunset. At the same time, a highly insulated envelope is required to limit heat losses and preserve the thermal energy accumulated during the day.

- During summer, the primary objectives are to prevent excessive solar gains and to exploit periods when the external environment can facilitate heat dissipation. External shading, suitable glazing ratios, envelope insulation, and the strategic arrangement of openings can reduce overheating. Nighttime ventilation can then remove accumulated heat and cool the building's internal thermal mass, provided outdoor conditions are sufficiently favorable. The stored cooling effect can help moderate indoor temperature fluctuations during the following day. In climates where nighttime air remains relatively warm, earth-coupled ventilation or other supplementary passive-cooling measures may be required.

These principles can be applied across a wide range of climatic contexts, although the complexity, spatial requirements, and construction costs of the necessary strategies vary considerably. In mild climates, a relatively limited set of measures may be sufficient to achieve substantial reductions in heating and cooling demand. In more severe climates, the design may require greater insulation, increased thermal storage, more sophisticated solar control, additional ventilation infrastructure, or supplementary environmental systems. Consequently, the feasibility and economic advantages of a fully passive solution must be assessed for each project rather than assumed to be universal. Even where complete independence from mechanical heating and cooling is impractical, a carefully developed bioclimatic design can reduce the capacity and energy consumption of the systems required to maintain indoor comfort.

2.3.1. Passive Solar Heating and Heat-Retention Strategies

In winter, a *Deep Bioclimatic Building* is designed to exploit available solar radiation while limiting the subsequent dissipation of the captured heat [8]. Achieving this objective requires the coordinated design of building orientation, glazed surfaces, shading devices, insulation, and internal thermal mass.

During periods of useful solar exposure, movable shading devices should be positioned to permit solar radiation to enter the building, provided that overheating and glare are avoided. Solar energy transmitted through the glazing can then be absorbed by internal floors, walls, and other thermally massive elements, increasing their temperature and contributing to the warming of the occupied spaces. The glazing area, orientation, configuration, and thermal properties must be determined in relation to the building's calculated heating demand, the available solar resource, and the potential for unwanted heat losses.

The thermal performance of this strategy depends not only on the quantity of solar radiation admitted but also on the building's ability to retain and redistribute the resulting heat. A highly insulated envelope is therefore essential, as it limits outward heat transfer during both daylight hours and the colder nighttime period. Thermal mass can further moderate indoor temperature fluctuations by storing energy when heat gains are available and releasing it when indoor temperatures decline. Its effectiveness depends on its quantity, thermal properties, position within the insulated envelope, and degree of thermal coupling with the occupied spaces.

The heating strategy should be developed progressively through quantitative assessment of solar gains, envelope heat losses, thermal storage capacity, and expected indoor temperature variations. If the initial configuration does not provide sufficient heat under the most demanding winter conditions, the design may require adjustments to glazing dimensions, insulation levels, thermal mass, or other passive solar-heating measures. In colder climates, achieving the desired indoor conditions may require a more elaborate combination of strategies and a more rigorous assessment of performance during periods of limited solar availability.

The objective is to reduce the gap between available passive solar gains and the building's heating demand while ensuring that the heat captured during the day remains available when it is most needed. Whether this balance can be achieved without supplementary heating must be established through climate-specific energy calculations and, where possible, dynamic thermal simulation.

2.3.2. Passive Cooling and Nighttime Heat Dissipation

During summer, a *Deep Bioclimatic Building* seeks to maintain acceptable indoor temperatures by minimizing heat gains and exploiting favorable conditions for the removal of accumulated heat [8, 22, 23].

This requires the coordinated implementation of solar protection, envelope insulation, thermal mass, and an appropriate ventilation strategy.

The first measure is to limit the entry of unwanted solar radiation through external shading, controlled glazing areas, and an envelope configuration adapted to the local solar trajectory. Once solar gains have been reduced, nighttime ventilation can remove heat accumulated in internal surfaces and building components. When outdoor air is cooler than the building's internal thermal mass, ventilation promotes convective heat transfer from the building to the incoming air, lowering the temperature of the thermally active elements. The resulting reduction in stored heat can help delay indoor overheating during the following day.

The effectiveness of nighttime ventilation depends on the temperature difference between indoor surfaces and outdoor air, the duration of ventilation, the available airflow rate, and the arrangement of air inlets and outlets. Ventilation should therefore be intensified when outdoor conditions are most favorable, while maintaining adequate indoor air quality, security, and control over humidity. A fixed operating period cannot be assumed to be optimal in every location; the timing and duration should be determined from local hourly weather data and the building's thermal response.

In climates where nighttime temperatures remain above the desired indoor comfort range, direct ventilation alone may not provide sufficient cooling. Under these circumstances, earth-coupled air passages or underground galleries may be considered to reduce the temperature of incoming outdoor air through heat exchange with the surrounding ground. The effectiveness of such systems depends on ground temperature, soil characteristics, passage length and geometry, airflow rate, and moisture conditions. Their design must also address condensation, drainage, hygiene, and the prevention of microbial growth.

Where the climate and building configuration are suitable, nighttime ventilation and earth-coupled cooling can be combined with substantial thermal mass and effective solar protection to preserve lower indoor temperatures during the day. Nevertheless, the ability of these strategies to maintain thermal comfort without mechanical cooling must be demonstrated through a full assessment of the local climate, internal gains, occupancy patterns, and building performance.

From an economic perspective, passive systems may reduce long-term energy consumption and dependence on mechanical equipment. Their initial construction costs, maintenance requirements, and spatial implications should, however, be evaluated against the costs and performance of the systems they are intended to replace. In particularly demanding climates, a hybrid approach may provide a more reliable and cost-effective solution than a strictly passive configuration.

2.3.3. Thermal Mass and the Position of Insulation Within the Envelope

The effectiveness of passive heating and cooling depends not only on the architectural strategies employed but also on the relationship between thermal mass and insulation. In the approach proposed here, insulation should generally be located toward the exterior of the principal thermally massive envelope, allowing the internal structure and selected interior surfaces to remain thermally coupled to the occupied spaces.

This arrangement helps preserve the contribution of internal thermal mass by reducing heat exchange between the massive elements and the outdoor environment. During winter, internal surfaces can absorb useful solar and internal heat gains and release stored energy as indoor temperatures decline. During summer, the same mass can absorb heat from the interior, provided that unwanted gains are limited and that the stored heat can subsequently be removed through appropriate nighttime ventilation or other cooling strategies.

The thermal mass of a building can be increased through the use of dense construction materials, masonry, concrete, earth-based elements, or other materials with suitable thermal properties. Where technically

appropriate, excavated soil or recovered construction materials may also contribute to thermal storage, potentially improving material efficiency and reducing waste. Their suitability must be assessed in relation to structural safety, moisture control, durability, embodied impacts, and construction requirements.

Greater mass does not automatically guarantee superior performance, nor does it necessarily entail lower construction costs. The relevant design objective is to provide an appropriate quantity and distribution of thermally active material in combination with adequate insulation, effective solar control, and a reliable means of dissipating excess heat. Excessive thermal mass may be ineffective or even counterproductive when the climate, ventilation regime, or pattern of internal heat gains does not allow the stored energy to be removed at the appropriate time.

Accordingly, the design of the envelope should integrate insulation, thermal mass, glazing, shading, and ventilation as interdependent components of a single thermal-regulation system. Their combined performance, rather than any individual construction measure, determines the extent to which a building can maintain acceptable indoor conditions while minimizing its reliance on mechanical heating and cooling.

3. Results. Case Study: *PHANTOM Eco-tower*

In order to analyze the energy and sustainability benefits of *deep bioclimatic buildings*, the thermodynamic behavior of a *deep bioclimatic building* is analyzed in depth. This building does not require air conditioning or heating devices to maintain a comfortable internal temperature everityme. Consequently, the building consumes little energy, making it very economical to convert it into an energy self-sufficient building.

3.1. General Information

PHANTOM Eco-tower is an iconic residential building designed for future construction in Miami, USA, projected by Dr. Architect Luis de Garrido (Figs. **7-13**). The building comprises five dwellings per floor: three three-bedroom units and two one-bedroom units. However, because all internal partitions are demountable, the residential layouts can be readily reconfigured in response to changing user requirements. Individual dwellings can therefore be enlarged or reduced over time, providing a high degree of spatial adaptability while extending the functional usefulness of the building.

Several intermediate floors are dedicated to landscaped communal areas that provide spaces for social interaction, recreation, and leisure. The roof is also extensively landscaped and incorporates a shared swimming pool. One of the building's most distinctive architectural features is the continuous system of surrounding terraces, which performs a dual function. In addition to providing outdoor living spaces for residents, the terraces act as passive solar-control elements, reducing direct solar gains and contributing to the maintenance of comfortable indoor temperatures. The building incorporates an efficient architectural and functional organization that seeks to maximize the use of the available built floor area while simultaneously integrating communal, residential, and environmental functions (Figs. **14-20**).

The project aims to achieve a very high level of sustainability for a high-rise residential building. This objective involves optimizing resource use, minimizing actual energy consumption, reducing waste generation and emissions, producing the limited energy required on site through solar-thermal and photovoltaic systems, minimizing economic and maintenance costs, and extending the building's service life. The skyscraper is designed to achieve zero actual energy consumption, whereby its basic operational energy requirements can be met without dependence on externally supplied energy. Its thermal performance is based primarily on a specific deep bioclimatic design intended to enable passive thermal regulation without reliance on energy-intensive mechanical heating or cooling systems.

Natural ventilation and passive cooling of the dwellings are facilitated by an internal courtyard (Fig. **20**) that channels relatively cool air from the building's lower levels towards the residential units. This configuration promotes continuous air movement and contributes to the dissipation of internal and solar heat gains. In addition, all interior spaces are designed to receive natural daylight whenever adequate solar radiation is available, thereby

reducing the need for artificial lighting during daytime conditions. Collectively, these strategies integrate spatial adaptability, passive environmental control, renewable energy generation, and resource efficiency into a unified high-rise residential architecture.



Figure 7: *PHANTOM Eco-tower.* Miami (USA*)* (Projected by Luis de Garrido).



Figure 8. *PHANTOM Eco-tower.* Miami (USA) (Projected by Luis de Garrido).



Figure 9: *PHANTOM Eco-tower.* Miami (USA). Upper view.



Figure 10: *PHANTOM Eco-tower.* Miami (USA).



Figure 11: *PHANTOM Eco-tower.* Miami (USA).



Figure 12: *PHANTOM Eco-tower.* Miami (USA). Upper view.



Figure 13: *PHANTOM Eco-tower.* Miami (USA). Upper view.

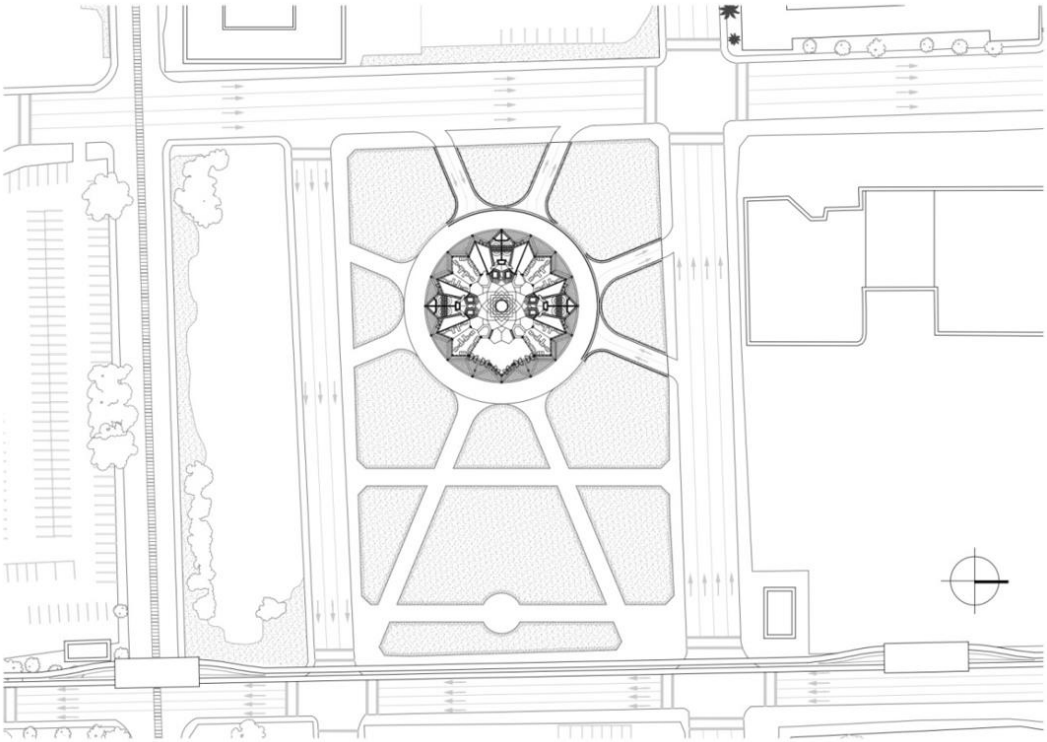


Figure 14: *PHANTOM Eco-tower.* Miami (USA). Location.

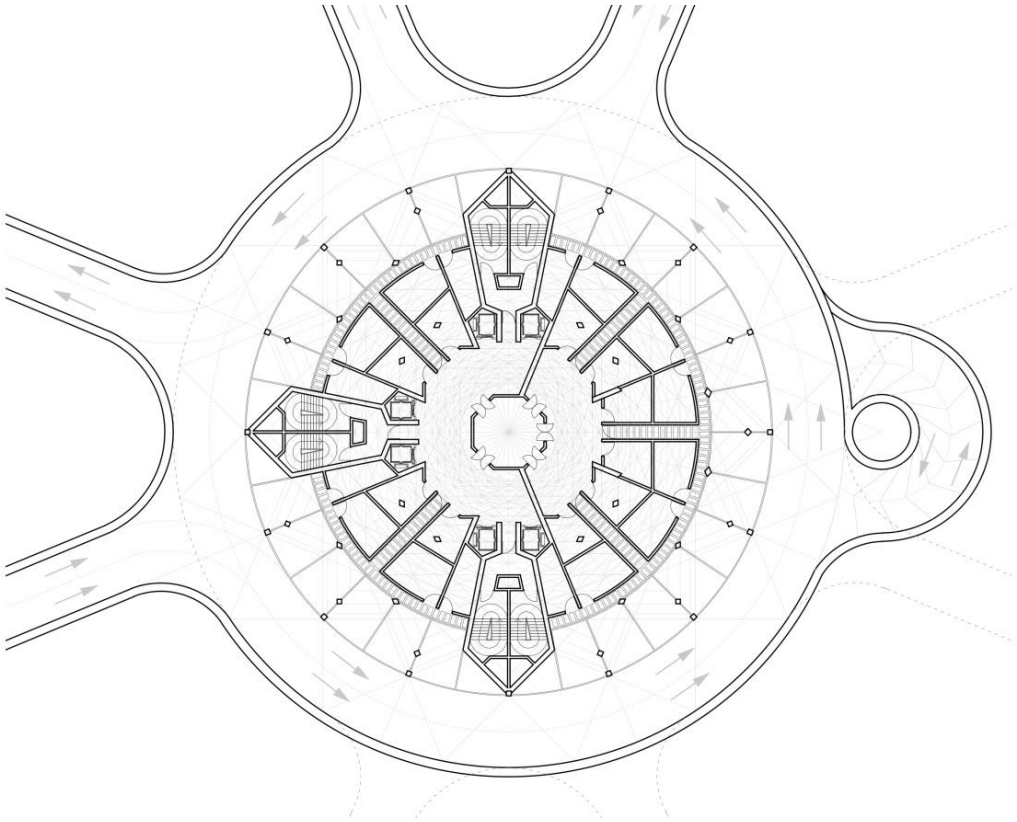


Figure 15: *PHANTOM Eco-tower.* Ground floor plan layout.

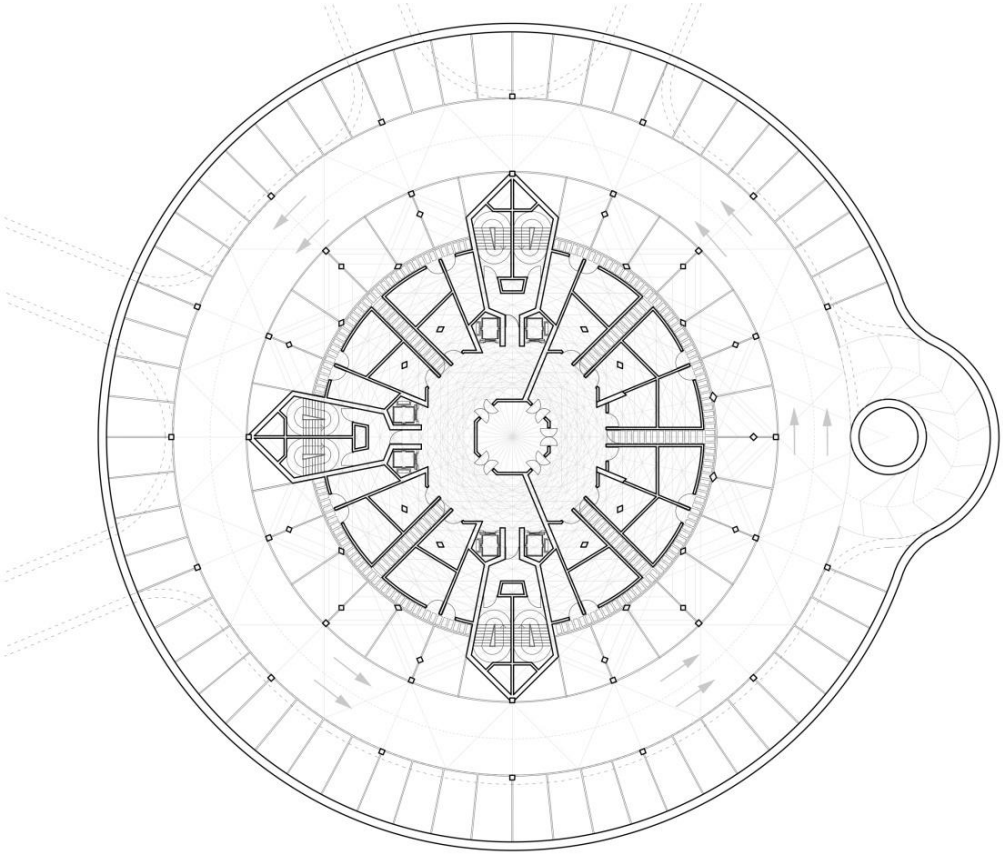


Figure 16: *PHANTOM Eco-tower.* Underground levels.

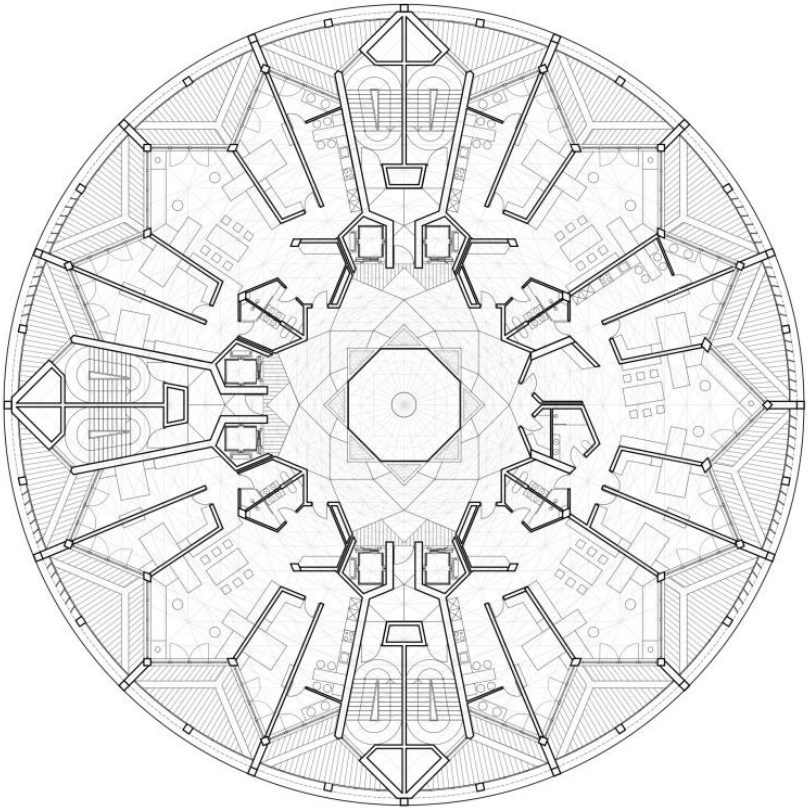


Figure 17: *PHANTOM Eco-tower.* Upper levels plan layout.

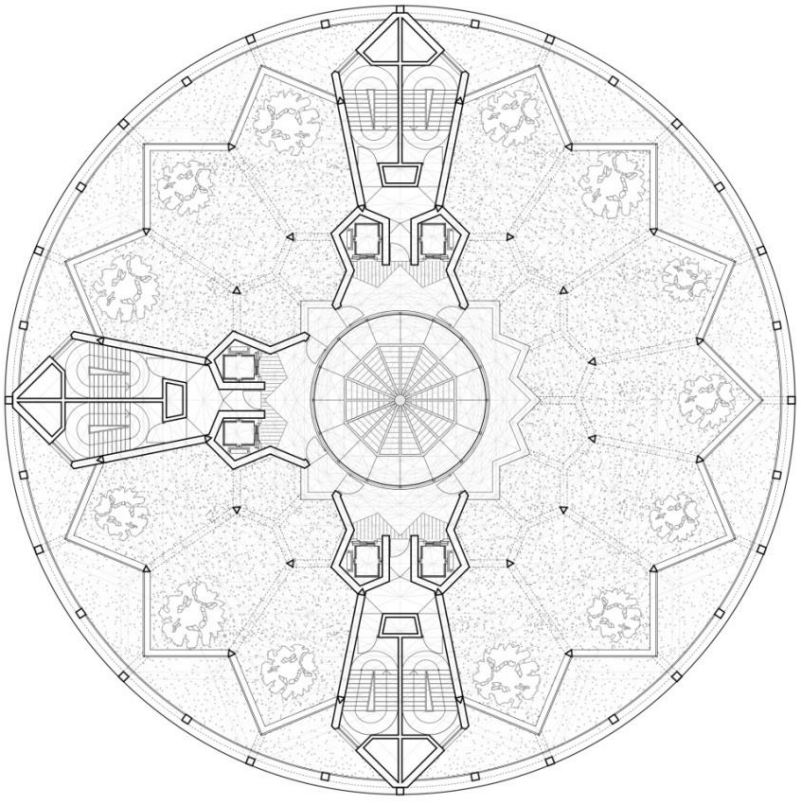


Figure 18: PHANTOM Eco-tower.Green roof.

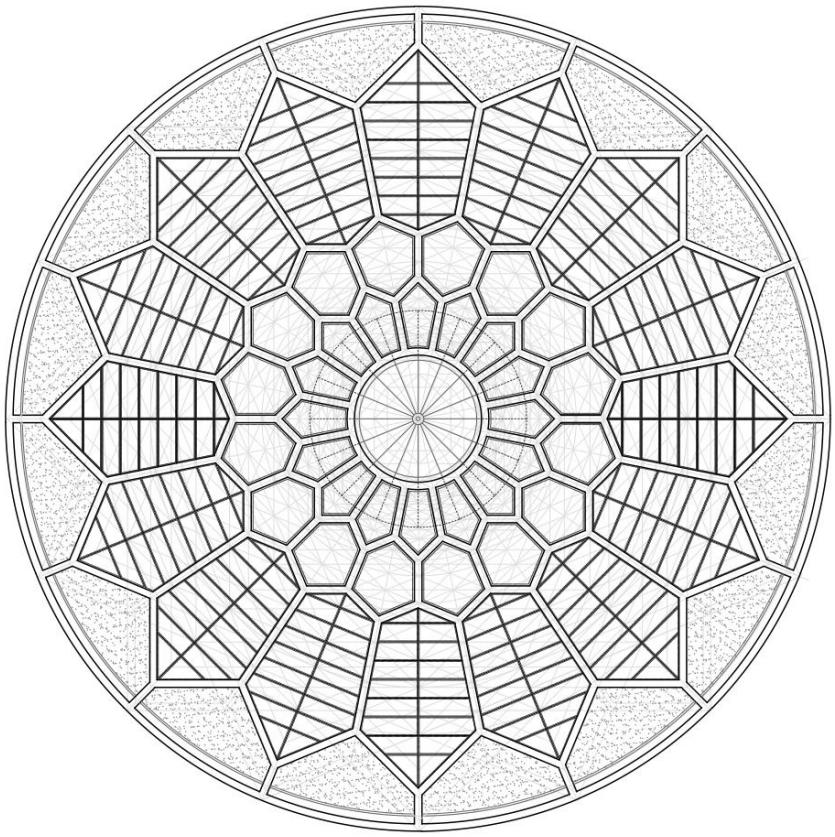


Figure 19: PHANTOM Eco-tower. Roof.

The building is conceived using standardized and industrialized components and incorporates a fully demountable construction system. Consequently, its components can be recovered, repaired, and reused indefinitely, thereby extending their useful life and minimizing resource consumption and construction-related waste.

3.2. Deep Bioclimatic Design

In this study, *deep bioclimatic design* is defined as creating buildings capable of thermal self-regulation, providing a comfortable interior temperature (20º-24º), without the need for heating and air conditioning equipment. Achieving this requires good professional skills, although in extreme climates, occasional heating may still be needed. The energy savings of bioclimatic design are often measured as the "bioclimatic level". In this article, we focus on a 100% bioclimatic approach, in which the *PHANTOM Eco-tower* demonstrates the ability to provide comfortable indoor temperatures without any mechanical devices.

In certain environments characterized by extremely low or high temperatures, achieving a building based on *deep bioclimatic design* principles is more challenging. Conversely, in climatic contexts with moderate temperatures, the incorporation of bioclimatic strategies capable of maintaining appropriate indoor thermal conditions is considerably easier. Nevertheless, even under extreme climatic conditions, it is possible to develop buildings based on *deep bioclimatic design* that can thermally self-regulate their indoor environments and provide thermal comfort without relying on conventional heating or air-conditioning systems.

In Miami, thermal conditions are relatively moderate throughout the year (Figs. **21** and **22**), which considerably facilitates the incorporation of bioclimatic strategies aimed at both heat gain and generation and the dissipation and reduction of excessive thermal gains. Consequently, through an appropriate combination of bioclimatic design strategies, it is possible to maintain comfortable indoor thermal conditions without the need for mechanical heating or cooling systems [8, 18-20].

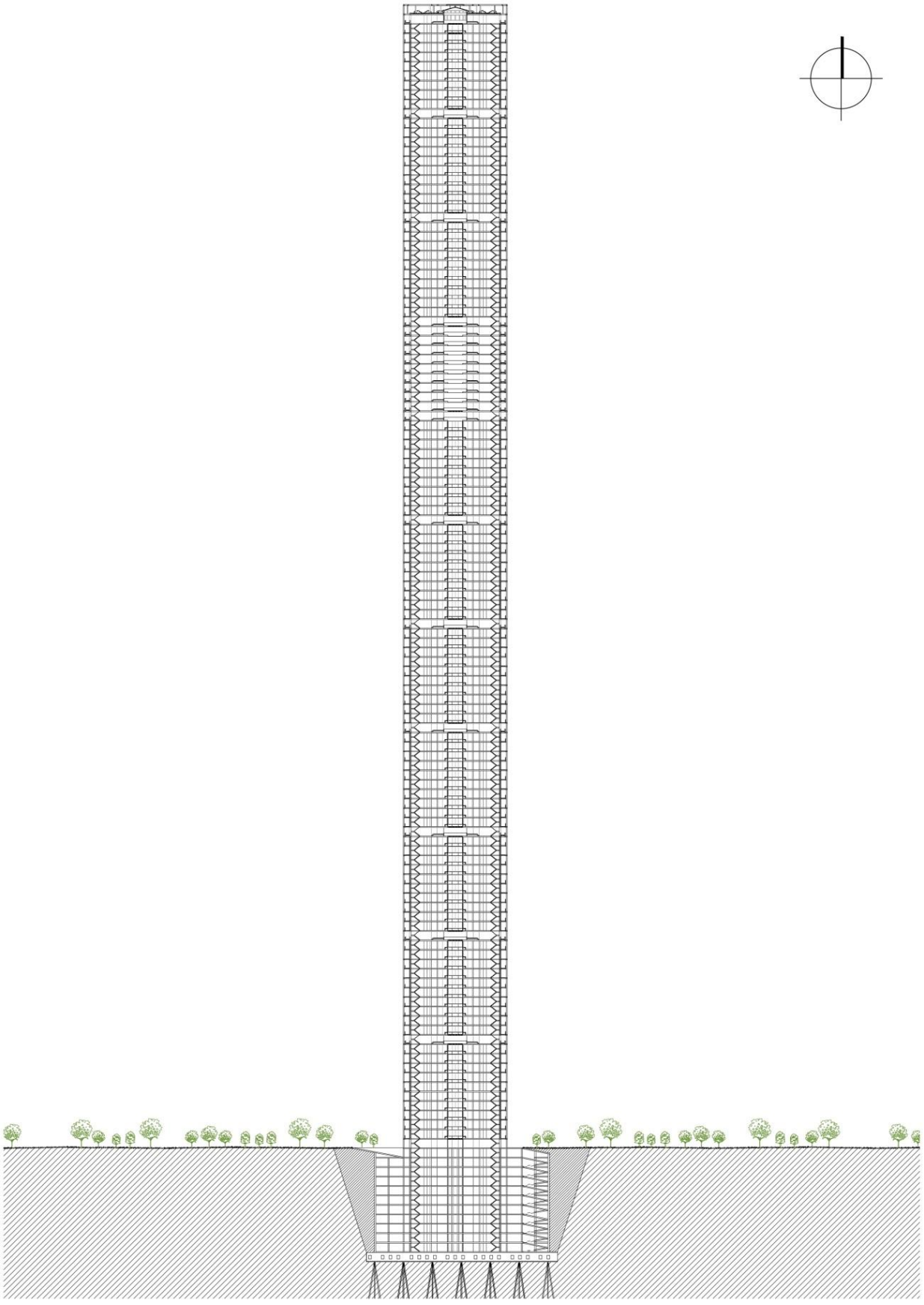


Figure 20: PHANTOM Eco-tower. Section.

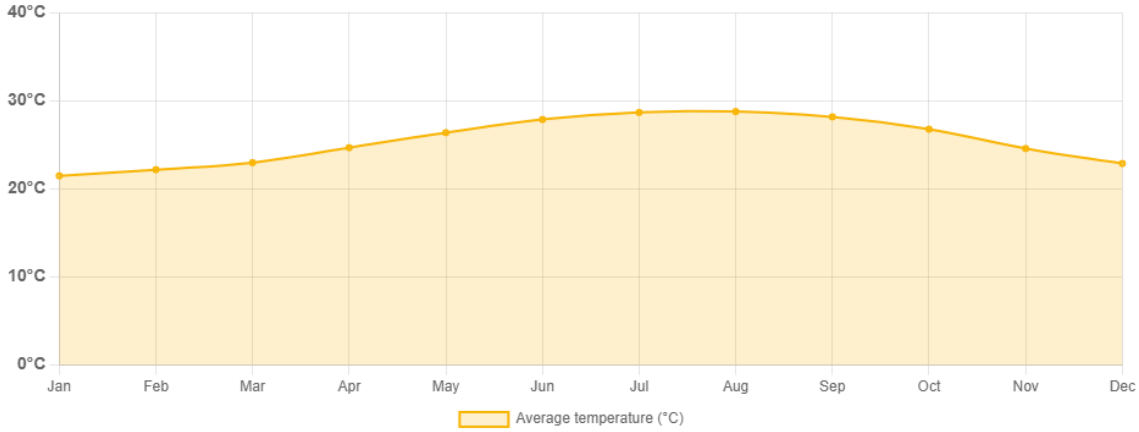


Figure 21: Average temperatures throughout the year in Miami. (Source: https://weather-and-climate.com/average-monthly-min-max-Temperature,miami-beach-florida-us,United-States-of-America).

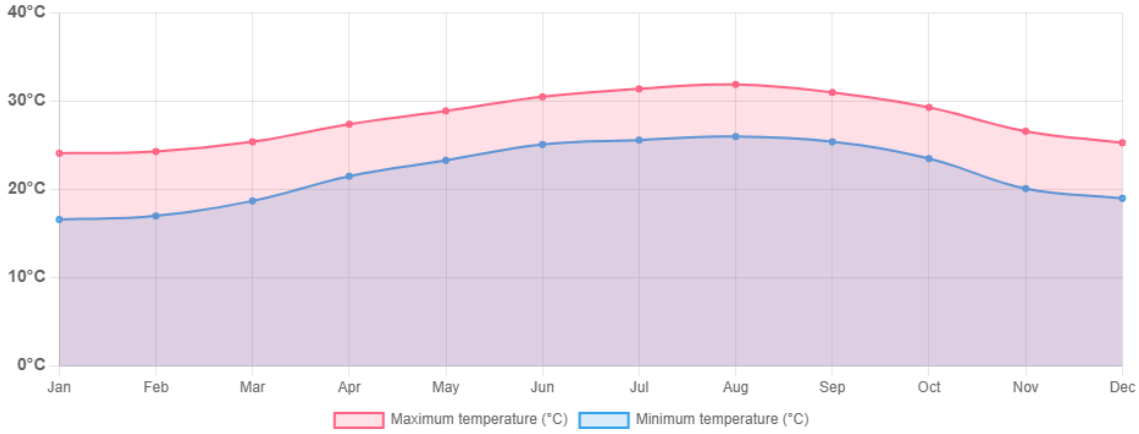


Figure 22: Maximum and minimum temperatures throughout the year in Miami. (Source: https://weather-and-climate.com/average-monthly-min-max-Temperature,miami-beach-florida-us,United-States-of-America).

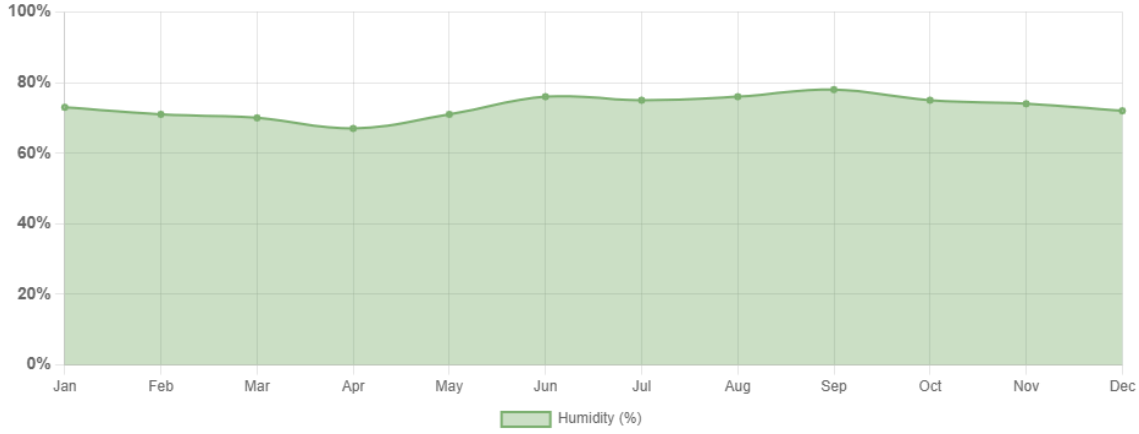


Figure 23: Average humidity throughout the year in Miami (Source: https://weather-and-climate.com/average-monthly-min-max-Temperature,miami-beach-florida-us,United-States-of-America).

3.2.1. Bioclimatic Heating

During winter, daytime temperatures in Miami generally remain within or close to the desired indoor comfort range. Under these conditions, the building should avoid excessive direct solar radiation through the glazed

surfaces while still allowing the controlled penetration of diffuse and indirect solar radiation. The objective is therefore to minimize the greenhouse effect associated with excessive direct solar gains while retaining the beneficial contribution of daylight and diffuse solar radiation. At the same time, indoor humidity should be reduced to approximately 50% (Fig. **23**).

The terraces have been precisely dimensioned and positioned to achieve this balance. Their geometry prevents direct solar radiation from reaching the glazed surfaces during winter (also in summer) while allowing diffuse and indirect solar radiation to enter the dwellings. This configuration limits excessive solar heat gains during the daytime while maintaining adequate natural illumination and avoiding unnecessary overheating.

At night, however, outdoor temperatures decrease substantially. Consequently, the building requires a *high level of thermal inertia* to retain, throughout the night, the thermal conditions achieved during the daytime. The combination of internal thermal mass and external insulation reduces the rate of heat loss and allows the building to maintain relatively stable indoor temperatures without conventional heating systems.

The building incorporates several specific architectural strategies to support passive thermal regulation during winter (Figs. **24** and **25**), including:

- North–south orientation, establishing a controlled relationship between the building envelope and solar radiation.
- Minimized glazed surface area, sufficient to provide views and natural daylight while limiting unwanted thermal gains. The glazed surfaces are strategically positioned so that the terraces and solar-control elements allow diffuse and indirect solar radiation to enter while substantially restricting direct solar radiation.
- High thermal inertia on the interior side of the building envelope, allowing the thermal conditions achieved during the daytime to be retained for a longer period during the night.
- Adequate thermal insulation on the exterior side of the building envelope, reducing heat transfer between the interior and exterior environments.

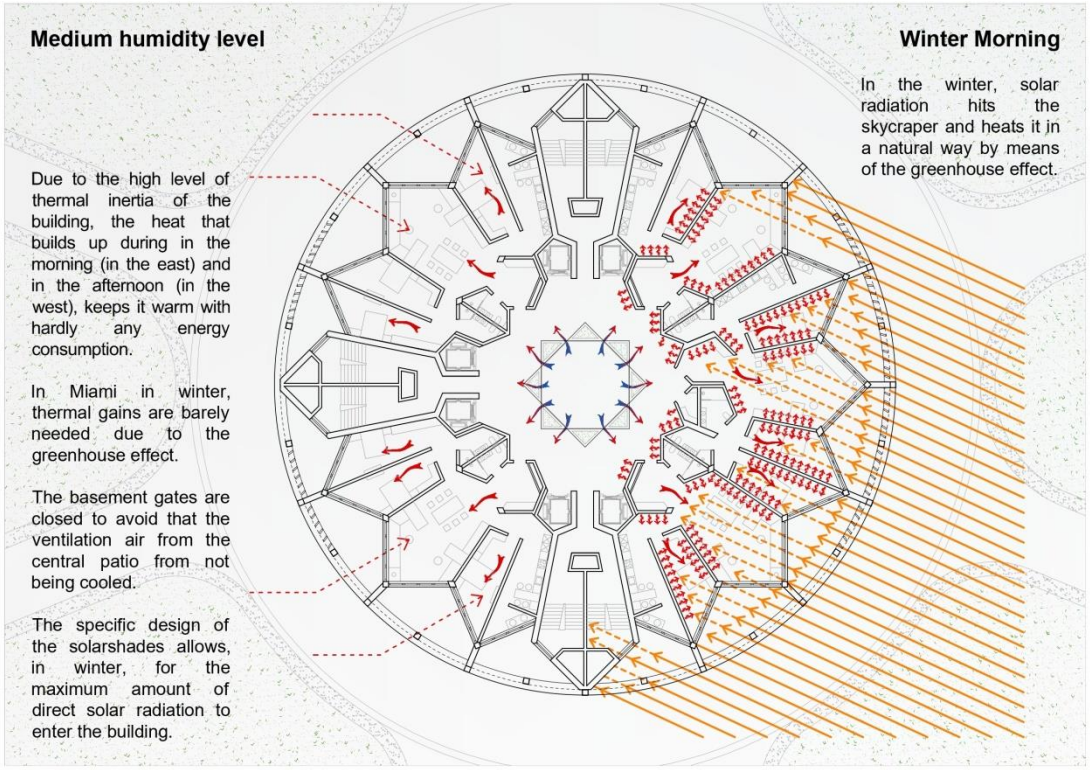


Figure 24: *PHANTOM Eco-tower.* Bioclimatic operating scheme in winter. Plan layout.

- Architecturally integrated solar protection, specifically designed to prevent excessive direct solar radiation from reaching the glazing.
- Functional zoning, with the principal occupied spaces located predominantly on the south side and service spaces concentrated on the north side.
- Controlled natural ventilation through the central courtyard. During daytime periods, ventilation air from the southern side of the building is transferred through the central courtyard and distributed toward the dwellings. During nighttime, the ventilation fans are switched off to minimize unnecessary air exchange and preserve the thermal conditions accumulated within the building.
- Passive humidity control through hygroscopic materials. Several trays containing silicate salts are positioned within the central courtyard to absorb moisture from the air passing through the system. This mechanism is intended to reduce indoor relative humidity and maintain it at approximately 50%, thereby improving thermal comfort without relying exclusively on conventional mechanical dehumidification.

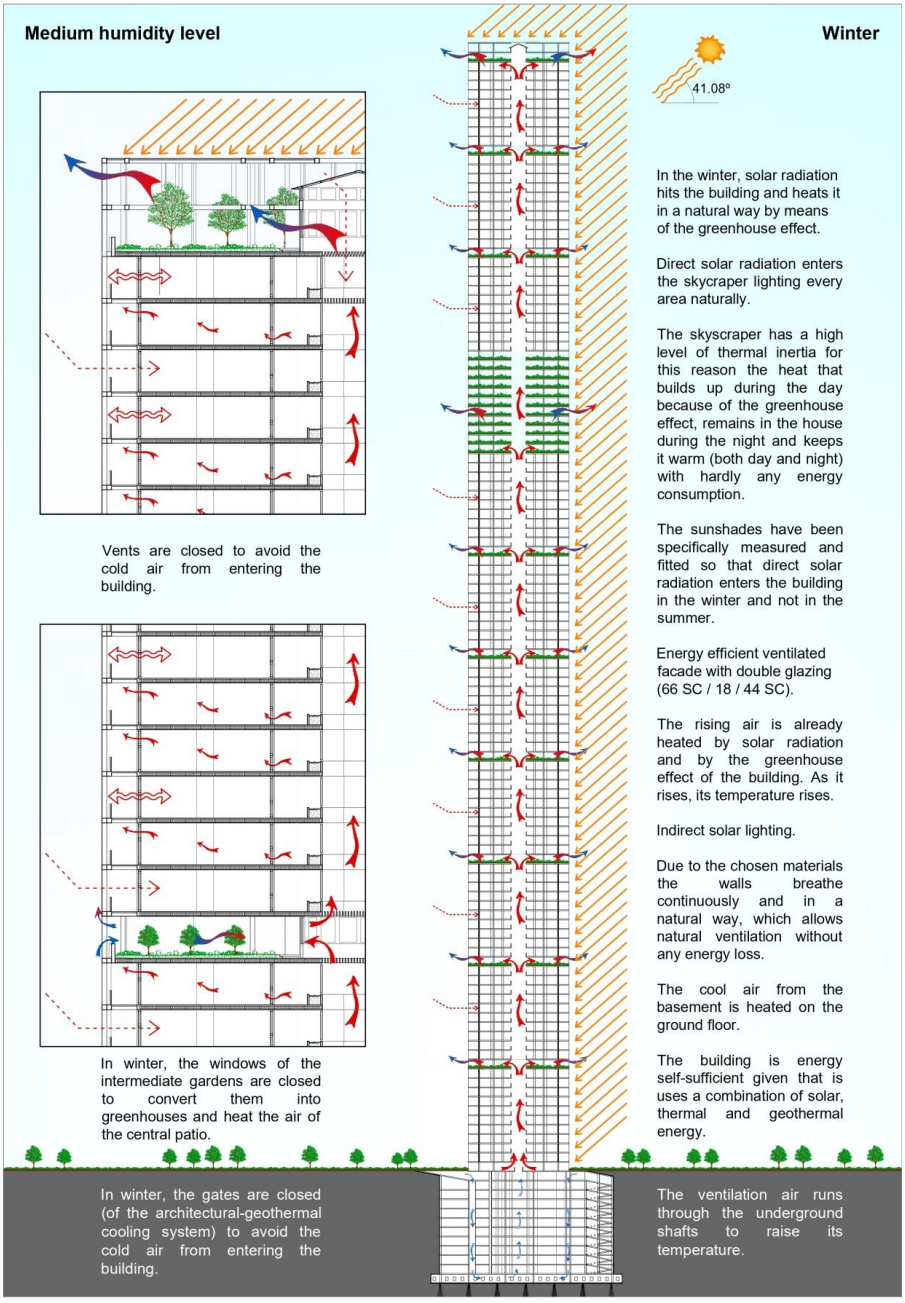


Figure 25: *PHANTOM Eco-tower.* Bioclimatic operating scheme in winter.

Taken together, these strategies allow the building to respond differently to daytime and nighttime conditions. During the day, the architectural configuration limits excessive direct solar gains while permitting useful diffuse radiation, whereas during the night, thermal inertia and external insulation reduce heat losses and preserve the thermal conditions established during the preceding daytime period. The resulting approach integrates *solar control, thermal mass, insulation, controlled ventilation, and passive humidity regulation* as complementary components of the building's overall deep bioclimatic strategy.

3.2.2. Bioclimatic Cooling

For approximately eight months of the year, outdoor temperatures in Miami exceed the established indoor thermal comfort temperature. Consequently, the dwellings must be protected as extensively as possible from both direct and indirect solar radiation, while a continuous natural ventilation and passive cooling system must be established. This system should also contribute to reducing indoor relative humidity to approximately 50%, thereby improving thermal comfort under Miami's humid climatic conditions.

The building is designed to achieve summer thermal regulation through a combination of complementary architectural strategies (Figs. **26** and **27**), including:

- North–south orientation, with the principal façades and solar-control strategies configured to minimize undesirable solar gains.
- High thermal inertia on the interior side of the building envelope, allowing the structure to absorb and moderate heat gains and delay their transmission to occupied spaces.
- Adequate thermal insulation on the exterior side of the building envelope, reducing heat transfer from the external environment toward the interior.
- Cooling through underground galleries, where incoming air is cooled before being introduced into the building.
- Enhanced nocturnal cooling through optimized natural ventilation, using cooler outdoor air during nighttime to dissipate accumulated heat.
- Comprehensive solar protection, designed to minimize the penetration of both direct and indirect solar radiation during the summer period.
- Functional zoning with occupied spaces oriented toward the south and service spaces toward the north, contributing to the overall environmental regulation of the dwellings.

In addition, the building is specifically designed to exploit the lower temperatures of nocturnal outdoor air. During the night, this air is drawn into the building and passes through underground galleries, where it is further cooled before entering the occupied spaces. This cooled air contributes to the removal of heat accumulated within the building during the preceding day and progressively lowers the temperature of the building's internal mass.

During daytime, the building remains relatively cool as a result of the combined effect of solar protection, high internal thermal inertia, and external thermal insulation. The thermal mass absorbs and moderates residual heat gains, while the external insulation limits heat transfer from the exterior environment. This combination reduces the rate at which external heat reaches the occupied spaces and allows the cooling achieved during the night to be maintained throughout the following day.

Under the design conditions considered, the building is intended to maintain a maximum indoor temperature of approximately 23°C during summer daytime periods, while nighttime temperatures are expected to remain within approximately 20–22°C. The resulting thermal behavior is achieved primarily through the coordinated interaction of passive architectural strategies rather than through conventional mechanical air-conditioning.

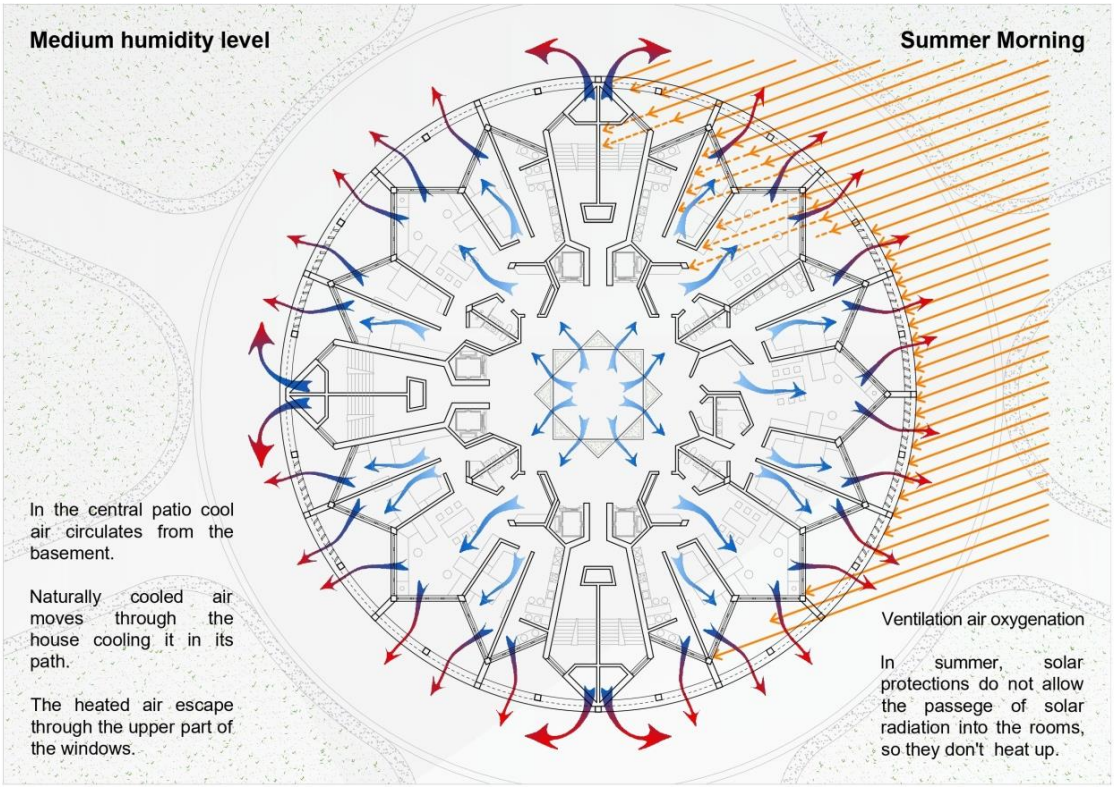


Figure 26: *PHANTOM Eco-tower.* Bioclimatic operating scheme in summer. Plan layout.

3.3. Quantification of the Energy Efficiency of PHANTOM Eco-tower

Comparatively assessing the energy savings achieved by a skyscraper incorporating *Deep Bioclimatic Design* is a complex task. The starting point is that, under the climatic conditions of Miami, it is possible to design a skyscraper capable of thermally self-regulating and maintaining comfortable indoor temperatures without the need for conventional heating or air-conditioning systems. This can be achieved at an additional construction cost lower than the cost of installing conventional heating and air-conditioning equipment. The resulting benefits include a substantial reduction in energy consumption throughout the building's entire life cycle, higher levels of natural lighting, greater balance and integration with the natural environment, the elimination of noise, vibrations, and odours associated with conventional building services, the absence of operational emissions from these systems, and more efficient use of interior space.

When estimating a building's energy savings, a fundamental difficulty is determining the appropriate reference building, since no two buildings are exactly alike. The strategy adopted in this study is therefore to compare the *PHANTOM Eco-tower* with an otherwise identical building designed without bioclimatic principles, maintaining the same floor area, geometry, architectural characteristics, height, and other relevant parameters. In principle, any energy-consumption value could be assigned to the conventional reference building, since the objective is to determine the difference in energy consumption between a building incorporating *Deep Bioclimatic Design* and an equivalent conventional building. Nevertheless, this study uses a documented building with the lowest energy consumption identified for Miami as its reference case. This choice is intended to demonstrate that Deep Bioclimatic Design can achieve substantially greater energy savings than those obtained merely by improving the energy efficiency of the installed technologies and adding a modest amount of insulation.

The minimum energy savings attributable to *Deep Bioclimatic Design* are defined here as the complete elimination of energy consumption for heating and air conditioning, together with a reduction of at least 50% in energy consumption for lighting. Further savings can also be achieved through reductions in maintenance and cleaning requirements, among other factors. However, the present study deliberately adopts a conservative estimate of the savings. The actual reduction in energy consumption could therefore be even greater.

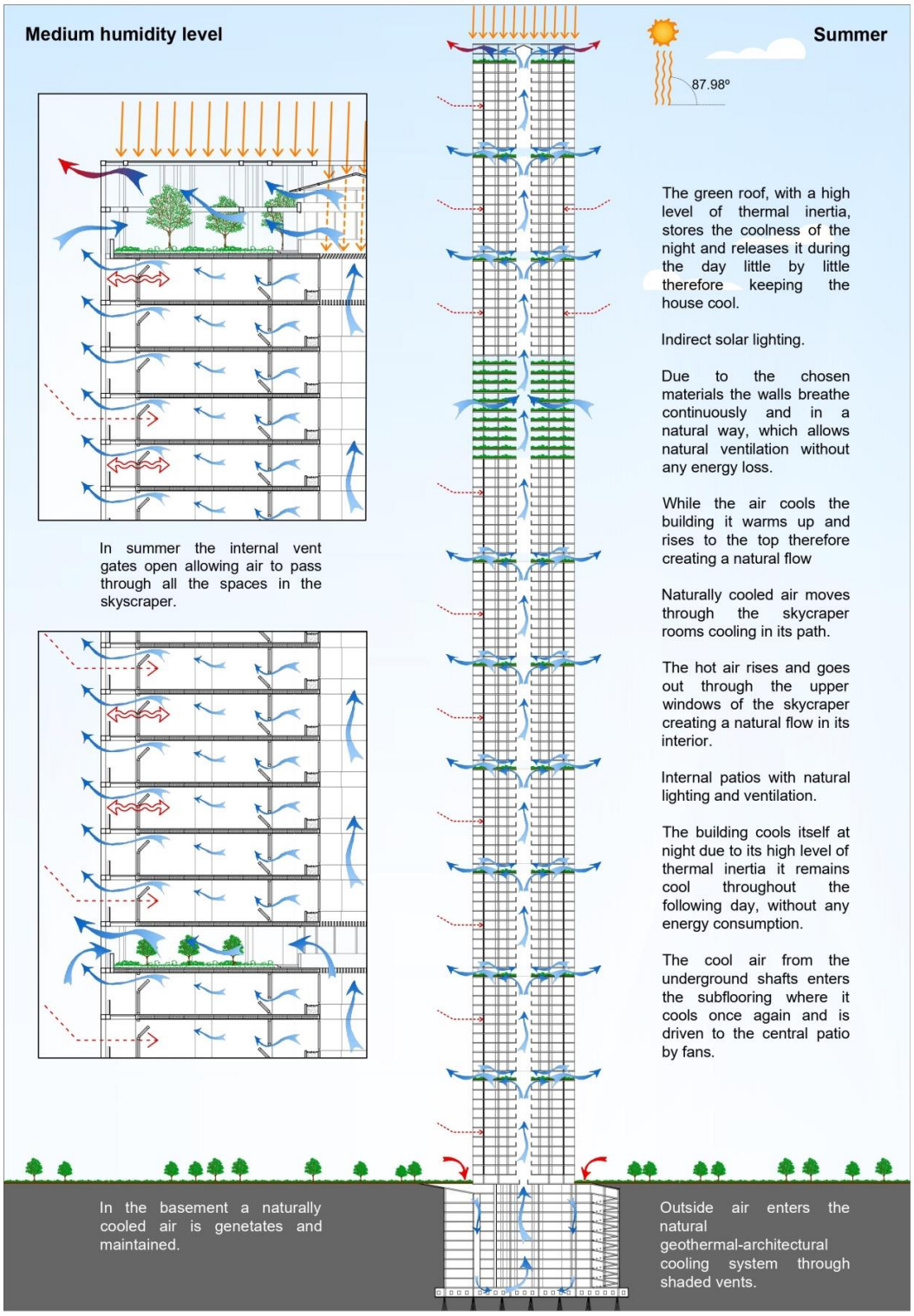


Figure 27: *PHANTOM Eco-tower.* Bioclimatic operational scheme for summer. The building maximizes protection against solar radiation and cools itself by chilling outdoor air at night, further cooling it underground.

To quantify the energy efficiency of *PHANTOM Eco-tower*, its energy consumption is compared with the energy consumption of a conventional building of the same characteristics constructed in the same area. To be able to make a comparison we have compared *PHANTOM Eco-tower* with respect to its hypothetical version as a baseline reference: *PHANTOM-no-bio*. That is, with identical characteristics, but with a conventional design and average energy needs for the area. It is clear that, depending on its design, level of insulation, and thermal inertia, each

building can have different energy consumption. Therefore, *PHANTOM-no-bio* has been assigned an average energy consumption based on existing buildings in the area where the *PHANTOM Eco-tower* is built.

3.3.1. Conventional Multifamily Residential Building Energy Consumption. PHANTOM-no-bio

A study provides a relevant benchmark for assessing the energy performance of multifamily residential buildings in subtropical climates [24]. The authors modelled a reference multifamily residential building in accordance with the *2015 International Energy Conservation Code* (IECC) and reported an energy use intensity (EUI) of 106.00 kWh/m²·year. Although this value should not be interpreted as the measured energy consumption of a specific building in Miami, it provides a robust reference for residential buildings operating under climatic conditions comparable to those of Miami. Importantly, the study also reports an average EUI of 115.8 kWh/m²·year for existing condominium and multifamily buildings in Hawaii, indicating that actual energy consumption in existing subtropical residential buildings may be higher than that of the code-compliant reference model [24] (Table **1**).

On this basis, the 106.00 kWh/m²·year reference EUI is adopted in the present study as the baseline energy performance against which the proposed *PHANTOM Eco-Tower* is evaluated. Accordingly, a hypothetical conventional version of the building, designated *PHANTOM-no-bio*, is assumed to have an energy performance equivalent to this reference benchmark. This approach provides a conservative and reproducible baseline for quantifying the potential energy savings associated with the implementation of deep bioclimatic design. Rather than representing the measured consumption of a particular Miami skyscraper, *PHANTOM-no-bio* constitutes a standardized reference scenario against which the performance of *PHANTOM Eco-Tower* can be systematically compared.

Meguro and Glassman (2021) further disaggregate the reference building's total energy consumption into several end-use categories, including cooling/HVAC, equipment and plug loads, lighting, domestic hot water, and elevators [24].

Table 1: Total energy consumption per m² of PHANTOM-no-bio.

Usage	kWh/m²·Year	Approx. %
Cooling/HVAC	43.46	41%
IT equipment	24.38	23%
Lighting	19.08	18%
A.C.S.	14.84	14%
Elevators	4.24	4%
TOTAL	**106.00 kWh/m²·year**	**100%**

3.3.2. Deep Bioclimatic Multifamily Residential Building Energy Consumption. PHANTOM Eco-tower

Due to its specific bioclimatic design, the *PHANTOM Eco-tower* can achieve thermal self-regulation without the need for heating or air-conditioning systems. All spaces have been designed to ensure adequate daylighting throughout the day and appropriate natural ventilation. In addition, all lighting fixtures are designed to use highly energy-efficient LED technology. Consequently, the energy consumption associated with air-conditioning systems is completely eliminated, while energy consumption for lighting and domestic hot water (DHW) production is reduced by at least 57%.

Taken together, these strategies suggest that, at a minimum, the *PHANTOM Eco-tower* would consume approximately half the energy of the conventional baseline reference building.

Accordingly, the estimated energy consumption of the *PHANTOM Eco-tower* is 45.58 kWh/m²·year, corresponding to only 43% of the energy consumption of the lowest-energy multi-family residential building documented in Miami (Table **2**).

Table 2: Total energy consumption per per m² of *PHANTOM Eco-tower.*

Usage	kWh/m²·Year	Approx. %
Cooling/HVAC	-	
IT equipment	24.38	23%
Lighting	9.54	9%
A.C.S.	7.42	7%
Elevators	4.24	4%
TOTAL	**45.58 kWh/m²·year**	**43%**

4. Quantification of the Sustainable Level of PHANTOM Eco-tower

Previous studies have demonstrated that *deep bioclimatic design* can contribute up to 24.07% to the overall sustainability performance of buildings [8]. In addition, several comparative assessments have been conducted between the CEDES system and the ten most important and representative *Green Building Rating Systems* (GBRS) currently in use: ASGB, BEAM, BREEAM, DNGB, GBI, GG, GS, IGBC, LEED, and SBTools. These comparative analyses have shown that CEDES provides a more appropriate, consistent, and effective assessment of building sustainability than the other systems considered [20].

Accordingly, this section assesses the sustainability performance of the *PHANTOM Eco-tower* using the CEDES system. First, the CEDES categories and indicators are presented, together with the specific weighting assigned to each indicator. The overall sustainability performance of the *PHANTOM Eco-tower* is then calculated based on the resulting scores.

4.1. Quantification of the Sustainable Level of PHANTOM Eco-tower Using CEDES

To determine the sustainability performance of the *PHANTOM Eco-tower* according to the CEDES system, each relevant building attribute is assessed through the corresponding indicators, with each indicator assigned a score ranging from 0 to 1 according to the degree to which its specified criteria are satisfied. The individual indicator scores are subsequently aggregated within each of the eight CEDES categories, thereby obtaining a partial score for each category. The sum of the eight category scores produces an overall value ranging from 0 to 5. This value is then multiplied by two to express the final CEDES sustainability score on a standardized scale ranging from 0 to 10 (Tables **3–10**).

Applying this assessment procedure to the *PHANTOM Eco-tower* results in a final CEDES sustainability score of 8.98406 out of 10, indicating a very high overall level of sustainability according to the CEDES assessment framework (Table **11**). This result reflects the extensive integration of sustainability strategies within the building design, particularly those associated with its deep bioclimatic design approach. The high score indicates that sustainability has been incorporated as a fundamental design principle rather than as a set of isolated technological interventions.

The resulting assessment is particularly relevant because the CEDES methodology evaluates sustainability through a comprehensive set of environmental, energy-related, bioclimatic, resource-efficiency, and building-performance criteria. Consequently, the high overall score obtained by the *PHANTOM Eco-tower* provides quantitative evidence of the advanced sustainability performance achieved by its integrated design strategy.

These results support the consideration of the *PHANTOM Eco-tower* as a highly advanced example of sustainable high-rise design and demonstrate the potential of *deep bioclimatic design* to contribute substantially to the sustainability performance of tall buildings. In this respect, the project provides a relevant reference for the development of future high-rise buildings in which passive environmental strategies and comprehensive sustainability criteria are incorporated from the earliest stages of architectural design.

Table 3: Scoring process using indicators of "optimization of resources" category.

Name of the Category, Subcategory 1, Subcategory 2 and Indicator	Score 0-5	Indicator Weight	Final Score
1. Optimization of resources 18%			
1.1. Use of natural resources			
1.1.1. Water			
1.1.1.1. Rain water	5	0.00432	0.02160
1.1.1.2. Groundwater	5	0.00288	0.01440
1.1.2. Vegetation			
1.1.2.1. Wild vegetation	5	0.00135	0.00675
1.1.2.2. Unprocessed wood	1	0.00180	0.00180
1.1.2.3. Vegetable waste	5	0.00135	0.00675
1.1.3. Soil			
1.1.3.1. Not elaborated stones	2	0.00225	0.00450
1.1.3.2. Soil	5	0.00225	0.01125
1.1.4. Choice of site			
1.1.4.1. Use of not arable land	5	0.00054	0.00270
1.1.4.2. Accessibility	4	0.00054	0.00216
1.1.4.3. Positive impact on the place	5	0.00072	0.00360
1.2. Resource optimization			
1.2.1. Amount of resources needed			
1.2.1.1. Resources needed in construction	5	0.00388	0.01940
1.2.1.2. Resources needed throughout the lifecycle of building	5	0.00259	0.01295
1.2.1.3. Resources needed for building maintenance	5	0.00129	0.00645
1.2.1.4. Abundance of resources for component manufacturing	5	0.00518	0.02590
1.2.2. Durability level of components and materials	5	0.02916	0.14580
1.2.3. Waste utilization level	1	0.01620	0.01620
1.2.4. Reusability of components			
1.2.4.1. Use of previously used components	1	0.00550	0.00550
1.2.4.2. Component reparability level	4	0.01101	0.04404
1.2.4.3. Component reusability level	2	0.01101	0.02202
1.2.4.4. Disassembly level. Reconfigurability and expandability	1	0.02754	0.02754
1.2.5. Component recycling			
1.2.5.1. Use of recycled components	2	0.00162	0.00324
1.2.5.2. Use of recycled grey water	5	0.00162	0.00810
1.2.5.3. Component recycling level	3	0.00324	0.00972
1.2.6. Level of exploitation of resources			
1.2.6.1. Refined design	4	0.02700	0.10800
1.2.6.2. Industrialization level	4	0.01800	0.07200
1.2.7. Functional durability of components	5	0.01080	0.05400
1.2.8. Functional adaptation of components	5	0.00720	0.03600
Total			**0.67131**

Table 4: Scoring process using indicators of "reduction in energy consumption" category.

Name of the Category, Subcategory 1, Subcategory 2 and Indicator	Score 0-5	Indicator Weight	Final Score
2. Reduction in energy consumption 34%			
2.1. Energy consumption in obtaining materials	5	0.01462	0.07310
2.2. Energy consumption in transportation of materials/components	5	0.00748	0.03740
2.3. Energy consumption in transportation of labor	5	0.00442	0.02210
2.4. Energy consumption in building construction process	5	0.03910	0.19550
2.5. Energy consumption by building throughout its lifecycle			
2.5.1. Energy consumption in building accessibility			
2.5.1.1. Accessibility to the area	4	0.00276	0.01104
2.5.1.2. Accessibility to the rooms of the building	5	0.00276	0.01380
2.5.2. Energy consumption by building devices			
2.5.2.1. Heating	5	0.03480	0.17400
2.5.2.2. Air-conditioning	5	0.03480	0.17400
2.5.2.3. Human technological adequacy	5	0.00497	0.02485
2.5.2.4. Ventilation systems	5	0.00497	0.02485
2.5.2.5. Lighting	5	0.00497	0.02485
2.5.2.6. Home appliances	5	0.00994	0.04970
2.5.2.7. Telecommunication systems	5	0.00497	0.02485
2.5.3. Energy consumption in building maintenance			
2.5.3.1. Cleaning	5	0.00165	0.00825
2.5.3.2. Repairs	5	0.00221	0.01105
2.5.3.3. Improvements	5	0.00165	0.00825
2.6. Bioclimatic architectural design			0.86843
2.6.1. Location	4	0.00389	0.01556
2.6.2. Correct N-S orientation	5	0.01557	0.07785
2.6.3. Appropriate architectural typology	5	0.04671	0.23355
2.6.4. Efficacy of sun protections	5	0.01557	0.07785
2.6.5. Architectural heating systems	5	0.01557	0.07785
2.6.6. Architectural cooling systems	5	0.01557	0.07785
2.6.7. Proper thermal inertia of building	5	0.01557	0.07785
2.6.8. Proper building insulation	5	0.01557	0.07785
2.6.9. Natural ventilation	5	0.00389	0.01945
2.6.10. Thermal bridges	5	0.00778	0.03890
2.7. Energy consumption in demolishing/disassembling	3	0.00816	0.02448
Total			**1.27068**

Table 5: Scoring process using indicators of "use of natural energy sources" category

Name of the Category, Subcategory 1, Subcategory 2 and Indicator	Score 0-5	Indicator Weight	Final Score
3. Use of natural energy sources 13%			
3.1. Solar energy			
3.1.1. Thermal solar energy	5	0.0546	0.27300
3.1.2. Photovoltaic solar energy	5	0.0234	0.11700
3.2. Geothermal energy			
3.2.1. Geothermal energy without heat pump	5	0.0312	0.15600
3.2.2. Geothermal energy with heat pump	0	0.0078	0
3.3. Renewable energies for the natural ecosystem			
3.3.1. Wind power	0	0.0039	0
3.3.1. River and sea energy	0	0.0052	0
3.3.1. Energy from underground sources	0	0.0039	0
Total			**0.54600**

Table 6: Scoring process using indicators of "reduction of waste and emissions" category.

Name of the Category, Subcategory 1, Subcategory 2 and Indicator	Score 0-5	Indicator Weight	Final Score
4. Reduction of waste and emissions 12%			
4.1. Waste and emissions generated in obtaining materials			
4.1.1. Waste	4	0.0072	0.02880
4.1.2. Emissions	4	0.0168	0.06720
4.2. Waste and emissions generated in manufacturing			
4.2.1. Waste	5	0.0036	0.01800
4.2.2. Emissions	5	0.0144	0.07400
4.3. Waste and emissions generated in transport			
4.3.1. Waste	5	0.0006	0.00300
4.3.1. Emissions	5	0.0054	0.02700
4.4. Waste and emissions generated in construction process			
4.4.1. Waste	5	0.0120	0.06000
4.3.1. Emissions	5	0.0120	0.06000
4.5. Waste and emissions generated in building maintenance			
4.4.1. Waste	5	0.0072	0.03600
4.3.1. Emissions	5	0.0168	0.08400
4.6. Waste and emissions generated in demolition of building			
4.4.1. Waste	3	0.0216	0.06480
4.3.1. Emissions	4	0.0024	0.00960
Total			**0.53240**

Table 7: Scoring process using indicators of "health and quality of life of building occupants" category

Name of the Category, Subcategory 1, Subcategory 2 and Indicator	Score 0-5	Indicator Weight	Final Score
5. Health and quality of life of building occupants 8%			
5.1. Harmful emissions to natural ecosystem	5	0.016	0.08000
5.2. Harmful emissions to human health	5	0.024	0.12000
5.3. Number of illnesses of building occupants	5	0.024	0.12000
5.4. Degree of well-being of building occupants	5	0.016	0.08000
Total			**0.40000**

Table 8: Scoring process using *indicators* of *"economic cost" category.*

Name of the Category, Subcategory 1, Subcategory 2 and Indicator	Score 0-5	Indicator Weight	Final Score
6. Economic cost 10%			
6.1. Direct economic cost in building construction	4	0.040	0.16000
6.2. Indirect economic cost in building construction	5	0.005	0.02000
6.3. Economic cost in maintenance			
6.3.1. Materials	5	0.002	0.01000
6.3.1. Labor	5	0.006	0.03000
6.3.1. Technological devices	5	0.006	0.03000
6.3.1. Cleaning	5	0.006	0.03000
6.4. Cost of emissions and waste management			
6.5. Cost of treating diseases and illnesses	5	0.005	0.02500
6.6. Economic revaluation of the building	5	0.005	0.02500
6.7. Economic revaluation of the environment	5	0.005	0.02500
6.8. Construction speed	4	0.005	0.02000
6.9. Cost of demolishing/disassembling	4	0.005	0.02000
Total			**0.39500**

Table 9: Scoring process using indicators of "social adequacy" category

Name of the Category, Subcategory 1, Subcategory 2 and Indicator	Score 0-5	Indicator Weight	Final Score
7. Social adequacy 3%			
7.1. Local level of economic development	5	0.0060	0.03000
7.2. Local technological level	3	0.0060	0.01800
7.3. Local quality preferences	4	0.0030	0.01200
7.4. Local design preferences	5	0.0060	0.03000
7.5. Local preferences in construction systems	3	0.0060	0.01800
7.6. Local type of family unit	4	0.0030	0.01200
Total			**0.12000**

Table 10: Scoring process using indicators of "complementary sustainable aspects" category.

Name of the Category, Subcategory 1, Subcategory 2 and Indicator	Score 0-5	Indicator Weight	Final Score
8. Complementary sustainable aspects 2%			
8.1. Adaptability to change and flexibility of the building	2	0.006	0.01200
8.2. Social aesthetic appeal of building	5	0.006	0.03000
8.3. Ecological regeneration of environment	5	0.008	0.04000
Total			**0.08200**

Table 11: Overall score using CEDES.

Category	Score
1. Optimization of resources	0.67131
2. Reduction of energy consumption	1.74532
3. Use of natural energy sources	0.54600
4. Reduction of waste and emissions	0.53240
5. Increase in the quality of life of the occupants	0.40000
6. Reduction in economic cost	0.39500
7. Social adequacy	0.12000
8. Others	0.08200
Total (0 - 5)	4.49203
Total (0 - 10)	8.98406

5. Limitations

Three main limitations should be acknowledged in this study.

First, the applicability of *Deep Bioclimatic Design* (DBD) is subject to climatic and site-specific constraints. Although a building with deep bioclimatic design can provide a comfortable temperature without the need for heating or air conditioning equipment, its effectiveness depends on the interaction between local climate, solar access, building orientation, surrounding obstructions, and the thermal properties of the site. For example, in cold climates, a building overshadowed by neighbouring structures may be unable to capture sufficient solar radiation to meet its heating requirements through passive solar gains and the greenhouse effect. In hot climates, ground-coupled cooling can provide a valuable means of reducing indoor temperatures, although combinations of particularly adverse thermal conditions may limit its effectiveness. Consequently, DBD cannot guarantee the complete elimination of mechanical heating and cooling under every conceivable climatic and site condition. Nevertheless, even in extreme climates or unfavourable locations, the application of DBD principles can substantially reduce reliance on mechanical systems, allowing any remaining demand to be met through low-power, low-emission technologies and thereby minimising operational energy consumption.

Second, the study evaluates a design proposal that has not yet been constructed. The *PHANTOM Eco-tower* is presented as a design-based case study intended to demonstrate and assess the potential of DBD when applied to a high-rise building in Miami. Since the project has not been built, its actual operational energy consumption and in-use thermal performance cannot yet be empirically verified. The results should therefore be interpreted as design-based estimates rather than measurements obtained from an occupied building. Nevertheless, the design analysis indicates that the proposed combination of passive solar control, natural ventilation, daylight

optimisation, and alternative cooling strategies could maintain indoor thermal comfort under Miami's climatic conditions without conventional heating and air-conditioning systems. This constitutes the principal design objective and intended contribution of the proposal, although its ultimate performance will require confirmation through post-occupancy monitoring or an equivalent form of empirical validation.

Third, the comparative assessment is subject to methodological constraints. Direct comparisons between buildings are inherently difficult because energy consumption is influenced by numerous variables, including climate, orientation, geometry, floor area, envelope insulation, glazing characteristics, occupancy patterns, operating schedules, and installed equipment. These differences make it challenging to establish a fully equivalent conventional baseline for the *PHANTOM Eco-tower*. To address this issue, the study compares the projected energy performance of *PHANTOM* with that of a low-energy reference building in Miami, rather than with an unrepresentative conventional building. The comparison is intended to provide a demanding benchmark against which to assess the potential benefits of DBD, rather than to establish a universally applicable reduction factor. The proposed design eliminates the modelled demand for conventional space heating and air conditioning and substantially reduces lighting demand through its daylight-oriented design. However, the magnitude of the resulting energy savings should be interpreted in the context of the assumptions and characteristics of the selected reference building. Further validation using harmonised simulation assumptions, equivalent occupancy and operating conditions, and, where possible, measured operational data would strengthen the robustness and generalisability of the comparison.

6. Discussion

The results support the potential of *deep bioclimatic design* as an alternative to conventional approaches in which thermal comfort is primarily achieved through mechanical conditioning. While conventional bioclimatic design generally seeks to reduce the energy demand associated with heating and cooling systems, *deep bioclimatic design* pursues a more ambitious objective: designing the building itself to achieve a high degree of thermal self-regulation and, under appropriate climatic conditions, eliminate the need for conventional air-conditioning [7, 25-30].

This distinction is particularly relevant in warm climates such as Miami, where cooling represents a major component of residential building energy demand. Instead of designing the building first and subsequently introducing mechanical systems to compensate for its thermal deficiencies, the proposed methodology incorporates climatic conditions from the earliest stages of architectural design. Orientation, solar exposure, glazing, shading, natural ventilation, envelope performance, and spatial organization are therefore treated as interconnected variables whose combined effects determine the building's thermal behavior.

The analysis of *PHANTOM Eco-tower* provides a relevant proof of concept for this approach. The proposed building has an estimated energy consumption equivalent to approximately 43% of that of the selected high-performance multifamily residential benchmark, representing an estimated reduction of approximately 57%. More importantly, the design demonstrates the potential to eliminate conventional air-conditioning through architectural and passive strategies rather than simply improving the efficiency of mechanical cooling systems. This distinction is particularly relevant because it addresses the source of energy demand rather than only its technological compensation.

The results also indicate that the effectiveness of bioclimatic design cannot be expressed through a universal percentage of energy reduction. Performance depends on the interaction between climatic conditions, building geometry, orientation, envelope characteristics, solar radiation, ventilation potential, internal gains, and occupancy. Consequently, buildings located in similar climatic conditions may achieve substantially different results. This reinforces the importance of a systematic *deep bioclimatic design methodology* rather than relying exclusively on individual passive strategies or on the experience and intuition of the architect.

The economic implications are similarly context-dependent. In relatively benign climates, *deep bioclimatic buildings* may be achieved with limited additional construction complexity. In more demanding environments, additional architectural systems may be required, potentially increasing initial costs. However, these costs should

be considered in relation to the mechanical systems that can potentially be avoided, as well as to the long-term reductions in energy consumption and maintenance. The economic viability of *deep bioclimatic design* should therefore be evaluated through life-cycle comparisons rather than solely through initial construction costs.

The proposed methodology is potentially transferable to other climatic contexts, although its specific strategies cannot be directly replicated without adaptation. More extreme climates may require additional passive systems, greater envelope optimization, or more complex architectural solutions, potentially resulting in higher construction costs. Thus, the main transferable contribution of this research is not a fixed building solution, but a systematic design methodology capable of adapting passive strategies to the environmental characteristics of each site.

Importantly, *PHANTOM Eco-tower* is a proposed building designed for future construction. Therefore, the energy and sustainability results presented in this study should be interpreted as performance estimates derived from the proposed design rather than as measurements obtained from an operational building. Nevertheless, the analysis demonstrates the feasibility of applying the proposed methodology to a complex high-rise residential building and provides a quantitative basis for assessing its potential environmental performance.

Further research should apply the methodology to additional building proposals in different climatic zones and subsequently validate its predictions through monitoring of constructed projects. Such studies should evaluate not only operational energy consumption and thermal comfort, but also construction cost, life-cycle cost, embodied carbon, and long-term performance. This would help establish the climatic and economic conditions under which *deep bioclimatic design* can become a technically and economically competitive alternative to conventional mechanically conditioned buildings.

Overall, the *PHANTOM Eco-tower* project suggests that the role of sustainable architecture can extend beyond reducing the energy consumption of mechanical systems toward reducing or, under appropriate conditions, eliminating the need for them. The proposed *deep bioclimatic design methodology* therefore represents a promising pathway for developing high-rise buildings in which thermal comfort and energy efficiency are achieved primarily through architectural design itself.

7. Conclusions

This study demonstrates that *deep bioclimatic design* can provide a fundamentally different approach to the design of high-rise multifamily residential buildings, in which thermal comfort is addressed primarily through the architectural configuration of the building rather than through the subsequent addition of mechanical conditioning systems. The principal contribution of this research is the formulation and application of a systematic *deep bioclimatic design methodology* capable of integrating climatic analysis, solar geometry, thermal behavior, natural ventilation, daylighting, envelope optimization, and passive environmental strategies from the earliest stages of the design process. This approach shifts the conventional design paradigm from one based on compensating for thermal deficiencies through mechanical equipment toward one in which the building itself becomes the principal mechanism for achieving indoor environmental comfort.

The results obtained for the *PHANTOM Eco-tower* provide particularly relevant evidence of the potential of this methodology. The building was conceived to achieve a high degree of passive thermal self-regulation under the climatic conditions of Miami, with the objective of maintaining acceptable indoor thermal conditions without conventional air-conditioning systems. Consequently, the proposed design eliminates the operational energy consumption associated with air-conditioning, which is particularly significant in hot climates where cooling frequently represents one of the largest components of building energy demand. This finding is especially relevant because it demonstrates that the elimination of air-conditioning equipment does not necessarily require a reduction in residential comfort, but can instead be pursued through a fundamentally different architectural design strategy.

The methodology also incorporates complementary passive strategies to reduce the remaining operational energy demand. All spaces are designed to receive adequate daylight throughout the day and to benefit from appropriate natural ventilation, while highly energy-efficient LED lighting is employed throughout the building.

These measures, together with the optimization of the building envelope and solar control, substantially reduce the need for energy-intensive building services. The resulting design therefore demonstrates that significant reductions in operational energy demand can be achieved not merely by improving the efficiency of mechanical equipment, but by reducing or eliminating the need for such equipment in the first place.

The quantitative results reinforce the significance of this approach. The estimated energy consumption of the *PHANTOM Eco-tower* is approximately 43% of that reported for a highly energy-efficient multifamily residential benchmark in Miami, corresponding to an energy reduction of approximately 57% relative to that reference building. This result is particularly relevant because the reduction is achieved in a high-rise multifamily building, a building type generally associated with substantial cooling, lighting, and domestic hot-water demands. The findings therefore suggest that the application of *deep bioclimatic design* at the architectural level can make a substantial contribution to reducing operational energy demand even in complex and energy-intensive building typologies.

The CEDES assessment provides additional evidence of the comprehensive nature of the proposed design. The *PHANTOM Eco-tower* achieved a final sustainability score of 8.98406 out of 10, demonstrating that its performance is not attributable to a single technological intervention but to the coordinated integration of multiple environmental, energetic, material, and architectural strategies. Within this integrated framework, *deep bioclimatic design* constitutes a central component because it addresses one of the most fundamental sources of building energy demand: the need to mechanically compensate for inadequate climatic adaptation.

The broader contribution of the study therefore lies not only in the performance achieved by the *PHANTOM Eco-tower*, but in the methodological implications of the design process. The proposed *deep bioclimatic design methodology* establishes a structured framework through which the climatic characteristics of a site can be translated into architectural decisions concerning orientation, solar exposure, glazing, shading, envelope configuration, natural ventilation, thermal behavior, and spatial organization. Because these decisions are incorporated progressively throughout the design process, the methodology can potentially be adapted to other buildings and climatic contexts, provided that the relevant climatic parameters and passive strategies are appropriately recalibrated and validated.

Importantly, the findings should not be interpreted as evidence that conventional air-conditioning can be eliminated from all buildings or climatic conditions. Rather, they demonstrate that its necessity should not be assumed a priori. Under appropriate climatic conditions and with sufficiently rigorous architectural optimization, *deep bioclimatic design* can make the elimination of conventional air-conditioning a realistic design objective. This represents an important conceptual advance over approaches in which mechanical cooling is treated as an unavoidable component of contemporary high-rise residential architecture.

Overall, this research establishes *deep bioclimatic design* as a potentially transformative methodology for sustainable high-rise architecture. Its principal innovation is to place climatic adaptation and passive thermal regulation at the core of the architectural design process, with the explicit objective of minimizing, and where conditions permit, eliminating dependence on conventional air-conditioning. The *PHANTOM Eco-tower* demonstrates the feasibility and potential magnitude of this approach, achieving substantial energy reductions while maintaining a very high overall sustainability performance. Further research should apply the methodology to additional climatic zones, building typologies, and real-world monitored buildings in order to validate its generalizability, quantify its long-term performance, and establish the climatic and architectural conditions under which mechanical cooling can be systematically minimized or eliminated.

Conflict of Interest

There are no conflicts of interest

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References

[1] Balali A, Yunusa-Kaltungo A. PSAT: A knowledge-based decision support tool for selecting passive energy consumption optimisation strategies in buildings. Energy Build. 2025;341:115849. https://doi.org/10.1016/j.enbuild.2025.115849.

[2] Al Mindeel T, Spentzou E, Eftekhari M. Energy, thermal comfort, and indoor air quality: Multi-objective optimization review. Renew Sustain Energy Rev. 2024;202:114682. https://doi.org/10.1016/j.rser.2024.114682.

[3] Zuhairy AA, Sayigh AAM. The development of the bioclimatic concept in building design. Renew Energy. 1993;3(4-5):521-533. https://doi.org/10.1016/0960-1481(93)90118-Z.

[4] Hamid A, Marafia AH. Thermal comfort and the development of bioclimatic concept in building design. Renew Sustain Energy Rev. 1998;2(1-2):3-24. https://doi.org/10.1016/S1364-0321(98)00009-4.

[5] Szokolay SV. Bioclimatic architecture and solar energy. In: Auliciems A, editor. Human bioclimatology. Advances in Bioclimatology. Vol. 5. Berlin, Heidelberg: Springer; 1998. https://doi.org/10.1007/978-3-642-80419-9_5.

[6] Pan Y, Zhong W, Zheng X, Xu H, Zhang T. Natural ventilation in vernacular architecture: A systematic review of bioclimatic ventilation design and its performance evaluation. Build Environ. 2024;253:111317. https://doi.org/10.1016/j.buildenv.2024.111317.

[7] Kokatnur T, Ferreira S, Akkoç BK, Markarian E, Nojedehi P, Qiblawi S, et al. A review of passive design strategies and their effect on thermal resilience in low-income households. Energy Build. 2025;348:116508. https://doi.org/10.1016/j.enbuild.2025.116508.

[8] De Garrido L. Energy, thermodynamic and sustainable analysis of a bioclimatic and self-sufficient house. Casa Blasco. J Sustain Dev. 2026;19(4):1-31. https://doi.org/10.5539/jsd.v19n4p1.

[9] Taherian H, Peters RW. Advanced active and passive methods in residential energy efficiency. Energies. 2023;16(9):3905. https://doi.org/10.3390/en16093905.

[10] Zhao J, Carter K. Barriers and opportunities in the design and delivery of social housing Passivhaus for adaptive comfort. In: Proceedings of the 9th Windsor Conference: Making Comfort Relevant; 2016 Apr 7-10; Cumberland Lodge, Windsor, United Kingdom.

[11] Lavaf Pour Y. Self-shading facade geometries to control summer overheating in UK Passivhaus dwellings for current and future climate scenarios [dissertation]. University of Liverpool; 2017. https://doi.org/10.17638/03009183.

[12] Costanzo V, Fabbri K, Piraccini S. Stressing the passive behavior of a Passivhaus: An evidence-based scenario analysis for a Mediterranean case study. Build Environ. 2018;142:265-277. https://doi.org/10.1016/j.buildenv.2018.06.035.

[13] Sadineni S, Madala S, Boehm R. Passive building energy savings: A review of building envelope components. Renew Sustain Energy Rev. 2011;15(8):3617-3631. https://doi.org/10.1016/j.rser.2011.07.014.

[14] Colclough S, O'Leary T, Hewitt N, Griffiths P. The near Zero Energy Building standard and the Passivhaus standard: A case study. In: Design to Thrive: Proceedings Volume 1, PLEA 2017 Conference. 2017;1:385-392.

[15] Elaouzy Y, El Fadar A. Energy, economic and environmental benefits of integrating passive design strategies into buildings: A review. Renew Sustain Energy Rev. 2022;167:112828. https://doi.org/10.1016/j.rser.2022.112828.

[16] Hu M, Zhang K, Nguyen Q, Tasdizen T. The effects of passive design on indoor thermal comfort and energy savings for residential buildings in hot climates: A systematic review. Urban Clim. 2023;49:101466. https://doi.org/10.1016/j.uclim.2023.101466.

[17] Salata F, Ciardiello A, Dell'Olmo J, Ciancio V, Ferrero M, Rosso F. Geometry optimization in the schematic design phase of low-energy buildings for all European climates through genetic algorithms. Sustain Cities Soc. 2024;112:105639. https://doi.org/10.1016/j.scs.2024.105639.

[18] Perera US, Weerasuriya AU, Zhang X, Ruparathna R, Tharaka MGI, Lewangamage CS. Selecting suitable passive design strategies for residential high-rise buildings in tropical climates to minimize building energy demand. Build Environ. 2025;267:112177. https://doi.org/10.1016/j.buildenv.2024.112177.

[19] Park J, Lee KH, Lee SH, Hong T. Benefits assessment of cool skin and ventilated cavity skin: Saving energy and mitigating heat and grid stress. Build Environ. 2024;247:111027. https://doi.org/10.1016/j.buildenv.2023.111027.

[20] De Garrido L. CEDES: A taxonomic and LCA-based Green Building Rating System for sustainable building design. Environ Sustain Indic. 2026;30:101164. https://doi.org/10.1016/j.indic.2026.101164.

[21] Iskandar L, Bay-Sahin E, Martinez-Molina A, Beeson ST. Evaluation of passive cooling through natural ventilation strategies in historic residential buildings using CFD simulations. Energy Build. 2024;308:114005. https://doi.org/10.1016/j.enbuild.2024.114005.

[22] Monge Palma R, Castro Medina D, Guerrero Delgado MC, Sánchez Ramos J, Montero-Gutiérrez P, Álvarez Domínguez S. Enhancing the building resilience in a changing climate through a passive cooling roof: A case study in Camas (Seville, Spain). Energy Build. 2024;321:114680. https://doi.org/10.1016/j.enbuild.2024.114680.

[23] Al-Assaad D, Sengupta A, An P, Breesch H, Afshari A, Amaripadath D, et al. Resilient passive cooling strategies during heat waves: A quantitative assessment in different climates. Build Environ. 2025;274:112698. https://doi.org/10.1016/j.buildenv.2025.112698.

[24] Meguro W, Glassman EJ. Evaluating energy targets and efficiency measures in multifamily subtropical buildings through automated simulation. Technol Archit Des. 2021;5(1):82-95. https://doi.org/10.1080/24751448.2021.1863676.

[25] Kim J, Yeom S, Hong T. Analyzing the cooling effect, thermal comfort, and energy consumption of integrated arrangement of high-rise buildings and green spaces on urban heat island. Sustain Cities Soc. 2025;119:106105. https://doi.org/10.1016/j.scs.2024.106105.

[26] Egerlid H, Wang X, Thuvander L, Maiullari D. Carbon efficiency of passive cooling measures in future climate scenarios: Renovating multi-family residential buildings in a Swedish context. Energy Build. 2025;334:115502. https://doi.org/10.1016/j.enbuild.2025.115502.

[27] Amaripadath D, Levinson R, Rawal R, Attia S. Multi-criteria decision support framework for climate change-sensitive thermal comfort evaluation in European buildings. Energy Build. 2024;303:113804. https://doi.org/10.1016/j.enbuild.2023.113804.

[28] Mejía-Parada C, Mora-Ruiz V, Attia S. Bioclimatic design recommendations for novel cluster analysis-based mapping for humid climates with altitudinal gradient variations. J Build Eng. 2024;82:108262. https://doi.org/10.1016/j.jobe.2023.108262.

[29] Balali A, Yunusa-Kaltungo A. Selection of passive energy consumption optimisation strategies for buildings. Renew Sustain Energy Rev. 2025;210:115222. https://doi.org/10.1016/j.rser.2024.115222.

[30] Es-sakali N, Pfafferott J, Mghazli MO, Cherkaoui M. Towards climate-responsive net zero energy rural schools: A multi-objective passive design optimization with bio-based insulations, shading, and roof vegetation. Sustain Cities Soc. 2025;120:106142. https://doi.org/10.1016/j.scs.2025.106142.