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Optimizing Building Envelope Design for Energy Efficiency in Hot Arid Climates: A Review

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Abstract: *The depletion of fossil fuels and their environmental impact necessitate a shift towards renewable energy sources and improved energy efficiency in buildings. This review explores strategies to minimize energy consumption for heating, cooling, and lighting through thoughtful design of building shapes and orientations in urban environments. Specifically, the focus is on hot arid climates, such as those found in the central plateau of Iran (e.g., Isfahan, Semnan, Kashan, Kerman). Key considerations include maximizing solar gain during colder months and minimizing it during hotter months by optimizing building form and orientation. Factors influencing optimal window-to-wall ratios, such as energy efficiency, natural lighting, and thermal comfort, are discussed. Passive cooling techniques, including insulation, thermal mass, shading, reflective coatings, and passive cooling systems, are reviewed for their effectiveness in reducing energy use and enhancing indoor comfort. This paper provides insights into integrated architectural approaches tailored to hot arid climates to promote sustainable building practices.*

Keywords: *Building envelope, energy efficiency, hot arid climates, window-to-wall ratio, passive cooling, thermal comfort, sustainable design.*

I. INTRODUCTION

The depletion of fossil fuel resources, along with their inefficient use and costly impact on the environment, means that utilizing renewable energy sources and optimizing energy usage are unavoidable. These days, the amount of energy required to provide heat, cooling, and lighting can be decreased by carefully planning the shape and orientation of urban structures and spaces. The external envelope of the structures must be designed to receive the most amount of solar radiant energy during the colder months of the year and the least amount during the hotter months in order to obtain a sustainable shape and form of the building in terms of energy efficiency. The construction and design of buildings and urban spaces in these areas are based on obtaining the least amount of energy possible during the hot months of the year through appropriate orientation, minimizing the area of surfaces facing radiation, and maximizing the amount of shading on surfaces [1]. This is because the central plateau of Iran has distinctive geographic conditions and a hot, dry climate. By analysing the quantity of radiation energy absorbed by the vertical surfaces of buildings in the cities of Isfahan, Semnan, Kashan, and Kerman, this study seeks to identify the ideal form, aspect ratios, and orientation of structures in line with the climate of the region. structure shape has a big impact on how much energy a structure uses. Designing a building with a proper shape and orientation are two of the most important aspects of integrated architecture. An essential first step in the layout of sustainable buildings is determining the ideal building geometry [2]. A considerable amount of building energy is used worldwide to provide the necessary thermal and visual comfort [3–4]. Any air-conditioned or naturally ventilated building's indoor thermal comfort and lighting energy are significantly influenced by the building shape and other related aspects in addition to the construction materials. The building's design, orientation, and window to wall ratio (WWR) are the most significant factors influencing the indoor environment's thermal comfort and lighting energy requirements. The best thermal comfort and energy efficiency may only be attained by carefully combining these connected elements [5-7].

“Clear glazing area” refers only to the open area of the window, not the vertical frame or frame (usually the glazing area accounts for about 80% of all windows), and “whole wall wall” uses the entire area from floor to ceiling. -the external height of the wall above the floor. The rule of thumb is that for adequate insulation in cold climates, the window-to-wall ratio should be 40% or lower, regardless of whether a higher window with a higher R-value (lower U-value) allows more. In hot weather, a higher rate may be used even if it is not a well-insulated window, as long as the window does a good job of blocking the sun's heat.

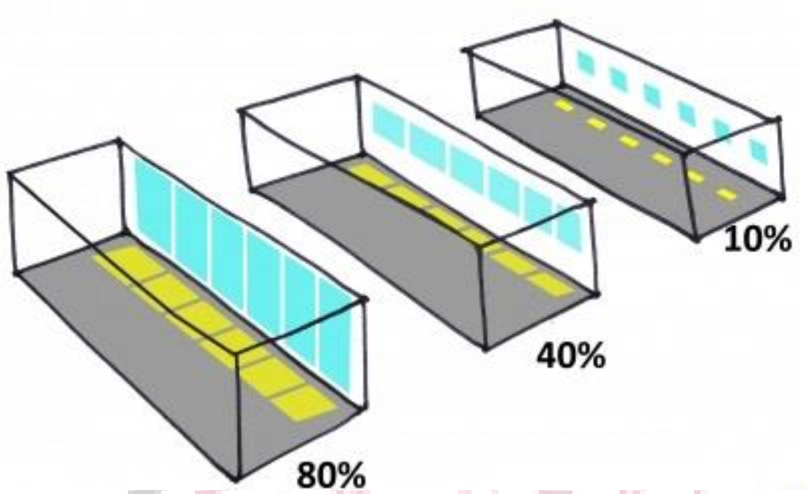

Figure 1 Window-to-Wall Ratio

$$[Window\ Wall\ Ratio] = \frac{[Net\ Glazing\ Area]}{Gross\ Wall\ Area]}$$

II. FACTORS INFLUENCING OPTIMAL WINDOW-TO-WALL RATIO

Determining the optimal window-to-wall ratio for office buildings involves a comprehensive assessment of multiple factors to achieve a balanced design that enhances energy efficiency, natural lighting, thermal comfort, and overall building performance. Energy efficiency considerations are paramount, as the ratio directly influences heating and cooling loads. In hot climates, minimizing solar heat gain through strategic placement and shading of windows is critical to reduce cooling demands. Conversely, in cold climates, a higher window-to-wall ratio can capitalize on passive solar heating during winter months, thereby lowering heating requirements. Natural lighting is another key consideration, with windows serving as primary sources of daylight that can significantly reduce reliance on artificial lighting. Effective daylighting design involves optimizing window sizes and placements to ensure uniform light distribution while mitigating glare and excessive solar heat gain. Thermal comfort is equally crucial, with fenestration choices impacting indoor temperature stability. High-performance glazing, shading systems, and insulation techniques play pivotal roles in regulating heat transfer and enhancing occupant comfort throughout the year. Ultimately, achieving the optimal window-to-wall ratio involves a nuanced approach that integrates architectural design, climatic considerations, and energy performance goals to create office environments that are both sustainable and conducive to occupant well-being. Three optimal intervals of Window-to-Wall Ratios at a series of building orientations corresponding to the daylight factor, mean maximum indoor temperature and mean indoor air velocity are determined respectively, based on the criteria of national codes and thermal comfort ranges.

The optimal window-to-wall ratio in office buildings is influenced by several key factors that vary depending on climate conditions and design objectives. Understanding these factors is crucial for achieving a balance between energy efficiency, natural lighting, thermal comfort, and overall building performance.

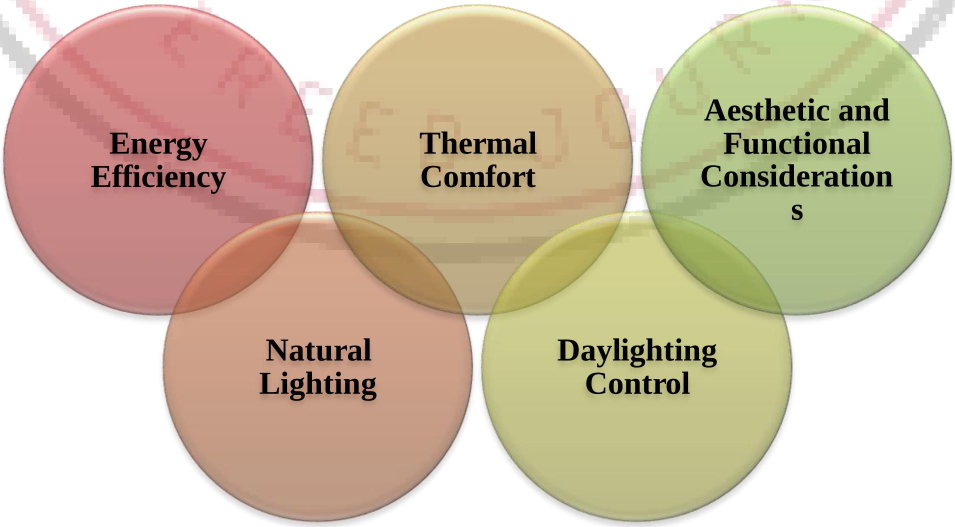

Figure 2 Factors Influencing Optimal Window-to-Wall Ratio

Energy Efficiency: One of the primary considerations in determining the window-to-wall ratio is its impact on the building's energy consumption. In hot climates, excessive glazing can lead to increased solar heat gain, requiring more energy for cooling. Conversely, in cold climates, a higher ratio can capitalize on passive solar heating during winter, potentially reducing heating demands. The goal is to strike a balance that minimizes overall energy use while maximizing the benefits of daylight and solar gain.

Natural Lighting: Windows play a vital role in providing natural daylight, which not only reduces the need for artificial lighting but also enhances occupant well-being and productivity. The distribution and size of windows should be optimized to ensure even daylight penetration deep into the building interior while minimizing glare and excessive contrast. Daylight modeling and simulations help determine the ideal window-to-wall ratio to achieve desired lighting levels throughout the day and across different seasons.

Thermal Comfort: Fenestration design significantly influences thermal comfort within a building. The window-to-wall ratio impacts both heat gain and loss, affecting indoor temperatures. Strategies such as using high-performance glazing, external shading devices, and thermal breaks in window frames help mitigate thermal discomfort by reducing heat transfer and maintaining stable indoor conditions. Climate-specific approaches ensure that fenestration solutions are tailored to local weather patterns and seasonal variations.

Daylighting Control: Effective daylighting design goes beyond simply increasing window area. It involves considering the orientation of windows, the use of shading devices to manage direct sunlight, and the integration of light shelves or reflective surfaces to enhance daylight distribution. These strategies optimize the quality of natural light while minimizing the potential for glare and solar heat gain, thereby improving visual comfort and reducing energy consumption related to lighting and cooling.

Aesthetic and Functional Considerations: The window-to-wall ratio also influences the architectural aesthetics and functional layout of office spaces. Balancing the desire for expansive views and natural light with privacy concerns and the need for wall space for furniture and equipment placement requires careful planning. Design solutions such as varying window sizes, using clerestory windows, or incorporating internal courtyards can achieve a harmonious balance between aesthetic appeal and functional efficiency.

By considering these factors holistically, architects and engineers can determine the optimal window-to-wall ratio that best suits the specific requirements of office buildings in different climates, promoting energy-efficient, comfortable, and visually appealing environments for occupants.

III. LITERATURE REVIEW

Ahmad and Memon (2024) [17] utilized Energy Plus simulations to optimize cooling energy savings in residential buildings by integrating phase change materials (PCM) into their envelopes. Their study evaluated PCM melting temperatures and various ventilation strategies across 45 cities spanning 15 climate zones globally. Introducing novel indicators, HS and HR, to measure heat stored and released by PCM, respectively, they conducted an economic analysis and assessed environmental impacts, including carbon intensities associated with power generation. Significant energy savings were noted across all climates, especially in arid and warm temperate zones, highlighting PCM's effectiveness in conjunction with controlled ventilation.

Refahi et al. (2024) [18] investigated optimal placements of PCM wallboards within building walls, comparing single-layer versus double-layer PCM configurations with different melting points. Their study revealed that PCM wallboard positioning alongside thermal insulation layers significantly influences building energy consumption. They identified optimal configurations for different floors, showcasing energy savings up to 6.6% for heating and 2.8% for cooling across the building. This research underscores the importance of strategic PCM wallboard placement in enhancing building energy efficiency and thermal performance.

Mehrpour et al. (2024) [19] simulated a net-zero energy building (NZEB) in Shiraz, Iran, using Design Builder software. Their study focused on minimizing cooling and heating demands, generating a Pareto front to represent trade-offs between these objectives. By integrating PCMs into the building envelope, they achieved significant energy consumption reductions, underscoring PCM technology's potential to enhance sustainability in buildings within cold and semi-arid climates.

Terhan and Ilgar (2023) [20] investigated the impact of integrating two PCMs into exterior walls at varying thicknesses and melting temperatures on building energy performance. Analyzing four types of walls across different thicknesses, they found substantial annual energy savings (up to 21.32%) with specific PCM configurations. Their study highlights PCM integration in exterior walls as effective for improving building energy efficiency across diverse climatic conditions.

Al-Yasiri and Szabó (2023) [21] evaluated the passive integration of PCM into building envelopes without ventilation, focusing on indoor temperature stabilization and energy savings during hot summers. Their findings demonstrated PCM's effectiveness in stabilizing indoor temperatures and reducing thermal load, emphasizing optimal PCM application in roofs for maximum efficiency in hot climates.

Dardouri et al. (2023) [22] analyzed the energy-saving potential of PCM-integrated buildings in Mediterranean climates. Using Energy Plus simulations, they assessed PCM application in building roofs and south walls under varying conditions. Their results indicated significant energy demand reductions (up to 41.6%) based on PCM type, melting temperature, and location within the building envelope.

Kaihoul et al. (2021) [23] explored passive design strategies influenced by traditional Algerian architecture to reduce cooling and heating loads in hot-dry climates. Their study applied psychometric chart evaluation, on-site measurements, and dynamic simulations to optimize thermal behavior and energy demand in residential buildings, providing insights into climate-responsive design practices.

Kumar et al. (2020) [24] investigated the impact of window-to-wall ratio on energy consumption across different Indian climates using Design Builder software. Their study highlighted optimal glazed surface area configurations for minimizing energy consumption while enhancing thermal comfort, contributing to efficient building envelope design.

Alyami (2024) [25] assessed thermal insulation's impact on reducing energy consumption in residential buildings in Riyadh, Saudi Arabia. Using Design Builder simulations, they identified optimal insulation materials and thicknesses, achieving substantial reductions in energy demand and carbon emissions, surpassing current building standards.

Tewari et al. (2019) [26] focused on enhancing thermal comfort in Indian office buildings using Direct Evaporative Cooling (DEC) systems. Their study employed Energy Plus simulations and field data to validate thermal models, demonstrating DEC's potential to significantly reduce thermal discomfort hours during the summer season.

Yong et al. (2017) [27] conducted a factorial experimental design to evaluate building envelope design factors' impact on cooling and heating loads across US climate zones. Their study provided regression models to optimize building performance through strategic selection of design factors tailored to each climate region.

Faragallah (2022) [28] highlighted passive design strategies in enhancing thermal comfort and reducing cooling demands in hot, arid climates like Siwa Oasis, Egypt. Their research emphasized incorporating specific climatic design parameters during building design to foster comfortable indoor environments irrespective of external weather conditions.

IV. TECHNIQUES TO REDUCE LOW ON ENERGY USE FOR BUILDING COOLING

The ambient temperature of a location relies on its seasonal climate and geographical position. Similarly, the indoor temperature of a building is influenced by outdoor climatic factors such as temperature, wind speed, and solar radiation, as well as architectural considerations like wall thickness and window-to-wall ratio, and the thermal properties of building materials (such as thermal conductivity and specific heat). The ideal comfort range for room temperature typically spans from 21°C to 25°C. Temperatures exceeding 25°C necessitate cooling measures, while temperatures below 21°C require heating. Effective thermal insulation and controlling ventilation levels are essential for regulating indoor temperatures. Additionally, passive cooling techniques can be employed to enhance comfort by lowering indoor temperatures. Building cooling can be achieved through two primary methods:

1.2.1 Layout of envelopes

The word "building envelope" refers to a home's roof, walls, windows, floors, and walls. The building's summertime heat uptake and wintertime heat loss are managed by the envelope. Through passive design, envelopes significantly lessen climatic extremes. In the summer, a well-planned enclosure minimizes solar heat gain and increases cooling air flow. Enclosures reduce heat loss to the outside world during the winter by absorbing and storing solar heat.

A. Insulation

Insulation is necessary to keep a building cool in the summer and warm in the winter because it functions as a barrier to heat flow. A well-designed and insulated structure will minimize greenhouse gas emissions while also providing year-round comfort and lowering the amount of energy needed for heating and cooling. The choice of the right kind and amount of insulation will depend on the local climate. It should be determined if insulation is required to let in heat during the winter or to keep it out during the summer (or both). The requirements of seasonal and daily fluctuations in air temperature must be met by insulation. By preventing moisture issues like condensation, insulation in the ceiling can help weatherproof a building and lower the interior temperature. Certain varieties of glass wool insulation are also capable of soundproofing. Insulation installation is most cost-effective when done during construction. Modern building materials with good insulating properties include straw bales, rendered extruded polystyrene sheets, hollow expanded polystyrene blocks, and aerated concrete blocks.

B. Thermal mass

Thermal management refers to the ability of building materials to absorb heat. High density materials such as stone and brick require more thermal energy to transfer heat, so they are said to have thermal mass. Common materials such as wood have low thermal properties. Thermal mass acts as a thermal battery. In colder regions, it absorbs the sun's heat during the day, and at night, the same thermal air releases the heat, keeping the house comfortable. While good buildings must gain or lose a lot of energy to change their temperature, deep houses use only a small amount of energy or loss. Thermal quality is especially useful when there is a temperature difference between day and night outside. Proper use of heating can delay the flow of heat through the building envelope by up to 10 to 12 hours, allowing the house to stay warmer at night in winter and cooler during the day in summer. Using thermal efficiency throughout the building can improve comfort and reduce energy costs. The same concept can be extended to tropical regions by storing the cooling energy available in the early morning hours and recovering the same energy during the day to cool the home. Improper use of heating can cause heat to build up overnight in summer heat or absorb all of the heat generated during the night in winter.

C. Shading

The building's and the outdoor areas' shade lowers summertime temperatures, enhances comfort, and conserves energy. For every square meter of surface, direct solar radiation may produce the same amount of heat as one bar radiator. Shade can obstruct up to 90% of this heat. It is essential to shade glass to prevent undesired heat gain. In a building, unprotected glass is frequently the main cause of unintentional heat absorption. Sunlight's radiant heat travels through glass, gets absorbed by the structure and furniture, and then radiates back out again. Heat that has been reradiated has a different wavelength and cannot easily escape through the glass. Because of the greenhouse effect, radiant heat can be "trapped" in most climates; however, this must be avoided in the summer. To lessen summertime heat gain, wall and roof surfaces should be shaded, especially if they are heavy or dark in color. The amount of shading needed depends on the climate and direction of the home.

D. Reflective coatings

Innovative and affordable materials for reducing solar cooling load have been developed as a result of recent studies on highly reflective materials for outdoor wall painting. The surface temperature of reflective material is around 15°C cooler than that of routinely used material of the same color. The switchable glazing technique provides transparent components with sun control. The market now offers electrochromic glazing, which has been significantly enhanced for load reduction. Heat sinks, greenery, and cool materials can all work together to lower the temperature within a building.

1.2.2 Methods of Passive Cooling

In order to reduce the cooling burden, passive cooling solutions make use of thermal capacitance, shade, and carefully planned microclimates. In order to disperse surplus heat from a building to a natural heat sink using the processes of convection, evaporation, and radiative cooling as well as ground cooling, heat sinks such as atmospheric air, sea, earth, etc. are necessary. The adoption of passive cooling methods aids in the effort to cut greenhouse gas emissions. The following are three different kinds of hybrid and passive cooling systems and methods:

- Buried pipes that act as earth-to-air heat exchangers.
- Parts of evaporative cooling.
- Ventilation strategies.

A. Earth to air heat exchangers

Air is sucked from the environment using an electric fan and cooled by circulating it underground. The coldness of the earth is transferred to the air and it is injected into the building. It was verified experimentally that a 2-5°C reduction of peak indoor temperature can be obtained as the depth of earth to air heat exchanger ranges between 1.5 to 6.5m respectively. Many buildings have been designed and monitored and the performances of these buildings has been proved.

B. Cooling by evaporation

The evaporative principle is used by a direct evaporating cooling system to cool the air entering the building. When water vapor evaporates, it absorbs heat from the surrounding air, causing the air to cool. Because of the lower humidity in these areas, this technique is more successful in the interior and desert than in coastal areas. Buildings can be efficiently cooled by an indirect evaporative cooling system without having to raise the indoor air's moisture content. Indirect evaporative cooling systems of the plate type are more efficient than other kinds of cooling systems.

C. Ventilation techniques

When the outside temperature drops, outside air is pumped into the building for cooling reasons and to fulfill the occupancy-based fresh air requirements. An interior atmosphere that is both cozier and healthier can be achieved through ventilation strategies. The following are some examples of ventilation methods for low-energy buildings:

- **Natural ventilation:** These buildings will be naturally ventilated. Here, the residents regulate the ventilation by opening the windows.
- **Advanced natural ventilation:** In this case, natural elements other than windows—like thermal chimneys and wind towers—control the direction and flow of the ventilating air. Solar chimneys are the natural draft components using the solar energy to build up stack pressure, and thus driving the air flow through the chimney. In a wind tower, air enters the towers of the wind ward facade and leaves at the lower part to the inside of the building. Air may be cooled by the convective or the evaporative principle through the tower.
- **Mechanical Ventilation:** To supply air for ventilation, these buildings typically contain local or central fans.
- **Mixed Ventilation Mode:** These buildings have a mechanical cooling system in addition to one of the ventilation systems mentioned above. We shall not classify the mechanical cooling system as a passive cooling method. A deeper

comprehension of air flow phenomena and anticipated comfort benefits is necessary for effective use of ventilation systems, especially in urban settings.

D. Night cooling

Incoming energy, mostly from the sun, and departing energy from the earth's surface as a result of nighttime sky radiation regulate the daily variation in air temperature. As seen in Figure 1.1, the air temperature rises in locations where incoming solar energy exceeds outgoing solar energy (orange shade), and falls in locations where outgoing solar energy due to sky irradiation exceeds incoming solar energy (blue shade).

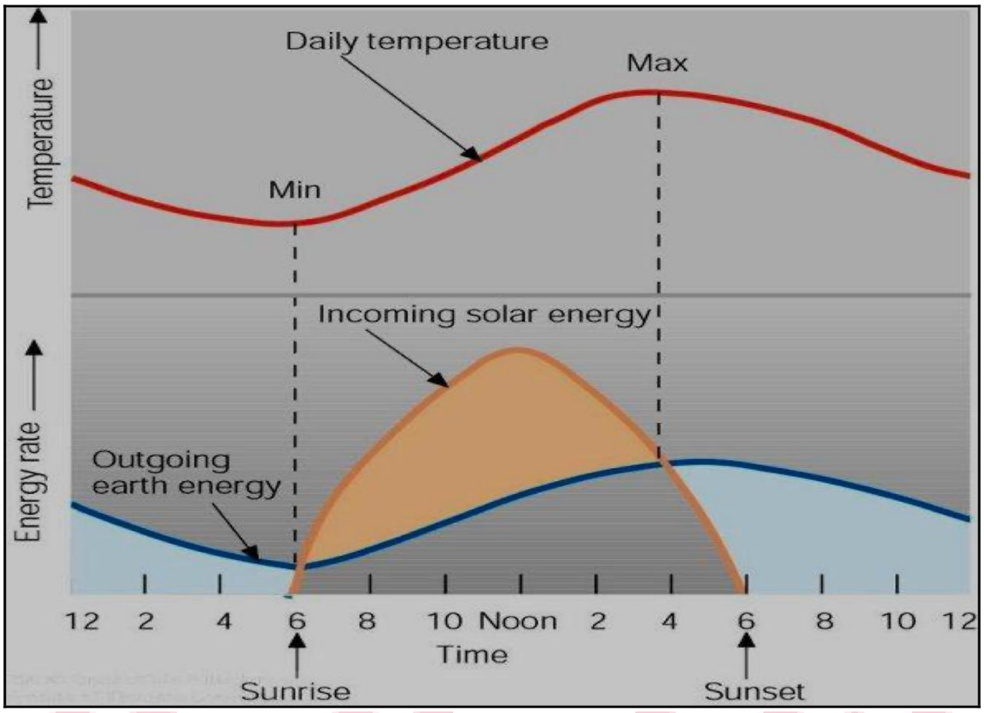

Figure 3 Atmospheric air temperature energy balance

A building with a high thermal mass with proper utilization is sufficient for year-round thermal management. There are various methods adopted for the passive cooling of buildings. Night ventilation is one such method by which the structural components are cooled, thus providing reduced temperature of indoor air conditions for the following day. In places where the daily variations of the ambient temperature are high, night ventilation is highly suitable. In free cooling, apart from a sensible storage system, the latent heat thermal energy storage system (LHTES) is also used as a storage medium which stores the coldness of the ambient air during early morning and supplies it with a time delay during the day. Phase change materials become the natural storage options because of the small temperature difference between the day indoors and night outdoors.

V. CONCLUSION

Designing energy-efficient buildings in hot arid climates requires a holistic approach that considers building form, orientation, and fenestration design. Optimal window-to-wall ratios must balance energy performance with daylighting and thermal comfort goals. Passive cooling techniques such as insulation, thermal mass, shading, and reflective coatings play crucial roles in mitigating temperature extremes and reducing reliance on mechanical cooling systems. By integrating these strategies into building design, architects and engineers can create sustainable environments that minimize energy consumption, enhance occupant comfort, and contribute positively to the environment. Future research should continue to explore innovative materials and technologies to further improve the energy performance of buildings in hot arid climates.

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