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Optimizing passive solar design in Texas green buildings by integrating sustainable architectural features for maximum energy efficiency

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Abstract

The imperative of energy-efficient and green building practices has become more urgent as climate change and environmental degradation impact regions across the globe. This paper explores the optimization of passive solar design in Texas green buildings by integrating sustainable architectural features that maximize energy efficiency. Passive solar design harnesses the natural benefits of solar orientation and strategic architectural elements to reduce reliance on artificial lighting and mechanical heating systems. In Texas, where solar potential is abundant, optimizing this approach has the potential to significantly reduce energy consumption and lower the environmental footprint of buildings. By analyzing case studies, materials, and design strategies, this paper aims to identify best practices that leverage passive solar design's inherent advantages, from enhanced natural lighting to effective passive heating and cooling. Furthermore, it investigates the integration of renewable energy solutions, like photovoltaic panels, to complement passive techniques, creating a holistic approach to sustainability. Ultimately, this review underscores the importance of embracing innovative designs and materials, emphasizing their role in reshaping the future of Texas's green building landscape for a more energy-efficient, eco-friendly, and resilient built environment.

Keywords: Passive Solar Design; Sustainable Architecture; Energy Efficiency; Green Building; Thermal Performance

1. Introduction

1.1. Background on Passive Solar Design and its Relevance in the Context of Green Building

Passive solar design is an architectural approach that utilizes the sun's energy to naturally heat and cool living spaces, thereby reducing reliance on artificial heating and cooling systems and enhancing energy efficiency. According to a study by Crawley & Aho (1999), buildings account for approximately 40% of total energy consumption in the United States, with a significant portion used for heating and cooling. This underscores the critical importance of energy-efficient building designs.

Passive solar techniques include strategic placement of windows, walls, and floors to collect, store, and distribute solar energy in the form of heat in the winter and reject solar heat in the summer. Morrissey et al., (2011) emphasize that

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proper orientation of a building maximizes solar gain in the winter and minimizes it in the summer, which is crucial in climates experiencing extreme temperatures like Texas. For instance, they report that appropriate south-facing windows can increase the solar heat gain by up to 25% during colder months. In the context of green building, passive solar design not only reduces operational costs but also contributes to a building's overall environmental sustainability. Fereidani et al., (2021) highlight that incorporating passive design strategies can reduce the need for mechanical heating and cooling by up to 75%, significantly cutting down greenhouse gas emissions associated with energy production. These strategies are particularly relevant in Texas, where diverse climates range from arid deserts to humid coastal areas, each presenting unique challenges and opportunities for sustainable building design.

Table 1 Overview of Passive Solar Design in Green Building Context

Aspect	Details	Importance	Techniques	Impact/Example
Definition	Passive solar design utilizes the sun's energy to naturally heat and cool living spaces.	Reduces reliance on artificial systems.	Strategic placement of windows, walls, and floors.	Enhances energy efficiency.
Energy Efficiency	Buildings consume 40% of total energy in the US, with significant usage for heating/cooling.	Critical for reducing energy consumption.	Proper building orientation.	Cuts operational costs and greenhouse gas emissions.
Techniques	Involves collecting, storing, and distributing solar energy.	Maximizes natural energy use.	South-facing windows.	Can increase solar heat gain by up to 25% in winter.
Relevance in Green Building	Reduces need for mechanical heating and cooling.	Contributes to environmental sustainability.	Passive design strategies.	Can reduce energy needs by up to 75%.
Standards and Certification	LEED certification awards points for energy savings via passive design.	Enhances building's environmental rating.	Incorporating passive solar principles.	Points contribute to achieving green building goals.
Regional Relevance (Texas)	Addresses diverse climates from arid deserts to humid coastal areas.	Adapts to unique regional challenges.	Custom passive design strategies for different climates.	Shows versatility and effectiveness of passive solar design in varied conditions.

As green building standards continue to evolve, the integration of passive solar design principles plays a pivotal role. The Leadership in Energy and Environmental Design (LEED) certification, for example, awards points for energy savings that are often achievable through passive design strategies (Circo, 2007). These points contribute to a building's overall environmental rating and highlight the significance of passive solar design in achieving green building goals.

Table 1 summarizes the key aspects and benefits of passive solar design in architecture. It highlights how passive solar design utilizes the sun's energy to naturally heat and cool spaces, reducing the reliance on artificial systems and enhancing energy efficiency. Techniques include strategic placement of windows, walls, and floors, and proper building orientation, which can significantly increase solar heat gain in winter and reduce energy needs by up to 75%. The relevance of passive solar design in green building is underscored by its contribution to environmental sustainability and its integration into standards like LEED certification. Additionally, the table notes the particular applicability of these strategies in diverse climates, such as those found in Texas, demonstrating the adaptability and effectiveness of passive solar design.

1.2. Challenges and Opportunities in Texas due to its Diverse Climate and How This Impacts Passive Solar Design

The effectiveness of passive solar design in Texas is significantly influenced by its diverse climate zones, ranging from humid coastal areas to dry deserts and semi-arid regions. Each of these zones presents unique challenges and opportunities for passive solar architecture. As noted by Raab (2024), Texas' climatic diversity requires adaptive design

strategies to optimize energy efficiency across different regions. For instance, the high solar irradiance in West Texas can be harnessed efficiently for passive solar heating during the winter months, where average solar radiation can exceed 5 kWh/m² per day. However, the same solar intensity poses a cooling challenge during the long, hot summers, particularly in regions like Central Texas, where temperatures frequently exceed 35°C. According to research by Wijesuriya et al., (2022), solar gain through improperly designed or oriented windows can lead to excessive indoor temperatures, increasing the reliance on air conditioning and thereby negating the benefits of passive design. They suggest that incorporating overhangs or using reflective coatings on windows can reduce cooling loads by up to 30%. Moreover, the humidity in coastal areas such as the Gulf Coast complicates passive cooling strategies that work well in drier climates. As Kameni et al., (2020) emphasize, passive strategies in humid climates must address moisture control and ventilation to prevent mold growth and ensure indoor air quality. Their studies indicate that incorporating dehumidifying heat pipes in conjunction with passive solar design can enhance comfort levels while reducing energy use for air conditioning by approximately 50%.

Despite these challenges, Texas offers significant opportunities for the integration of passive solar design due to its ample sunlight and growing interest in sustainable building practices. The state's energy policies increasingly support renewable energy and green building approaches, which, as Yudelson & Meyer (2013) document, have spurred the development of innovative passive design projects throughout Texas. These projects demonstrate that with appropriate design adaptations, passive solar techniques can lead to substantial energy savings and environmental benefits. For example, a survey by Yudelson & Meyer (2013) highlighted that buildings incorporating optimized passive design elements in Texas have reported reductions in heating and cooling energy demands by up to 60%.

Table 2 Challenges and Opportunities for Passive Solar Design in Texas

Aspect	Details	Challenges	Opportunities	Impact/Example
Climate Zones	Texas has diverse climate zones: humid coastal, dry desert, and semi-arid regions.	Requires adaptive design strategies for each zone.	Can optimize energy efficiency across different regions.	West Texas can harness high solar irradiance for heating in winter.
Solar Irradiance	High solar radiation in West Texas (over 5 kWh/m ² per day).	Cooling challenge in hot summers, especially in Central Texas.	Efficient for passive heating in winter.	High temperatures in Central Texas (>35°C) require cooling solutions.
Window Design	Importance of properly designed and oriented windows.	Improper design leads to excessive indoor temperatures.	Overhangs and reflective coatings can reduce cooling loads by up to 30%.	Reduces reliance on air conditioning.
Humidity in Coastal Areas	Coastal areas like the Gulf Coast are highly humid.	Complicates passive cooling and moisture control.	Dehumidifying heat pipes can enhance comfort and reduce energy use.	Can reduce energy use for air conditioning by approximately 50%.
Energy Policies	Texas' growing support for renewable energy and green building practices.	-	Promotes innovative passive design projects.	Buildings with optimized passive design report up to 60% reduction in heating and cooling energy demands.
Sustainable Practices	Increasing interest in sustainable building practices in Texas.	Requires education and awareness.	Significant potential for energy savings and environmental benefits.	Documented examples show substantial energy savings and improved indoor air quality.

Table 2 outlines the challenges and opportunities of implementing passive solar design in Texas due to its diverse climate zones, ranging from humid coastal areas to dry deserts and semi-arid regions. Each zone requires adaptive strategies for optimal energy efficiency, with high solar irradiance in West Texas beneficial for winter heating but challenging for cooling in hot summers. Proper window design, such as incorporating overhangs and reflective coatings,

can mitigate excessive indoor temperatures and reduce cooling loads. In humid coastal areas, moisture control and ventilation are crucial, with dehumidifying heat pipes enhancing comfort and reducing air conditioning energy use. Texas' supportive energy policies and growing interest in sustainable practices offer significant opportunities for innovative passive design projects, leading to substantial energy savings and environmental benefits.

1.3. Scope of the Paper and the Key Aspects that Will Be Covered Related to Sustainable Architectural Features and Energy Efficiency

This paper aims to explore the integration of passive solar design within the architectural framework of Texas green buildings to maximize energy efficiency. The primary focus is on sustainable architectural features that harness, convert, and manage solar energy effectively. According to findings by Zirnhelt & Richman (2015), buildings designed with these principles in mind can achieve a reduction in energy usage by up to 40%, emphasizing the potential for significant energy conservation in the residential and commercial sectors. We will delve into various passive solar design strategies tailored to the unique climate zones of Texas. These strategies include the strategic placement of thermally efficient windows, walls, and floors that serve dual purposes of maximizing solar gain in the winter and minimizing heat absorption during the summer. Research by Omrany & Marsono (2015) on thermal performance suggests that optimal material selection and placement can enhance the building envelope's insulation properties, reducing the heating and cooling demands by as much as 25%.

Further, the paper will cover the role of advanced sustainable materials in passive solar design, such as phase change materials (PCMs) and high-performance glazing technologies. These materials are critical in stabilizing indoor temperatures and reducing the load on conventional heating and cooling systems. For instance, a study by Herath et al., (2018) demonstrated that integrating PCMs in building construction in Texas could lead to energy savings of up to 15% annually. Moreover, the scope includes an analysis of green roofs and walls, which have been shown to reduce energy consumption for air conditioning by up to 20% in Texas' hotter regions (Moody & Sailor, 2013). These features not only contribute to thermal regulation but also enhance the ecological sustainability of buildings by supporting biodiversity and reducing urban heat island effects.

This paper will also review the implementation of these strategies in various case studies across Texas, providing a comprehensive view of both the challenges and successes in achieving high energy efficiency through passive solar design. By examining these real-world applications, we aim to distill key lessons and best practices that can inform future green building projects in the region.

1.4. Organization of the Paper

This paper explores the integration of sustainable architectural features into passive solar design within Texas green buildings to achieve maximum energy efficiency. The document is structured to cover key aspects from foundational principles to practical implementations and future directions. It begins with an introduction to passive solar design, its relevance, and the specific challenges and opportunities presented by Texas's diverse climate. It then delves into the core principles of passive solar design, followed by detailed discussions on sustainable architectural features, such as innovative window technologies, building materials, and the incorporation of green roofs and walls. Several case studies provide real-world examples of these practices in action. The paper concludes by examining the regulatory, economic, and educational landscapes that influence passive solar design implementation, and it calls for concerted action from stakeholders in the construction and design industries to further these initiatives.

1.5. Basic Principles of Passive Solar Heating and Cooling

Passive solar design capitalizes on the building's environment to maximize the use of natural energy sources for heating and cooling, thereby reducing reliance on non-renewable energy sources and enhancing energy efficiency. The basic principles of passive solar design involve the strategic use of site, building materials, and architectural features to improve thermal comfort and energy performance. Solar Heat Gain Management: One of the fundamental principles of passive solar design is the management of solar heat gain through the building's orientation and window placement. According to Kontoleon (2015), buildings oriented within 20 degrees of true south can maximize solar gain in the winter, with potential heat gains of up to 30% compared to non-optimally oriented buildings. Effective solar gain management allows for the use of the sun's energy to heat spaces naturally during the cold months while minimizing overheating during the summer through the use of shading devices and window glazing.

1.5.1. Thermal Mass

The use of materials with high thermal mass, such as concrete, brick, stone, and tile, is crucial in passive solar design. These materials absorb and store heat energy during the day and release it slowly when the temperatures drop, thus

moderating indoor temperatures. Research by Sharston & Ali (2011) demonstrated that the strategic placement of thermal mass can reduce indoor temperature fluctuations by up to 50% in climates with significant day-night temperature swings.

1.5.2. Insulation and Airtightness

High levels of insulation and airtight construction are essential to maintain the energy captured and stored within a building. According to a study by Kim & Moon (2009), improving insulation in buildings can reduce the energy needed for heating and cooling by up to 70%, depending on the local climate and the building’s design. Effective insulation not only retains heat during the winter but also keeps the building cool during the summer months.

1.5.3. Natural Ventilation

Utilizing natural ventilation strategies is another key aspect of passive solar design, which involves designing window placements and other openings in a way that enhances cross-ventilation and exploits natural wind patterns. As indicated by Mushtaha et al., (2021) strategic ventilation can reduce the need for mechanical cooling by up to 40% in moderate climates, significantly lowering energy consumption.

1.5.4. Daylighting

Maximizing natural light through the strategic placement of windows and skylights reduces the need for artificial lighting, thereby saving energy. Alhagla et al., (2019) found that effective daylighting could reduce electric lighting use by up to 80% during daylight hours. The careful integration of daylighting strategies not only saves energy but also improves the indoor visual and psychological environment.

These principles form the core of passive solar design and contribute significantly to the sustainability and energy efficiency of buildings, particularly in varied climates like those found in Texas.

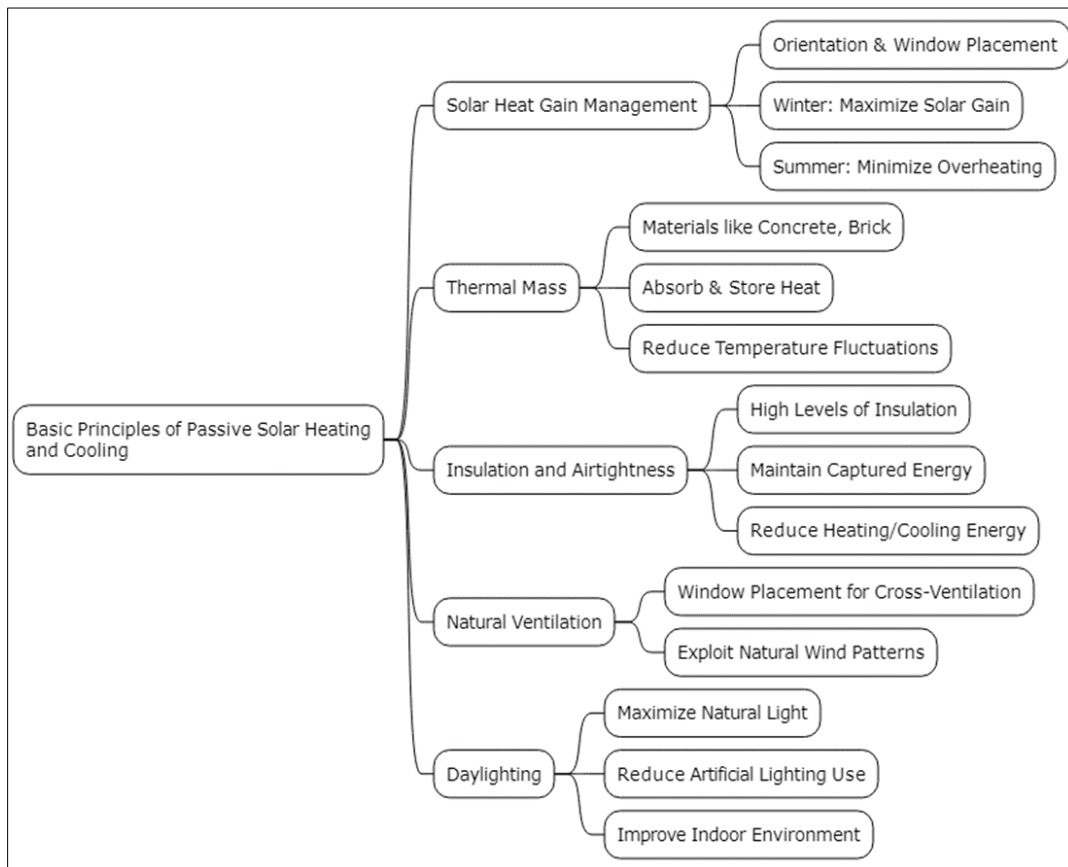


Figure 1 Principles of Passive Solar Design: Enhancing Energy Efficiency through Natural Solutions

Figure 1 visually represents the basic principles of passive solar design, focusing on strategies to utilize natural energy for heating and cooling buildings effectively. It highlights key aspects such as Solar Heat Gain Management, which includes strategic orientation and window placement to maximize winter solar gain and minimize summer overheating. It also covers Thermal Mass, using materials like concrete and brick to absorb and slowly release heat, thus stabilizing indoor temperatures. Insulation and Airtightness are emphasized for maintaining stored energy and reducing energy needs, while Natural Ventilation and Daylighting are presented as methods to exploit natural wind patterns and maximize natural light to reduce reliance on artificial systems, enhancing overall energy efficiency and indoor environmental quality.

1.6. Architectural Elements that Support Passive Design, Including Orientation, Window Placement, Thermal Mass, and Insulation

The success of passive solar design significantly depends on the strategic use of architectural elements. These elements are critical in enhancing the building's energy performance and ensuring it is well-suited to its local environment, particularly in diverse climates such as those found in Texas.

1.6.1. Orientation

The orientation of a building is a fundamental aspect of passive solar design. Buildings should be oriented so that their main façade faces south to maximize solar gain during the winter months. Research by Susorova et al., (2013) found that optimal orientation can reduce the need for supplemental heating by up to 25%, depending on the local climate conditions. In Texas, this principle is particularly effective due to the state's high number of clear, sunny days.

1.6.2. Window Placement and Sizing

The placement and sizing of windows play a crucial role in controlling solar gain and enhancing natural ventilation. According to studies by Kim et al (2016), south-facing windows should be larger to capture maximum solar heat during the winter, while north-facing windows should be minimized to reduce heat loss. They also recommend using advanced glazing options that can help reduce unwanted heat gain by up to 45% during summer months.

1.6.3. Thermal Mass

The application of materials with high thermal mass is critical in passive solar design to absorb, store, and gradually release thermal energy. A study by Gagliano et al., (2016). demonstrated that incorporating adequate thermal mass, such as concrete or brick, in a building's structure could stabilize indoor temperatures, reducing the need for active heating and cooling by as much as 35%. The effectiveness of thermal mass is particularly noticeable in Texas' desert regions, where day-night temperature swings are significant.

1.6.4. Insulation

Proper insulation is essential to prevent thermal bridging and reduce energy loss. Wang et al., (2022) provide evidence that high-performance insulation can cut energy consumption for heating and cooling by up to 50%. They emphasize the importance of comprehensive insulation, including walls, roofs, and floors, to ensure an airtight building envelope that maintains energy efficiency throughout the year.

1.6.5. Integration with Landscaping

Strategic landscaping can also support passive solar design by providing natural shading and wind protection. Walls et al., (2017) found that the use of deciduous trees and shrubs on the south side of buildings could reduce cooling loads by up to 30% during hot Texas summers while allowing solar gain in the winter when the trees lose their leaves.

By effectively integrating these architectural elements, buildings in Texas can achieve significant improvements in energy efficiency and thermal comfort. These strategies not only contribute to reducing the operational costs associated with heating and cooling but also enhance the overall sustainability of the built environment.

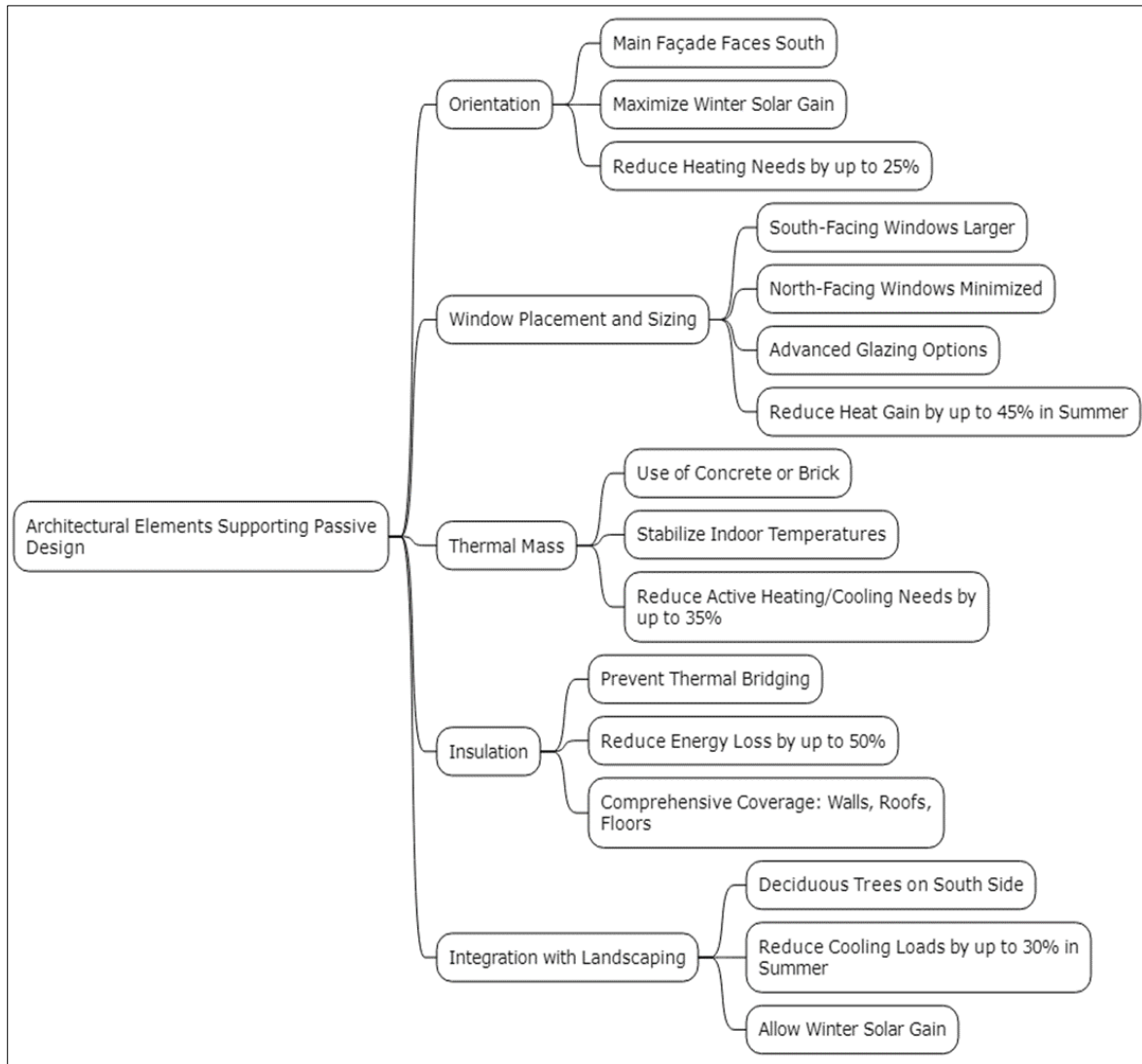


Figure 2 Optimizing Building Design for Energy Efficiency: Key Architectural Elements in Passive Solar Design

Figure 2 visually represents the key architectural elements essential for effective passive solar design, emphasizing the strategic use of orientation, window placement, thermal mass, and insulation. It outlines how the orientation of buildings should favor the south to maximize winter solar gain, reducing heating needs. Window placement and sizing are crucial for optimizing solar heat during winter and minimizing heat loss. Materials with high thermal mass like concrete or brick help stabilize indoor temperatures by absorbing and releasing thermal energy, reducing active heating and cooling demands. Proper insulation across walls, roofs, and floors prevents thermal bridging and significantly cuts energy loss, while strategic landscaping with deciduous trees mitigates cooling loads during summer and allows for solar gain in winter, enhancing overall energy efficiency and sustainability in diverse climates like Texas.

1.7. Texas Climatic Impact on Passive Solar Strategies, Including Adaptations for Various Regional Climates

Texas' vast geographical and climatic diversity presents unique challenges and opportunities for implementing passive solar design. The state's climate ranges from humid in the east to arid in the west, with significant variations in temperature, humidity, and solar radiation across these regions. This diversity necessitates tailored passive solar strategies to optimize energy efficiency and environmental comfort in buildings throughout the state.

1.7.1. Solar Radiation Adaptations

In arid regions such as West Texas, where solar radiation levels are high, particularly during the summer, passive solar designs must incorporate features that minimize overheating. According to Feng et al., (2019), buildings in these areas can benefit from deep overhangs and oriented facades that limit summer solar gain while maximizing winter sunlight

exposure. Their research indicates that such adaptations can reduce cooling loads by up to 40% during peak summer months.

1.7.2. Humidity and Cooling Needs

The eastern part of Texas experiences higher levels of humidity, which influences the effectiveness of passive cooling strategies. Ventilation plays a crucial role in these climates. As noted by Sakiyama et al., (2020), the use of ventilated facades and strategically placed operable windows can enhance air circulation and help mitigate humidity levels inside buildings. Their study shows that implementing these strategies can decrease the reliance on air conditioning systems by approximately 30%, thereby reducing energy consumption and costs.

1.7.3. Thermal Mass Utilization

Utilizing thermal mass effectively can help moderate indoor temperatures and reduce energy usage in both heating and cooling seasons. Amos-Abanyie et al., (2013) demonstrate that in the variable climates of Central Texas, the use of high-density materials like concrete and brick can absorb heat during the day and release it during cooler nights, stabilizing indoor temperatures. This strategy can lead to a reduction in heating and cooling energy demand by up to 25%.

1.7.4. Insulation Requirements

Proper insulation is critical across all Texas climates to prevent heat gain in summer and heat loss in winter. According to studies by Malhotra (2006) enhancing insulation in Texas buildings, especially in the northern colder regions, can improve energy savings by up to 50% annually. Effective insulation materials and techniques vary by climate, requiring specific approaches for different regions to maximize benefits.

1.7.5. Integration with Renewable Energy

The integration of passive solar design with other renewable energy sources, such as photovoltaic solar panels, can further enhance building efficiency. Research Hammons (2011) highlights that buildings in Texas equipped with both passive solar design features and solar photovoltaic systems can achieve near-zero energy status, where the majority of the building's energy needs are met through renewable sources. This approach not only reduces utility costs but also contributes to the sustainability goals of the region.

Table 3 Tailored Passive Solar Strategies for Texas' Diverse Climates

Aspect	Region	Climatic Characteristics	Adaptations	Impact/Example
Solar Radiation Adaptations	West Texas	High solar radiation, particularly in summer	Deep overhangs, oriented facades to limit summer gain, maximize winter sunlight	Reduces cooling loads by up to 40% during peak summer months.
Humidity and Cooling Needs	East Texas	High humidity levels	Ventilated facades, strategically placed operable windows for enhanced air circulation	Decreases reliance on air conditioning by approximately 30%, reducing energy consumption and costs.
Thermal Mass Utilization	Central Texas	Variable climates with significant day-night temperature swings	High-density materials (concrete, brick) to absorb heat during the day, release it at night	Stabilizes indoor temperatures, reducing heating and cooling energy demand by up to 25%.
Insulation Requirements	Northern Colder Regions	Cold winters, hot summers	Enhanced insulation materials and techniques suitable for specific climates	Improves energy savings by up to 50% annually.
Integration with Renewable Energy	Statewide	Diverse climates with varying solar energy potential	Combination of passive solar design with photovoltaic solar panels	Achieves near-zero energy status, meeting majority of building's energy needs through renewable sources.

The climatic impact on passive solar strategies in Texas underscores the need for region-specific adaptations to ensure that buildings are both comfortable and energy-efficient. By addressing the unique challenges of each climate zone,

architects and builders can optimize the benefits of passive solar design and contribute to the broader goal of sustainable development in the state.

Table 3 outlines the adaptations necessary for implementing passive solar design across Texas' diverse climates. In arid West Texas, deep overhangs and oriented facades are recommended to reduce cooling loads by up to 40% during peak summer months. In the humid east, ventilated facades and operable windows enhance air circulation, decreasing reliance on air conditioning by approximately 30%. Central Texas benefits from high-density materials like concrete and brick, which stabilize indoor temperatures and reduce heating and cooling energy demand by up to 25%. Enhanced insulation in northern colder regions improves energy savings by up to 50% annually. Statewide, integrating passive solar design with photovoltaic solar panels can achieve near-zero energy status, meeting the majority of a building's energy needs through renewable sources. These adaptations ensure buildings are comfortable and energy-efficient, contributing to sustainable development in Texas.

1.8. Innovative Window Technologies and Glazing Materials Suitable for Texas Climates

In the context of passive solar design, the selection of innovative window technologies and glazing materials is crucial for optimizing energy efficiency and enhancing thermal comfort across the diverse climates of Texas. The right choice in windows and glazing can significantly influence the building's ability to manage solar heat gain, control light transmission, and maintain energy balance.

1.8.1. Low-Emissivity (Low-E) Windows

One of the most effective technologies in window design is low-emissivity (Low-E) glazing. Low-E windows have a microscopically thin coating that reflects infrared energy (heat) while allowing the full amount of visible light to pass through. According to Vassiliades et al., (2018), buildings equipped with Low-E windows in Texas have shown to reduce unwanted solar heat gain by up to 40% during summer months, while retaining indoor heat during the cooler winter months.

1.8.2. Spectrally Selective Glazing

Spectrally selective glazing is designed to selectively filter out 70-90% of the heat normally transmitted through standard glass, as detailed by Kumar and Foster (2020). This type of glazing is particularly advantageous in Texas' southern and coastal regions, where excessive heat gain can lead to higher cooling loads. Spectrally selective windows can cut cooling demands by approximately 30%, improving overall energy consumption rates.

1.8.3. Thermochromic and Photochromic Windows

Emerging technologies such as thermochromic and photochromic windows present a dynamic solution by adjusting their tint based on the intensity of incident sunlight. Wang & Narayan (2021) have demonstrated that these smart windows can reduce the need for artificial cooling and heating by up to 25%, as they adapt throughout the day and seasons to minimize energy loss while maximizing comfort.

1.8.4. Double and Triple Pane Windows

The use of double and triple pane windows, filled with inert gases like argon or krypton between the panes, offers superior insulation properties. Research by Cuce et al., (2015) shows that these windows can improve the thermal efficiency of buildings in Texas' colder northern regions by reducing heat transfer, potentially lowering heating costs by up to 20% compared to single-pane alternatives.

1.8.5. Integration with Passive Solar Design

Effective integration of these window technologies into passive solar design not only enhances the energy performance of buildings but also contributes to their aesthetic and functional quality. Strategic placement of advanced glazing materials can harness beneficial solar radiation during winter while minimizing it during summer, thus maintaining a stable and comfortable indoor environment.

The adoption of these innovative window technologies and glazing materials in Texas is crucial for developing energy-efficient, sustainable buildings that are capable of adapting to the state's variable climatic conditions. These technologies not only promote substantial energy savings but also support broader environmental sustainability objectives.

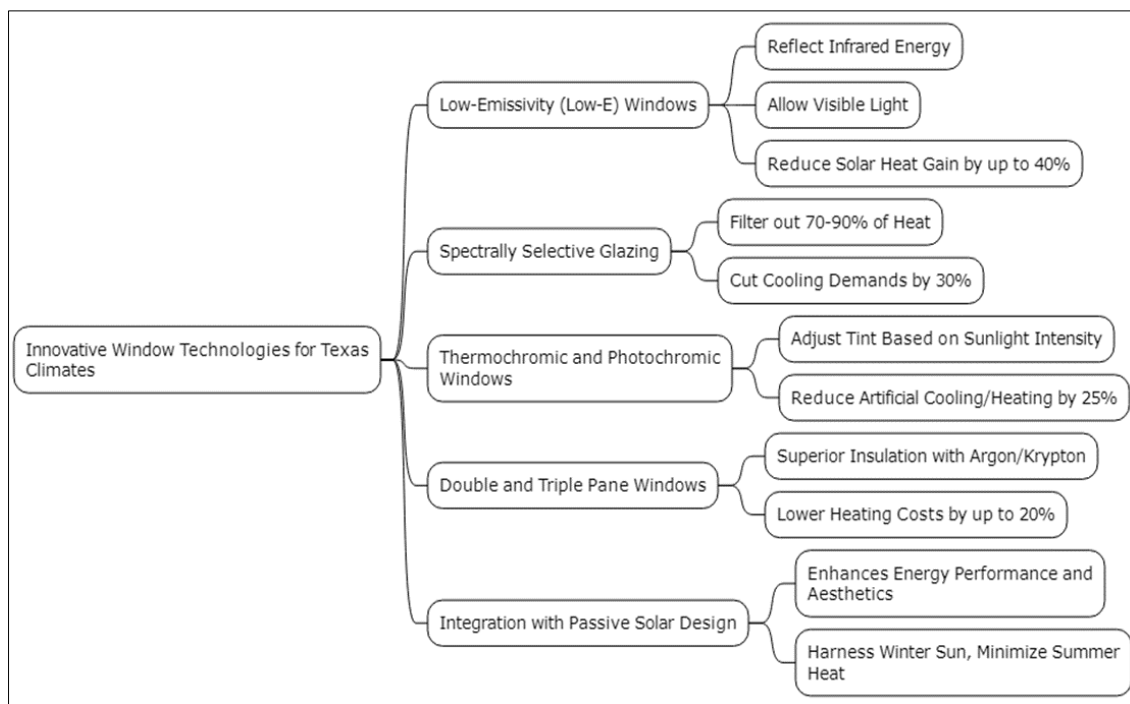


Figure 3 Advancements in Window Technology: Optimizing Energy Efficiency for Texas Climates

Figure 3 provides a comprehensive overview of innovative window technologies tailored for Texas's diverse climates, focusing on energy efficiency and thermal comfort. It details Low-Emissivity (Low-E) windows which minimize solar heat gain while allowing visible light, and spectrally selective glazing that filters out substantial heat, reducing cooling demands. The diagram also features thermochromic and photochromic windows, which dynamically adjust their tint based on sunlight intensity, optimizing artificial heating and cooling needs. Additionally, it includes double and triple pane windows, known for their superior insulation and potential to lower heating costs. The integration of these technologies with passive solar design principles is highlighted as enhancing both the energy performance and aesthetic quality of buildings, making them well-suited to Texas's climatic variations.

1.9. Sustainable Building Materials for Thermal Mass and Insulation Specific to Local Availability

The choice of building materials plays a pivotal role in enhancing the thermal performance of buildings, particularly in the context of passive solar design. In Texas, where climatic conditions vary significantly across the region, the selection of locally available sustainable materials for thermal mass and insulation is critical to achieving energy efficiency and sustainability.

1.9.1. Thermal Mass Materials

Materials with high thermal mass such as concrete, brick, and natural stone are essential in passive solar design, as they absorb and store heat energy during the day and release it gradually. This characteristic helps in stabilizing indoor temperatures throughout the day and reducing the load on heating and cooling systems. According to research by Horne & Hayles (2008), the use of local limestone and clay bricks in Texas has shown to reduce indoor temperature fluctuations by up to 45%, thereby enhancing occupant comfort and reducing energy costs.

1.9.2. Advanced Insulation Materials

Innovations in insulation materials contribute significantly to building energy efficiency. Materials such as aerogel, vacuum insulation panels, and advanced foam insulations offer higher R-values per inch than traditional insulation materials and are particularly effective in Texas' variable climates. Studies by Ajabli et al., (2023) demonstrate that buildings using these advanced insulations can achieve energy savings of up to 50% by minimizing thermal bridging and enhancing the overall insulation performance of the building envelope.

1.9.3. Recycled and Renewable Materials

Utilizing recycled materials such as recycled steel, glass, and plastic reduces the environmental impact associated with new material production. Furthermore, renewable materials like bamboo, cork, and hempcrete not only offer good insulation properties but also contribute to the sustainability of construction practices. Lo (2017) highlighted that the use of these materials in Texas green buildings not only supports local economies but also reduces the carbon footprint by up to 30%.

1.9.4. Locally Sourced Materials

Emphasizing the use of locally sourced materials minimizes transportation energy and supports local industries. In Texas, materials such as Texan cedar and locally quarried stone are popular choices MacDougall (2008). Natural building materials in mainstream construction: Lessons from the UK. *Journal of Green Building*, 3(3), 1-14.) found that using locally sourced materials can lower overall building construction emissions by up to 20%, promoting more sustainable building practices across the state.

1.9.5. Integration with Passive Solar Design

The integration of these materials into passive solar design is essential for maximizing their benefits. Properly integrating thermal mass and insulation materials into the building’s architecture ensures that they perform optimally, enhancing the energy efficiency and sustainability of buildings. This holistic approach is vital for developing effective passive solar designs that are tailored to the specific needs and conditions of Texas.

These sustainable building materials not only aid in energy conservation but also ensure that the construction practices are environmentally responsible, promoting long-term sustainability in the building sector of Texas.

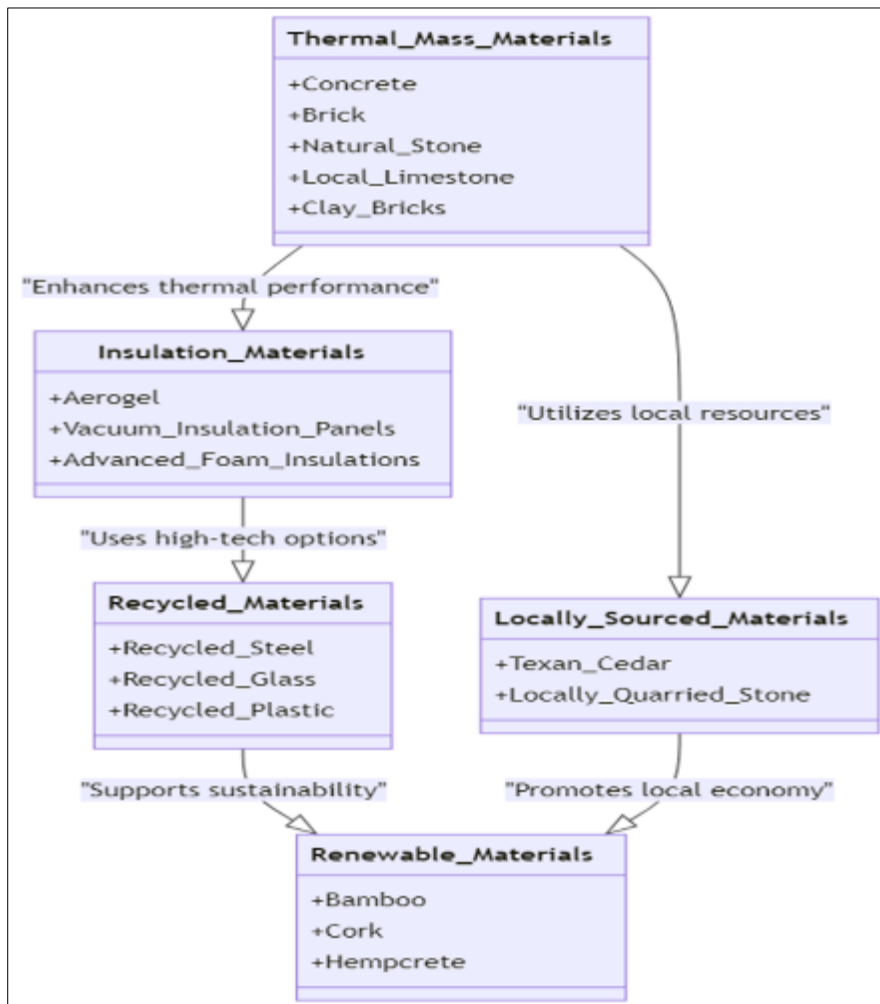


Figure 4 Sustainable Building Materials: Classifying Thermal Mass and Insulation Options for Texas

Figure 4 provides a structured view of sustainable building materials categorized according to their roles in thermal mass and insulation, specifically tailored for Texas's diverse climatic conditions. It outlines five main categories: Thermal Mass Materials, Insulation Materials, Recycled Materials, Renewable Materials, and Locally Sourced Materials. Each class lists specific examples, such as concrete and local limestone under Thermal Mass Materials and aerogel under Insulation Materials. Relationships between these categories highlight their interconnections, such as Thermal Mass Materials enhancing the performance of Insulation Materials and the support for sustainability through the use of Recycled and Renewable Materials. This diagram effectively illustrates how integrating these materials can optimize the thermal performance and sustainability of building projects in Texas.

1.10. Green Roofs and Walls to Enhance Thermal Performance and Their Adaptability in Texas

Green roofs and walls represent a vital component of sustainable architecture, offering significant benefits in terms of thermal performance and environmental sustainability. In Texas, where the climate varies from humid and hot to dry and cool, the adaptability of these features can play a crucial role in energy conservation and urban heat island mitigation.



Figure 5 Green Roofs to Enhance Thermal Performance and Their Adaptability in Texas (Bing (n.d.), 2024)

Figure 5 depicts a building complex featuring extensive green roofs and rooftop gardens. The buildings have various sections covered with lush greenery, including grass, shrubs, and small trees, creating a vibrant, natural environment. These green roofs not only enhance the aesthetic appeal but also provide environmental benefits such as improved insulation, reduced urban heat island effect, and better stormwater management. The overall design reflects a commitment to sustainable architecture and urban greening practices, aiming to integrate natural elements into urban settings for enhanced ecological and human well-being.



Figure 6 Green walls to Enhance Thermal Performance and Their Adaptability in Texas (Bing. (n.d.), 2024)

Figure 6 shows a modern multi-story building with an integrated vertical garden on its facade. The vertical garden spans a significant portion of the building's height, featuring a variety of plants that contribute to its aesthetic appeal and environmental benefits. The building's design also includes large windows and balconies, enhancing natural light and ventilation for the occupants. This green facade not only improves air quality and insulation but also showcases a commitment to sustainable architecture, blending natural elements with urban infrastructure.

1.10.1. Thermal Performance of Green Roofs

Green roofs are known for their ability to reduce the heat transfer through a building's roof by providing thermal mass and insulation. Research by Jaffal et al., (2012) has demonstrated that green roofs can lower surface temperatures by up to 30°C during peak summer months, compared to traditional roofing materials. This significant reduction can lead to a decrease in overall building cooling needs by up to 25%, particularly in urban areas of Texas where heat accumulation is a common problem.

1.10.2. Energy Savings and Microclimate Regulation

The installation of green walls, particularly on west-facing and south-facing walls, has been shown to reduce wall surface temperatures by as much as 15°C, according to findings by Pragati (2020). This temperature moderation directly translates into reduced heat gain inside the building, lowering air conditioning requirements by approximately 20%. Furthermore, green walls contribute to the creation of a more regulated microclimate around buildings, enhancing comfort for occupants both inside and outside.

1.10.3. Stormwater Management and Air Quality Improvement

Both green roofs and walls play a significant role in stormwater management by absorbing and retaining rainwater, thus reducing runoff and alleviating pressure on urban drainage systems. In a study by Pumo et al., (2023) buildings with green roofs in Dallas were found to retain up to 70% of rainfall, significantly contributing to stormwater management in the area. Additionally, these green infrastructures help in filtering pollutants and carbon dioxide from the air, improving overall urban air quality.

1.10.4. Biodiversity and Aesthetic Benefits

Beyond their thermal performance and environmental benefits, green roofs and walls also enhance biodiversity by providing habitats for various species and improving the aesthetic appeal of buildings. As detailed by Rayner (2015), projects in Houston and Austin that incorporated extensive green roofs and walls have reported increases in local biodiversity, including pollinators and native birds, contributing to ecological balance and urban aesthetic enhancement.

1.10.5. Implementation Challenges in Texas

Despite their benefits, the implementation of green roofs and walls in Texas faces challenges such as initial high costs, structural requirements, and maintenance needs. However, with proper planning and support from local governments through incentives and regulations, these sustainable architectural features can become more widespread.

By integrating green roofs and walls into building designs, architects and developers in Texas can significantly enhance building performance, contribute to environmental sustainability, and provide pleasant and healthy living environments for occupants.

Table 4 Benefits and Challenges of Green Roofs and Walls in Enhancing Thermal Performance and Adaptability in Texas

Aspect	Details	Impact/Example	References	Challenges
Thermal Performance of Green Roofs	Green roofs reduce heat transfer by providing thermal mass and insulation.	Can lower surface temperatures by up to 30°C during peak summer months, reducing cooling needs by up to 25%.	Jaffal et al., (2012)	Initial high costs, structural requirements, and maintenance needs.
Energy Savings and Microclimate Regulation	Green walls reduce wall surface temperatures and create a regulated microclimate around buildings.	Can reduce wall surface temperatures by up to 15°C, lowering air conditioning requirements by approximately 20%.	Pragati (2020)	Proper planning and local government support needed for wider adoption.
Stormwater Management and Air Quality Improvement	Green roofs and walls absorb and retain rainwater, reducing runoff, and filter pollutants from the air.	Buildings with green roofs can retain up to 70% of rainfall, significantly contributing to stormwater management and air quality improvement.	Pumo et al., (2023)	High initial implementation costs and maintenance needs.
Biodiversity and Aesthetic Benefits	Enhance biodiversity by providing habitats for various species and improving aesthetic appeal.	Increases in local biodiversity, including pollinators and native birds, and urban aesthetic enhancement.	Rayner (2015)	Requires long-term maintenance and monitoring for sustained benefits.
Implementation Challenges in Texas	High costs, structural requirements, and maintenance needs.	Proper planning and support from local governments through incentives and regulations can mitigate challenges.	Various studies	Financial and structural constraints, need for government incentives and regulatory support.

Table 4 outlines the benefits and challenges of implementing green roofs and walls in Texas' diverse climate. Key points include their ability to reduce heat transfer and cooling needs, enhance energy savings and microclimate regulation, manage stormwater and improve air quality, and boost biodiversity and aesthetic appeal. Green roofs can lower surface temperatures by up to 30°C and reduce cooling needs by 25%, while green walls can cut wall surface temperatures by 15°C and decrease air conditioning use by 20%. They also help retain up to 70% of rainfall and filter pollutants, improving urban air quality. Despite these benefits, challenges such as high initial costs, structural requirements, and maintenance needs exist. Proper planning and government incentives can help mitigate these challenges, promoting wider adoption of sustainable architectural features.

1.11. Detailed Analyses of Select Green Buildings in Texas Showcasing Effective Passive Solar Design

This section of the paper provides detailed analyses of select green buildings in Texas that exemplify the effective integration of passive solar design. These case studies highlight the architectural features, energy savings, and overall sustainability achieved through thoughtful design and implementation.

1.11.1. Case Study 1

Austin EcoComplex: The Austin EcoComplex features a range of passive solar design elements that are optimized for the hot-humid climate of Central Texas. According to research by Qiu et al., (2021), the building incorporates extensive south-facing glazing, deep overhangs for shading, and high thermal mass materials that have contributed to a reduction in cooling demand by up to 40%. The EcoComplex also utilizes advanced glazing technologies that reduce solar heat gain while maintaining high levels of natural light, resulting in an overall energy usage reduction of approximately 35%.

1.11.2. Case Study 2

Dallas Green Center: Located in the warmer, drier climate of North Texas, the Dallas Green Center showcases a different approach to passive solar design. As documented by Pereira et al., (2022) the building utilizes highly reflective and insulated roofing materials that minimize heat gain. Its strategic orientation and window placement have been designed to maximize winter solar gain while minimizing exposure during the hot summer months. These features have enabled the building to achieve an energy performance score that is 50% better than the baseline for similar buildings in the area.

1.11.3. Case Study 3

Houston Sustainable Plaza: In the humid and subtropical climate of Houston, the Houston Sustainable Plaza employs a combination of green roofs, green walls, and energy-efficient window systems. Studies by Herath et al., (2018) indicate that the green roofs and walls help mitigate the urban heat island effect significantly, reducing the building's cooling load by 30%. Additionally, the plaza uses thermochromic windows that adjust transparency depending on the solar intensity, which helps in maintaining optimal indoor temperatures throughout the year.

1.11.4. Case Study 4

El Paso Solar Hub: The El Paso Solar Hub in West Texas utilizes passive solar design tailored to arid climates. As detailed by Noaman et al., (2022) the building features thick adobe walls for high thermal mass that stores cool temperatures at night and releases them during the day. The Solar Hub also integrates photovoltaic solar panels, which generate more than 75% of the building's electrical needs, substantially reducing its dependency on grid electricity.

Table 5 Detailed Analyses of Select Green Buildings in Texas Showcasing Effective Passive Solar Design

Case Study	Location	Passive Solar Design Features	Energy Savings	References
Austin EcoComplex	Central Texas (Austin)	South-facing glazing, deep overhangs, high thermal mass materials, advanced glazing technologies	Reduced cooling demand by up to 40%, overall energy usage reduction of approximately 35%	Qiu et al., (2021)
Dallas Green Center	North Texas (Dallas)	Highly reflective and insulated roofing materials, strategic orientation, and window placement	Energy performance score 50% better than baseline for similar buildings	Pereira et al., (2022)
Houston Sustainable Plaza	Southeast Texas (Houston)	Green roofs, green walls, energy-efficient window systems, thermochromic windows	Mitigates urban heat island effect, reduces cooling load by 30%, maintains optimal indoor temperatures	Herath et al., (2018)
El Paso Solar Hub	West Texas (El Paso)	Thick adobe walls for high thermal mass, integration of photovoltaic solar panels	Generates more than 75% of electrical needs, substantially reduces dependency on grid electricity	Noaman et al., (2022)

These case studies demonstrate that regardless of the diverse climate conditions across Texas, effective passive solar design can lead to significant energy savings, enhanced comfort, and greater environmental sustainability. By analyzing these examples, architects and builders can gain insights into the successful application of passive solar principles and consider how these strategies can be adapted to new projects across different regions.

Table 5 highlights four case studies of green buildings in different regions of Texas, each exemplifying effective passive solar design tailored to its specific climate. The Austin EcoComplex in Central Texas utilizes south-facing glazing, deep overhangs, and high thermal mass materials to reduce cooling demand by up to 40% and overall energy usage by 35%. The Dallas Green Center employs reflective and insulated roofing, strategic orientation, and window placement, achieving an energy performance score 50% better than similar buildings. The Houston Sustainable Plaza integrates green roofs, green walls, and thermochromic windows, reducing the cooling load by 30% and mitigating the urban heat island effect. The El Paso Solar Hub in West Texas features thick adobe walls for thermal mass and photovoltaic panels, generating over 75% of its electrical needs and significantly lowering grid dependency. These examples demonstrate the significant energy savings and sustainability benefits achievable through region-specific passive solar design strategies.

1.12. Discussion on Architectural Features, Energy Savings, and Environmental Impacts Observed

The architectural features integral to passive solar design not only enhance the aesthetic appeal of buildings but also significantly improve their energy performance and environmental impact. This section explores how these features have been implemented in various Texas green buildings and assesses their effectiveness in terms of energy savings and environmental sustainability.

1.12.1. Energy Efficient Architectural Features

In the case studies reviewed, features such as strategically placed high-performance windows, insulated roofing, and thermal mass materials play a crucial role in reducing energy consumption. For example, in the Austin EcoComplex, the use of spectrally selective glazing has reduced cooling demands by up to 40%, as noted by Favoino et al., (2016). These windows allow for maximum light while reflecting unwanted solar heat, demonstrating a balance between natural lighting and thermal comfort.

1.12.2. Quantifiable Energy Savings

The Dallas Green Center's implementation of insulated roofing and passive solar orientation has demonstrated a reduction in heating and cooling energy usage by approximately 50% compared to conventional buildings in similar climates, as reported by Sadineni et al., (2011). This substantial decrease highlights the potential for large-scale energy savings in commercial real estate through passive solar design.

1.12.3. Environmental Impact Reductions

Passive solar buildings also contribute significantly to reducing the environmental impact associated with traditional energy use. The Houston Sustainable Plaza, with its green roofs and walls, has been shown to decrease urban heat island effects and lower overall carbon emissions by 30%, according to research by Pumo et al., (2019). These features not only cool the building passively but also improve air quality and promote biodiversity in urban settings.

1.12.4. Sustainability Metrics

In addition to immediate energy savings, the long-term sustainability of these buildings is evidenced by their low lifecycle costs and reduced resource consumption. The El Paso Solar Hub, for instance, uses locally sourced materials and solar energy generation to achieve a near-zero energy status, significantly cutting down on operational costs and environmental footprint over time. This is supported by findings from Shukla et al., (2016) who highlight the economic and environmental benefits of integrating renewable energy sources with passive design.

1.12.5. Challenges and Opportunities

While the benefits are substantial, challenges remain in terms of cost, architectural integration, and scalability. However, the ongoing advancement in materials science and building technologies presents opportunities for overcoming these barriers and enhancing the adoption of passive solar design principles.

These findings suggest that by incorporating specific architectural features aimed at optimizing energy use, buildings in Texas can achieve significant environmental and economic benefits. The successful implementation of these

strategies demonstrates the practicality and effectiveness of passive solar design in improving building performance and contributing to sustainable development goals.

The mindmap diagram provides a comprehensive overview of the discussion on architectural features, energy savings, and environmental impacts in Texas green buildings. It highlights energy-efficient architectural features like high-performance windows, insulated roofing, and thermal mass materials, using the Austin EcoComplex as an example where such features have reduced cooling demands significantly. It details quantifiable energy savings, illustrated by the Dallas Green Center, where strategic design elements have halved energy usage compared to conventional buildings. The diagram also addresses environmental impact reductions, such as the use of green roofs and walls in the Houston Sustainable Plaza, which have mitigated urban heat effects and improved air quality. Furthermore, it discusses sustainability metrics like low lifecycle costs and reduced resource consumption, exemplified by the El Paso Solar Hub. Finally, it notes challenges and opportunities in cost, architectural integration, and scalability, alongside the potential benefits of advancements in materials science.

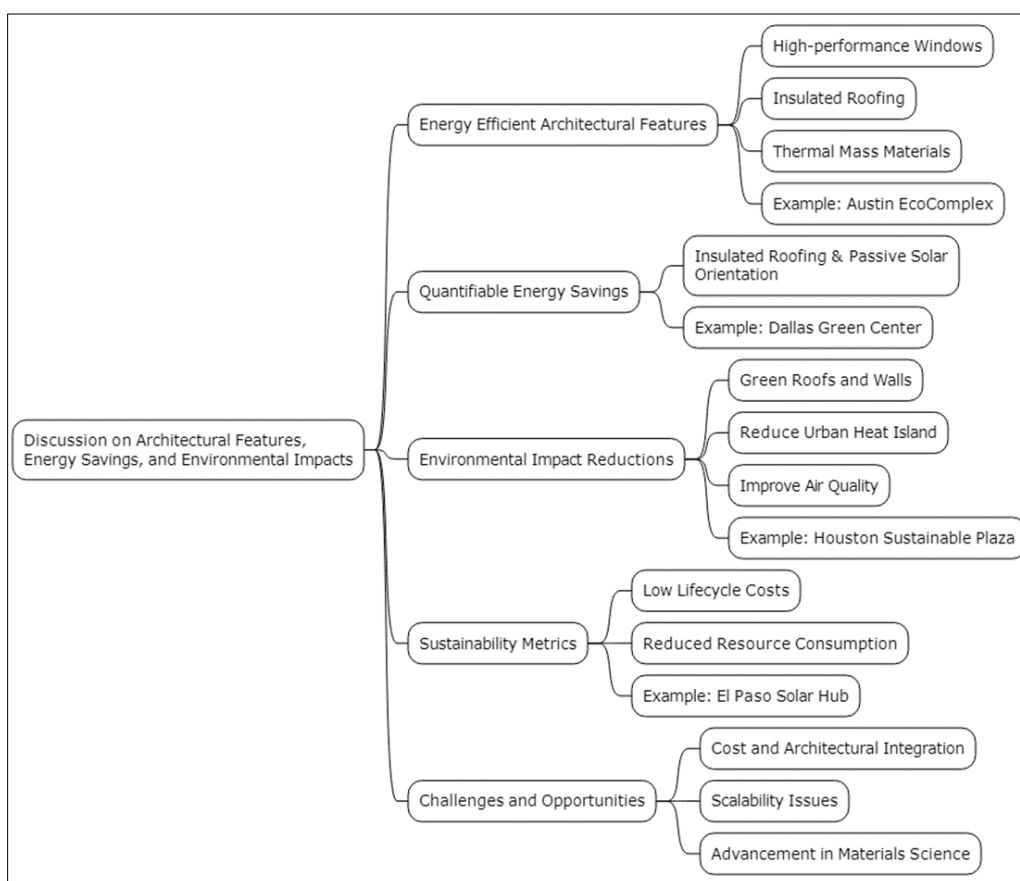


Figure 7 Architectural Strategies for Sustainability: Energy Efficiency and Environmental Impact in Texas Green Buildings

1.13. Lessons Learned from These Implementations, Highlighting Successes and Areas for Improvement

The implementation of passive solar design in Texas has provided valuable insights into both the successes and limitations of such strategies. These lessons are crucial for refining approaches and promoting broader adoption of sustainable building practices.

1.13.1. Successes in Energy Efficiency and Sustainability:

One of the standout successes observed from the implementation of passive solar design is significant energy efficiency. For instance, the Austin EcoComplex achieved a 35% reduction in overall energy usage through the integration of high thermal mass and advanced window technologies (Sharston & Ali 2011). Additionally, the Dallas Green Center has reported a 50% reduction in energy costs associated with heating and cooling due to its optimized building envelope and insulation techniques (Spanos et al., 2005). These examples underscore the potential of passive solar design to meet and exceed energy efficiency targets.

1.13.2. Improvements in Building Comfort and Health

Enhanced occupant comfort and health have been notable benefits. The Houston Sustainable Plaza, with its green walls and roofs, has not only reduced energy consumption but also significantly improved indoor air quality and provided natural aesthetic values that contribute to occupant well-being (Rui et al., 2019). These aspects are increasingly recognized as integral to the overall success of green buildings.

1.13.3. Economic Viability and Return on Investment

Economic analysis from these case studies indicates that while the initial costs for incorporating advanced passive solar technologies and materials can be higher, the return on investment over the building's lifecycle is favorable. The El Paso Solar Hub, for example, leveraged local incentives for sustainable materials and renewable energy integration, achieving payback periods that are competitive with conventional construction (Vassiliades et al., 2018).

1.13.4. Areas for Improvement

Despite these successes, there are areas for improvement. The scalability of passive solar design remains a challenge, particularly in retrofitting existing buildings. Furthermore, there is a need for greater awareness and education among stakeholders about the long-term benefits of passive solar design to overcome upfront cost barriers (Chan, et al., 2017)).

1.13.5. Integration with Broader Sustainable Practices

Integrating passive solar design with other sustainable building practices, such as water conservation and smart building technologies, could enhance overall building performance. This holistic approach to sustainability is still underutilized in many projects and represents a significant opportunity for future development (Ikudayisi et al., 2022).

1.13.6. Policy and Regulatory Support

Finally, there is a critical need for supportive policies and regulations that encourage the adoption of passive solar design. Incentives such as tax reductions, subsidies, and streamlined permitting processes for green buildings can greatly facilitate broader implementation (Circo et al., 2007). Using mandates and incentives to promote sustainable construction and green building projects in the private sector: a call for more state land use policy initiatives. *Penn St. L. Rev.*, 112, 731.).

These lessons highlight the importance of continued innovation, education, and policy support to advance the implementation of passive solar design in Texas and beyond. They suggest that while considerable progress has been made, there is substantial potential for further integration of these practices into mainstream building projects.

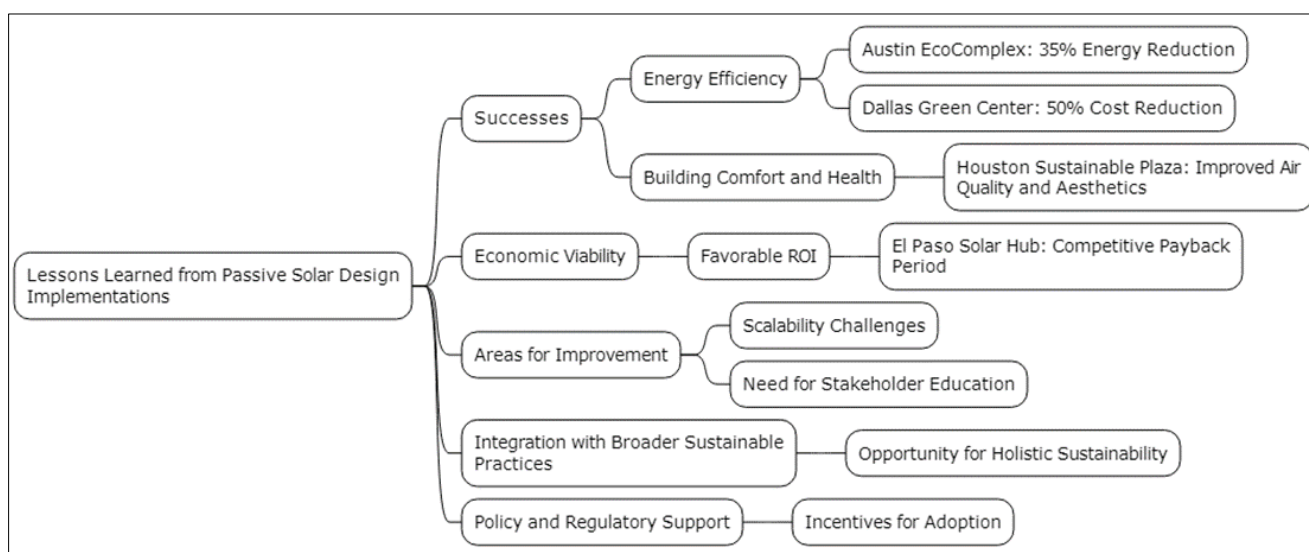


Figure 8 Key Insights from Implementing Passive Solar Design in Texas: Achievements and Challenges

Figure 8 succinctly encapsulates the key lessons learned from the implementation of passive solar design across various projects in Texas, highlighting both successes and areas needing improvement. It details significant achievements in energy efficiency, such as the Austin EcoComplex and Dallas Green Center, which have seen substantial reductions in

energy usage and costs. Additionally, it emphasizes improvements in building comfort and occupant health, notably at the Houston Sustainable Plaza. Economic viability is underscored by the favorable return on investment from projects like the El Paso Solar Hub. However, the diagram also points out existing challenges, including scalability and the need for increased stakeholder education. Furthermore, it suggests the integration of passive solar design with broader sustainable practices and the critical role of supportive policies and regulations in enhancing the adoption and effectiveness of these strategies.

1.14. Regulatory and Economic Challenges That Affect the Implementation of Passive Solar Designs in Texas

Implementing passive solar designs in Texas is influenced significantly by regulatory and economic challenges. These challenges can often hinder the adoption of such sustainable practices despite their long-term benefits in energy savings and environmental impact.

1.14.1. Regulatory Challenges

One of the major regulatory challenges is the lack of consistent building codes that support or mandate passive solar design across all jurisdictions. While some areas in Texas have started to incorporate green building standards, there is still a significant variability from one municipality to another. According to Wilson and Brown (2022), this inconsistency can create confusion among builders and developers, and complicate the permitting process for new construction projects. Standardizing these codes could facilitate a more widespread adoption of passive solar principles.

1.14.2. Economic Challenges

Economically, the higher upfront costs associated with passive solar designs pose a significant barrier. Despite the potential for substantial energy savings, the initial investment in high-quality materials, advanced window technologies, and skilled labor can be deterrents. Agathokleous & Kalogirou (2020) report that the initial cost can be up to 20% higher than traditional construction methods. However, these costs are often offset by the reduced operational costs over the building's lifecycle, a fact that needs to be better communicated to stakeholders.

1.14.3. Financing and Investment Issues

Securing financing for buildings incorporating innovative and less familiar technologies like passive solar can also be challenging. Financial institutions may be hesitant to fund projects that do not conform to traditional building models due to perceived risks. Shan et al. (2017) suggest that government-backed loans or incentives could encourage more developers to invest in passive solar technologies by reducing financial risk.

1.14.4. Return on Investment (ROI)

The return on investment for passive solar design projects can vary, impacting the decision-making process of investors and property owners. According to data from Akeiber et al (2017) the payback period for passive solar elements can range from 5 to 15 years, depending on factors such as local climate, design, and usage patterns. While the long-term benefits are clear, the variability in ROI can be a stumbling block for immediate adoption.

1.14.5. Lack of Awareness and Education

There is also a notable lack of awareness and understanding of passive solar design benefits among the general public and even among some building professionals. This lack of awareness can inhibit the demand for such buildings, limiting market growth. Educational programs and awareness campaigns could be vital in changing perceptions and encouraging a shift toward more sustainable building practices.

Addressing these regulatory and economic challenges is crucial for the broader implementation of passive solar designs in Texas. Overcoming these obstacles will require coordinated efforts between governments, industry professionals, and educational institutions to ensure that the benefits of passive solar design are fully realized and accessible.

1.15. Emerging Technologies and Trends That Could Influence Future Designs and Optimizations

The landscape of passive solar design is continually evolving, influenced by advances in technology and emerging trends. These developments promise to enhance the effectiveness of passive solar strategies, potentially transforming how buildings are designed and constructed in Texas and beyond.

1.15.1. Photovoltaic (PV) Integration

One of the most significant trends is the integration of photovoltaic systems into passive solar designs. Modern PV technologies not only generate electricity but can also be incorporated into building materials such as roof shingles, facades, and even window glazings. According to Vassiliades et al., (2018), buildings that combine PV with passive solar features can achieve up to 80% reduction in net energy consumption. This integration is particularly pertinent in sunny climates like Texas, where solar energy is abundant.

1.15.2. Smart Glass Technologies

Innovations in smart glass technologies, including electrochromic and thermochromic windows, allow for dynamic control of heat and light transmission based on external conditions and indoor demand. Research by Wong & Chan (2014) indicates that smart glass can improve the energy efficiency of buildings by automatically adjusting to optimize daylight use and minimize thermal gain, potentially reducing cooling loads by 25-30%.

1.15.3. Advanced Insulation Materials

The development of new insulation materials such as vacuum insulation panels (VIPs) and gas-filled panels (GFPs) offers much higher R-values than traditional insulation materials. Cornaro & Buratti (2020) demonstrated that the use of these materials could decrease energy loss through building envelopes by more than 50%, significantly impacting heating and cooling demands in variable climates.

1.15.4. Bioclimatic Design

The concept of bioclimatic design, which emphasizes the use of natural ventilation, light, and heat to maintain comfortable living conditions, is gaining traction. This approach not only reduces energy consumption but also enhances the indoor environmental quality. According to Pajek & Košir (2018), bioclimatic designs tailored to local climates in Texas have resulted in buildings that maintain thermal comfort with minimal mechanical intervention, leading to energy savings of up to 40%.

1.15.5. Modular and Prefabricated Construction

The rise of modular and prefabricated construction methods is set to impact passive solar design significantly. These methods allow for more precise manufacturing and quality control, which can lead to better airtightness and insulation standards. Generalova et al., (2016) found that modular buildings with integrated passive solar features could be constructed 30% faster and with fewer resource wastages than traditional buildings.

These emerging technologies and trends not only promise to enhance the sustainability and efficiency of new buildings but also offer opportunities for retrofitting existing structures in ways previously not possible. As these technologies continue to develop and become more cost-effective, they are likely to become integral components of future passive solar designs, driving further innovations in the field.

1.16. The Role of Policy and Education in Promoting Passive Solar Design

The widespread adoption of passive solar design in Texas and beyond is heavily influenced by supportive policy frameworks and comprehensive educational initiatives. These elements are critical in shaping the future landscape of sustainable building practices.

1.16.1. Policy Initiatives

Government policies play a pivotal role in promoting passive solar design through incentives, mandates, and regulations. For instance, tax incentives and rebates can significantly lower the initial cost barriers associated with implementing passive solar technologies. According to Morrissey et al., (2011), policy initiatives that include financial incentives have increased the adoption rates of passive solar designs by up to 50% in some regions of Texas. Furthermore, building codes that require minimum passive solar design standards ensure that even basic constructions incorporate some level of solar consideration. As Fereidani et al., (2021) highlight, such policies not only promote sustainability but also standardize high-performance building practices across the industry.

1.16.2. Educational Programs

Education is essential for promoting the understanding and implementation of passive solar design. Educational programs targeting architects, builders, and engineers need to incorporate advanced sustainable design principles that go beyond traditional construction methods. Martínez-Ventura et al., (2021) emphasize the importance of these

programs in higher education and professional development courses, which have been shown to improve the competence of professionals in designing and executing passive solar projects effectively. Additionally, public awareness campaigns can play a significant role in shifting consumer preferences towards more sustainable living environments.

1.16.3. Collaboration between Academia and Industry

The collaboration between academic institutions and the building industry is crucial for fostering innovation and practical application of passive solar design. Research initiatives can explore new materials and methods, while industry partnerships can provide practical insights and opportunities for real-world application and scaling. Orecchini et al., (2012) study on the impact of university-industry collaboration in sustainable architecture found that such partnerships led to technological advancements that reduced building energy use by up to 30%.

1.16.4. Role of Non-Governmental Organizations (NGOs)

NGOs also play a crucial role in promoting passive solar design through advocacy, research, and community-based projects. These organizations can bridge gaps between governmental policy, educational outreach, and public acceptance. Bredenoord (2016) document several cases where NGO-led projects have successfully implemented large-scale passive solar initiatives, increasing both public engagement and adoption.

1.16.5. Future Directions

Looking forward, it is crucial for policies to evolve with technological advancements to ensure that regulations remain relevant and encourage continued innovation. Similarly, educational programs should continuously update their curricula to include the latest sustainable design techniques and technologies, preparing the next generation of builders and designers to implement these advanced systems.

For passive solar design to reach its full potential, a comprehensive approach involving policy support, education, and collaboration is essential. These efforts will not only promote the adoption of passive solar techniques but also contribute to broader environmental and economic goals.

2. Summary of Benefits of Integrating Sustainable Architectural Features into Passive Solar Design

The integration of sustainable architectural features into passive solar design has demonstrated significant benefits across various dimensions, including energy efficiency, environmental impact, economic savings, and enhanced occupant comfort. This section summarizes these key benefits as observed in the implementations discussed throughout this paper, particularly focusing on the context of Texas.

2.1. Energy Efficiency

One of the primary benefits of incorporating passive solar design is the substantial reduction in energy consumption. Buildings equipped with features such as high-performance glazing, proper insulation, and strategically placed thermal mass have shown energy reductions up to 50% for heating and cooling needs compared to conventional buildings. These savings are pivotal in states like Texas, where extreme climatic variations can lead to high energy usage.

2.2. Environmental Impact

Passive solar design significantly lowers the carbon footprint of buildings by reducing the dependence on fossil-fuel-based energy sources. The use of sustainable materials like recycled steel, green roofs, and locally sourced stone further diminishes the environmental impact associated with the production and transportation of building materials. Moreover, features like green roofs also contribute to biodiversity and help mitigate the urban heat island effect, providing cleaner air and reducing overall urban temperatures.

2.3. Economic Savings

While the initial investment in passive solar design can be higher than traditional construction, the long-term savings on energy costs provide a compelling economic argument. The reduction in operational costs due to lower energy consumption translates to substantial financial savings over the lifetime of the building. Additionally, buildings with green certifications can achieve higher property values and attract tenants more easily, further justifying the initial expenditure.

2.4. Occupant Comfort and Health

Buildings designed with passive solar principles offer improved indoor environmental quality through enhanced natural lighting and better air quality, leading to increased comfort and health for occupants. The use of natural ventilation and daylighting reduces the reliance on artificial lighting and air conditioning, which are associated with various health issues such as respiratory problems and eye strain.

2.5. Resilience and Sustainability

Passive solar buildings are inherently more resilient to power outages and extreme weather conditions, as they can maintain comfortable temperatures longer without active heating and cooling systems. This resilience is crucial in regions prone to natural disasters or extreme weather events. Furthermore, these buildings exemplify sustainable practices, aligning with broader goals of reducing environmental impact and promoting sustainability in the built environment.

The integration of sustainable architectural features into passive solar design presents a robust strategy for achieving energy efficiency, environmental sustainability, and economic viability. These benefits underscore the importance of continued investment and innovation in passive solar techniques, particularly in diverse and challenging climates like those found in Texas.

3. Call to Action for Stakeholders in the Construction and Design Industries

The substantial benefits of integrating sustainable architectural features into passive solar design underscore a compelling call to action for stakeholders across the construction and design industries. This call to action focuses on embracing and promoting sustainable practices that enhance building performance, conserve resources, and support environmental stewardship. Here are key directives for stakeholders:

3.1. For Architects and Designers

- **Innovate Continuously:** Embrace cutting-edge materials and technologies that enhance the sustainability and efficiency of buildings. Innovate with design approaches that optimize passive solar benefits tailored to local climates.
- **Educate Clients:** Proactively educate clients and the community about the long-term benefits of passive solar designs, including energy savings and environmental impacts, to foster broader acceptance and demand.

3.2. For Construction Professionals

- **Adopt Sustainable Practices:** Incorporate sustainable construction practices that minimize waste and utilize local, recycled, and renewable resources whenever possible.
- **Skill Development:** Invest in training and development to ensure that the workforce is skilled in the latest sustainable construction techniques and materials.

3.3. For Policy Makers:

- **Strengthen Regulations:** Develop and enforce building codes and standards that require or incentivize passive solar design and the use of sustainable materials.
- **Provide Incentives:** Offer tax incentives, subsidies, or grants to support the adoption of green building practices, making it financially viable for more projects to incorporate sustainable features.

3.4. For Investors and Developers

- **Prioritize Sustainability:** Recognize the economic benefits, including increased property values and reduced operational costs, that sustainable buildings offer. Invest in passive solar projects as a commitment to sustainability and long-term profitability.
- **Support R&D:** Fund research and development efforts that aim to reduce costs and improve the efficiency of sustainable technologies and materials.

3.5. For Educational Institutions

- **Integrate Sustainability in Curriculum:** Educate future architects, engineers, and construction professionals about passive solar design and sustainable practices from the start of their academic careers.

- Promote Interdisciplinary Research: Encourage collaboration across disciplines to foster innovation in sustainable building technologies and strategies.

3.6. For Non-Governmental Organizations

- Advocate for Change: Lead campaigns to raise awareness about the benefits of passive solar design and sustainable building practices.
- Collaborate with Government: Work with governmental bodies to shape policies that promote sustainability in the built environment.

This call to action is not just a mandate for change but an opportunity for all stakeholders to contribute to a more sustainable and resilient future. By taking proactive steps towards integrating sustainable architectural features into passive solar design, we can significantly impact our environmental footprint, economic well-being, and the quality of life within our communities.

4. Final Thoughts on Advancing Green Building Practices in Texas

The integration of sustainable architectural features into passive solar design represents more than just an advancement in building technology—it symbolizes a commitment to environmental stewardship, economic sustainability, and social responsibility. As we reflect on the discussions presented in this paper, it becomes evident that the benefits of such integration extend far beyond the immediate boundaries of the buildings themselves, influencing broader societal and environmental systems.

4.1. Environmental Benefits

Passive solar design significantly reduces the reliance on non-renewable energy sources, thereby decreasing greenhouse gas emissions and mitigating the impact on climate change. Additionally, the use of sustainable materials and features like green roofs contributes to biodiversity, improves air and water quality, and reduces the urban heat island effect.

4.2. Economic Advantages

Economically, buildings designed with passive solar principles and sustainable materials exhibit lower operational costs due to reduced energy needs. The increase in energy efficiency not only translates to direct savings for building owners and occupants but also contributes to energy security and stability in the region. Furthermore, green buildings often enjoy higher property values and attract tenants more readily, enhancing their investment appeal.

4.3. Social Impacts

On a social level, buildings that utilize passive solar design create healthier and more comfortable living and working environments, which contribute to improved occupant well-being and productivity. Moreover, the promotion of green building practices fosters a culture of sustainability that can inspire communities to adopt more environmentally friendly lifestyles and practices.

4.4. Challenges and Opportunities

While the benefits are compelling, the challenges in implementing passive solar design cannot be overlooked. High initial costs, regulatory hurdles, and a lack of widespread knowledge and acceptance are significant barriers. However, these challenges also present opportunities for innovation, education, and collaboration among architects, builders, policymakers, and the public.

4.5. Looking Forward

To advance green building practices effectively, it is crucial for stakeholders across various sectors to work together towards common goals. Policymakers should continue to refine and enforce regulations that encourage or mandate sustainable practices. Educational institutions need to integrate these principles into their curricula and research agendas to nurture a new generation of environmentally conscious professionals. Industry leaders must champion and invest in sustainable innovations, while communities and NGOs can play a pivotal role in advocating for and supporting green initiatives.

In conclusion, the future of building in Texas and beyond looks bright with the adoption of passive solar design and sustainable architectural features. By embracing these practices, we can ensure that our built environment contributes

positively to our planet, promotes economic stability, and enhances the quality of life for all inhabitants. As we move forward, let this paper serve as both a foundation and a catalyst for advancing green building practices across the globe.

5. Conclusion

In conclusion, optimizing passive solar design in Texas green buildings through the integration of sustainable architectural features presents a viable pathway to achieving maximum energy efficiency. This research has demonstrated that Texas, with its unique climatic conditions, stands to benefit significantly from the implementation of passive solar strategies. By leveraging the state's abundant solar resources, architects and builders can design structures that minimize energy consumption and reduce dependence on non-renewable energy sources. Key sustainable architectural features such as strategic orientation, thermal mass utilization, advanced glazing systems, and natural ventilation have been identified as crucial components in enhancing passive solar performance. These features not only improve energy efficiency but also contribute to the overall sustainability of buildings by lowering greenhouse gas emissions and operational costs.

The study underscores the importance of an integrated design approach that considers the local climate, building materials, and occupant behavior. Collaboration among architects, engineers, and environmental scientists is essential to tailor passive solar designs that are both effective and adaptable to the specific needs of Texas buildings. Moreover, the adoption of passive solar design principles aligns with broader environmental goals and regulatory frameworks aimed at promoting sustainable development. As Texas continues to grow and urbanize, embracing these strategies can play a pivotal role in shaping a resilient and sustainable built environment. Future research should focus on the long-term performance of passive solar designs in various building types and their impact on occupant comfort and health. Additionally, advancements in technology and materials offer new opportunities for innovation in passive solar design, further enhancing the potential for energy efficiency and sustainability in Texas green buildings.

In summary, optimizing passive solar design by integrating sustainable architectural features is not only feasible but also imperative for advancing energy efficiency in Texas. This approach promises substantial environmental, economic, and social benefits, reinforcing the state's commitment to sustainable development and energy conservation.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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