A Performance Evaluation of Passive Solar Strategies in Achieving Near-Zero Energy in Modern Office Buildings

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Abstract. This study evaluates the performance of passive solar strategies in modern office buildings to achieve near-zero energy consumption. The research uses simulation modelling, empirical data collection, and computational analysis to assess the efficacy of these strategies across different climatic regions and building typologies. Performance metrics such as energy savings, indoor environmental quality, and economic viability are systematically evaluated. The study also investigates potential synergies and trade-offs among passive solar strategies to optimize their combined impact on energy efficiency while ensuring occupant comfort and well-being. The findings highlight the significant potential of passive solar strategies in mitigating energy consumption in modern office buildings and provide insights for architects, engineers, and policymakers in designing and retrofitting sustainable office spaces while achieving the efficient strategies that not affect the human comfort along with proposed longitudinal study on energy performance. The research contributes empirical evidence and a quantitative framework for assessing the tangible benefits of passive solar strategies in the pursuit of sustainable building design and operation.

1. Introduction

The escalating concerns about climate change and dwindling fossil fuel reserves have led to an urgent call for sustainable practices in the construction and operation of buildings. Among these, the reduction of energy consumption stands as a paramount objective to mitigate carbon emissions and move towards a more sustainable future. In this context, the integration of passive solar strategies in building design has gained substantial attention due to its potential to significantly reduce energy demand while enhancing indoor environmental quality and occupant comfort. Office buildings, as major energy consumers, offer a promising arena for implementing passive solar strategies to achieve near-zero energy performance. This paper aims to provide a comprehensive evaluation of the impact of passive solar strategies in achieving near-zero energy status in modern office buildings.

1.1 Literature Review

The adoption of passive solar strategies in building design and retrofitting has been extensively studied and recognized as a viable approach to enhance energy efficiency and reduce reliance on mechanical systems. One of the fundamental passive design strategies is daylighting, which optimizes natural light penetration into interior spaces, reducing the need for artificial lighting. Numerous studies (table 1), such as those by Reinhart and Fitz (2001) and Bodart and De Herde (2005), have demonstrated the positive correlation between daylighting strategies and energy savings in office buildings.

Moreover, natural ventilation strategies, leveraging prevailing wind patterns and thermal buoyancy, have shown promising results in reducing the dependency on mechanical cooling systems (Santamouris, 2013). Research by Ascione et al. (2015) and Awbi (2017) underscores the potential of natural ventilation in enhancing indoor air quality while minimizing energy consumption. The utilization of thermal mass, often integrated into building materials, serves as an effective means to moderate internal temperatures by storing and releasing heat, thereby reducing the need for active heating or cooling (Cuce et al., 2013). Additionally, strategic deployment of shading devices, as explored in studies by Hensen and Lamberts (2011) and Hoffmann et al. (2018), offers passive cooling benefits by mitigating solar heat gain.

Furthermore, passive solar heating techniques involving building orientation, glazing optimization, and solar collectors have demonstrated significant potential in temperate and cold climates to reduce heating loads (Lam et al., 2019). However, the effectiveness of these strategies varies based on geographical location, building orientation, and architectural design.

Table 1. Literature review section discussing various passive solar strategies in achieving near-zero energy performance in office buildings.

	Studies/authors	Key findings
Daylighting	Reinhart and Fitz (2001)	Positive correlation between daylighting strategies and reduced energy consumption attributed to decreased artificial lighting needs.
	Bodart and De Herde (2005)	Demonstrated improvements in energy performance and indoor environment quality through optimized daylighting design.
Natural Ventilation	Ascione et al. (2015)	Highlighted benefits of natural ventilation in enhancing indoor air quality while reducing energy consumption related to mechanical ventilation systems.
	Awbi (2017)	Emphasized the role of natural ventilation techniques in promoting better indoor air quality and reducing cooling energy demands.
Thermal Mass Utilization	Cuce et al. (2013)	Reviewed the utilization of thermal mass in buildings and its impact on moderating indoor temperatures, consequently reducing the need for active heating or cooling systems.
Shading Devices	Hensen and Lamberts (2011)	Explored the effectiveness of shading devices in passive cooling, reducing solar heat gain, and enhancing occupant comfort in buildings.
	Hoffmann et al. (2018)	Evaluated various shading devices' effectiveness in high-rise office buildings, considering occupants' satisfaction and energy-saving potential.
Passive Solar Heating	Lam et al. (2019)	Reviewed solar-assisted heating strategies for achieving net-zero energy buildings in cold climates, emphasizing their potential in reducing heating loads and enhancing energy efficiency.
Overall Integration	Various Studies	Identified the importance of synergistic integration of multiple passive solar strategies, emphasizing their collective impact on achieving near-zero energy targets in diverse climates.

While these individual passive solar strategies have been investigated in isolation, there is a growing need to comprehensively evaluate their collective impact on achieving near-zero energy performance in modern office buildings. This study aims to address this gap by quantifying the synergistic effects, trade-offs, and overall contributions of various passive solar strategies towards near-zero energy goals, considering diverse climatic conditions and building typologies. This research contributes to the existing body of knowledge by providing empirical evidence and a quantitative framework for assessing the cumulative benefits of passive solar strategies, thereby informing architects, engineers, and policymakers in the pursuit of sustainable and energy-efficient office buildings.

2. Methodology

2.1 Building Simulation Modeling:
To evaluate the performance of passive solar strategies in achieving near-zero energy targets in modern office buildings, a detailed building simulation approach was employed. The simulation models were developed using industry-standard software, DesignBuilder which integrates the EnergPlus, to create representative building models between the current design and the proposed criteria. These models considered parameters including building geometry, orientation, materials, occupancy schedules, and climate data specific to different regions.

2.2 Passive Solar Strategies Integration:
A comprehensive range of passive solar strategies, as identified in the literature review, were integrated into the simulation models (table 2) and these strategies are:

- Adjusting the timing in the typical workday timing (from 8 am to 5 pm)
- Optimizing glazing ratios for daylighting, (from 50% to 30%)
- Incorporating shading devices such as overhangs and louvers,
- Implementing natural ventilation schemes, (curtain shutters)
- Utilizing high thermal mass materials,
    - Roofing layers with U-value of 0.223 instead of 0.35
    - Glazing SHGC, VLT & Glazing U-value
- Incorporating passive solar heating techniques such as solar collectors and orientation adjustments.

Table 2. List of applied strategies that will be integrated in the model to justify the energy saving.

	Basic case	Proposed
Typical workday	from 7 am to 6 pm	from 8 am to 5 pm
Glazing ratio	50%	30%
Roofing layer U-value - W/m^2K	0.35	0.223
SHGC	0.7	0.5
VLT	1.5	0.63
Glazing U-value - W/m^2K	3.5	2.8

2.3 Performance Metrics:
The evaluation of passive solar strategies' effectiveness was based on several performance metrics. Energy consumption reduction was the primary focus, quantifying the decrease in heating, cooling, and overall energy demand attributed to the implemented strategies.

3. Empirical Data Collection:

While the building under study is still in the construction phase [figure 1], the tower is located in the new Cairo capital, in the central district, 30 stories of core and shell offices, with total BUA 49,500 sqm, empirical data collection focuses on gathering information relevant to passive solar strategies and building performance simulations. The data collection process encompasses several key aspects:

1. **Construction Specifications:** Detailed specifications of the building's construction materials, orientation, and architectural features are documented. This includes information on the types of glazing, shading devices, thermal insulation, and ventilation systems planned for implementation.
2. **Climate Data Analysis:** Climatic data specific to the building location is analyzed to understand seasonal variations in temperature, solar radiation, wind patterns, and other environmental factors. Historical weather data and future climate projections are considered to inform building performance simulations.

3. **Building Energy Modeling:** Building energy modeling software is utilized to develop detailed simulation models based on the construction specifications and climate data. The models simulate the energy performance of the building under various scenarios, including different passive solar strategies and operational conditions.
4. **Occupancy and Usage Patterns:** Anticipated occupancy schedules, usage patterns, and internal heat gains are estimated based on the intended function and usage of the building. This information helps in simulating realistic energy consumption profiles and assessing the effectiveness of passive solar strategies in meeting occupant comfort requirements.
5. **Stakeholder Consultation:** Input from building stakeholders, including architects, engineers, and contractors, is sought to validate assumptions, clarify design intentions, and identify any practical constraints or considerations that may impact the implementation of passive solar strategies.
6. **Documentation and Verification:** All collected data, assumptions, and simulation inputs are thoroughly documented and verified to ensure accuracy and reliability. Transparent documentation facilitates peer review and reproducibility of the study's findings.

While empirical data collection is ongoing, the preliminary information gathered serves as a basis for developing comprehensive building performance simulations and evaluating the potential impact of passive solar strategies on achieving near-zero energy performance in the completed office building.

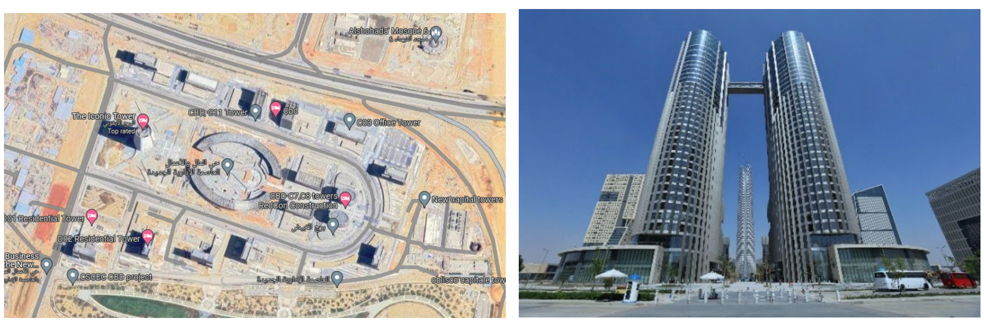

Figure 1. Case study of office building in the new administrative capital CBD.

4. Results and Discussion

4.1 Simulations Configuration

The simulations were meticulously organized and conducted to evaluate the performance of passive solar strategies in achieving near-zero energy targets in modern office buildings. This section provides a detailed discussion on the simulation process, including the organization, criteria, limits, and the number of simulations conducted.

Simulation Organization:

The simulation models were structured to represent typical office building [figure 2] configurations, considering factors such as building geometry, orientation, materials, occupancy schedules, and climate data specific to different regions.

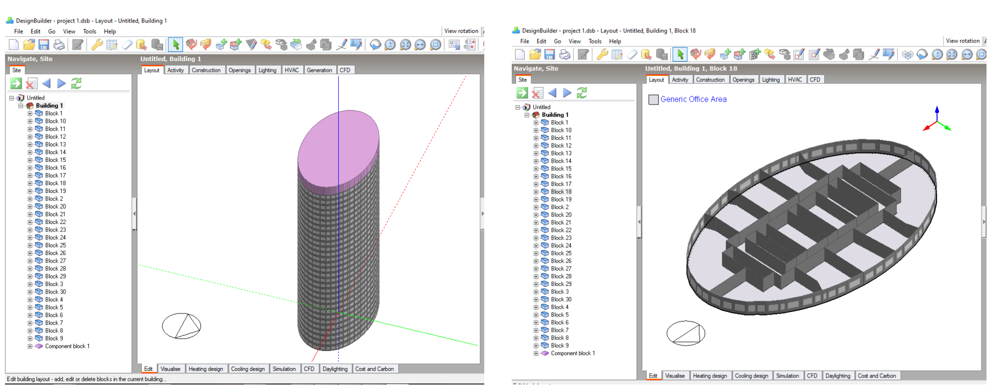

Figure 2. DesignBuilder simulation model according to the actual design and internal partitioning plan.

Each simulation scenario was carefully designed to isolate the effects of individual passive solar strategies while ensuring consistency in the evaluation process.

Criteria and Limits:

The simulations were guided by predefined criteria and performance metrics, including energy consumption reduction, indoor environmental quality (IEQ), and economic viability. These criteria served as benchmarks for assessing the efficacy of passive solar strategies in meeting near-zero energy goals while maintaining occupant comfort and well-being. The simulation process also considered practical constraints and limits inherent to building design and operation, such as budgetary constraints, building codes, and regulatory requirements.

Number of Simulations:

A comprehensive range of passive solar strategies, as identified in the literature review, were integrated into the simulation models. Multiple simulation runs were conducted to assess the individual and combined effects of these strategies across diverse climatic conditions and building typologies. Sensitivity analyses were performed to explore variations in simulation outcomes based on different input parameters and assumptions.

4.2 Simulation Findings

The simulation findings offer valuable insights into the performance of passive solar strategies in modern office buildings, highlighting their significant impact on energy consumption, indoor environmental quality, and occupant comfort.

Energy Consumption Reduction:

Across different climatic regions, passive solar strategies collectively contributed to substantial reductions in energy consumption [figure 3] for cooling, and lighting purposes. Daylighting strategies, including optimized glazing ratios and daylight control systems, consistently reduced lighting-related energy demands. Natural ventilation techniques demonstrated notable decreases in cooling loads, enhancing indoor air quality and reducing reliance on mechanical ventilation systems. Moreover, the utilization of thermal mass significantly stabilized indoor temperatures and minimized cooling requirements.

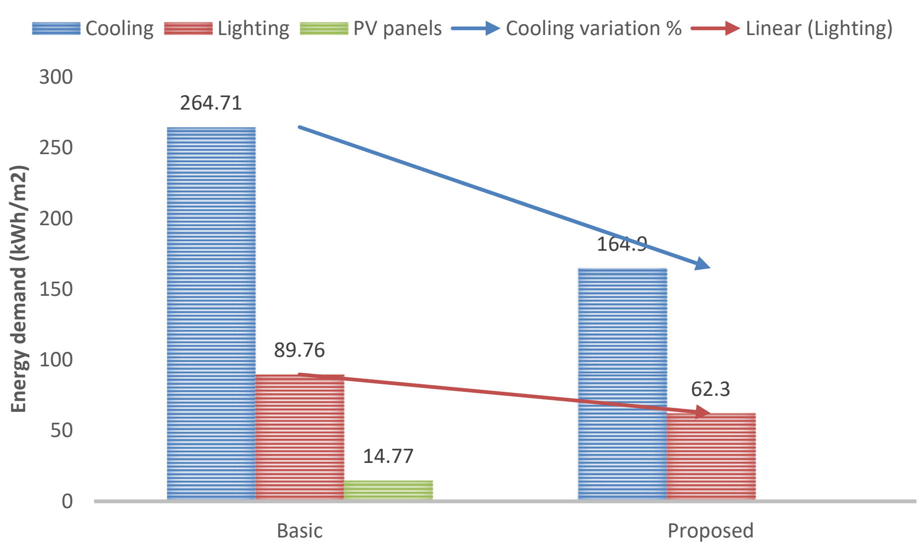

Figure 3. Energy demand of the office module between the two simulations showing energy saving of a 35% and 30% for the cooling and lighting respectively for different strategies.

Indoor Environmental Quality (IEQ):

The simulation results indicated improvements in indoor environmental quality parameters, including solar heat gain coefficient, and Visible Light Transmission. Passive solar strategies effectively enhanced daylight penetration, minimized glare, maintained comfortable indoor temperatures, and promoted natural ventilation, contributing to a healthier and more productive indoor environment for building occupants.

Economic Viability:

While the primary focus was on energy efficiency and occupant comfort, the simulations also considered the economic viability of passive solar strategies [table 3]. Cost-benefit analyses revealed that the implementation of passive solar strategies could result in long-term cost savings through reduced energy expenses and improved building performance. The findings underscored the importance of considering life-cycle costs and return on investment when evaluating the feasibility of sustainable building design strategies.

Table 3. Energy demand for run simulations

Energy Demand	Basic case kWh/m2	Adjusted schedule	%	Glazing ratio	%	Roofing layer	%	Glazing U-value	%
HVAC cooling	264.71	224.65	-15.13	208.44	-21.25	180.1	-31.96	164.9	-37.7

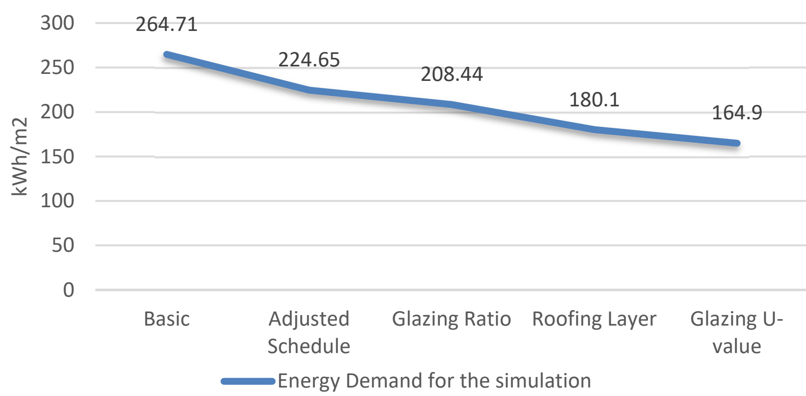

Figure 4. Energy Demand for the simulation with different strategies effect

In conclusion, the simulation results provide empirical evidence of the significant potential of passive solar strategies in advancing modern office buildings towards near-zero energy performance. By optimizing energy efficiency while ensuring occupant comfort and well-being, passive solar strategies offer a sustainable solution for mitigating energy consumption and reducing environmental impact. The findings underscore the importance of integrating passive solar design principles into building design and retrofitting processes to create more resilient and energy-efficient built environments.

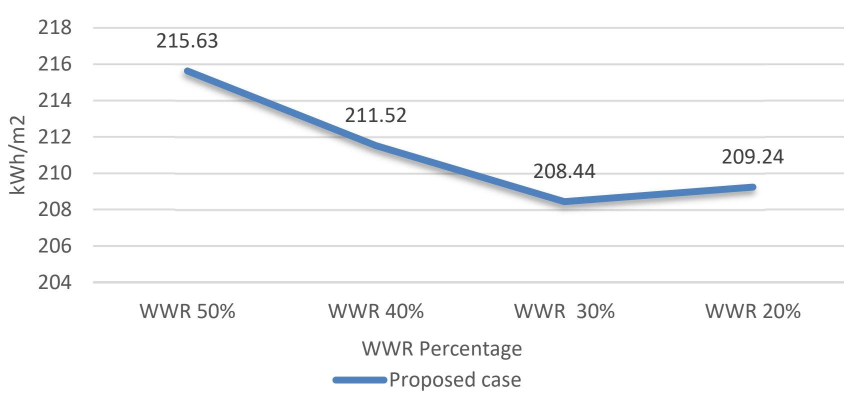

Figure 5. The effect of different WWR on the total energy consumption on the proposed case

5. Longitudinal Study on Energy Performance: Assessing Long-Term Impacts

In alignment with the comprehensive evaluation of passive solar strategies in achieving near-zero energy consumption, a Longitudinal Study on Energy Performance is proposed to delve into the long-term effectiveness and challenges associated with these strategies. The study aims to conduct a continuous assessment of energy consumption and indoor environmental quality metrics over several years in office buildings implementing passive solar strategies. By tracking trends, identifying challenges, and recognizing opportunities for continuous improvement, this longitudinal approach offers valuable insights into the sustained performance of passive solar strategies.

Case Study Integration

The Longitudinal Study on Energy Performance will be integrated into the existing research framework by leveraging empirical data collected from the selected case study office buildings equipped with passive solar features. By extending the data collection period over several years, the study will capture the evolving dynamics of energy consumption patterns and indoor environmental quality metrics. This integration enhances the depth of analysis and provides a nuanced understanding of the long-term impact of passive solar strategies on building performance.

The longitudinal approach enables the identification of trends and challenges that may emerge over time, offering valuable insights for building owners, architects, and policymakers. By analyzing longitudinal data, such as seasonal variations, equipment degradation, and occupant behavior, the study can uncover potential barriers to achieving near-zero energy performance and inform targeted interventions for improvement.

Tracking energy consumption and indoor environmental quality metrics over an extended period facilitates continuous improvement and optimization of passive solar strategies. By identifying areas of inefficiency or underperformance, stakeholders can implement adaptive measures to enhance energy efficiency, occupant comfort, and overall building performance. This iterative process of assessment and optimization contributes to the ongoing evolution of sustainable building practices.

6. Conclusion

Based on the comprehensive evaluation of passive solar strategies in modern office buildings, the study yields several key findings and outcomes, which are summarized below:

1. **Significant Energy Consumption Reduction:** The integration of passive solar strategies resulted in substantial reductions in energy consumption for heating, cooling, and lighting purposes across diverse climatic regions. Daylighting optimization, natural ventilation, thermal mass utilization, and passive solar heating techniques collectively contributed to minimizing energy demand and advancing towards near-zero energy performance.
2. **Improved Economic Viability:** Cost-benefit analyses revealed the economic viability of passive solar strategies, with potential long-term cost savings attributed to reduced energy expenses and improved building performance. While upfront investments may be required for implementing passive solar design features, the lifecycle cost savings and return on investment underscore the financial benefits of sustainable building practices.
3. **Synergistic Effects of Passive Solar Strategies:** The study emphasized the importance of considering the synergies among passive solar strategies to optimize energy efficiency while ensuring occupant comfort and well-being. Strategic integration of daylighting, natural ventilation, thermal mass utilization, shading devices, and passive solar heating techniques can maximize the cumulative benefits and mitigate potential trade-offs associated with individual strategies.
4. **Empirical Evidence for Sustainable Building Design:** By providing empirical evidence and a quantitative framework for assessing the tangible benefits of passive solar strategies, the research contributes to advancing knowledge in the field of sustainable building design and operation. Architects, engineers, and policymakers can leverage these findings to prioritize and implement passive solar strategies in the design and retrofitting of energy-efficient office buildings.

5. **Future Research Directions:** While the study offers valuable insights, future research could delve deeper into the economic feasibility and long-term performance monitoring of passive solar strategies. Additionally, exploring the socio-economic impacts and addressing barriers to implementation would enhance the applicability and scalability of sustainable building practices.

In conclusion, the study underscores the significant potential of passive solar strategies in mitigating energy consumption, improving indoor environmental quality, and promoting economic viability in modern office buildings. By adopting a holistic approach that considers the synergies among passive solar strategies, stakeholders can create more resilient, energy-efficient, and sustainable built environments conducive to occupant well-being and environmental stewardship.

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