ANALYSIS OF ENVIRONMENTALLY SUSTAINABLE PROJECTS IN THE FIELD OF GREEN ARCHITECTURE: USE OF NATURAL MATERIALS AND RENEWABLE ENERGY SOURCES

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Abstract: The article explores contemporary architectural trends focused on the establishment of sustainable and ecologically responsible environments. It scrutinizes projects incorporating natural building materials and renewable energy sources, evaluating their environmental impact and discerning their role in fostering sustainable development. Additionally, the article delves into alternative approaches for the utilization of materials during both the construction and operational phases of green buildings. A comprehensive analysis is presented, elucidating the intricacies of the "green building" concept, notable for its pronounced benefits in curtailing energy consumption for heating purposes. The salient characteristic of such structures lies in the integration of green design strategies and cutting-edge building materials. The article meticulously examines the efficacy of energy utilization within the context of a "green" architectural paradigm. Emphasis is placed on technologies and solutions conducive to diminishing energy expenditure, particularly in the domain of heating. This encompasses the deployment of renewable energy sources, optimal architectural configurations, and innovative engineering systems. The investigation reveals that the integration of green methodologies in construction is contingent not solely upon the reduction of energy consumption but also on the adoption of environmentally friendly and sustainable materials. Such materials not only serve to ameliorate the structural quality but also enhance the comfort of indoor spaces. The findings proffered by the analysis hold the potential to unveil novel avenues for the progressive refinement of green architecture and its application in construction

Keywords: Trombe wall, PV panels, Green building, Heat transfer, Energy efficiency.

1 Introduction

In recent years, the significance of green buildings has escalated concomitant with heightened interest in environmental concerns. Notably, both developed and developing nations have formulated distinct green building assessment systems and qualification methodologies. This trend signifies the pervasive adoption and acknowledgment of sustainable development principles within the construction industry. The concept of green building represents a contemporary approach in the construction, retrofitting, and operational phases of buildings, with a primary focus on leveraging advanced architectural solutions, engineering systems, and materials to curtail energy and material consumption. The primary objective involves the optimization of architectural structures to enhance the comfort and quality of indoor environments within buildings, concurrently mitigating impacts on the health of occupants. An integral consideration is the minimization of environmental ramifications throughout all phases of the life cycle of building structures. Broadly, green construction endeavors to diminish the aggregate environmental footprint of the construction industry. The advocacy for green building necessitates the formulation of guidelines and strategies to propel the development of the construction sector as a pivotal agent for transformative change.

The significance of construction and architecture in establishing conditions conducive to sustainable development is paramount, given their substantial influence on the configuration of our living spaces. The alignment of architecture with the natural environment is deemed an indispensable element in urban planning and architectural design. The escalating demand for housing engenders the intensive utilization of energy, resources, and raw materials, thereby contributing to heightened carbon emissions detrimental to the environment and human health. In the contemporary milieu, the multitude of adverse environmental effects necessitates the adoption of new technologies and materials in construction to mitigate the overall environmental impact. The preservation of urban ecology and the prudent utilization of finite energy resources are assuming growing significance. Developers are mandated to adopt enhanced and more sustainable building design methodologies to attenuate the deleterious environmental repercussions of construction activities. It is imperative to incorporate more sustainable and environmentally friendly materials into the building process to foster a more promising environmental future. The article systematically examines five eco-friendly building materials, presenting a comprehensive analysis of their advantages, disadvantages, service life, and economic considerations within the construction industry. These materials are posited as viable alternatives to traditional counterparts.

The study endeavors to elucidate the theoretical and methodological underpinnings, along with practical resolutions, directed towards establishing a sustainable architectural environment. By accentuating the facets of harmonizing architecture with the natural environment, the investigation seeks to discern how buildings can be seamlessly integrated into the natural landscape without compromising its ecological integrity. The research objectives encompass the formulation of concepts conducive to the creation of architectural solutions that explicitly consider the tenets of sustainability. The inquiry delves into the fundamental principles and concepts of sustainable architecture, with the methodological dimension elucidating approaches to implementing these principles in specific projects. In its practical dimension, the study entails an examination of extant instances of sustainable construction and the formulation of novel architectural solutions designed to foster equilibrium between development and nature conservation.

2 Literature Review

The imperative of sustainable development is gaining prominence in the formulation of contemporary architectural and urban planning solutions (Zhang et al., 2019). Sustainable progress, as conceptualized, entails a form of development that can persist without disrupting the ecological and social equilibrium over a relatively indefinite period. Within the European Union, the principles and policies of sustainable development stand as a primary objective, constituting a pivotal area of study. The forefront involvement of national and local authorities is evident in steering the development of urban planning, architecture, and construction systems management programs (Abyzov et al., 2023). This active engagement serves to facilitate the implementation of sustainable policies and strategies, fostering the creation of architecturally balanced and socially responsible solutions with enhanced environmental considerations.

Building standards oriented toward the reduction of energy consumption are characterized by their convenience, versatility, and environmental friendliness (Tran et al., 2022). The notion of a green building transcends being merely a commercial brand; it embodies a comprehensive design concept. These buildings exhibit the capability to achieve remarkable energy savings, surpassing 90% in comparison to conventional building standards and exceeding 75% for typical new constructions. Demonstrations of such notable energy savings have been particularly evident in warm climates, where energy consumption is predominantly allocated to cooling rather than heating (Veselka et al., 2020). The utilization of environmentally friendly materials in construction has emerged as a highly significant aspect of contemporary practices, particularly in the early 21st century. Rapid technological advancements, increased vehicular growth, and intensive production have collectively propelled humanity away from the traditional conditions that marked the inception of civilization. The selection of new housing is increasingly intertwined with considerations of environmentally friendly technologies, materials, and location. An examination of the literature underscores key arguments highlighting the significance of constructing green buildings, with an emphasis on the utilization of environmentally friendly building materials (Sangmesh et al., 2023). A primary argument centers on the utilization of environmentally benign materials, exemplified by wood, bamboo, and clay. These materials contribute to a diminution of the depletion of non-renewable resources, including metals and synthetic materials (Han et al., 2020). Eco-friendly materials exhibit commendable insulation properties, resulting in decreased energy consumption for heating and air conditioning purposes (Patel et al., 2021). Notably, the contemporary generation of building materials is characterized by the absence of toxin emissions, thereby promoting a healthful indoor climate. They refrain from emitting toxic gases, thereby averting allergic reactions in residents. Prevalent trends in green building and sustainable construction are observed in several countries, including Sweden, the Netherlands, Denmark, Germany, and Canada (Sinha et al., 2013). These nations actively engage in the implementation and development of green building projects, with many of them instituting certification programs and schemes such as BREEM, LEED, and DGNB to advocate and advance green building practices.

Global experience underscores the promising trend in green and environmentally friendly construction through the utilization of building materials crafted from hemp. Hempail UA has innovated an environmentally friendly material named Hempail Mix, formulated based on industrial hemp. Its composition encompasses lime and a proprietary substance developed by the company. Hempail Mix serves as both an independent insulation material and a foundation for building blocks. Noteworthy for its environmental friendliness, this material exhibits a versatile array of applications in construction, rendering it an innovative choice for green building projects (Krueger et al., 2019). The terms "green" construction and "passive" construction, while not synonymous, are frequently employed within the realm of sustainable construction and may encompass analogous principles. A green building is defined as a structure that incorporates environmentally friendly technologies and materials with the objective of mitigating the environmental impact associated with construction activities (Mokal et al., 2015). Characteristics of green buildings may encompass the utilization of renewable energy sources, high energy efficiency, adoption of environmentally friendly building materials, water management, and air quality enhancement, among other aspects.

Passive house: a structure meticulously engineered with a heightened level of insulation and airtightness to efficaciously retain heat indoors, leveraging natural heat sources like solar radiation and minimizing internal heat loss. Passive buildings harness the thermal and light attributes of the surroundings to stabilize internal temperatures without relying on active heating or air conditioning systems. While these concepts maintain distinctions, it is noteworthy that a green building may integrate passive elements in its design. Conversely, a passive building may incorporate green technologies to ensure heightened levels of energy efficiency and sustainability (Sabadash, 2023). The windows in a passive house are constructed with high-quality insulation, and these residences feature well-insulated exterior walls, roofs, and foundations. This design ensures heat retention within the building during winter and inhibits heat escape during summer (Yang et al., 2022). The ventilation system is engineered to provide fresh air without inducing drafts, thereby ensuring low radon levels and enhancing overall health conditions. Furthermore, a highly efficient heat recirculation system facilitates the reuse of heat contained in the exhaust air. The imperative to conserve energy and mitigate greenhouse gas emissions is increasingly applicable not only to small but also to large buildings. Achieving high efficiency involves the implementation of robust insulation and airtight design, strategically applied to eliminate "weak spots" throughout the entire building and mitigate heat loss (Klassen-Wigger et al., 2018). Passive buildings are characterized by minimal consumption of primary energy, thereby ensuring adequate resources for future generations and averting environmental damage. The energy expended in constructing passive buildings, often referred to as embodied energy, is minimal when juxtaposed with the energy reserves stored for future utilization (Nguyen & Macchion, 2023). Decisive actions regarding sustainable facility design are most efficaciously made in the initial stages of design and preceding the commencement of construction. However, conventional planning and construction methodologies do not inherently support a cohesive early decision-making process. Integration of sustainable considerations into design processes is imperative to preclude ineffectual adjustments and foster the realization of a sustainable environment during the construction phase (Zhou et al., 2023).

A "Passive House" emerges as a financially sound investment due to its enduring advantages, notably the absence of long-term heating and cooling costs. Furthermore, financial support is available for the construction of Passive Houses, aligning with the approach's emphasis on long-term perspectives, where conventional houses entail lower restoration costs in comparison to Passive Houses (Yuan et al., 2017). In the selection of construction materials, it is crucial to contemplate carbon dioxide emissions. Wood emerges as a preferable option, supported by studies across multiple countries demonstrating its significantly lower carbon dioxide emissions. This phenomenon can be attributed to the minimal energy consumption involved in the production of forest products and the potential substitution of fossil fuels with wood during the manufacturing process. Research indicates that the utilization of wood is more carbon-efficient compared to the application of reinforcing steel in aerated concrete or reinforced concrete. Opting for wood is also more environmentally prudent, given that wood residues can be repurposed in production processes (Ragheb et al., 2016).

Nevertheless, it is imperative to acknowledge the diversity among wood types. To achieve optimal results, numerous studies have been undertaken to ascertain the wood type that emits the least carbon dioxide (CO_2) across the construction, operation, and use phases. Bearing this in mind, the effective use of wood involves its combination with other materials like aerated concrete, clay plaster, or solid brick to ensure comprehensive insulation of building structures.

In the construction sector of India, escalating environmental concerns are driven by rapid urbanization. The heightened demand for housing results in the extensive consumption of energy, resources, and raw materials, thereby contributing to increased CO_2 emissions and adverse effects on human health and ecosystems (Wang et al., 2021). In this context, the use of suitable building materials becomes crucial to diminish the ecological footprint. Urban areas bear the brunt of climate change, experiencing elevated temperatures, abbreviated winter periods, and unpredictable alterations in monsoon precipitation. Developers should prioritize the advancement of improved and more sustainable design methodologies to mitigate the adverse environmental impact of their buildings. Utilizing environmentally friendly materials with a minimal ecological footprint is imperative (Reijenga & Kaan, 2011). Central to achieving this objective is the flexibility to employ locally available materials. The passive house concept delineates insulation standards for both new and existing buildings. This comprehensive concept incorporates not only thermal insulation but also ventilation standards, forming a robust foundation for achieving low energy consumption (Gu & Ma, 2023). Before the widespread application of the passive house concept, it is essential to scrutinize the environmental and health aspects of the insulation materials integral to the concept (Taner et al., 2021).

Hence, the primary research inquiries aimed to juxtapose the thermal and physical properties of insulation materials concerning the energy efficiency of green buildings, considering both technical and environmental dimensions. Upon assessment, expanded polystyrene emerged as the most suitable insulation material for passive use and home renovation. This preference stems from the availability of multiple recycling methods for expanded polystyrene. The study also conducted tests on plant fibers.

2.1 Examples of green construction projects: Chocolate Ecodom

The walls of the dwelling are constructed with sheet wood utilizing a distinctive technological approach, a design choice made to avoid complications and preserve the clarity of lines by eliminating intricate angles. To mitigate the impact of intense summer sunlight, a ventilated facade, also constructed from wood, is implemented. Insulating the structure is a polyvinyl chloride membrane coupled with hemp technical wool, reflecting a commitment to environmentally friendly construction materials. The overarching principle guiding this construction is the pursuit of maximal comfort for residents while minimizing environmental impact. Considerable emphasis was placed on the design quality of the residence. The house features an abundance of electrical access points and is outfitted with sensors, lighting controls, radio dispatchers, and remote control systems to facilitate efficient management of artificial lighting. The fireplace, aside from delineating spatial divisions, serves the dual purpose of providing supplemental heating to the room when needed. Primary heating of the house is accomplished through a surface heating system, complemented by integrated backup radiators. The water supply is sourced from a well. Additionally, an air conditioning and mechanical ventilation system has been incorporated to uphold comfortable conditions within the building.

The construction exclusively employs natural materials and Ecotech technology. This distinctive technology is grounded in a dual wooden frame structure known as Larsontimber, complemented by the application of an ecological mixture derived from industrial hemp, acknowledged as an optimal environmentally friendly material. The Ecotech technology utilized is subject to a patented status.

A distinctive feature is the implementation of the Ecodom radius roof, renowned for its elevated strength and a comprehensive reduction in structural load attributed to the integrated tie-in system.

Advantages:

- Substantially reduced roof area in comparison to traditional roofs, accommodating high loads efficiently.
- Prevents the accumulation of snow.
- Facilitates the elimination of additional space (attic), resulting in the creation of supplementary internal volume.
- Contributes to the formation of a distinctive silhouette for the house.

A passive house model incorporating a Trombe wall represents a distinctive construction engineered to optimize the efficient utilization of solar energy and enhance the overall energy efficiency of the building. The Trombe wall serves as a system enabling the harnessing of solar heat to warm and regulate the temperature within the structure.

The principal features of a passive house model incorporating a Trombe wall are outlined as follows:

- Solar Trombe Wall: Positioned on the south or southwest facade of a building, the Solar Trombe wall serves as a substantial structure designed for the storage of heat derived from solar radiation. The intricacies investigated in this study pertain to structural enhancements and technological advancements within Trombe walls. Various dimensions of these walls, including energy efficiency, exergy (the available energy for use), economic viability, and environmental impact (4E), are scrutinized from four distinct perspectives. Ultimately, the study concludes by summarizing the findings and providing insights into challenges and future opportunities within the realm of Trombe walls (Wang et al., 2020).
- Heat Storage Material: Typically, materials possessing high heat storage capacity, such as aerated concrete or wood, are employed to retain heat for prolonged durations.
- Ventilation System: A ventilation system is implemented to disperse the heated air. Warmed air, interacting with the solar wall, is introduced into the house.
- Temperature Control: Automated and manual temperature control systems are utilized to optimize energy utilization and regulate temperature.
- Effective Insulation: Complementing the solar wall, the residence incorporates efficient insulation to minimize heat loss, thereby reducing energy costs.

The Trombe wall passive house model exemplifies an innovative approach to green construction. Through the incorporation of solar energy utilization and efficient heat management, this model plays a pivotal role in diminishing energy consumption and enhancing the environmental sustainability of the building.

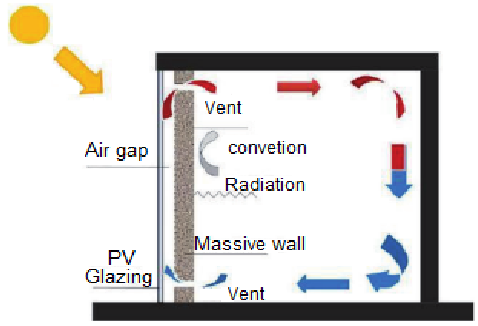

Figure 1. Schematic Representation of the Trombe Wall (Taner, et al., 2021)

A model of a passive house with a Trombe wall is presented, simplified to a basic room featuring a Trombe wall on the south side with dimensions of width 5050 mm × depth 6050 mm (plus 350 mm for the Trombe wall) × height 3000 mm. The building parameters are tailored for Kyiv, factoring in meteorological conditions.

The Trombe wall comprises:

- 4 mm window glass;
- 150 mm air layer;
- 2 mm black paint coating;
- 200 mm aerated concrete wall.

The absorptive capacity (and emissivity) of both the aerated concrete wall and black paint is set at 1.0, as per the material characteristics.

3 Research Methods

Various scenarios, each with distinct boundary conditions and configurations, were simulated to ascertain the temperature distribution within the room and the optimal utilization of the ventilation damper. The modeling encompassed scenarios with the vent dampers closed within the aerated concrete core, considering both steady-state and transient modes. To comprehensively evaluate the advantages and drawbacks of the investigated system over a year, three representative days in different seasons were selected, specifically: January 1 in winter, April 1 in spring, and July 1 in summer.

The following test conditions were simulated:

- Closed Configuration: This involved a closed setting with closed air ventilation valves (Variants 1 and 2).
- Open Air Ventilation Valves: Another scenario was simulated with the air ventilation valves open (Variant 3).
- Transitional Period (April 1): This variant accounted for the transitional period between winter and summer, with the flaps in the aerated concrete core in an open position (Variant 4).

- Average Summer Day (PV Panels): Variant 5 was considered on an average summer day, incorporating openings in the exterior glass and photovoltaic (PV) panels along the glass designed to prevent room overheating (Wang et al., 2020).
- For each of the options, turbulent heat transfer regimes were taken into account, utilizing the Navier-Stokes equations, the Reynolds-Averaged Navier-Stokes (RANS) turbulence model, and a radiation model. Both the liquid and air were treated as ideal gasses, and all differential equations were formulated as second-order. The model was visualized using Comsol Multiphysics Version 6.1.

Cases 1, 3, and 5 were concurrently examined at a specific time, precisely at noon. To ensure a precise simulation of heat accumulation, certain cases were evaluated during the transitional period of the day, commencing from 9 am to 8 pm (cases 2 and 4). This approach considerably extends the computational time and necessitates increased computing resources. However, it provides a more nuanced comprehension of the data, unattainable in steady-state simulations, and is imperative for a precise assessment of the system (Pryhara et al., 2022).

The k-ε equation model was employed in the analysis. The impact of radiation was investigated utilizing the Discrete Ordinates (DO) radiation model. The DO radiation model facilitates the determination of radiation considering translucent walls and surface-to-surface radiation issues. Additionally, the sun position vector and lighting parameters were established.

To assess the dynamics of changes in outdoor air and ground temperature throughout the day, an analysis was conducted using the Climate Data Store - Copernicus environment.

Table 1. Material properties

Material	Density [kg/m³]	Heat capacity [J/(kg·K)]	Thermal conductivity [W/(m·K)]	Absorption coefficient [m^(-1)]	Refractive index [-].
Air	1.006.43	0.0242	0	1	-
Aerated concrete	2000	960	1.5	1.7	0
Black paint	2100	1050	1.6	1.7	0
Glass	2500	840	0.81	200	1.5
Wood	700	2310	0.173	0.4	0

4 Research Results

The steady-state simulation was executed for a representative winter day, specifically January 1 at 13:00. During this simulation, the valves in the aerated concrete core were in a closed position. Figure 2 illustrates the temperature field within the Trombe wall.

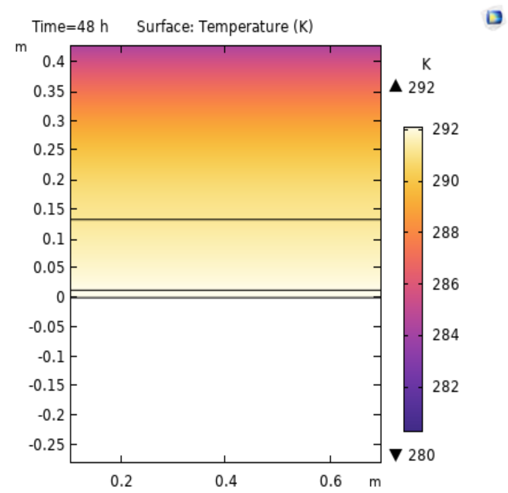

Figure 2. Temperature Field in the Trombe Wall for Variant 1

The average indoor temperature for Case 1, characterized by low cloudy weather conditions (Sun direction vector: -0.301014, Y: 0.311061, Z: 0.788119, and solar coefficient 0.71), is 19 °C.

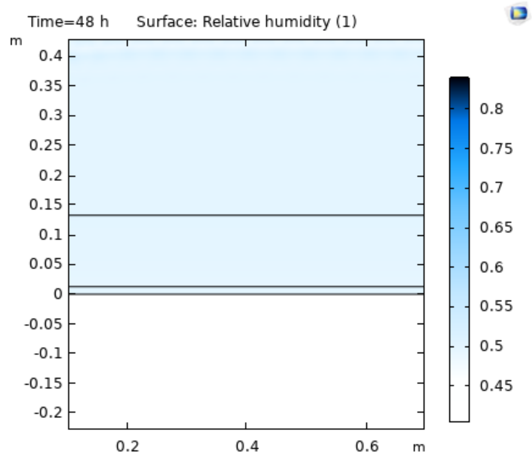

Figure 3. Relative Humidity of the Trombe Wall

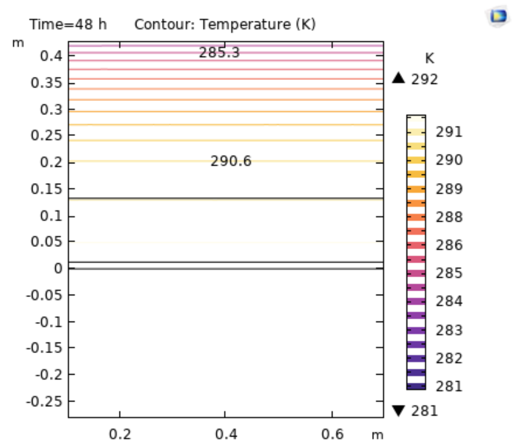

Figure 4. Radiation Heat Flux in Case 1

The average radiation heat flux measures approximately 68.5 W/m².

Variant 2:
The simulation was executed as a transient analysis for January 10 throughout the day, spanning from 9 am to 8 pm, with the valves in the aerated concrete core closed. The average temperature within the Trombe wall fluctuated from -5 °C at 20:00 to 4.7 °C at noon.

Variant 3:
The steady-state simulation was conducted for a typical winter day, specifically January 10 at noon, with the valves in the aerated concrete core open. Figure 2 depicts the temperature field in both the Trombe wall and the room.

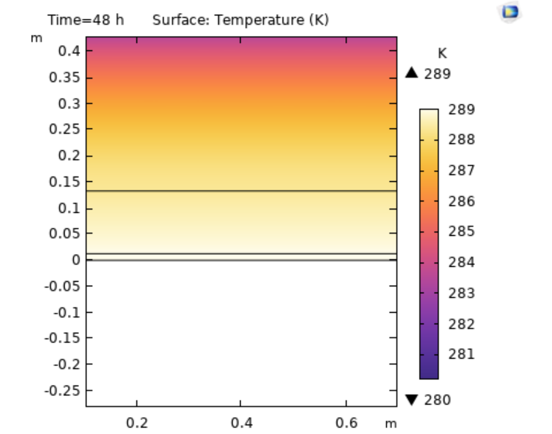

Figure 5. Temperature Field in the Trombe Wall (Case 3)

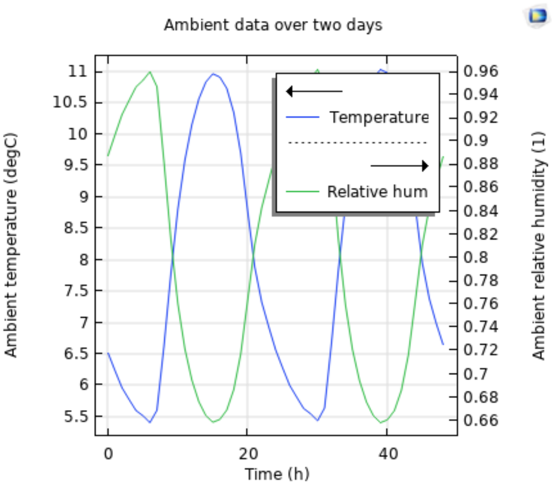

Figure 6. Temperature and Humidity Variations in the Trombe Wall (Case 3)

The average indoor temperature registers at 15.9 °C.

Transient simulations were also conducted during the winter-summer transition of 2023, specifically on April 1, throughout the day from 9 to 20 hours, with the valves in the aerated concrete core open. The average temperature within the Trombe wall fluctuated from 14.32 °C at 20:00 to 25.41 °C at noon. The maximum average temperature attainable in the room reached approximately 20.59 °C. Based on these findings, it is advisable to close the dampers in the aerated concrete core from 4 p.m. to 9 a.m. to prevent the room from cooling.

Case 5:
This scenario represents a typical summer day (July 1 at noon), where the sashes in the aerated concrete core are closed to prevent the room from overheating.

The simulation was conducted under stationary conditions and revealed that PV panels exert a significant impact on preventing overheating. The average temperature at point C is 25.8 °C. It is noteworthy that photovoltaic solar panels (PV panels), responsible for electricity generation, play a crucial role in the effective operation of cooling systems. Specifically, approximately 60% of energy is consumed during summer days, amounting to 3 kWh/m2, with an average capacity of 1 kWh for cooling devices operating for an average of 36 hours per week.
The velocity field in the Trombe wall was simulated under the assumption of a wind speed of 0.5 m/s at the inlet. Lastly, the radiative heat flux [W/m²] on the inner surface of the aerated concrete core was determined for the summer building with PV panels.

The mean value of the radiation heat flux amounted to approximately 24.2 W/m², attributable to the substantial influence of the PV panels serving as external protection against direct sunlight.

5 Discussion

In the architectural domain, the integration of green building principles is achieved through the adoption of advanced architectural solutions, the utilization of innovative engineering systems and materials aimed at diminishing energy and material consumption, enhancing structural quality, optimizing internal environment comfort, and mitigating adverse impacts on residents' health throughout the entire life cycle of building structures (Tran, et al., 2022). This strategy aims to advance green building practices in Ukraine by establishing novel standards and fostering awareness of sustainable construction within the country. The integration of eco-technologies into residential construction is gaining prominence globally, offering an efficient alternative to conventional building methods. Green building standards encompass the establishment of a comfortable indoor climate, emphasizing that the quality of the living environment is intricately linked to the environmental safety of building materials (Reijenga & Kaan, 2011).

The primary tenet of green construction is to mitigate the environmental impact of a product over its complete life cycle. Building materials should be ecologically sound, devoid of emitting toxic substances that could detrimentally affect human health over an extended duration. This approach facilitates the creation of living spaces that are not only energy-efficient but also environmentally friendly.

The conceptual framework outlined in this study was developed to enhance a holistic comprehension of building materials, contribute to the realization of sustainable development goals, and illustrate how the judicious selection of suitable building materials can yield enduring sustainability outcomes within the realm of green building (Abyzov, et al., 2023). A diverse array of factors, encompassing environmental, economic, and social dimensions, were taken into account, influencing the sustainability of material choices in construction and their repercussions on the environment and society.

6 Conclusions

The modeling showcased a substantial influence of the Trombe wall on the internal temperature of the model house employing meteorological data for Kyiv. Under winter conditions, the Trombe wall exerted a notable impact on indoor temperatures, averaging 14.7 °C for case 2.

However, during summer conditions, the Trombe wall functions as an additional heat load. The integration of PV panels enables them to serve as a supplementary cooling resource. It is noteworthy that PV panels, producing electricity, become an essential component for the effective functioning of cooling systems. Specifically, about 60% of energy is utilized on summer days, equivalent to 3 kWh/m2, with average power consumption for cooling devices of 1 kWh and an average operational duration of 36 hours per week.

Hence, within the Ukrainian climate conditions, the Trombe wall emerges as a viable solution. Nevertheless, to address the ultimate inquiries regarding system efficiency, it becomes imperative to optimize energy consumption. Additionally, considering the potential requirement for supplementary energy for cooling is crucial to determining the cost-effectiveness of utilizing primary energy for heating.

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Primary Paper Section: A

Secondary Paper Section: AL, EH