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2025

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ÚSTAVU STAVITELSTVÍ FA ČVUT V PRAHE

PROGRAM

09:00 - ÚVOD
09:10 - 10:45 - PREZENTÁCIA VÝSKUMNEJ ČINNOSTI DOKTORANDOV (BLOK 1)
10:45 - 11:00 - COFFE BREAK
11:00 - 12:30 - PREZENTÁCIA VÝSKUMNEJ ČINNOSTI DOKTORANDOV (BLOK 2)
12:45 - 13:30 - OBED (ALŽBETKA)
14:00 - 15:00 - KOMENTOVANÁ PREHLIADKA MODERNIZOVANEJ SNG (VAJANSKÉHO NÁBREŽIE)

*program je predbežný, jeho zmena je vyhradená

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doc. Ing. Lenka Prokopová, PhD.
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doc. Ing. Rastislav Ingeli, PhD.
Ing. Peter Hanuliak, PhD.
doc. Ing. Daniela Bošová, Ph.D.
doc. M.A. Jan Stolín

VÝSTUP

ŠPECIÁLNE VYDANIE MLADEJ VEDY - PREZENTUJÚCI ÚČASTNÍCI ODOVZDAJÚ ODBORNÉ ČLÁNKY NA RECENZIU V TERMÍNE DO 31.5.2025

24 Apríl, 2025

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EVALUATING THE PERFORMANCE OF ACTIVE GLAZING TYPE AND DECIDUOUS TREES FOR SEASONAL SHADING OF TROMBE WALLS

HODNOTENIE VÝKONNOSTI TYPU AKTÍVNEHO ZASKLENIA A LISTNATÝCH STROMOV PRI SEZÓNNOM TIENENÍ TROMBEHO STIEN

Tomáš Hakszer, Peter Hanuliak[1]

Tomáš Hakszer pôsobí ako interný doktorand na Stavebnej fakulte Slovenskej technickej univerzity v Bratislave. Vo svojom výskume sa venuje problematike simulovania adaptívnych fasád. Peter Hanuliak pôsobí ako odborný asistent na Stavebnej fakulte Slovenskej technickej univerzity v Bratislave. Vo svojom výskume sa venuje najmä problematike denného osvetlenia budov a konštrukčnej tvorby budov.

Tomáš Hakszer works as an internal PhD student at the Faculty of Civil Engineering of the Slovak Technical University in Bratislava. His research is focused on simulation of adaptive facades. Peter Hanuliak works as an assistant professor at the Faculty of Civil Engineering of the Slovak Technical University in Bratislava. In his research, he mainly deals with the problematics of daylighting and constructions of buildings.

Abstract

Trombe walls, effective for passive solar heating, often suffer from summer overheating. This study evaluates active glazing and deciduous trees as seasonal shading strategies. Dynamic simulations quantified incident solar radiation on Trombe wall in Bratislava. Three variants were compared: baseline (V1), active glazing (V2) and deciduous trees (V3). Orientations analyzed included south, east and west Trombe wall configurations. Active glazing (V2) showed the highest annual solar reduction (e.g., 73.7% for south). V2 provided precise summer shading, drastically cutting gains (e.g., south July: 4.6 kWh/m² from 55.1 kWh/m²). Deciduous trees (V3) offered significant passive shading (46.7% annual south reduction). Both strategies substantially enhance Trombe wall viability by mitigating overheating risks. Optimal strategy selection depends on specific project goals and design priorities.

Key words: trombe wall, passive solar, seasonal shading, active glazing, deciduous trees

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Abstrakt
Trombeho steny, efektívne pre pasívne solárne vykurovanie, často trpia letným prehrievaním. Táto štúdia hodnotí aktívne zasklenie a listnaté stromy ako stratégie sezónneho tienenia. Dynamické simulácie kvantifikovali dopadajúce slnečné žiarenie na Trombeho stenu v Bratislave. Porovnávali sa tri varianty: základný (V1), aktívne zasklenie (V2) a listnaté stromy (V3). Analyzované boli konfigurácie Trombeho steny orientované na juh, východ a západ. Aktívne zasklenie (V2) preukázalo najvyššiu ročnú redukciu slnečného žiarenia (napr. 73,7 % pre juh). V2 zabezpečilo presné letné tienenie, drasticky znižujúc zisky (napr. juh júl: 4,6 kWh/m² z 55,1 kWh/m²). Listnaté stromy (V3) ponúkli významné pasívne tienenie (46,7 % ročná redukcia pre juh). Obe stratégie podstatne zvyšujú využiteľnosť Trombeho stien znížením rizika prehrievania. Výber optimálnej stratégie závisí od konkrétnych cieľov projektu a priorít návrhu.
Kľúčové slová: trombeho stena, pasívna solárna energia, sezónne tienenie, aktívne zasklenie, listnaté stromy

Introduction

Currently, climate change and climate risks are manifesting more intensely and rapidly than scientists, politicians and institutions anticipated. There is also insufficient societal preparedness for this reality and for addressing this trend. This is also evident from the analysis from March 2024 by the European Environment Agency, the European Climate Risk Assessment, which assessed climate risks in the EU territory. Some climate conditions have even reached critical levels. This is manifesting in all monitored areas: ecosystems, food production, health, infrastructure as well as the economy and finance.[1]

A key goal of the modern construction industry and architecture is climate resilience. To achieve this goal, it is necessary to seek and utilize new and innovative solutions, materials and technologies so that buildings can adapt to and simultaneously withstand changing climate conditions and so that their energy consumption is reduced.[2] A positive and beneficial response in the construction industry is the investigation of the impact of greening, which demonstrates that vegetation has a positive influence on the surrounding environment and can support the reduction of energy consumption.[3,4]

Currently, buildings are also increasingly designed as adaptive, dynamically responding to changing environmental conditions by integrating systems that utilize renewable energy sources directly into facades, roofs or other structural elements. Various technologies and components for facades are available, for example: adaptive mobile solar shading devices, electrochromic glazing and other intelligent glazing, photovoltaic and photothermal systems integrated into the building envelope, phase-change materials (embedded in various building structures, dynamic thermal insulation, components utilizing wind energy, interactively controllable window systems, self-regulating ventilation, etc. [5,6]
Passive solar design represents a cornerstone strategy in the pursuit of energy-efficient buildings, aiming to reduce reliance on active heating, ventilation and air-conditioning systems.

Passive approaches leverage natural energy flows and building design elements to maintain thermal comfort, offering pathways to significant energy savings and reduced environmental impact. Among the established passive techniques, the Trombe wall stands out as a classic example of an indirect-gain solar heating system. Popularized in the mid-20th century, though its fundamental principles date back to ancient uses of thermal mass, the Trombe wall is designed to capture solar energy, store it within a massive wall and release it gradually into the living space. The primary advantage of incorporating a Trombe wall into a building design is its ability to provide significant passive solar heating, thereby reducing the dependence on conventional, energy-consuming heating systems.[7,8,9]

Typically, a Trombe wall consists of a massive wall positioned on the equator-facing side of a building (south-facing in the Northern Hemisphere) to maximize winter solar exposure. This wall is separated from the exterior environment by a layer of glazing (commonly double glazing for better insulation) with an air gap between the glazing and the wall's outer surface. The wall itself is constructed from materials with high thermal capacity, such as concrete, masonry (brick, stone) or adobe, enabling it to store significant amounts of heat. The outer surface of the massive wall, facing the sun is typically painted a dark color to maximize the absorption of this incident sunlight.[9]

However, the very effectiveness of the Trombe wall in capturing solar heat during winter presents a significant challenge during warmer months. The system's inability to inherently differentiate between desirable winter heat gain and undesirable summer heat gain leads to a critical issue: overheating. Excessive solar gains during summer or even transition periods can cause thermal discomfort and substantially increase cooling energy demands, potentially negating the winter heating savings. This inherent duality necessitates careful design considerations and often requires the implementation of seasonal control or mitigation strategies to ensure year-round viability.[10,11]

Effectively managing seasonal solar gain through appropriate design and control is critical to realizing the full potential of Trombe walls as year-round passive solar solutions. This necessity justifies comparative studies, such as the subsequent investigation of active glazing and deciduous trees as shading strategies to evaluate different mitigation approaches.

To synthesize the key characteristics of selected shading strategies reviewed, Table 1 provides a comparative summary based on the literature. This table highlights the differences in their operating mechanisms, control methods, typical performance ranges and key advantages and disadvantages.

Methodology

The primary objective was to quantify the incident solar radiation on the Trombe wall surface under various shading strategies. The geometric basis for the study was a 3D model of a object featuring a Trombe wall (Fig. 1, left) and its surrounding site (Fig. 1, right). The Trombe wall is shaded by an adjacent building at an angle of 25-degree (Fig. 2), representing a typical urban or semi-urban context. The Trombe wall itself was modeled as a system comprising the external glazing, a 100 mm air cavity and an internal massive layer with a dark surface.

This model was developed using Rhinoceros V8[12], a 3D modeling software. For the dynamic environmental simulations and solar radiation analysis, ClimateStudio V2.0[13,14] was utilized. ClimateStudio facilitates the calculation of annual, monthly and hourly solar radiation incident on selected surfaces, deriving solar and sky radiation from meteorological datasets representative of historically typical conditions.

Feature	Active Glazing Type	Deciduous Tree/Vegetation
Mechanism	Dynamically modulates glazing transmittance[15]	Seasonal foliage change blocks summer sun, allows winter sun[3,4,16,17,18]
Control	Electrical/Gas stimulus (Automated/User)[19]	Natural phenological cycle
Typical Summer Performance	Low SHGC (0.09-0.12) in tinted state ; Reduces cooling load[20]	High radiation block (e.g., 70-85%) under full canopy[21]
Winter Solar Access	Good in clear state (SHGC 0.39-0.46)[22]	Good through bare branches, some obstruction remains [23]
Key Advantages	Dynamic control of heat & light; Integrated; Comfort benefits[24]	Natural seasonal adaptation; Passive; Aesthetic/Ecological co-benefits[25]
Key Disadvantages/ Challenges	High initial cost; Complexity (wiring, controls); Durability concerns; Control strategy dependence [26,27,28]	Quantification/Modeling difficulty; Space/Time for growth; Maintenance; Less precise control[25]

Table 1 - Comparative Overview of Investigated Trombe Wall Shading Strategies based on Literature Review
Source: Authors

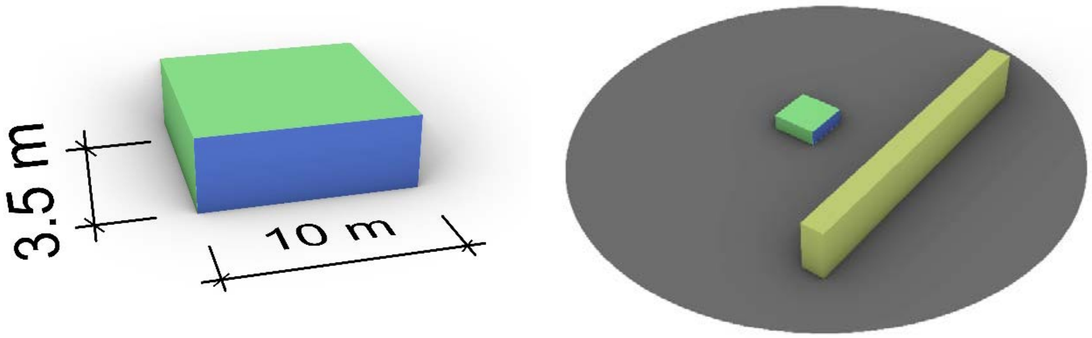

Fig. 1 – 3D model of the building with a Trombe wall (left) and 3D model of the overall site layout (right)
Source: Authors

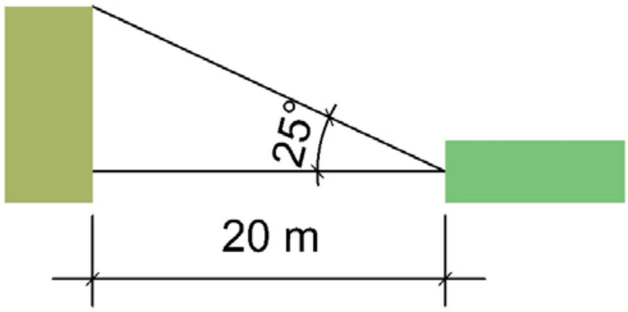

Fig. 2 – Side View Showing Shading Scenario
Source: Authors

The simulations were conducted using climate data for Bratislava, Slovakia (48.15°N, 17.11°E). A Typical Meteorological Year (TMY) weather file, generated with Meteonorm V8 software[29] was incorporated with an hourly time step to represent the local climatic conditions (Fig. 3).

Three distinct scenarios (V1, V2 and V3) were established to investigate the effectiveness of different Trombe wall shading strategies:

- V1 (Baseline): Represented the Trombe wall with standard double glazing. The specific properties of this glazing are listed in Table 2. No additional shading elements are applied.
- V2 (Active Glazing type): Implemented an active glazing system on the Trombe wall. This system switched between a clear state and a tinted state, with the tinted state active from the beginning of May to the end of September annually (Fig. 4). The specific optical and thermal properties for both states are detailed in Table 2.
- V3 (Deciduous Trees): Introduced deciduous trees as a shading element. The trees were modeled with a canopy bottom height of 3.5 meters, a canopy top height of 14 meters and an approximate canopy radius of 5.5 meters. The specific layout and arrangement of these trees on the site are illustrated in Fig. 5.

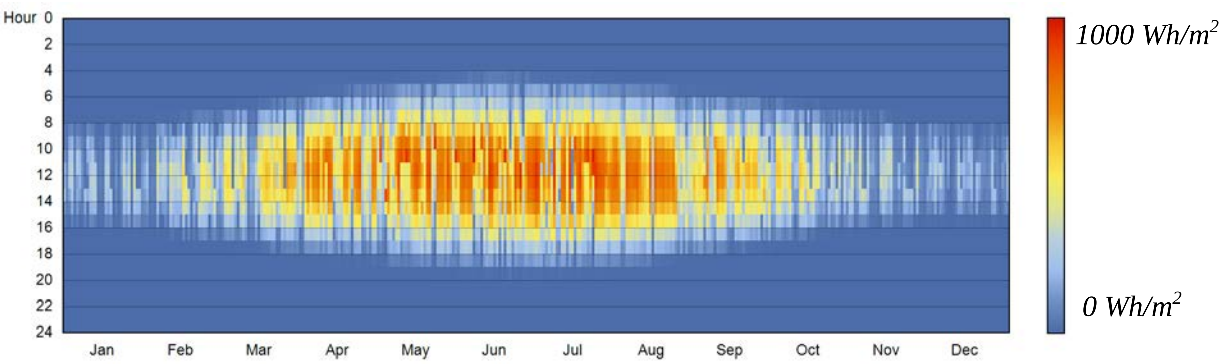

Fig. 3 – Annual course of global solar radiation on the horizontal surface – Bratislava
Source: Authors

To accurately simulate the dynamic shading effect of deciduous trees, they were modeled as blocks with dynamic leaf materials within ClimateStudio. This advanced feature allows for the representation of seasonal foliage changes. The software automatically adjusts leaf color

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and density at each simulation time step based on the geographical latitude and time of year (Fig. 6). This effectively simulates the presence of full foliage in summer, color transition and leaf fall in autumn, bare branches in winter and gradual leaf growth in spring.[30]

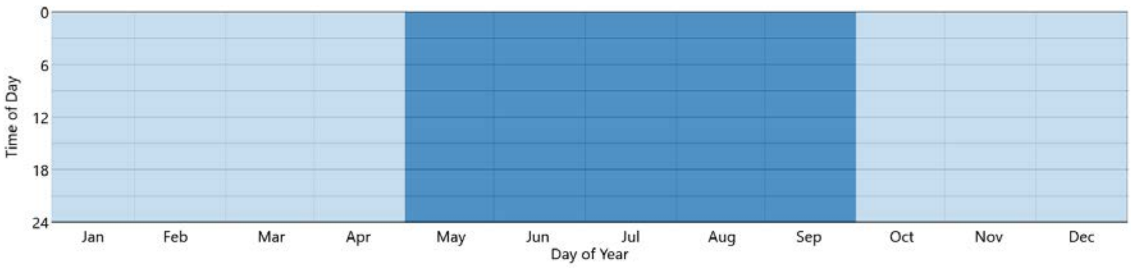

Fig. 4 – Schedule: Active glazing type (0 - clear state, 1 - tinted state)
Source: Authors

Each of these scenarios was simulated for three different cardinal orientations of the Trombe wall: South, East and West to understand the orientation-dependent efficacy of each strategy. The optical and energy properties of the glazing systems used in the Trombe wall for different variants are detailed in Table 2. The light reflectance factors for the main relevant surfaces within the simulation environment, such as the ground, external walls and the internal surface of the Trombe wall, are provided in Table 3.
The core metric for comparison across scenarios was the total solar radiation incident on the Trombe wall's internal surface, analysed annually, monthly and hourly.

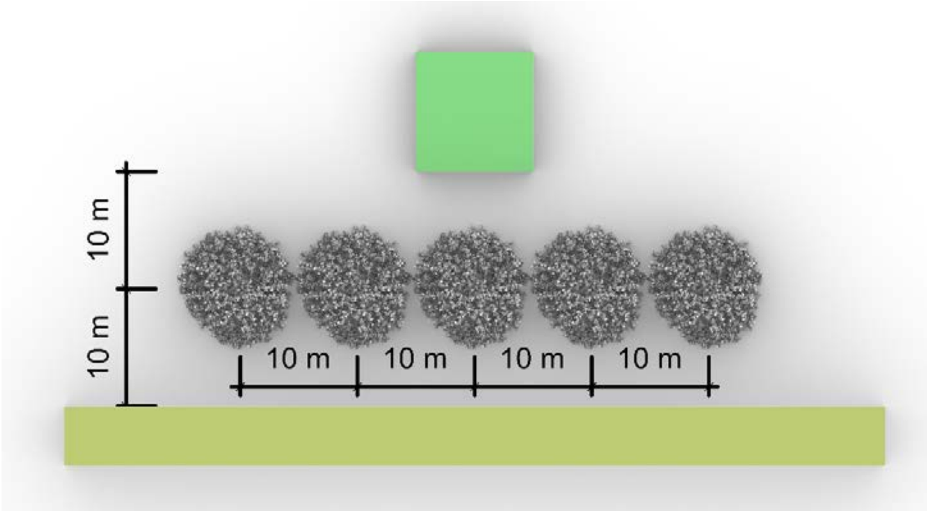

Fig. 5 – Plan View - Tree Arrangement in V3
Source: Authors

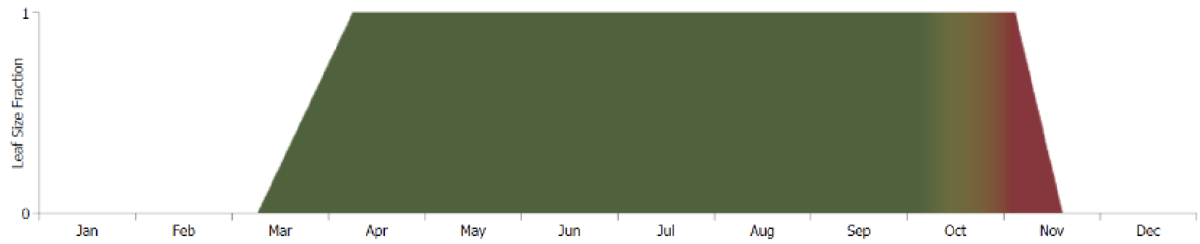

Fig. 6 – Schedule: Dynamic material applied to leaves
Source: Authors

Glazing System	Reflectance ratio (visible light) [-]	Transmittance ratio (visible light) [-]	g-value [-]	U - value [W/(m^2.K)]
Double glazing (V1,V3)	0,15	0,77	0,70	2,69
Active glazing type in clear state (V2)	0,07	0,38	0,39	1,80
Active glazing type in tinted state (V2)	0,04	0,06	0,10	1,80

Table 2 - Optical and energy properties of glazing
Source: Authors

Surface name	Light reflectance factor [-]
Ground	0,20
External walls	0,30
Internal surface of the Trombe wall	0,05

Table 3 - Light reflectance factor of the main surfaces
Source: Authors

Results

The simulations quantified the incident solar radiation on the Trombe wall's internal surface under three distinct scenarios (V1: Baseline, V2: Active Glazing, V3: Deciduous Trees) across south, east and west orientations.

Fig. 7 illustrates the total annual solar radiation incident on the Trombe wall for each variant and orientation. This figure compares the overall yearly solar exposure, highlighting how each shading strategy (V2 and V3) influences the total energy received by the Trombe wall compared to the V1 baseline across the different orientations. Generally, the south-facing Trombe wall is expected to receive the highest annual solar radiation in the baseline scenario, with varying reductions observed for V2 and V3.

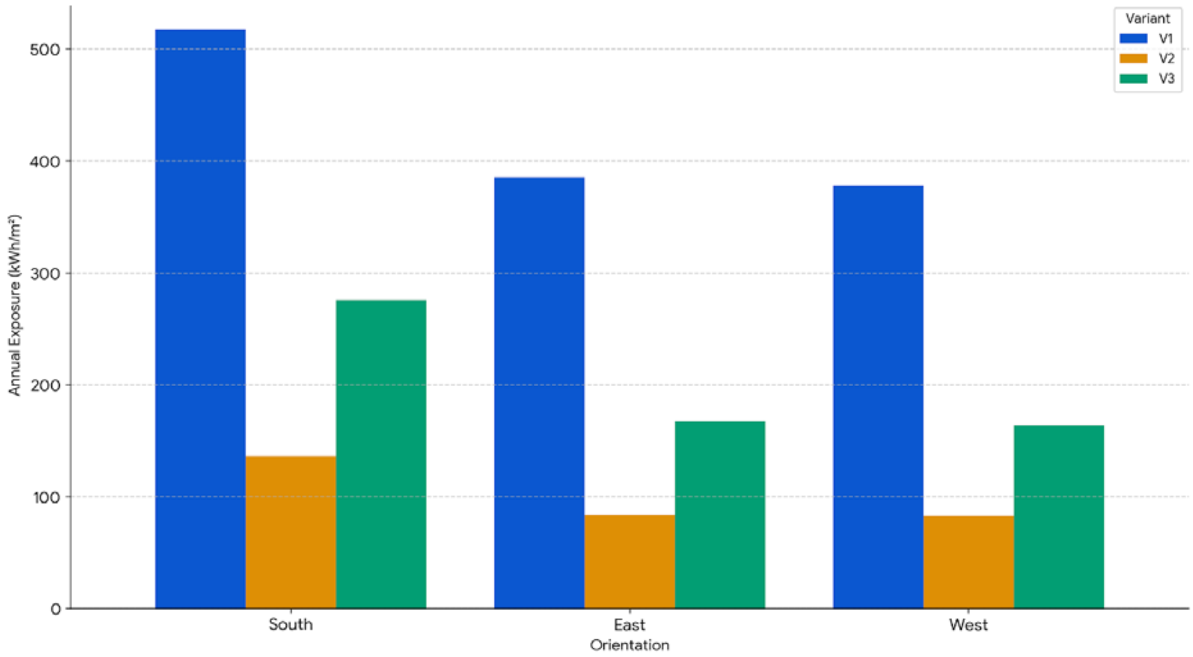

Fig. 7 – Annual solar radiation for each variant and orientation
Source: Authors

The monthly distribution of mean cumulative solar radiation provides insight into the seasonal performance of each strategy:

- South-Facing Trombe Wall: Fig. 8 shows the monthly solar radiation for the south-facing Trombe wall. In the V1 baseline, this typically shows high gains in winter and shoulder months and lower gains in peak summer due to higher sun angles. V2 (Active Glazing) would demonstrate reduced radiation from May to September when tinted. V3 (Deciduous Trees) would show reduced radiation during summer months due to foliage and higher radiation during winter when leaves are absent.
- East-Facing Trombe Wall: Fig. 9 presents the monthly solar radiation for the east-facing Trombe wall. This orientation primarily receives morning sun. The V2 and V3 scenarios are expected to show significant reductions during summer mornings compared to V1.
- West-Facing Trombe Wall: Fig. 10 displays the monthly solar radiation for the west-facing Trombe wall. This orientation receives afternoon sun, often contributing to overheating risk in summer. Both V2 and V3 strategies would be crucial here in reducing summer afternoon solar gains compared to V1.

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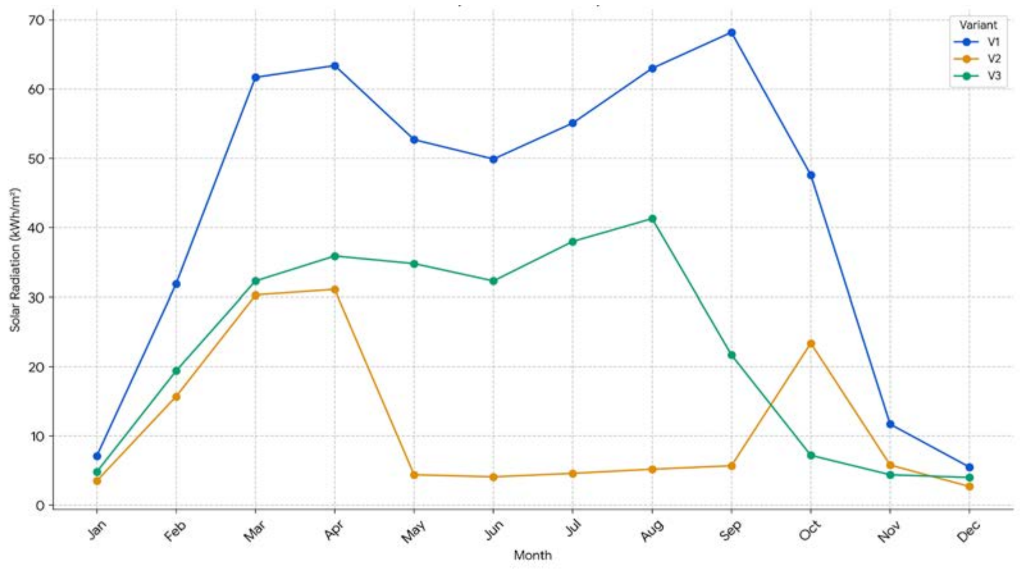

Fig. 8 – Mean cumulative solar radiation for each month of the year on a south-facing Trombe wall
Source: Authors

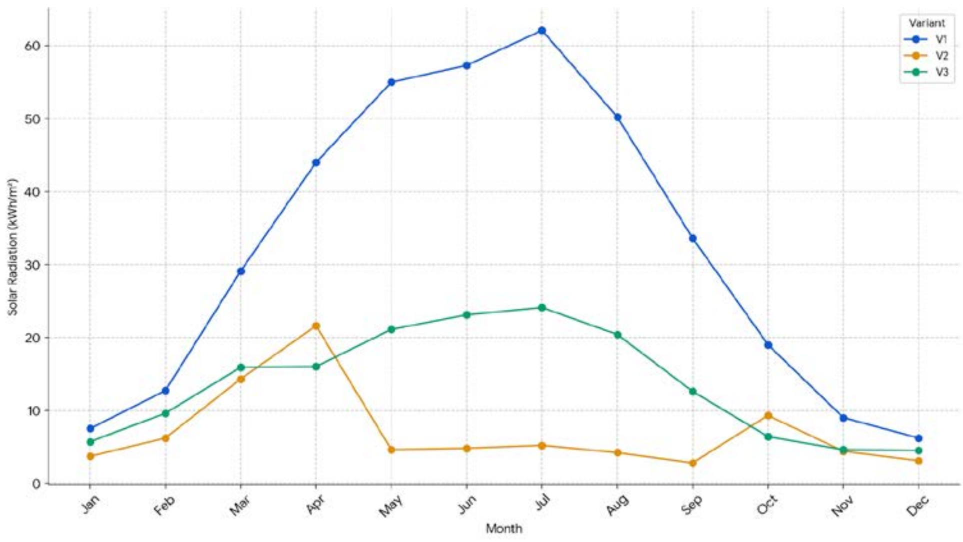

Fig. 9 – Mean cumulative solar radiation for each month of the year on a east-facing Trombe wall
Source: Authors

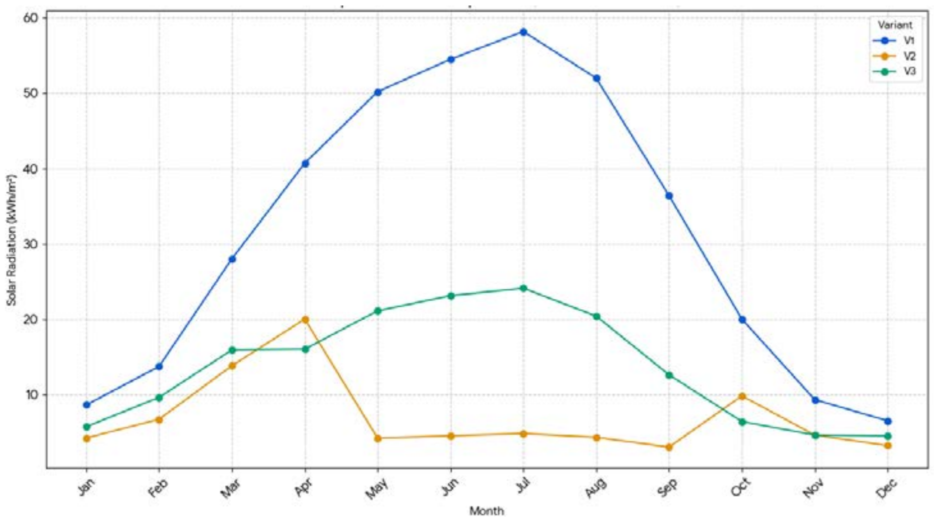

Fig. 10 – Mean cumulative solar radiation for each month of the year on a west-facing Trombe wall
Source: Authors

The hourly solar radiation data, visualized as heatmaps, reveal the daily operational dynamics of solar gain for each variant and orientation:

- V1 (Baseline):
  - Fig. 11 (South): Shows high solar gains concentrated around midday for the V1 baseline on a south-facing Trombe wall, particularly during the winter and shoulder months.
  - Fig. 12 (East): Illustrates morning solar gains throughout the year for the V1 baseline on an east-facing Trombe wall.
  - Fig. 13 (West): Depicts afternoon solar gains for the V1 baseline on a west-facing Trombe wall, which are observable and can be particularly intense during summer months.
- V2 (Active Glazing Type):
  - Fig. 14 (South): Demonstrates the effect of the active glazing in V2 on hourly solar radiation for the south-facing wall. This would typically show significantly reduced solar radiation during midday hours from May to September when the glazing is in its tinted state and higher transmission during other months when it is clear.
  - Fig. 15 (East): Shows the impact of active glazing on morning solar gains for the east-facing wall in V2, with expected reductions from May to September due to the tinted state.
  - Fig. 16 (West): Illustrates how active glazing in V2 affects afternoon solar gains for the west-facing wall, with the tinted state reducing intense summer afternoon sun from May to September.
- V3 (Deciduous Trees):
  - Fig. 17 (South): Displays how deciduous trees in V3 influence hourly solar radiation on the south-facing Trombe wall. This is characterized by significant shading and thus reduced solar gains during summer midday hours when the

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canopy is full and increased solar access during winter when the branches are bare.

- Fig. 18 (East): Shows the effect of deciduous trees on morning solar gains for the east-facing wall in V3, with the tree canopy reducing radiation primarily during summer mornings.
- Fig. 19 (West): Illustrates the impact of deciduous trees on afternoon solar gains for the west-facing wall in V3. The trees provide shading that mitigates intense summer afternoon sun, while allowing more solar penetration in winter.

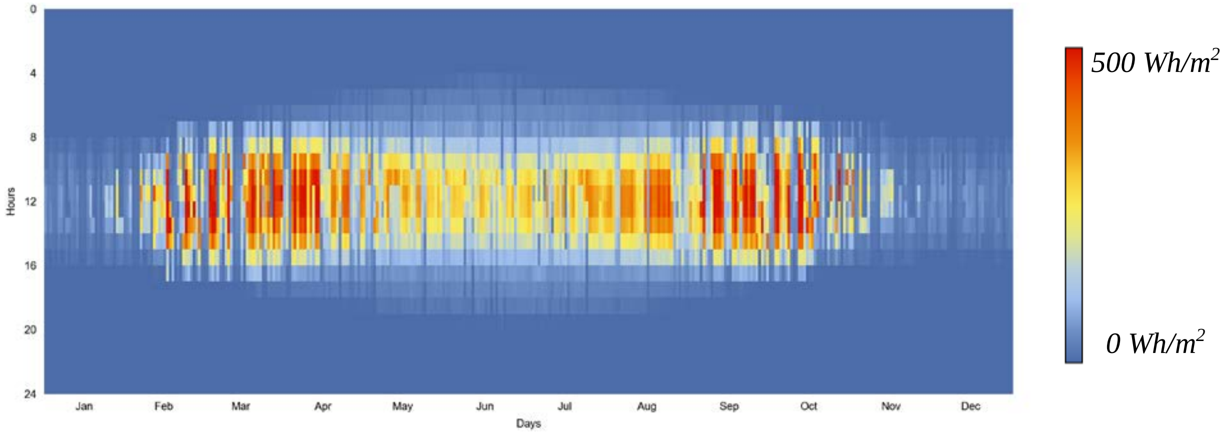

Fig. 11 – V1 - Hourly solar radiation falling on a south-facing Trombe wall
Source: Authors

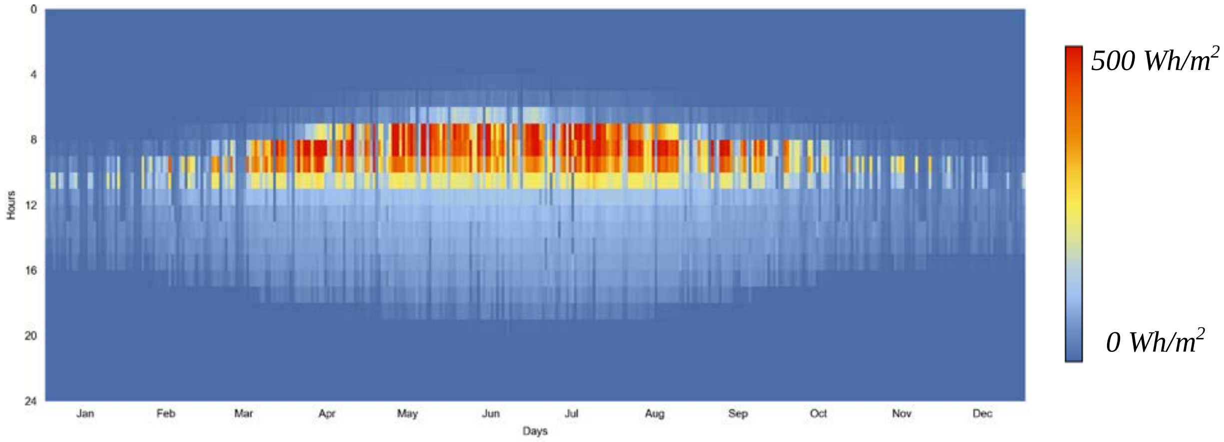

Fig. 12 – V1 - Hourly solar radiation falling on a east-facing Trombe wall
Source: Authors

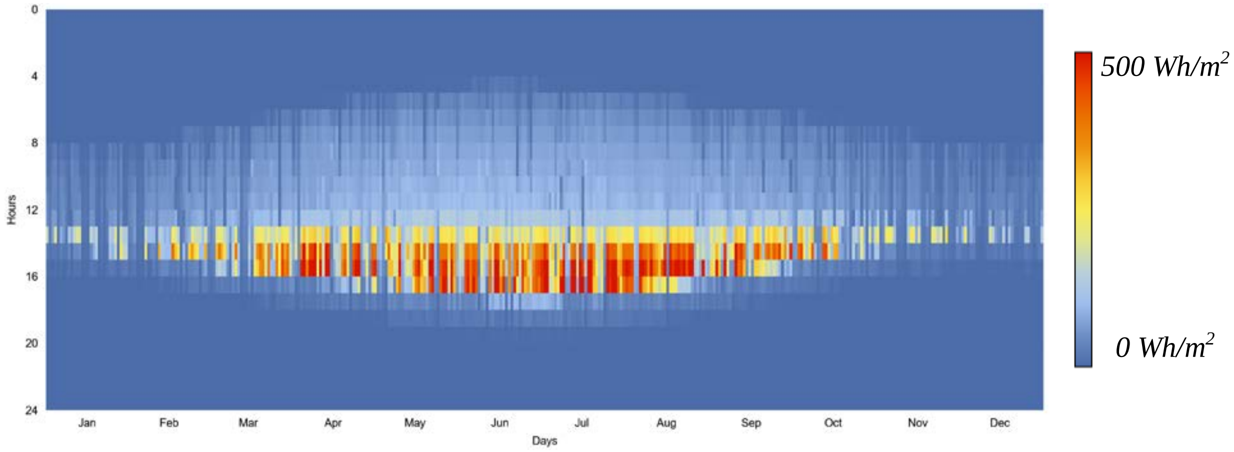

Fig. 13 – V1 - Hourly solar radiation falling on a west-facing Trombe wall
Source: Authors

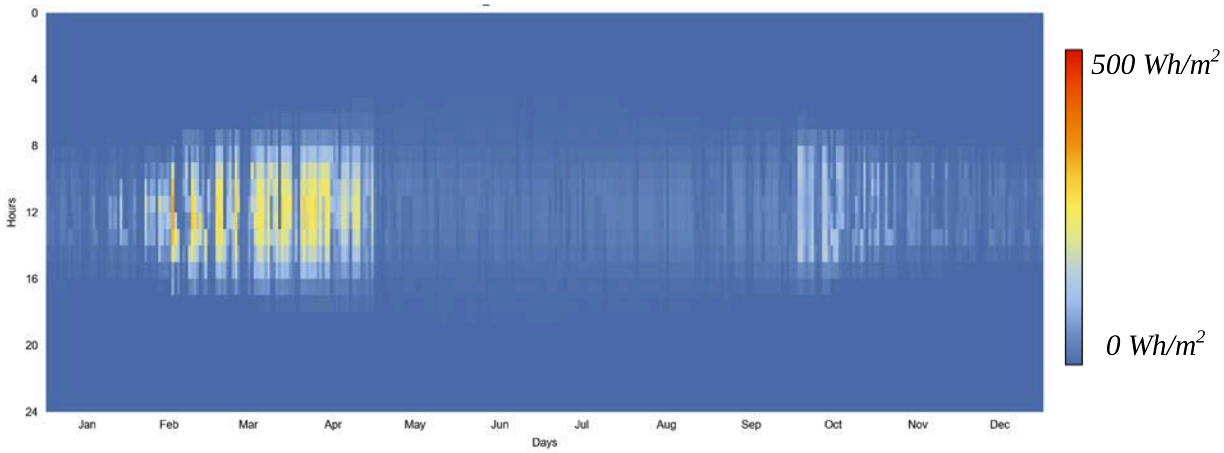

Fig. 14 – V2 - Hourly solar radiation falling on a south-facing Trombe wall
Source: Authors

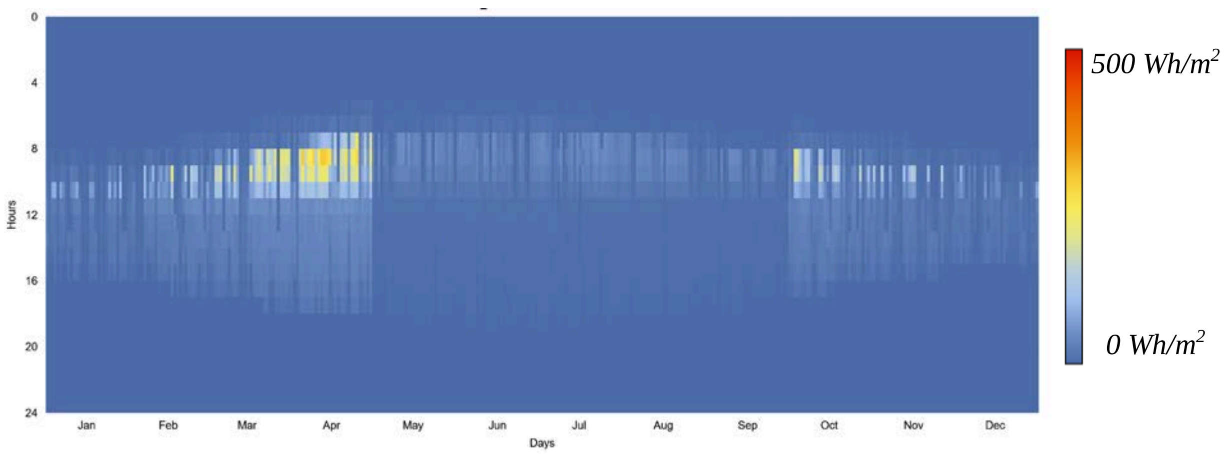

Fig. 15 – V2 - Hourly solar radiation falling on a east-facing Trombe wall
Source: Authors

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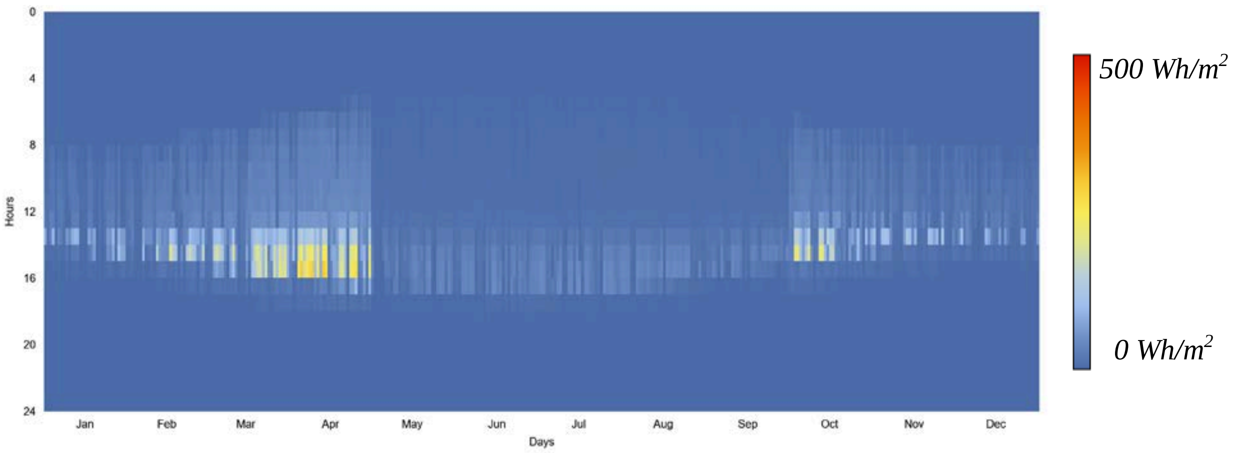

Fig. 16 – V2 - Hourly solar radiation falling on a west-facing Trombe wall
Source: Authors

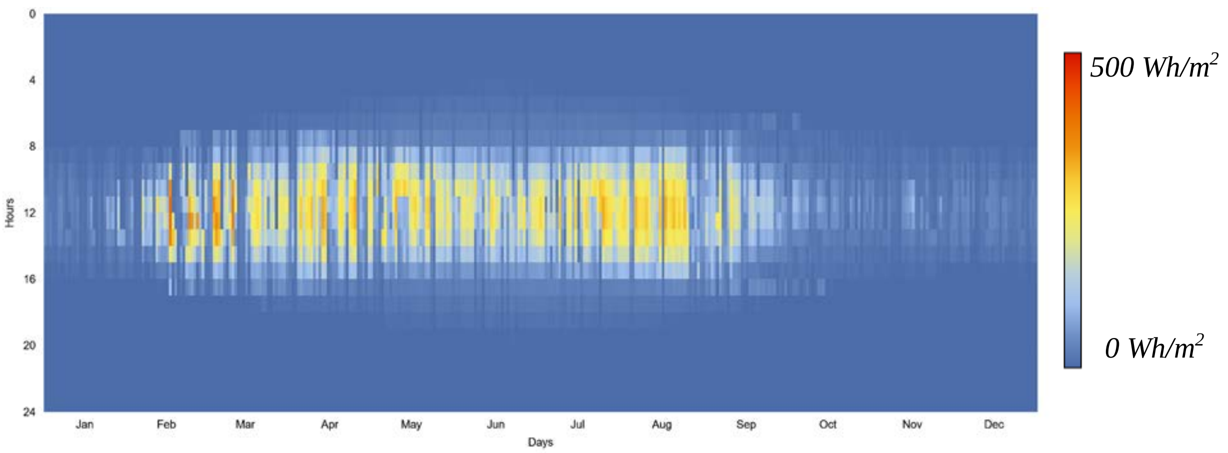

Fig. 17 – V3 - Hourly solar radiation falling on a south-facing Trombe wall
Source: Authors

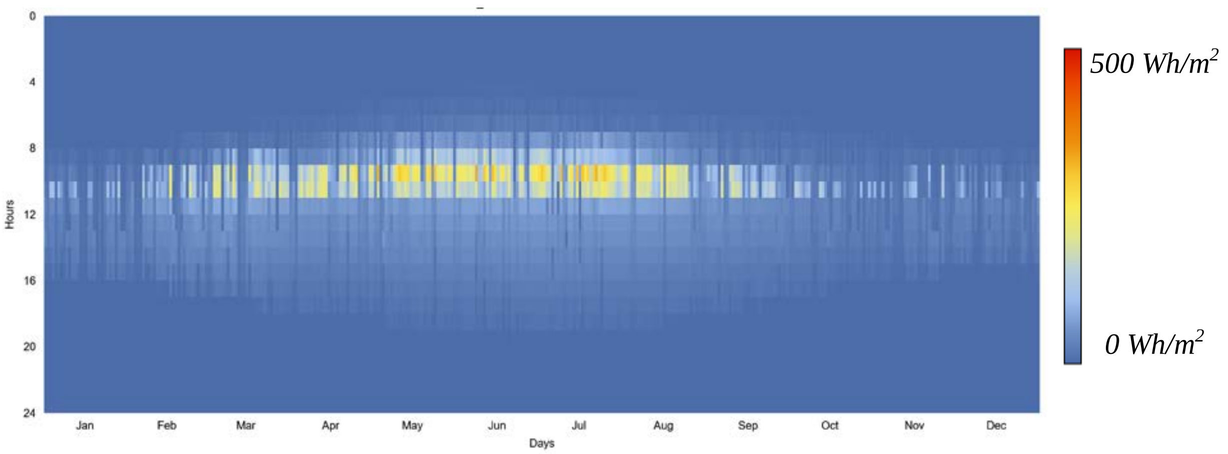

Fig. 18 – V3 - Hourly solar radiation falling on a east-facing Trombe wall
Source: Authors

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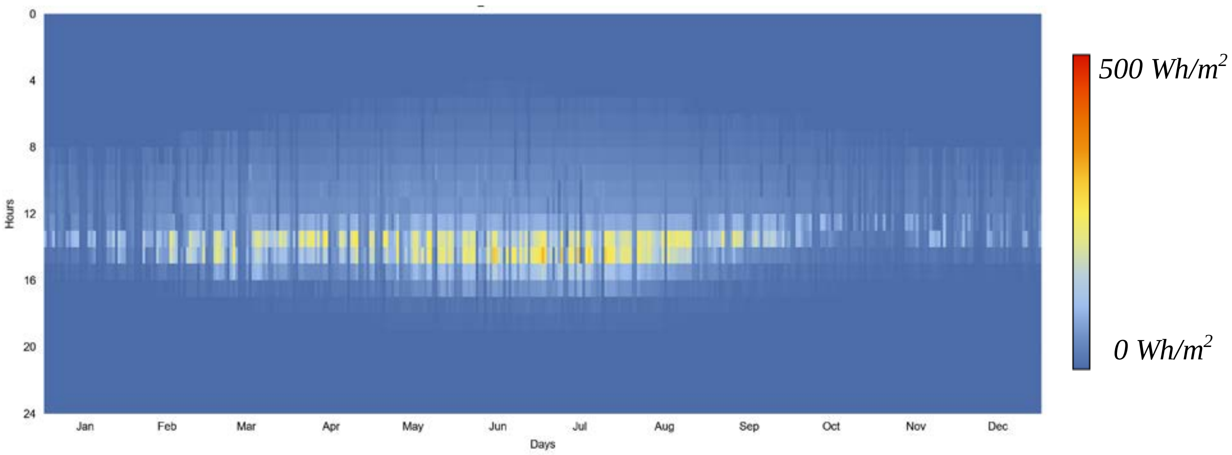

Fig. 19 – V3 - Hourly solar radiation falling on a west-facing Trombe wall
Source: Authors

Discussion

The findings of this study demonstrate the significant potential of both active glazing (V2) and deciduous trees (V3) to modulate solar radiation incident on Trombe walls, thereby addressing the critical challenge of seasonal overheating while attempting to preserve beneficial winter gains. The primary objective was to quantify this incident solar radiation under these varied shading strategies and the results indicate distinct performance characteristics for each approach.

Annually, both strategies achieved considerable reductions in solar radiation compared to the V1 baseline across all orientations (Fig. 7). For the south-facing Trombe wall, which received the highest baseline radiation (517.7 kWh/m² for V1), the active glazing (V2) led to an annual total of 136.3 kWh/m², a reduction of approximately 73.7%. Deciduous trees (V3) resulted in an annual total of 276.0 kWh/m², a 46.7% reduction. Similar significant reductions were observed for east and west orientations, with V2 consistently providing a greater overall annual reduction than V3. For instance, on the east orientation, V1 received 385.6 kWh/m², while V2 received 84.0 kWh/m² (a 78.2% reduction) and V3 received 167.4 kWh/m² (a 56.6% reduction).

The active glazing strategy (V2) demonstrated highly effective and precise seasonal control, aligning with its operational schedule (tinted May-September, Fig. 4). During the summer period (May-September), solar radiation incident on the Trombe wall was drastically reduced. For the south-facing wall, V2's summer radiation (May-Sep sum: 24.0 kWh/m²) was minimal compared to V1's 286.7 kWh/m². For example, in July, V1 received 55.1 kWh/m² while V2 received only 4.6 kWh/m² on the south face. This substantial reduction, evident in the monthly data (Fig. 8-10) and hourly heatmaps (Fig. 14-16), directly addresses the risk of summer overheating often associated with Trombe walls.

During the heating season (October-April), when the active glazing was in its clear state, it still allowed for solar gains, albeit lower than the V1 baseline due to its inherent g-value of 0.39 compared to V1's 0.70. For example, in January, the south-facing V2 Trombe wall received 3.5 kWh/m² compared to V1's 7.1 kWh/m².

Deciduous trees (V3) offered a more passive, natural approach to seasonal shading. The full summer foliage (Fig. 6) provided considerable shading, leading to a notable decrease in summer solar radiation compared to V1, though less dramatically than V2. For the south-facing wall during the summer months (May-Sep), V3 allowed a total of 168.1 kWh/m² compared to V1's 286.7 kWh/m². In July, V3 received 38.0 kWh/m² on the south face, a reduction from V1's 55.1 kWh/m² but significantly more than V2's 4.6 kWh/m². The hourly patterns (Fig. 17-19) would visually confirm this diffuse and partial shading effect during summer.

In winter, when the trees were bare, solar access was largely restored, crucial for the Trombe wall's heating function. For the south-facing wall in January, V3 received 4.8 kWh/m², which is less than V1 (7.1 kWh/m²) indicating some obstruction even by bare branches, but more than V2 (3.5 kWh/m²) in that month. This demonstrates the "smart" passive nature of deciduous trees, although the level of winter solar access is dependent on tree species, branch density and pruning, which the generic model approximates. The transition periods of spring and autumn also show the dynamic effect of foliage development and fall, with radiation levels for V3 falling between V1 and the summer-shaded V3 values.

Comparing the two strategies, active glazing (V2) provides a more definitive and controllable reduction in solar gains, especially during summer, making it highly effective for preventing overheating. Its annual reduction in solar radiation was consistently higher than that of deciduous trees across all orientations. This is particularly beneficial for east and west orientations where summer sun can be intense and contribute significantly to overheating; V2 reduced annual west-facing radiation by 78.0% from V1's 378.1 kWh/m² to 83.1 kWh/m², while V3 reduced it by 56.6% to 164.1 kWh/m².

Deciduous trees (V3), while offering less absolute summer shading than V2, still provide significant benefits. Their passive nature, aesthetic contributions and potential ecological co-benefits are advantageous. However, the effectiveness of trees is less precise and can be influenced by factors such as growth rate, species-specific canopy density and maintenance. The data shows that even bare branches in winter cause some reduction in solar gains compared to the unobstructed baseline (e.g., V3 South Jan: 4.8 kWh/m² vs V1 South Jan: 7.1 kWh/m²).

The choice between active glazing and deciduous trees, or a combination, would depend on specific project goals, climate, orientation, budget (active glazing often has higher initial costs) and aesthetic preferences. Both strategies effectively enhance the Trombe wall's viability by mitigating its primary drawback - summer overheating - while adapting to seasonal needs for solar energy. The study underscores that managing solar gains through such adaptive strategies is crucial for optimizing the year-round performance of Trombe walls.

Conclusion

This study investigated the performance of active glazing (V2) and deciduous trees (V3) as seasonal shading strategies to mitigate overheating in Trombe walls, a common challenge that can negate their winter heating benefits. The primary aim was to quantify the incident solar radiation on the Trombe wall surface under these strategies compared to a baseline (V1) across south, east and west orientations in Bratislava.

The findings demonstrate that both evaluated strategies significantly reduce the annual solar radiation incident on the Trombe wall compared to the V1 baseline, thereby enhancing its year-round viability.

- Active glazing (V2) proved to be highly effective, achieving the largest annual solar radiation reduction across all orientations, for instance, a 73.7% reduction for the south-facing wall (from 517.7 kWh/m² in V1 to 136.3 kWh/m² in V2). Its scheduled operation (tinted May-September) provided precise and substantial reduction of solar gains during summer months, drastically cutting radiation (e.g., south-facing July: V1 at 55.1 kWh/m² vs V2 at 4.6 kWh/m²) and effectively preventing overheating. However, due to the inherent properties of its clear state, V2 also resulted in lower solar gains during the heating season compared to the V1 baseline.
- Deciduous trees (V3) offered a passive, nature-based shading solution, achieving a notable annual solar radiation reduction (e.g., 46.7% for the south-facing wall, from 517.7 kWh/m² in V1 to 276.0 kWh/m² in V3). This strategy significantly reduced summer solar gains (e.g., south-facing July: V1 at 55.1 kWh/m² vs V3 at 38.0 kWh/m²) due to foliage, while allowing increased solar penetration during winter when branches were bare, although some obstruction remained.

Both strategies successfully address the critical issue of summer overheating in Trombe walls, making them more adaptable to varying seasonal conditions. The choice between active glazing and deciduous trees will depend on specific project requirements, including the desired level of control, budget constraints, aesthetic considerations and the balance sought between summer shading and winter solar gains. This research underscores the importance of integrating adaptive shading solutions to optimize the performance and extend the applicability of Trombe wall systems in contemporary building design.

Limitations and Future Considerations

This study utilized a specific active glazing schedule and a generic deciduous tree model with fixed dimensions. Real-world performance could vary with different control strategies for active glazing or diverse tree species and maturity. Future research could explore optimizing active glazing control based on real-time conditions and investigating a wider range of tree species and planting configurations.

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