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Seasonally Shaded Trombe Wall for Improved Annual Thermal Comfort and Energy Performance in a Hot Summer - Cold Winter Climate

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A B S T R A C T

Addressing the critical challenge of summer overheating in passive solar systems, this study evaluates the year-round thermal and energy performance of a seasonally shaded and fan-assisted Trombe wall in Beijing's Hot-Summer - Cold-Winter (HSCW) climate. Using a simulation-based approach, four facade configurations were compared against a standard south-facing window baseline. Results demonstrate that while an unshaded Trombe wall (TW) reduces annual heating demand by 27%, it imposes a 25% cooling penalty. The permanent deployment of external blinds (TW+Blinds) from May to September effectively mitigates this impact, reducing the cooling load by 13% compared to the unshaded configuration and limiting the final summer penalty to only 8.7% above the baseline.
The hybrid configuration, incorporating both seasonal shading and an auxiliary cavity fan (TW+Blinds+Fan), achieves the highest overall performance, delivering a 30.3% reduction in annual heating demand and a 14% net saving in total annual energy use. Furthermore, annual thermal habitability improves by 20.7% based on the frequency of occupied hours maintained within the 20 °C to 26 °C safety range. The analysis identifies seasonal shading as the primary driver for annual balance, while the performance decrease observed in April reveals that fixed-schedule fan assistance introduces operational trade-offs during transitional months.

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1. INTRODUCTION

The building sector is one of the largest energy consumers worldwide, responsible for approximately 30-40% of total final energy use and global greenhouse gas emissions (IEA 2025). Improving building energy efficiency has therefore become a central focus of sustainable development policies. In residential and office buildings, space heating and cooling account for most of the energy demand, and the reliance on mechanical heating, ventilation and air conditioning (HVAC) systems raises concerns about operational costs and environmental impacts (Santamouris and Vasilakopoulou 2021). Consequently, there is a growing consensus

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on the need for advanced building envelopes to mitigate these issues. For instance, the integration of thermal energy storage materials (Elhamy and Mokhtar 2024) and self-powered solar facades (Qian et al. 2026) have recently emerged as highly effective strategies to alleviate HVAC loads and enhance indoor thermal comfort.

Passive solar heating technologies offer an effective way to reduce dependence on conventional energy sources while maintaining indoor comfort. Among these technologies, the Trombe wall system, first developed by Felix Trombe and Jacques Michel in the 1960s, has been widely studied as a simple and cost-effective strategy to improve winter comfort and reduce heating loads (Hu et al. 2017). A typical Trombe wall consists of a massive dark coloured wall that absorbs solar radiation, an external glazing layer, and an air cavity between the wall and the glazing. During winter, solar energy is absorbed and stored in the wall and is then gradually released into the indoor space, providing delayed heat gains.

A major drawback of conventional Trombe wall systems is the risk of overheating during summer (Bevilacqua et al. 2022). Excessive solar gains can raise indoor temperatures above the comfort range and increase the need for mechanical cooling, which can offset a part of the winter energy savings. Consequently, the integration of shading devices and ventilation strategies has been proposed to regulate solar gains and mitigate overheating (Simões et al. 2021).

China provides a particularly relevant context for the study of Trombe walls. The country has committed to achieving the dual carbon targets of peaking carbon emissions before 2030 and reaching carbon neutrality by 2060. Within China, the HSCW climate zone, which includes Beijing, presents specific challenges: winters are long and cold and require significant heating, whereas summers are hot and humid and require cooling. The need for robust adaptive facades is further emphasised by the increasing frequency of extreme temperature variations recently observed across Eastern China (He et al. 2026). In this climate, Trombe wall designs must balance winter heating benefits with summer overheating mitigation, which is crucial for sustainable building design in this region.

Previous studies have reported that Trombe wall systems can reduce winter heating loads by up to 30% (Duan et al. 2016). However, in HSCW regions their application remains limited, mainly because of the summer overheating risk. Different approaches have been tested to address this limitation, including external shading devices (Bevilacqua et al. 2022), natural ventilation through operable vents (Briga-Sá et al. 2021), and fan assisted ventilation (Zhu et al. 2022). While some recent studies address multi-seasonal behaviour, many still focus primarily on single seasons, such as winter heating. Furthermore, there remains a lack of comprehensive year-round assessments that directly compare these alternative Trombe wall configurations and quantify the combined effects on energy use and thermal comfort in climates such as that of Beijing.

This article addresses these gaps by presenting a simulation-based comparative study of Trombe wall systems with shading and ventilation strategies in the HSCW climate of Beijing. The main aim is to evaluate the year-round thermal comfort and energy performance of four building configurations: a base case with a south-facing window, a Trombe wall without additional control, a Trombe wall with external blinds, and a Trombe wall with blinds and fan-assisted ventilation. The models are assessed in terms of heating and cooling energy demand, fan electricity consumption, and thermal comfort performance. Specifically, the evaluation quantifies the occupied hours within the 20 °C to 26 °C range, distinguishing between periods of summer overheating and winter overcooling. The analysis examines the trade-offs between energy savings and comfort and identifies which solution offers the most favourable overall balance.

2. LITERATURE REVIEW

The Trombe wall has become one of the most studied passive solar heating systems for buildings over the past five decades. It is based on a simple physical concept in which solar radiation passes through a sun facing glazing layer, is absorbed by a massive dark coloured storage wall, and is then transferred to the indoor space with a time delay through conduction, long wave radiation, and natural convection (Szyszka 2022). Because of this phase shift effect, indoor temperature swings are reduced, and winter heating demand can be lowered. Overall, the literature shows that Trombe wall performance is strongly climate dependent, with the largest benefits in locations that combine strong winter solar insolation with large diurnal temperature ranges (He et al. 2015; Simões et al. 2021).

In temperate and continental climates, monitored and simulated case studies report consistent winter benefits. Studies in Mediterranean locations and continental Europe show improved operative temperatures and reduced seasonal heating demand due to the daytime storage of solar heat and its delayed evening release

(Dabaieh and Elbably 2015; Simões et al. 2021; Stazi et al. 2012). In rural northern China, retrofits on south facing facades have raised nighttime indoor temperatures and reduced reliance on coal and biomass for heating (Liu et al. 2025; Xi et al. 2024). Mechanistically, winter performance depends mainly on thermal mass, solar collection, and air exchange. Thicker and denser walls extend the time lag of heat transfer but may delay heat release beyond occupancy hours; high solar heat gain glazing and dark absorptive coatings increase daily gains; and controlled airflow between cavity and room allows more rapid recovery of sensible heat during sunny hours (Briga-Sá et al. 2021; Zhu et al. 2022).

The same processes that provide useful winter gains can lead to substantial overheating in summer if seasonal management is poor. Heat stored in the wall and cavity can be released to the interior when it is not needed, raising peak indoor temperatures and, in some cases, increasing annual cooling demand (Briga-Sá et al. 2021). Field measurements in central Italy showed increases of about 1-2 °C in peak indoor temperature for unshaded Trombe walls, with evening discomfort extending into occupied periods (Stazi et al. 2012). Investigations in hot arid North Africa similarly reported serious overheating unless external shading or venting strategies were used (Dabaieh and Elbably 2015). In hot humid climates, this problem is even more critical because cooling loads are already high (Chen et al. 2021), so summer overheating is widely recognised as a main limitation of Trombe wall systems.

External shading and ventilation have therefore become central design strategies. Fixed overhangs can block high summer sun while admitting low angle winter radiation, but operable devices such as roller blinds and venetian blinds provide greater adaptability. Indeed, recent comparative assessments corroborate that dynamic solar control devices, such as movable external slats, are highly effective in mitigating summer overheating, significantly reducing cooling energy demands while improving year-round thermal comfort in temperate climates (Carbonari et al. 2025). Measurements and simulation studies show that external blinds reduce cavity air temperatures and indoor peaks, while causing little penalty for winter heating when they are retracted on sunny winter days (Bevilacqua et al. 2022; Stazi et al. 2012). Parametric analyses underline the importance of slat angle, openness factor, reflectance, and control logic (Zhu et al. 2022). For HSCW climates, the literature agrees that blinds should be deployed during summer daytime and retracted in sunny winter conditions, with intermediate adjustments during shoulder seasons.

Ventilation provides a complementary control dimension. Adding top and bottom vents enables buoyancy driven airflow through the cavity. In winter, opening both vents allows sun warmed cavity air to enter the occupied zone during daytime, while in summer, opening only the top vent to the outside while keeping the bottom vent closed allows hot air to be exhausted outdoors (Briga-Sá et al. 2021). Natural ventilation is attractive because it has negligible operational energy use, but its cooling effect is limited where outdoor air is already warm. To address these limitations, fan assisted Trombe walls use small fans either to deliver cavity air to the room in winter or to exhaust it outdoors in summer. Field retrofits and numerical simulations show that fan integration improves controllability and increases comfort hours (Dabaieh and Elbably 2015; Zhu et al. 2022). Several studies highlight this trade-off, showing that hybrid systems with fans reduce discomfort hours more effectively than purely passive configurations, but may increase annual energy if control strategies are not carefully designed (Isaia et al. 2019; Zhu et al. 2022). This tension between comfort and energy use is central for HSCW climates.

Building performance simulation has become a primary method for evaluating Trombe wall behaviour and for testing control strategies before implementation. EnergyPlus includes detailed physical models for short and long wave radiation, heat conduction in massive walls, and inter zone airflows, and it allows the implementation of control strategies using schedules or an Energy Management System to emulate winter harvesting, summer exhaust, and night purge operation (U.S. Department of Energy 2023).

While standard assessments often rely on the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices defined in ISO 7730 and ASHRAE 55 (ASHRAE 2020; International Organization for Standardization 2005), these steady-state models can be abstract when evaluating the critical safety margins of passive solar heating. For systems subject to large diurnal swings, a frequency-based analysis of indoor temperatures provides a more direct measure of habitability. Evaluating the number of hours within a specific range versus those spent in overheating or overcooling allows for a transparent quantification of seasonal risks (De Dear and Brager 2001; Nicol and Humphreys 2002). Studies applying these models to Trombe wall buildings still find persistent summer overheating and highlight the importance of simple and intelligible rules for occupants, such as when to retract blinds or open vents, which can sometimes outperform complex automated schedules when users follow them consistently (Briga-Sá et al. 2021; Stazi et al. 2012).

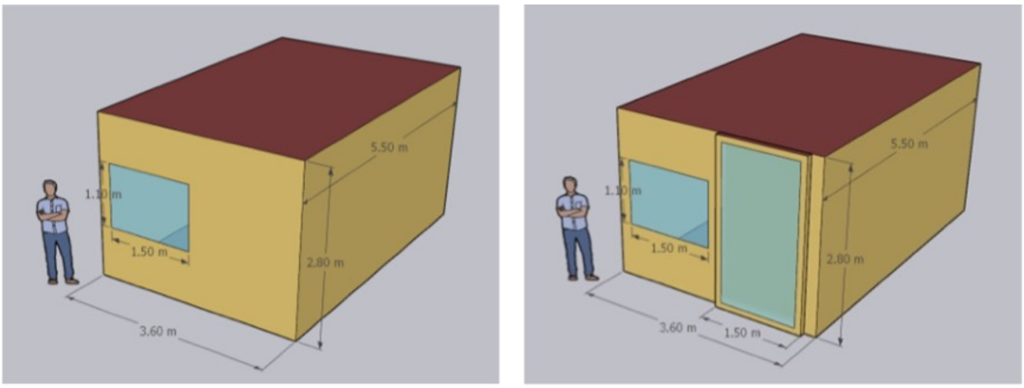
For HSCW climates such as Beijing, the literature points to a specific gap. Many studies confirm strong winter heating gains from Trombe walls and recognise the need for aggressive summer management through shading and ventilation (Sheng et al. 2024; Xiao et al. 2023). Recent work suggests that in severe cold and HSCW Asian climates, fan assisted hybrid operation can extend comfort hours beyond those achievable with passive designs alone, but the net energy advantage depends strongly on fan duty cycles, control thresholds, and seasonal operation strategies (Liu et al. 2018; Zhang et al. 2022). What remains less clearly quantified is the energy-comfort trade-off for Trombe wall systems in a representative HSCW context when geometry, envelope properties and climate data are held consistent and control strategies are explicitly compared. Against this background, the present study uses a Beijing-specific simulation framework to compare passive and fan-assisted Trombe wall configurations and to make this trade-off transparent for design and retrofit decision making in Chinese HSCW cities.

3. METHODOLOGY AND SIMULATION SETUP

This study uses building performance simulation to assess how Trombe wall systems affect thermal comfort and energy use in a HSCW climate, using Beijing as a representative case. Climate data are taken from the standard CSWD EPW file. A simple single person office is modelled and then modified step by step so that the impact of each strategy can be compared against a common reference.

3.1. CASE STUDY

The case study uses an isolated single room test cell designed to isolate Trombe wall behaviour. The main room measures 3.60 m × 5.50 m × 2.80 m, giving a floor area of 19.8 m² and a volume of about 55 m³. The long facade faces due south. In all four cases a south window of 1.50 m × 1.00 m is kept maintaining daylight and a common reference, with a sill height of 1.10 m above the floor. When a Trombe wall is present, it occupies a 1.50 m × 2.80 m section of the south facade, with a 0.10 m air cavity (which is simulated as a coupled thermal zone to calculate airflow) and a 0.40 m thick massive storage wall behind the glazing. The base model and the Trombe wall variant are shown in Figure 1(a) and Figure 1(b), respectively.



(a) **(b)**

Figure 1. Model geometry and construction: **(a)** Base model; **(b)** Trombe wall model with south-facing glazing.

Opaque constructions follow typical small test cells and are kept identical across all cases: external walls with 100 mm brick, 50 mm insulation and 19 mm gypsum board; a heavyweight concrete layer as the Trombe storage wall; single clear glazing over the cavity; and insulated lightweight roof and floor.

All simulations are run in EnergyPlus v9.6. Geometry is created in SketchUp and edited in the IDF editor. A time step of 10 minutes is used, with monthly shadow updates and full interior and exterior solar distribution. Outputs include hourly air and operative temperatures and solar gains for free running conditions, annual heating and cooling demands from a simplified system, and, in the assisted ventilation case, fan electricity use.

3.2. SIMULATION SCENARIOS

The room represents a simple residential space occupied by one person, giving an occupant density of approximately 0.05 persons/m². Occupancy is assumed from 07:00-09:00 and 17:00-23:00 on weekdays and throughout the day at weekends. The metabolic rate is 1.2 met (≈120 W/person) with a radiant fraction of 0.3. Thermal comfort indicators are evaluated only during these occupied hours.

Lighting and equipment gains are kept identical across all scenarios. Installed lighting power is 7 W/m², following a residential schedule that peaks in the evening; 60% of lighting heat is radiant and the remainder is convective. Miscellaneous equipment loads are also 7 W/m², with an evening-weighted schedule and a radiant fraction of 0.3.

The external blinds in the TW+Blinds and TW+Blinds+Fan cases are active during the summer season, defined as May to September 30. During the rest of the year, the blinds remain retracted to prioritise passive solar gains.

In TW+Blinds+Fan, an exhaust fan operates during the heating and shoulder seasons (October-April, 09:00-19:00 on all days) and remains off the rest of year. These common inputs help ensure that performance differences arise from Trombe wall, shading and ventilation strategies rather than changes in internal gains or occupancy. External blinds and the auxiliary fan operate as mutually exclusive seasonal strategies, with no operational overlap throughout the year. The conceptual diagrams for this seasonal control logic, illustrating the transition between summer solar blocking and winter heat harvesting, are presented in Figure 2.

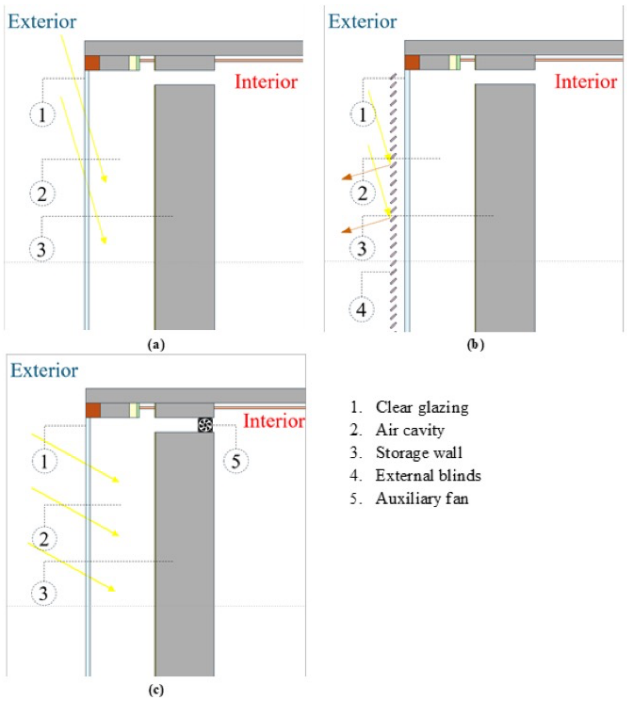


Figure 2. Conceptual diagrams of the seasonal control logic: **(a)** Classic Trombe wall (TW), where summer solar radiation heats the air cavity; **(b)** Trombe wall with external blinds added, which block solar gain to prevent overheating of the cavity; **(c)** Trombe wall with an auxiliary fan, where stored thermal energy is mechanically circulated into the interior zone during winter while blinds are retracted.

Table 1 summarises the four simulation scenarios. All share the same single-zone geometry, constructions and internal-gain assumptions; only the presence of the Trombe wall, external blinds and fan differs from one case to the next.

Table 1. Summary of the four simulated configurations and their key features.

Model	Description	Key Features	Purpose
Base Case	Reference model without Trombe wall	South-facing window (1.5 m × 1.0 m); opaque insulated wall elsewhere	Establish baseline for diurnal swing and overheating risk
TW	Trombe wall added	1.5 m × 2.8 m storage wall (0.40 m concrete) + 0.10 m air cavity + single glazing; no blinds, no fan	Measure passive storage effect
TW+Blinds	Trombe wall and Blinds added	Same as TW, with external blinds permanently deployed	Quantify shading impact on peaks

Model	Description	Key Features	Purpose
		(May 1st to September 30th; 24/7)	
TW+Blinds+Fan	Hybrid Trombe wall	Same as TW+Blinds, plus Fan assisting cavity ventilation (Oct 1st to Apr 30th; 09:00-19:00).	Evaluate active ventilation synergy

3.3. FAN STRATEGY AND EVALUATION SETUP

In TW+Blinds+Fan a small auxiliary fan supports cavity ventilation during the heating and shoulder seasons while avoiding additional cooling energy use in summer. The design air flow rate is scaled from a reference Trombe wall system using the ratio between the glazing areas, yielding 0.0061 m^3/s for this study. The fan is modelled as a constant-volume device with a pressure rise of 600 Pa, a total efficiency of 0.70 and a motor efficiency of 0.90. Under these assumptions, the electric power is about 5 W, and the yearly electricity use is approximately 11 kWh when the fan operates from 09:00 to 19:00 between October and April. The fan operation schedule was selected to synchronise with peak solar availability rather than occupancy. This preheating strategy allows the system to harvest solar heat during the day and store it within the building thermal mass and air. Apart from this fan object and schedule, TW+Blinds+Fan is identical to TW+Blinds.

To provide a comprehensive evaluation, thermal comfort and energy performance are assessed under two distinct operational modes. First, thermal comfort is evaluated under free running conditions, without any mechanical heating or cooling. Performance is evaluated based on the frequency of indoor air temperatures evaluated across all 8760 annual hours. The analysis categorises these hours into three distinct zones defined as comfort for indoor temperatures between 20 °C and 26 °C, overheating for values exceeding 26 °C, and overcooling for temperatures falling below 20 °C. This temperature-based approach directly assesses the system's ability to buffer seasonal extremes in the HSCW climate, instead of relying on static satisfaction indices such as the PMV. Crucially, ASHRAE Standard 55 restricts the adaptive model to buildings in free-running mode with prevailing outdoor temperatures between 10 °C and 33.5 °C (ASHRAE, 2020), rendering it invalid for a year-round evaluation in Beijing's extreme climate, where outdoor temperatures during occupied hours fluctuate between -14.0 °C and 37.0 °C.

Second, to quantify energy savings, annual heating and cooling demands are calculated separately using an ideal air-conditioning representation that strictly maintains the space within the 20 to 26 °C range.

3.4. LIMITATIONS

Although the Trombe wall cavity is simulated as a coupled thermal zone, the main occupied space is treated as a single, well-mixed air node. This modelling assumption introduces critical limitations that must be acknowledged. First, assuming a uniform interior air temperature fails to capture indoor thermal stratification and localised thermal discomfort caused by partial heating near the Trombe wall. Second, the model evaluates an isolated single room test cell, neglecting realistic multi-surface heat transfer interactions and inter-zonal airflow. In an actual building layout, heat delivered by the Trombe wall would naturally dissipate into adjacent unheated spaces. Consequently, omitting these room adjacency effects and whole-building cross-ventilation dynamics likely leads to a significant overestimation of both the Trombe wall's overall heating effectiveness and the extreme peak temperatures or overheating hours observed during summer. Furthermore, occupant behaviour is represented by fixed schedules rather than stochastic models, constructions do not cover the full building stock, and fan performance is idealised. Despite these limitations, this approach was necessary to isolate the facade's thermal behaviour, allowing for a direct and controlled comparison of the different Trombe wall options under a HSCW climate.

4. SIMULATION RESULTS

4.1 TYPICAL DAILY THERMAL PERFORMANCE

The short-term behaviour of the Trombe wall under Beijing's HSCW climate is examined using two typical days, 15 January and 15 July, for the four configurations.

On 15 January, outdoor temperature ranges from about -10 °C at night to around -6°C in the afternoon. In Figure 3(a) the Base case has the lowest indoor air temperatures, dropping to about -5 °C in the early morning and reaching only around -1.5 to -2 °C in the afternoon. Adding the Trombe wall (TW) shifts the whole profile upward: the afternoon peak increases to roughly -0.7 °C, while night-time temperatures are also 0.2 °C higher compared to the Base case. TW+Blinds is almost overlapping with TW, indicating a very similar winter behaviour. The TW+Blinds+Fan case is the warmest, briefly approaching 0 °C in mid-afternoon, but the extra improvement over the passive TW cases is 1.4 °C at its peak. Overall, the Trombe wall provides a clear winter benefit, increasing peak indoor temperatures by 0.7 °C compared with the Base case, with an additional peak gain of 1.4 °C provided by the fan.

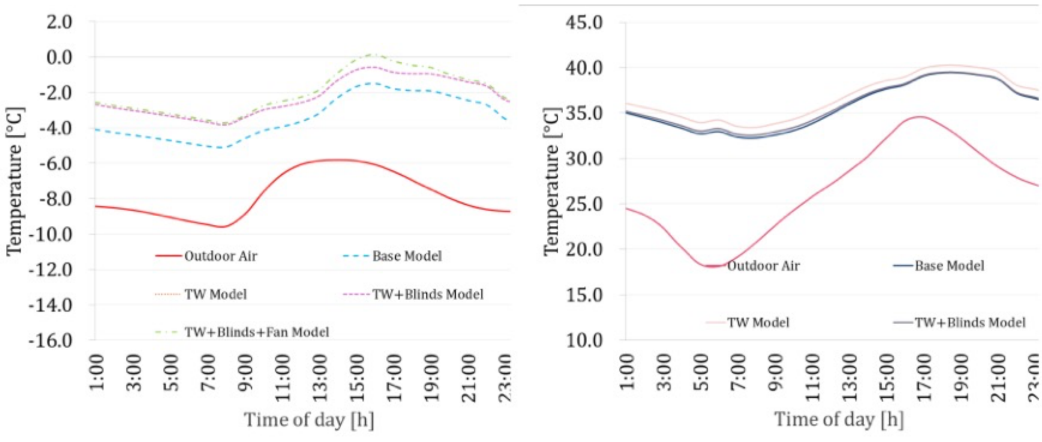


Figure 3. Hourly outdoor and main-room air temperature profiles under Beijing's extreme HSCW climate: **(a)** typical winter day (15 January); **(b)** typical summer day (15 July).

On 15 July, the outdoor temperature ranges from about 18 °C to roughly 34-35 °C in the late afternoon as shown in Figure 3(b). Indoors, the unshaded TW case produces the highest temperatures, reaching a peak of 39.5 °C, which is 0.6 °C higher than the Base case peak. When blinds are used, the indoor peak is reduced to 39.1 °C, remaining within 0.5% of the Base case, showing that shading suppresses 67% of the additional solar gain from the Trombe wall at the peak hour. TW+Blinds+Fan shows an identical profile to TW+Blinds, confirming that the inactive fan does not reduce overheating under these conditions.

4.2. ANNUAL THERMAL COMFORT ANALYSIS

Annual thermal comfort is evaluated using the hourly evolution of indoor air temperatures, Figure 4 presents the year-round temperature profiles for the four configurations, with dashed lines indicating the comfort band (20 °C to 26 °C). The performance is assessed by analysing the frequency of annual hours that fall within this range versus those categorised as overheating (> 26 °C) or overcooling (< 20 °C).

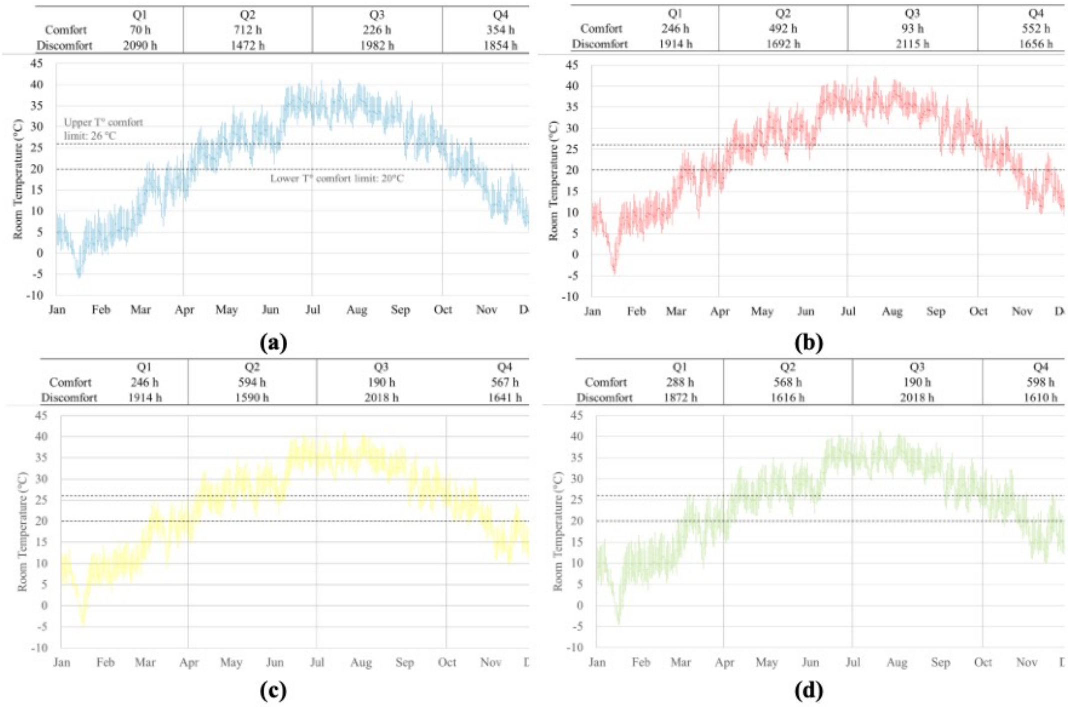


Figure 4. Annual evolution of hourly indoor air temperature for the four configurations: **(a)** Base; **(b)** TW; **(c)** TW+Blinds; **(d)** TW+Blinds+Fan; and comfort range limits (20 °C to 26 °C).

In the Base case, shown in Figure 4(a), the temperature profile confirms the extreme nature of the Beijing climate. During the winter months (January and February), indoor temperatures remain consistently below the comfort threshold, frequently dropping below 0 °C and reaching lows near -6 °C during the coldest nights without active heating. Conversely, in summer (July and August), the curve shifts entirely above the comfort zone, with peak temperatures regularly exceeding 30 °C and reaching up to 38 °C in extreme heat waves. This distribution indicates that the building envelope alone offers minimal buffering, resulting in severe cold stress in winter and significant heat stress in summer.

The unshaded Trombe wall configuration, illustrated in Figure 4(b), creates an upward shift that reduces annual overcooling hours by 13.9% compared to the Base case. In winter, this effect is beneficial. The solar heat gain raises minimum indoor temperatures by up to 3.7 °C during winter (e.g., from 1.9 °C to 5.6 °C on January 1st). However, this passive gain becomes detrimental in the cooling season. Without control, the summer profile in Figure 4(b) shows a 16.4% increase in annual overheating hours, with indoor peaks reaching 41.3 °C, well above the Base case levels. The system effectively alleviates winter overcooling but exacerbates summer overheating, leading to a thermal imbalance, that results in a 1.5% net increase in annual comfort hours.

The impact of the shading strategy is evident in Figure 4(c) (TW+Blinds). Here, the winter profile remains identical to the passive Trombe wall, preserving the solar heating benefits. However, during the summer period (May to September), the deployment of blinds reduces the seasonal cooling load by 13% compared to the unshaded case. The curve in Figure 4(c) shows summer temperatures that remain within 0.5% of the Base case values at the afternoon peak, hovering between 30 °C and 33 °C rather than spiking to 40 °C. This confirms that blocking direct solar radiation is effective in limiting the summer cooling penalty to 8.7% above the baseline, preventing the Trombe wall from becoming a significant heating load during warm months.

Figure 4(d) shows the profile for the fan-assisted configuration (TW+Blinds+Fan). While visually like the shaded case in summer, since the fan is largely inactive during peak heat, the fan provides a measurable benefit in the transitional and winter periods, increasing comfort hours in Q1 by 17% compared to the shaded passive case. The curve shows a further stabilisation of temperatures, particularly increasing the hours that sit just within the lower bound of the comfort zone (20 °C) by recovering stored heat during cooler evenings.

In the summer months from June to September, the configuration with the fan behaves identically to the TW+Blinds model, as the mechanical system remains inactive throughout the entire May-September season. Consequently, the fan provides 0% additional relief during the peak summer months, and the marginal 2.9% total increase in annual comfort hours is strictly due to its operation during the heating and shoulder periods.

This outcome reinforces that, in spaces dominated by strong radiant gains from a solar wall, comfort is more sensitive to radiation control through shading than to the moderate increases in air movement provided by the fan during its operational months.

Synthesising the results from Figure 4, it is evident that achieving year-round comfort in a climate with such extreme seasonal contrast remains a challenge. While the hybrid Trombe wall increases comfort hours in the coldest months by 311% relative to the Base case, it does not inherently eliminate overheating risk. The integration of external blinds is the primary driver for habitability, delivering a 15.5% increase in annual comfort relative to the unshaded Trombe wall, whereas the auxiliary fan provides an additional incremental benefit of only 2.9%. Consequently, these findings emphasise that maximising the hours within the 20 °C to 26 °C comfort zone depends less on additional hardware and more on control refinement, specifically regarding blind operation and seasonal switching logic, to reduce reliance on mechanical cooling.

Building on the hourly analysis, the aggregated annual metrics confirm that relatively small changes in facade control can shift the overall comfort balance. When all occupied hours are classified against the comfort threshold used in this study, the Base case achieves 1362 h within the comfort band, while the rest of the year is dominated by discomfort, split between 3325 h of overheating and 4073 h of overcooling. Introducing a passive Trombe wall produces only a marginal 1.5% increase in annual comfort hours, but it redistributes the discomfort: overcooling falls by 13.9%, while overheating surges by 16.4%. This indicates that the added solar storage helps in colder periods yet becomes a significant liability as outdoor temperatures increase.

The TW+Blinds configuration delivers a 17.3% improvement in annual habitability relative to the Base case. Comfort time rises to 1597 h, accompanied by a 5.7% reduction in overheating compared with the unshaded Trombe wall (down to 3651 h), while keeping overcooling 13.8% lower than the Base case. Adding the auxiliary fan in TW+Blinds+Fan optimises the annual balance further, achieving a 20.7% of total improvement over the baseline. Comfort peaks at 1644 h and overcooling decreases to its lowest value of 3371 h. Overall, the annual comparison indicates that seasonal shading is the primary driver for mitigating summer risks, while the fan provides a specific boost to heating efficiency during the cold and shoulder seasons.

Cold stress dominates in Q1 (Jan-Mar). The Base case records only 70 comfort hours alongside 2090 h of overcooling. The passive Trombe wall strategies result in a 251% increase in comfort hours (from 70 h to 246 h) compared to the Base case. The auxiliary fan provides a further benefit, raising comfort to 288 h and reducing overcooling to 1861 h, demonstrating its utility in scavenging heat during the coldest quarter.

In Q2 (Apr-Jun), the dynamics shift. The Base case achieves the highest comfort because the unshaded Trombe wall begins to overheat before the cooling season fully starts, causing a 31% reduction in comfort hours compared to the Base case. The TW+Blinds configuration recovers much of this loss, reaching 594 h, while the fan-assisted model records 568 h. This drops relative to the baseline highlights that fixed-schedule controls may struggle during transitional weeks when the wall stores unwanted heat.

During the peak heat of Q3 (Jul-Sep), the unshaded Trombe wall performs poorly, recording only 93 h of comfort and 2115 h of overheating. External blinds are essential here, restoring comfort to 190 h and reducing overheating to 2018 h. However, even with shading, the comfort hours remain 16% lower than the Base case performance (226 h), showing that residual heat storage impacts the environment more than a standard window.

In Q4 (Oct-Dec), the Trombe wall again mitigates cold conditions effectively. Comfort increases from 354 h in the Base case to 552 h with the passive Trombe wall, while overcooling falls from 1804 h to 1503 h. The shading strategy maintains similar performance (567 h comfort), but the fan-assisted system delivers the best result for this period, achieving 598 h of comfort and dropping overcooling to 1430 h. Table 2 summarises the annual behaviour, showing that the integrated hybrid system achieves a 20.7% net increase in annual comfort hours relative to the reference room. Seasonal shading proves essential for the annual balance by reducing overheating hours by 5.7% compared to the unshaded Trombe wall configuration. Furthermore, the combined effect of thermal mass and fan assistance delivers the maximum mitigation of cold stress, resulting in a 17.2% annual reduction in overcooling hours compared to the Base case.

Table 2. Yearly thermal comfort metrics for the four facade configurations: hours in comfort, overheating and overcooling.

Model	**Comfort**	**Overheating**	**Overcooling**
Base Case	1362 h	3325 h	4073 h
TW	1383 h	3870 h	3507 h
TW+Blinds	1597 h	3651 h	3512 h

Model	Comfort	Overheating	Overcooling
TW+Blinds+Fan	1644 h	3745 h	3371 h

4.3. ANNUAL HEATING AND COOLING LOADS

To compare the four Trombe wall configurations under HSCW climate conditions, annual heating and cooling demands were calculated using an ideal air-conditioning system that supplies exactly the load required to maintain the indoor temperatures within the defined comfort range (20 °C to 26 °C), without the influence of specific plant technologies or efficiencies. This idealised approach isolates the effect of the envelope and facade control strategies on thermal demand. For the configuration with blinds and an auxiliary fan (TW+Blinds+Fan), the fan electricity use is treated separately from the ideal loads and then included when discussing total annual energy use.

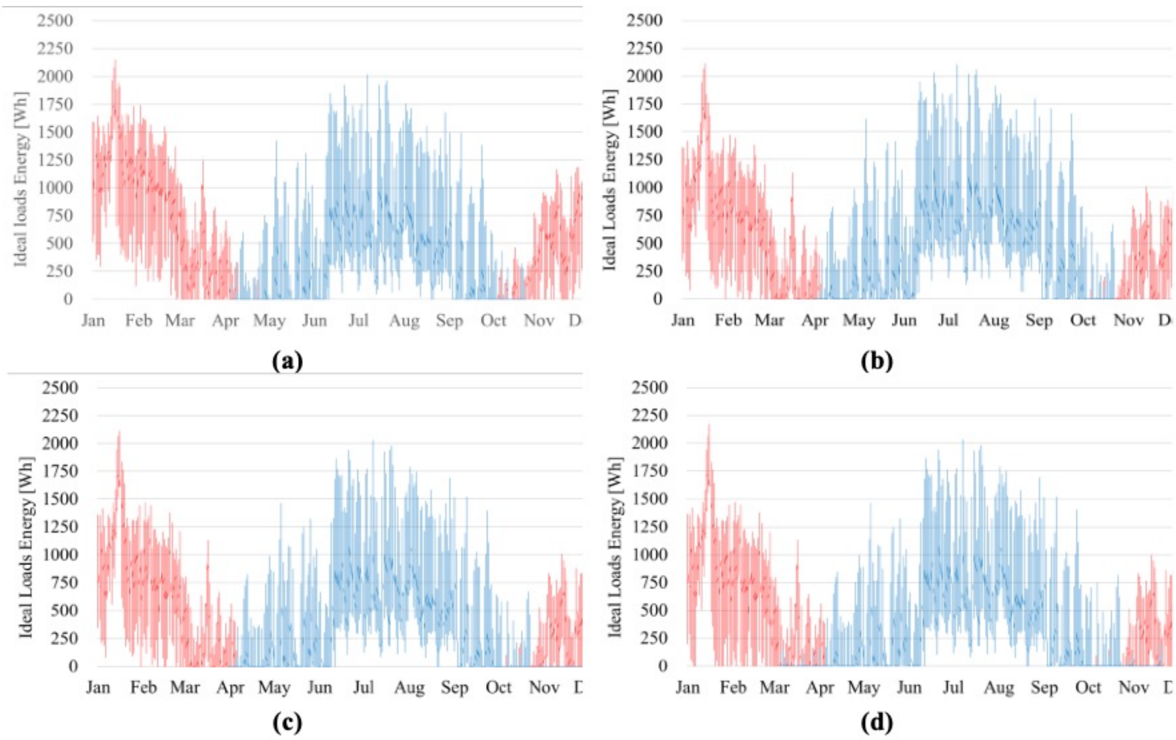


Figure 5. Annual ideal cooling (blue lines) and heating (red lines) loads energy (Wh) for the four configurations: **(a)** Base Model; **(b)** Trombe Wall; **(c)** Trombe Wall + Blinds; **(d)** Trombe Wall + Blinds + Fan.

Figure 5(a) shows a clearly bimodal demand profile for the Base case, which requires a total of 4.717 MWh of annual energy conditioning. Heating loads dominate the demand at 2.838 MWh, concentrated mainly from January to March and again from November to December, with the highest hourly heating spikes occurring during mid-winter cold spells. Cooling loads account for 1.879 MWh, concentrated from May to September and peaking in July-August, where the most intense and frequent cooling events occur. Overall, the figure confirms that the building requires substantial conditioning in both seasons, with winter heating representing 60% of the total annual thermal demand.

In the Trombe wall model shown in Figure 5(b), the same seasonal structure is preserved but the balance shifts. In winter, the massive wall behaves as a passive solar buffer: daytime gains are stored and released later, resulting in a 27% reduction in annual heating demand, particularly across the main heating months and into the early and late parts of the heating season. In contrast, cooling loads become more persistent through summer and the adjacent shoulder months, with a denser band of cooling events and sustained peaks through mid-summer. This configuration imposes a 25% annual cooling penalty, with the demand increasing from 1.879 MWh to 2.351 MWh.

In the TW+Blinds configuration, shown in Figure 5(c), the impact of seasonal shading becomes evident. In winter, when blinds are retracted, the annual heating demand remains identical to the unshaded Trombe wall at 2.077 MWh, confirming that the 27% passive heating benefit relative to the Base case is fully maintained. In summer, when blinds are deployed, the cooling profile is moderated, the seasonal cooling load is reduced by 13% relative to the unshaded Trombe wall. Cooling demand remains substantial, but seasonal shading clearly limits the most extreme cooling events and reduces the overall severity of the cooling penalty, to only 8.7% above the Base case baseline.

Finally, Figure 5(d) shows the TW+Blinds+Fan configuration. Under the tested flow rate and schedule, the auxiliary fan provides an additional 4.8% reduction in annual heating demand compared to the TW+Blinds case, lowering the load to 1.978 MWh. The main seasonal patterns are unchanged, and the fan does not materially reshape the cooling season because it is inactive during summer by design, resulting in a cooling load of 2.067 MWh. The benefit of the fan represents a cumulative 30.3% reduction in annual heating demand relative to the Base case. The fan is modelled with a design flow rate of 0.00610 m^3/s for the 3.38 m^2 glazing and an electric power of about 5 W, resulting in an annual electricity use of 0.011 MWh. This added consumption is negligible compared to the thermal demand reductions, allowing the hybrid configuration to achieve the lowest total annual energy use with a 14% net saving relative to the reference room.

Overall, the annual energy results summarised in Table 3 highlight the necessity of the hybrid approach. By successfully mitigating the severe cooling penalty of the passive solar wall while maximising winter heat recovery, the TW+Blinds+Fan configuration achieves the lowest total annual energy demand of 4.056 MWh, establishing the most favourable year-round energy balance among the evaluated scenarios.

Table 3. Annual energy breakdown (MWh) for the four configurations.

Model	Heating (MWh)	Cooling (MWh)	Fan (MWh)	Total (MWh)
Base Case	2.838	1.879		4.717
TW	2.077	2.351		4.428
TW+Blinds	2.077	2.042		4.119
TW+Blinds+Fan	1.978	2.067	0.011	4.056

5. DISCUSSION

The findings confirm that the Trombe wall is a highly effective solar buffer for Beijing's cold winters, providing a 27% reduction in annual heating demand. This performance aligns with established literature (Duan et al. 2016; Hu et al. 2017) for similar climates, validating the wall's thermal lag as a robust passive strategy for heat storage and delayed release. Quantitatively, the heating performance of the proposed hybrid system aligns strongly with recent literature on active Trombe walls. The 30% reduction in annual heating demand achieved by the fan-assisted configuration in this study is highly consistent with Zhu et al. (2022), who reported a 32.1% heating load reduction for a composite Trombe wall equipped with a temperature-controlled DC fan. Conversely, Xiao et al. (2023) demonstrated a significantly higher heating demand reduction of 61.4% for a fan-assisted Trombe wall in Nanjing, another Chinese HSCW city. This disparity highlights the impact of envelope properties; while the present study evaluates a standard single-glazed system for cost-effective retrofitting, Xiao et al. (2023) integrated low-emissivity glass and additional insulation layers, significantly suppressing conductive and radiative heat losses.

However, a persistent seasonal penalty remains during the peak cooling months. The 8.7% excess in cooling demand observed in the shaded cases relative to the Base case indicates that even with 24-hour shading, the thermal mass continues to radiate residual heat into the space. This suggests that in Beijing's climate, external shading is a necessity; while it effectively reduces the Trombe wall's cooling load by 13%, it cannot fully counteract the inherent heat-gain characteristics of the glazed cavity during peak summer. Regarding this summer performance, Bevilacqua et al. (2022) showed that proper shading and natural ventilation of a Trombe wall in a Mediterranean climate could yield net summer energy savings, reducing cooling needs by 9.5% relative to a traditional envelope. In contrast, the present study reveals that in Beijing's severe HSCW climate, even with permanent 24/7 external shading, the Trombe wall still imposes a cooling penalty. This comparison emphasises that while active Trombe walls can generate net summer benefits in milder climates, their application in extreme HSCW environments must primarily focus on aggressive mitigation of the inherent summer cooling penalty to ensure an overall positive annual energy balance.

The integration of seasonal blinds and fan-assisted ventilation is what transforms the system from a risky passive feature, which in its unshaded form provides only a marginal 1.5% net comfort increase due to a 16.4% surge in overheating hours, into a robust retrofit solution. The TW+Blinds+Fan configuration succeeds in harmonising conflicting seasonal requirements. It does not merely maximise a theoretical comfort index but physically maintains the indoor environment within the safe 20 to 26 °C range for 1644 hours annually, representing a 20.7% total improvement in habitability over the reference room. This stability is primarily driven by a 17.2% annual reduction in overcooling hours and the successful mitigation of the extreme temperature peaks that characterise unshaded solar storage systems. Beyond annual energy demand, this impact on thermal habitability can be contextualised against Sheng et al. (2024), who investigated Trombe wall ventilation in the HSCW climate of Wenzhou. While the present study achieves a 20.7% improvement in annual comfort, it notes a 20% decrease in comfort hours during Q2 due to fixed-schedule controls causing unwanted heat delivery. In contrast, Sheng et al. (2024) found that by optimising Trombe wall airflow specifically for natural ventilation, transitional months like May achieved the highest proportions of thermal comfort, reaching up to 47%. This quantitative contrast strongly reinforces the present study's conclusion that transitioning from fixed timers to real-time automated controls is essential to manage spring performance effectively.

Crucially, this improvement in comfort does not come at the expense of energy efficiency. The hybrid strategy achieves the lowest total annual energy demand (4.056 MWh), representing a net saving of 14% relative to the Base case. This indicates that the electricity consumed by the fan (approx. 0.011 MWh/year) represents only 1.6% of the total energy saved and 0.27% of the total annual demand. Overall, the 14% net annual energy saving demonstrates the viability of the seasonally shaded hybrid facade. Given the physical constraints of blind installation, the strategy of keeping them deployed 24/7 throughout the summer emerges as the primary control lever, reducing the Trombe wall's seasonal cooling load by 13% and limiting the final summer penalty to 8.7% above the baseline. These findings directly support China's 'dual carbon' targets for 2030 and 2060, providing a scalable strategy for residential decarbonisation without compromising summer habitability.

6. CONCLUSIONS AND FUTURE WORK

The findings demonstrate that the hybrid solar-storage facade achieves a favourable balance between efficiency and habitability in Beijing's climate. The optimised configuration (TW+Blinds+Fan) yields a 14% net reduction in annual energy use and a 20.7% improvement in annual thermal habitability. These results are driven by reducing annual overcooling hours by 17.2% and heating demand by 30.3% relative to the reference room. However, the quarterly analysis reveals that performance in transitional months is constrained by fixed-schedule controls. For instance, comfort hours in Q2 decrease by 20% relative to the baseline, as the system occasionally allows heat delivery when it is not required.

Regarding practical implementation, the permanent deployment of blinds during summer offers a highly feasible and scalable retrofit strategy that minimises the need for daily user intervention. However, the seasonal labour required for the initial installation at the start of summer and its subsequent removal remains a practical challenge that could affect user acceptance. Despite these promising results, it is important to acknowledge the limitations of this study. The findings rely purely on a simulation-based approach using a simplified single-zone model, idealised fan performance, and fixed operational schedules, which may differ from real-world multizone airflows and complex occupant behaviour.

Future work must include experimental field validation. Constructing a physical prototype would allow for the monitoring of actual thermal performance under real weather conditions. Alongside this field testing, future research should focus on implementing automated control logic where the fan and blinds respond to real-time indoor-outdoor temperature differentials rather than fixed timers. By preventing the unintentional heat delivery observed in spring and more effectively managing summer residual heat, such intelligent strategies are expected to push annual comfort beyond current levels and unlock even deeper energy savings.

AUTHOR CONTRIBUTIONS

Meixin Wu: Conceptualisation, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing – Original Draft. **Francisco Mateo-Elgueda**: Methodology, Software, Formal analysis, Validation, Writing – Original Draft, Writing – Review & Editing. **Yuehong Su**: Conceptualisation, Validation, Supervision, Project administration, Writing – Review & Editing.

COMPETING INTERESTS

The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA ACCESSIBILITY

The data used in this study will be made available upon request.

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DECLARATION OF GENERATIVE AI

The authors declare that Generative AI and AI-assisted tools were used in the writing process to improve the readability and language of the manuscript. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the integrity and accuracy of the published article.

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