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Review of providing the building's energy needs and the impact of solar walls on their performance

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ABSTRACT

This review paper discusses the use of solar walls in buildings, designed to absorb, store, and transfer thermal energy from the sun. Solar walls provide effective solutions for harnessing solar energy and can significantly enhance energy efficiency by reducing indoor temperatures by up to 50%. To optimize solar walls, strategies such as natural ventilation, shading, glazing, solar orientation, and techniques like catalytic processes can be employed, making them adaptable to various climates. New innovations in solar wall technology include transparent walls, building-integrated photovoltaics, and phase change materials. These multifunctional options aim for environmental compatibility and sustainability in building design. Solar walls not only enhance aesthetic appeal and usability but also contribute to energy production and cooling, while minimizing the building's environmental impact. In hot and humid regions, solar walls should be designed to limit heat ingress and, where possible, act as insulators or incorporate features that deter insects. Self-supporting walls are particularly well-suited for environmentally conscious building designs, promoting energy efficiency and providing effective methods for energy conservation.

Keywords*:* Building's Energy needs, Solar Walls, Performance

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1. INTRODUCTION

In an era marked by growing global concerns about climate change and environmental sustainability, the need to address energy waste has taken center stage. Amid growing global concerns about climate change and environmental sustainability, addressing energy waste has become a crucial priority. This urgency is underscored by the Sustainable Development Goals (SDGs) ("NL82-SDGs.Pdf," n.d.), the assessments from the Intergovernmental Panel on Climate Change (IPCC) (H. Lee et al. 2023), and commitments made during the United Nations Climate Change Conferences (COPs). The building and construction sector plays a vital role in this context, as it consumes vast resources and energy, straining ecosystems and depleting finite resources. The global consensus emphasizes the urgent need to shift from energy-intensive buildings to structures that achieve zero-energy or net-zero energy levels (Scott and Gössling 2021). This transition requires moving away from fossil fuels toward sustainable, renewable sources, reflecting a unified effort among nations to tackle climate change and mitigate the environmental impact of the built environment (Bauer and Menrad 2019) (Jacobson et al. 2017). Additionally, the construction sector accounts for over 35% of the total waste generated in the European Union, highlighting the need for innovative solutions to promote sustainability and reduce waste throughout the construction lifecycle (Ouédraogo et al. 2023). The GHG emissions from this sector are also concerning, stemming from material extraction, manufacturing, and building activities. These activities contribute 5–12% of national greenhouse gas (GHG) emissions ("Carbon Emissions and Policies in China's Building and Construction Industry" 2016), highlighting the need for mitigation. Up to 80% of these emissions could potentially be reduced through better material efficiency and sustainable building practices, but many existing buildings still require retrofitting ("Theoretical and Experimental Thermal Performance Assessment of an Innovative External Wall Insulation System for Social Housing Retrofit" 2018). About 35% of the EU's building stock is over 50 years old, with three-fourths being energy inefficient. Despite this, renovation occurs at just 1% annually ("Improving the Building Stock Sustainability in European Countries" 2022). In the U.S., targets for energy efficiency include achieving zero-energy status for new residential buildings by 2020 and for all new commercial buildings by 2030 (M. Hu and Qiu 2019). In December 2021, the EU proposed moving from Nearly Zero-Energy Buildings (NZEB) to Zero-Emission Buildings (ZEBs) to enhance sustainability in construction. This initiative aligns energy performance requirements for new constructions with the EU's long-term climate neutrality goals, emphasizing the "energy efficiency first principle." The proposed Zero-Emission Buildings (ZEBs) are defined by their exceptional energy performance, relying entirely on renewable sources and having no on-site carbon emissions from fossil fuels. ZEB requirements must be met starting 1 January 2030 for all new buildings and from 1 January 2027 for public authorities. The proposal also incorporates life-cycle Global Warming Potential (GWP) calculations to promote transparency in sustainability and emission reductions (Fetting, n.d.). Furthermore, a global analysis shows that 93% of the population resides in areas with an average daily solar energy potential of 3.0 to 5.0 kWh/kWp, highlighting solar energy's feasibility as a sustainable resource. Interestingly, practical solar PV output (PVOUT) is relatively consistent worldwide, influenced by factors like air temperature and solar irradiance (Bhanja and Roychowdhury 2023). Regions with lower solar radiation can achieve comparable PV power outputs to those with higher resources. Thus, solar energy emerges as a universally accessible renewable source. The success of these targets hinges on energy-efficient building envelopes, including insulation, windows, and roofing, which are essential for reducing primary energy consumption in buildings (Ghamari and Sundaram 2024).

To enhance energy performance, achieve net-zero GHG emissions, and extend the service life of buildings, there's a strong call to adopt innovative materials and technologies. Passive solar systems, like solar walls (SWs), significantly improve thermal storage capacity and heat transfer processes (D'Agostino et al. 2022). These advancements offer more than just traditional energy efficiency and GHG reduction benefits. Regions with ample sunlight can effectively utilize solar energy, making SWs a promising method for maximizing solar gains and reducing energy consumption. This research aims to evaluate the impact of SWs on the building sector, reviewing existing literature and operational principles, and analyzing practical applications and advancements in SW technology (Mavrigiannaki and Ampatzi 2016). Ultimately, this study seeks to highlight how SWs can contribute to sustainable, energy-efficient building environments and support global climate change initiatives while also enhancing indoor thermal comfort by regulating temperatures through effective solar energy management (Ghamari and Sundaram 2024).

The dual functionality of solar walls (SWs) makes them an attractive option for sustainable construction and renovation, helping to reduce energy consumption (Q. Li et al. 2021) and greenhouse gas emissions. SWs harness solar energy to generate electricity and provide heating or cooling, enhancing energy efficiency and overall building performance. By capturing solar radiation during the day and releasing it at night, they optimize energy usage for ventilation, heating, and cooling, thereby decreasing reliance on conventional energy sources and lowering carbon footprints (Kaushik and Kaul 1989).

Recent research shows a significant increase in interest in SWs and phase-change materials (PCMs). From 2014 to 2023, publications on PCMs rose from 28 to 152, while those on solar/Trombe walls grew from 18 to 100. This trend highlights the growing focus on these eco-friendly technologies in the research community. Figure 1, depicting the annual trends in publications related to phase-change materials (PCMs) and solar/Trombe walls from 2014 to 2023, is based on data collected from the Web of Science Core Collection. The analysis of this dataset reveals a notable surge in research output for both topics. In 2014, there were 28 publications on phase-change materials and 18 on solar/Trombe walls. Subsequent years demonstrated a consistent and steady growth in the number of publications. Notably, in 2023, the figures reached their pinnacle, with 152 publications on phase-change materials and 100 on solar/Trombe walls. These findings underscore a heightened interest and focus within the research community on these technologies, emphasizing their significance in the field (Yin et al. 2023) (Paul et al. 2024).

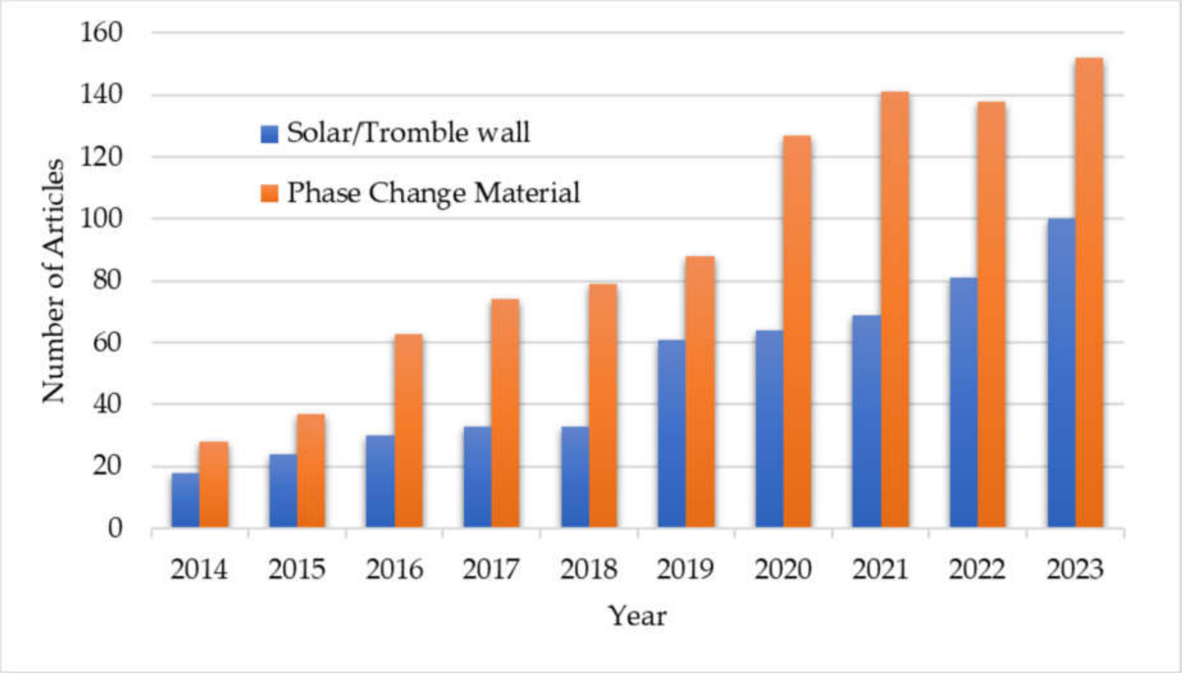
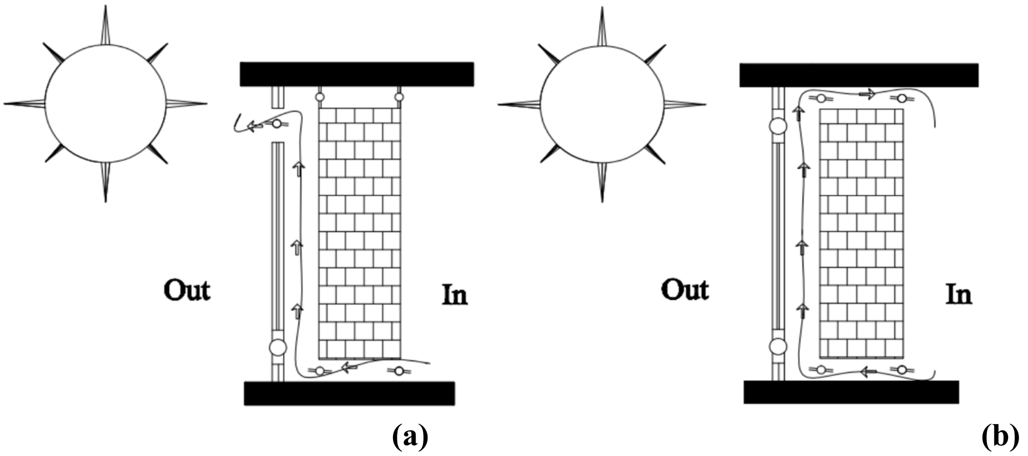


Figure 1. Trends in published articles by year on Trombe walls and phase-change materials from 2014 to 2023.

2- Overview of SWs

Solar walls (SWs) are innovative systems designed to capture and store solar heat through a glazed enclosure in a sturdy, south-facing wall made from materials like masonry or concrete (Masson et al. 2014). One notable variation is the Trombe wall (TW), which features strategically placed vents for controlled airflow, enhancing heat exchange (Aksamija 2017).

Popularized by French engineer Felix Trombe and architect Jacques Michel in the late 1950s and 1960s, modern TWs serve multiple functions, particularly in cold climates, where they can reduce heating energy consumption by up to 30%.evolved, with modern variations referred to as TWs (Figure 2). These versatile architectural elements serve multiple roles within buildings, particularly in cold climates, where they have demonstrated their efficacy in reducing heating energy consumption by up to 30%. energy consumption by up to 30% (Illampas et al. 2021).



(a) **(b)**

Figure 2. TW (day time periods): (a) summer; (b) winter.

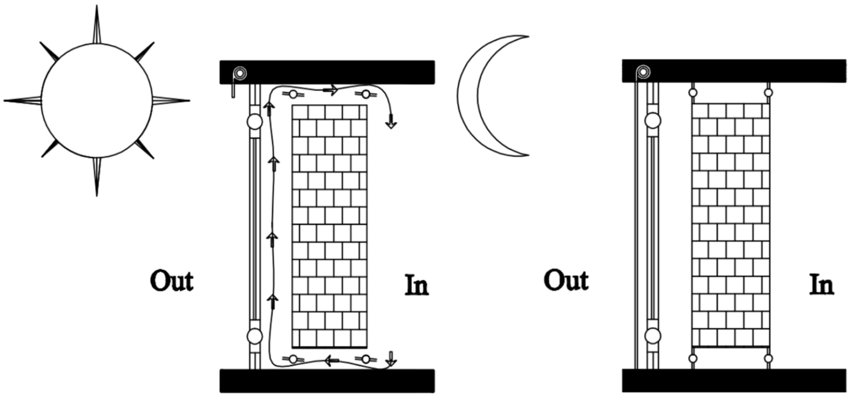
TW, a simple yet ingenious concept, consists of a massive wall positioned a short distance from a glazed surface, typically facing south to maximize sun exposure. Its fundamental principle is the thermo-circulation phenomenon (Mokni et al. 2022). When sunlight enters the glazing, the massive wall absorbs the solar flux and conducts some of this energy into the building. This initiates a natural air circulation process, where cooler air enters through a lower opening, and warm air exits through a higher one, effectively transferring solar heat into the living space. However, during periods of limited sunlight or colder temperatures, inverse thermo-siphon phenomenon can occur, leading to cooling of the interior (Z. Hu et al. 2017). To address this, innovative solutions like supple plastic films have been introduced to control airflow through the orifices, allowing for precise temperature regulation (Briga-Sá et al. 2021a). Composite thermal walls build on classical designs while effectively tackling heat loss during colder periods. They feature an insulating wall situated behind a massive wall. Solar energy is first absorbed by the massive wall and then transferred through convection via a thermo-circulation phenomenon that occurs between the two walls. When sunlight is limited, the openings in the insulating wall can be closed to minimize heat loss (Zhou et al. 2020).

Thermal walls (TWs) absorb direct and diffused solar radiation, transferring the heat to a thick interior wall through convection and conduction as the sun sets. An air gap of 3 to 6 cm between the sun-facing wall and the glazing helps release and store this heat, utilizing radiation and convection to enhance the thermal comfort of occupants (Saadatian et al. 2013).

The effectiveness of Trombe walls (TWs) improves with strategic air vent placement at the top and bottom. These vents reduce heat loss and promote thermos-circulation, allowing warmer air to rise into the interior and cooler air to escape. However, when air temperatures rise significantly, heat loss through glazing can increase. Adjusting vent management based on local weather and desired indoor temperatures is crucial to prevent overheating during summer, as TWs primarily provide passive heating.according to local weather conditions and the desired indoor temperatures (Ong 2003). Considering that TWs primarily serve the function of passive heating, it is essential to implement precautions to avert overheating during the summer months (Stazi et al. 2012). External shading and occlusion devices can be helpful. Incorporating air vents in structures like the Double-Ventilated Thermal Wall (DVTW) aids in cooling the air layer. Optimizing the thermal wall's design and managing air vents and shading devices is crucial for achieving the desired indoor temperature (Briga-Sá et al. 2021b).

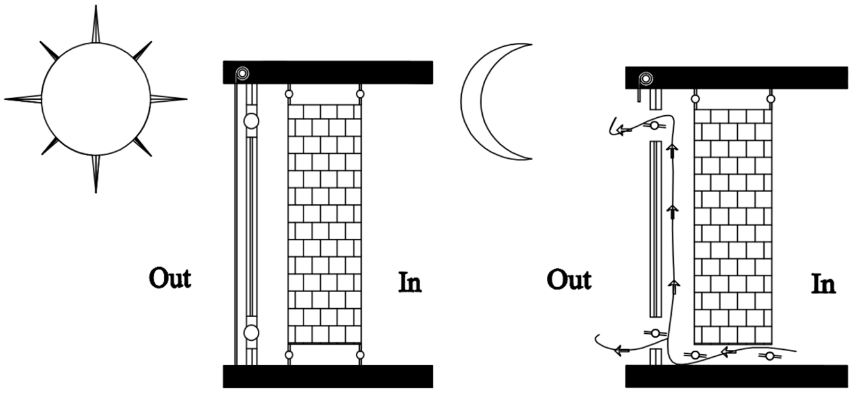
The ventilation system in the massive wall should activate only when the air temperature exceeds that of the room and space heating is needed. In winter, it's best to keep air vents and shading devices closed at night to prevent heat loss. In the summer, the ventilation system should remain closed during the day while utilizing shading devices; lighter-colored shades improve solar reflection. At night in summer, keeping air vents open and shading devices closed helps cool the air layer, with a DVTW aiding cross-ventilation in the building. Opening the bottom vents of the massive wall and the top vents of the glazing allows hot air circulation. Cross-ventilation through openings on the north facade cools the interior, as shown in Figure 3d. In winter, closing the vents creates a greenhouse effect, raising temperatures (Bevilacqua et al. 2022). Solar Disks (SDs) should be used wisely, not just to maximize solar gains. The wall's ventilation activates only when the air layer's temperature exceeds the interior, indicating a need for heating. At night, closing the air vents and using SDs helps retain warmth within the cozy interior (Briga Sá et al. 2017).

The text categorizes various types of solar technologies into five groups. The first is PV solar cells, which convert solar energy into electricity when integrated into walls. The second group consists of solar water walls that use water to absorb and convey solar energy. The third category features phase change materials (PCMs) that store and release energy during phase transitions. Fourth are double-skin facades, which provide environmental protection and controlled ventilation. Lastly, fluid walls use fluid-based systems to absorb and distribute solar heat, offering a versatile approach to solar energy in building design.



(a) **(b)**

Figure 3. Cont.



(c) **(d)**

Figure 3. Illustration of the operational modes of a TW as follows: (a) winter (daytime periods); (b) winter (nighttime periods); (c) summer (daytime periods); and (d) summer (nighttime periods).

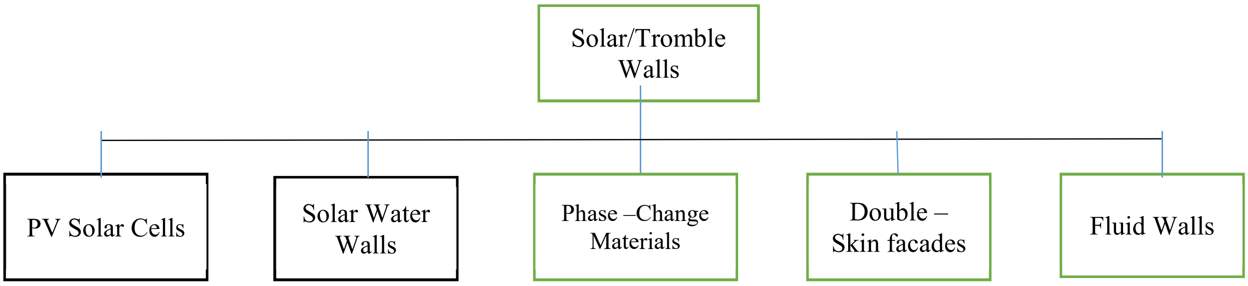


Figure 4. Classification of SW Technologies**.**

2.1. PV Solar Cells and the SW

Managing high temperatures in solar water (SW) systems is challenging, especially in hot climates. Traditionally, SWs focus on passive heating by absorbing solar radiation and transferring heat through natural convection. However, extreme heat can lead to overheating, reducing comfort and efficiency.

To combat this, researchers are integrating photovoltaic (PV) solar cells into SW designs, allowing for both passive heating and electricity generation. This approach optimizes resource use and improves overall system efficiency, spurring innovative research on enhancing energy generation and thermal performance (Ibrahim et al. 2023).

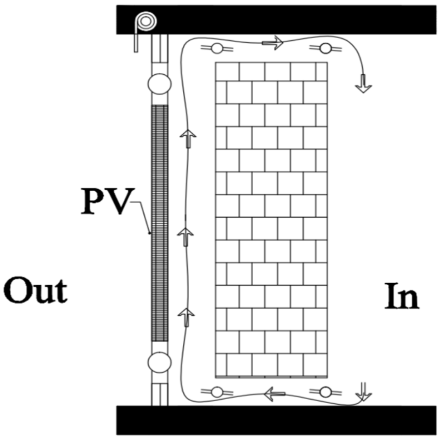


Figure 5. SW integrated with PV solar cells.

Traditionally, transpired walls (TWs) have focused on passive heating, but the integration of photovoltaic (PV) solar cells has expanded their role to active energy generation. A new system combines photocatalytic, PV, and TW technologies to simultaneously produce electricity, heat, and fresh air, demonstrating the benefits of a holistic energy approach. The research also examined how channel dimensions impact electrical and thermal performance, revealing that optimizing channel width and height significantly enhances system efficiency (Wu et al. 2020).

Indoor air quality is a key factor in building design. A study investigated the reduction of gaseous formaldehyde throughout the year while generating sustainable electricity using PV/T-TW. The research aimed to assess the role of PV-TW in indoor air purification and energy generation (Yu et al. 2020).

Yaxin Su and colleagues used computational fluid dynamics (CFD) to study heat transfer and airflow in a photovoltaic thermal wall (PV-TW) system, focusing on the gap distance between the PV panel and thermal wall. Their findings identified an optimal gap distance that maximizes airflow and heat transfer efficiency, which is vital for designing effective PV-TW systems that enhance solar energy harnessing and indoor thermal comfort (Su et al. 2016).

PV-TW systems effectively tackle energy efficiency and sustainability challenges, particularly in Saudi Arabia's arid climate, where maintaining indoor temperatures is crucial. These systems utilize Venetian blinds to manage shading and airflow, enhancing indoor comfort. Research by Kashif Irshad et al. highlighted significant economic and environmental benefits of integrating PV-TW systems in building designs, showing considerable cost savings and reduced carbon emissions in Malaysia. By harnessing solar energy for heating and electricity, these systems diminish reliance on traditional methods, yielding further advantages (Irshad et al. 2015). Table 1 summarizes the key findings from various studies focusing on the impact of PV solar cells on TWs.

2.2. Solar Water Wall

Solar energy for building heating and cooling has advanced with solar water walls, which replace traditional masonry with water-storage reservoirs. This innovative approach uses water's superior heat retention properties over air, enhancing passive heating strategies. It also improves heat reflection onto glazed surfaces, promoting environmentally responsive design and thermal comfort (Xu et al. 2022).

Table 1. Impact of PV solar cells on TWs.

Focus	Key Findings
TW with Air Purification, Photovoltaic, Heating, and Ventilation	• When increasing channel height to 1.4 m at 800 W/m2, the PC–PV–Trombe wall enhances ventilation, heat output, thermal, electrical efficiency, and clean air delivery with a 0.42 degradation in efficiency. • Channel width changes the impact of the PC–PV–Trombe wall, raising ventilation, electrical efficiency, and clean air delivery while decreasing heat output and thermal efficiency. Degradation peaks at 0.434 when there is low solar intensity. • Lower ambient temperatures hinder ventilation, thermal performance,and air purification. The PC–PV–Trombe wall, despite individual lag,excels in total efficiency under low solar radiation, highlighting its comprehensive solar potential.
Based on thermal catalytic oxidation process in winter	• The purified PV/T–Trombe wall demonstrated a daily air thermal efficiency of 36.6% and average electrical efficiency of 11.9% in winter. • The heat and mass transfer model indicated a formaldehyde conversion ratio of 0.445–0.550 and clean air delivery rate (CADR) of 42.5–81.6 m3/h. • Thermal catalytic oxidation enhanced solar utilization efficiency, resulting in a 13.6% electrical efficiency and 50.3% thermal and electrical efficiency considering formaldehyde degradation.

Effects of channel width on heat transfer and ventilation	• Numerical simulations using CFD for a built-in PV–Trombe wall channel revealed an optimum aspect ratio (b/H)opt of 1/5, chieving maximum airflow rate. The average Nusselt number exhibited increases with both heat flux and channel width, with a log-linear relationship observed in dimensionless analysis, leading to derived correlations for heat transfer and flow rate calculations.
Numerical model of PVTW_Ven in Saudi Arabia	• The PVTW_Ven configuration demonstrated lower outer and inner wall temperatures compared to TW_Ven, with reductions of 5.2 ◦C and 3.6 ◦C, respectively. • Heat transfer across TW_Ven was higher than PVTW_Ven, while the latter showed a 33.5% lower average heat gain due to blocked solar radiation. • Introducing a Venetian blind in both configurations facilitated systematic heat transfer, with TW_Ven's maximum blind temperature being 4.7 ◦C higher than PVTW_Ven's.
Double-glazed glass filled with argon	• Reduced room temperature and cooling load, as well as increased PV efficiency. The impact of air flow velocity plateaus after 1.75 m/s, making the PV–TW system with double-glazed glass filled with argon at 1.5 m/s the optimal choice for addressing energy consumption and environmental concerns in tropical regions.

The water-blind-based TW system features innovative components: a glass cover, water blinds with parallel microchannels, an air gap, a massive wall, and a water tank. Each slat acts as an efficient heat exchanger, circulating cold water from the tank to absorb solar radiation and returning it as heated water (Z. Hu et al. 2023). This design maximizes solar energy for space heating. Water's high specific heat, over four times that of masonry, is advantageous for heat storage but requires waterproof containers. Transparent glass containers with colored water and biocides serve as barriers, while absorbent glass supports and regulates sunlight. Protective measures like glazing and shading devices control solar radiation and maintain a balanced thermal environment.

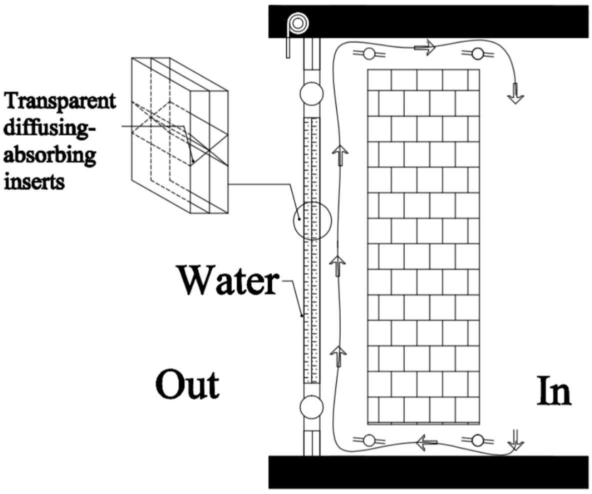


Figure 6. Operation principle of water TWs.

The sunward surface of these slats is designed for optimal solar energy absorption. An integrated radiator with the water tank allows for versatile system operation. Solar water walls provide excellent heat retention due to water's high specific heat capacity, surpassing that of materials like concrete and bricks, and they facilitate faster heat transfer to interior spaces compared to the air used in traditional systems (Ghamari and Sundaram 2024).

Researchers are enhancing solar water walls and integrating water sprayer systems into TW solar systems to improve efficiency. An innovative design in Yazd, Iran, with transparent walls in various orientations, showed better natural air ventilation and lower room temperatures than traditional systems. Additionally, experiments by Agurto et al. on a low-cost TW solar system with vertical water sprayers provided insights into its thermal performance across different climates.

Researchers have explored integrating water sprayers in thermodynamic (TW) solar systems, resulting in a 3.3% increase in efficiency over traditional systems and a 31% reduction in nighttime heat loss. These advancements promise significant improvements for energy-efficient and environmentally responsive building design. Solar water walls and optimized TW systems can enhance solar energy utilization for heating and cooling applications. Key studies on solar water walls are summarized in Table 2.

Table 2. Results from studies on solar water walls.

Focus	**Key Findings**
Research into Chinese solar greenhouses	• Achieving an 85.8% heat collecting efficiency; it released 80.4% of the collected heat for greenhouse heating during winter. • Retrofitting the water wall increased the minimum nighttime air temperature by an average of 3.3 ◦C, keeping it above 6.9 ◦C during consecutive overcast days and enabling warm season crop production throughout winter without supplemental heating.
Water-flowing channel and Venetian blind	• In hot water mode, the WBTW system achieved a mean thermal efficiency of 52.8%, 8.2% higher than the SCCW, with a slightly lower total heat loss coefficient of 5.1 W/(m2 K). • In natural ventilation mode, the WBTW system demonstrated a lower daily average wall temperature (43.1 ◦C) compared to the reference room wall (48.4 ◦C), emphasizing the importance of ventilation despite blinds and water circulation. • In air heating mode, the WBTW room temperature increased by 44 % compared to the CW room, while the combined air–water heating mode raised the indoor temperature by 21.5% during the day and 17.4% at night, enhancing thermal comfort.
Combination of solar chimney in hot and arid climates in Iran	• Utilizing a solar chimney alone decreased the room temperature by 0.1 –0 .2 ◦C, but combining it with a water-spraying system resulted in a room temperature reduction of about 9–14 ◦C and a relative humidity increase of 28–45%. • The solar chimney absorber facing west maximized the daily energy absorption, and the combination of solar chimney and

	water-spraying achieved the highest Air Changes per Hour (ACH) at noon, creating a comfortable indoor environment by compensating for air relative humidity deficiencies during the day.
Low-cost prefab TW in Chile	• A 30% increase in hours within the comfort temperature range during winter and a 25% improvement during summer emphasize its efficiency in enhancing indoor temperatures. • During winter, indoor thermal comfort hours increased by 69.35% in Chillán and 56.29% in Coronel, resulting in energy savings of 44.14 % and 25.35%, respectively, showcasing a significant impact on heating energy consumption.
Comparison between annual performance of the WBTW and two existing walls	• Monthly average thermal efficiency ranged from 20% to 60% in non-heating seasons and 30–50% during heating months. • In summer, CW, WBTW, and TW exhibited satisfying thermal insulation, in that order. In winter, WBTW demonstrated a mean heat transfer coefficient of 0.8 W/(m2 · K), outperforming TW (1.4 W/(m2 · K)) and CW (1.5 W/(m2 · K)). • The WBTW system reduced the overall thermal load by 42.6%, with an annual harvested energy of 435.7 kWh, making it an efficient alternative for achieving favorable insulation performance in winter and harnessing solar energy in summer and transition seasons.

2. 3. Leveraging Phase-Change Materials

The generation of electricity produces excess heat, impacting system efficiency and building comfort by causing temperature fluctuations and humidity issues. Passive Thermal Energy Storage (TES) with Phase Change Materials (PCMs) effectively addresses this by harnessing the latent heat properties of inorganic, organic, and eutectic materials. Incorporating up to 20% by weight of PCM in mortars can improve thermal properties and reduce HVAC energy consumption by up to 35%. However, thorough testing is essential to ensure effectiveness and prevent PCM leakage (Illampas et al. 2021).

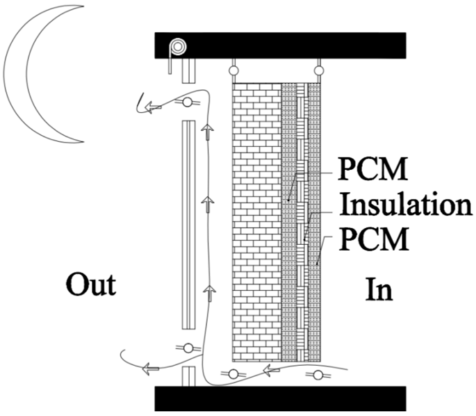


Figure 7. TW with PCM operation modes.

Incorporating phase change materials (PCMs) into a material's porous structure can effectively conserve heat through phase transitions during the day. This stored heat is released at night, helping to maintain comfortable temperatures. Research indicates that rooms with PCM-filled layers experience a nighttime temperature increase of about 20.2% compared to those without PCM, achieving a thermal storage efficiency of 76.2% (Elsaid et al. 2023).

Researchers have found that PCM-enhanced SW systems are effective. Simulations by Zhu et al. demonstrate that TW systems with PCM layers and insulation successfully reduce peak thermal loads in summer and winter (N. Zhu et al. 2021).

This reduction greatly impacts energy-efficient building designs by decreasing dependence on active heating and cooling systems. The use of double layers of phase change materials (PCMs), as studied by Shanshan Li and colleagues, helps manage summer overheating and winter temperature fluctuations. This enhances thermal comfort and livability while reducing energy demand for HVAC systems (S. Li et al. 2019). Enghok Leang and colleagues studied a composite concrete storage thermal wall (TW) with microencapsulated phase change materials (PCMs) and found that it significantly improved thermal performance over traditional TW systems. This innovative method has potential for enhancing year-round comfort in buildings, particularly in areas with temperature fluctuations (Leang et al. 2020). Table 3 presents diverse research findings on SWs integrated with PCMs.

Table 3 diverse research findings on SWs integrated with PCMs

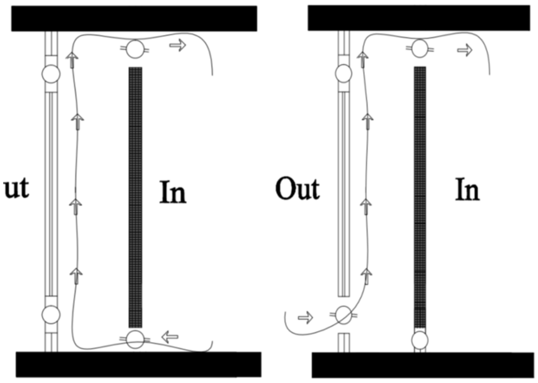
Focus	Key Findings
PCMs with Polymer-modified Cementitious Repair Mortar	• Despite reduced mechanical strength, mortars with 5%–10% microencapsulated PCMs exhibited a 3 ◦C peak indoor temperature reduction and effective attenuation of cyclical temperature

	variations during climatic chamber tests. • Microencapsulated PCM addition led to increased pore sizes, higher porosity, and reduced early stage water absorption, meeting EN 998-1 specifications for masonry coating mortars.
In summer and winter climates	• Insulation layers significantly enhance efficiency, reducing mass wall size and increasing effectiveness by up to 56%. • Coating materials improve SW effectiveness by 33%, contributing to better thermal performance in adverse weather conditions. • An air interlayer with a thickness of 0.3–0.35 m is essential for achieving the Trombe wall's outstanding thermal efficiency, especially in challenging weather. • Venetian blinds, serving as protective curtains, provide the best thermal insulation performance, boosting Trombe wall efficiency by 40%. • save up to 30% in summer cooling expenses and up to 50% in energy use during the heating season. • The average natural convective heat transfer of the traditional Trombe wall system increases by 14.4%, depending on the aspect ratio of the air cavity ratio.
TRNSYS and GenOpt	• Optimal parameters for PCM-enhanced Trombe wall: air gap, 0.05 m; shading length, 0.78 m; thermal storage thickness, 0.68 m; vents area, 0.6 m2; PCM melting: 16.5 ◦C, 27.75 ◦C. Annual loads: cooling, 754.7 kWh; heating, 477.8 kWh; total, 1232.5 kWh. • PCM-enhanced Trombe walls exhibited 7.56% and 13.52% greater annual energy savings.
Numerical study on thermal performance	• Optimal phase-change temperatures for external and internal PCMs were 30 ◦C and 18 ◦C, respectively. • In summer, the external PCMs prevented heat entry, improving indoor comfort and delaying peak temperatures. • In winter, the internal PCMs stored low-temperature residual heat, releasing it when needed, enhancing indoor comfort.

Thermal behavior of an individual house	• 20% reduction in one-year energy heating demand compared to a house without a solar Trombe wall. • 55.15% reduction in heating demand (energy savings) for Nice compared to a house without a solar Trombe wall.

2.4. Innovative Combinations

Solar windows (SWs) enhance energy efficiency and support sustainable practices with versatile designs for different architectural contexts. Key types include double-skin solar windows, fluid solar window systems, and custom solar windows. Double-skin solar windows consist of a dual-layer structure, featuring an outer transparent layer and an inner layer with solar components like photovoltaic (PV) panels (Gratia and De Herde 2007). Figure 8 shows the operational modes of a double-skin façade system. Panel (a) illustrates the mechanically ventilated airflow window, while panel (b) displays the naturally ventilated double-skin façade (Saelens et al. 2008). This innovative design harnesses solar energy through a transparent outer layer, providing insulation and weather protection. Double-skin SWs enhance thermal comfort, lower energy consumption, and improve indoor air quality, making them vital for sustainable building strategies. Positive findings from studies on double-skin SWs are summarized in Table 4. double-skin SWs are summarized in Table 4.



(a) (b)

Figure 8. Schematic representation of the working modes for double-skin facades: (a) mechanically
ventilated airflow window; (b) naturally ventilated double-skin facade.

Table 4. Results from studies on double-skin SWs.

Focus	Key Findings

Double-skin facade for a clustered housing unit	Increased heating loads were observed with greater cavity depth, while cooling loads decreased. The optimal cavity depth for all scenarios was 1.00 m. The Conventional DF system showed higher energy needs with deeper cavities, while BIPV and BIPV/T DF systems effectively reduced energy needs, with an optimal depth of 0.97 m. The Conventional DF system did not lower energy needs, unlike BIPV and BIPV/T systems, which are crucial for achieving nearly-zero-energy buildings (nZEBs) with high energy performance, supporting previous research on their effectiveness (Barone et al. 2023).
Semi-transparent PV double-skin facades	Ventilation in the STPV—DFS system lowers cavity temperatures by 1.35 °C to 2.21 °C compared to natural ventilation in June, October, and December. It also reduces net electricity demand for cooling and heating by 4.08%, 9.86%, and 14.05% with forced ventilation (Preet et al. 2023).
Solar chimney double-skin facade	. Larger opening areas between the accupant space and double-skin space yield higher ventilation rates, but exceeding 16 m2 may lead to a sharp decrease in the air change rate. Increasing the solar chimney height Improves ventilation rates and pressure difference distribution , resulting in a recommendation of a solar chimney height of more than two floors (Ding et al. 2005).

Fluid solar walls (SWs) are an innovative solar technology featuring fluid-filled channels within building structures. Solar radiation heats the fluid, storing thermal energy for efficient space heating. Their adaptability to various climates makes them ideal for regions with variable weather, enabling effective heat exchange at night or during cool periods. By leveraging solar energy, fluid solar walls reduce dependence on conventional heating and cooling systems, enhancing energy efficiency and promoting sustainability in buildings (Yang et al. 2008).

The adaptability of these SW combinations highlights their potential to improve energy efficiency and sustainability in various architectural and environmental contexts. As the demand for sustainable building solutions grows, these SW variations are valuable tools for architects and builders aiming for energy-efficient designs.

3. OPTIMIZING SW PERFORMANCE FACTORS

Solar walls (SWs) are crucial for sustainable architecture, harnessing solar energy for heating and cooling. Their effectiveness is influenced by several factors:

1- Climate: Sunnier regions improve SW efficiency.
2- Materials: Choosing the right glazing enhances heat absorption.
3- Shading Devices: They help regulate solar radiation and prevent overheating.
4- Orientation: Proper alignment with the sun maximizes sunlight exposure.
5- Insulation: Minimizes heat loss, while effective ventilation maintains thermal comfort.
6- Advanced Techniques: Integrating photo and thermal catalytic methods optimizes energy conversion.

3.1. Climate Condition

Research shows that SWs can save energy in different climates. In hot areas like Yazd, Iran, traditional SWs with water-spraying systems reduced indoor temperatures by 8 ◦C (Rabani et al. 2015).

PV-SWs (photo-voltaic shading walls) in Hefei, China, achieved a temperature reduction of 2.47 °C with insulation and an additional 2 °C with shading curtains. In Mediterranean climates like Ancona, Italy, SWs and PV-SWs with roller shutters reduced temperatures by 63% to 72.9% (Stazi et al. 2012).

In Malaysia’s hot-humid climate, poly-crystalline solar modules excelled, aligning well with solar radiation levels. A ventilated Trombe wall with double PCM wallboards (PCM-VTW) showed promise, reducing cooling load by 14.8% and heating load by 12.7%. Compared to shading devices, PCM-VTW lowered energy consumption by 5.83 kWh in summer and 3.54 kWh in winter, enhancing indoor comfort. In colder climates, a redesigned Trombe wall minimized heat loss through glazing, reducing annual energy consumption by 59% and cutting CO2 emissions by 18% compared to traditional designs (Kostikov et al. 2023).

3.2. Glazing

Glazing is essential for the performance and sustainability of solar window (SW) systems, affecting indoor illumination, thermal comfort, and solar energy use. The selection of glazing types is vital for passive heating and cooling systems, positioning SWs as an innovative sustainable option. It serves both aesthetic and functional roles in architecture by shaping indoor lighting, enhancing visual appeal, and regulating temperature, thus improving occupant comfort and optimizing solar energy control (Jelle et al. 2012).

Computational models were used to optimize energy consumption across various Asian climates, highlighting the significance of glazing properties like U-value, solar heat gain coefficient, and visible transmittance. Key findings indicate the need to minimize window size in most cases, adapt window placement by climate zone, evaluate specific window types, and consider the U-value's impact on energy use. The study emphasizes the importance of customizing window properties to suit specific climates for designing energy-efficient buildings (J. W. Lee et al. 2013).

Multi-layered facades with transparent elements blend visual appeal and practicality. The choice of glazing materials (clear, absorptive, or reflective glass), their placement (internal or external), and the number of layers are crucial for effectiveness. A comparison of glazing options in open-plan offices highlighted the importance of thoughtful glazing decisions for improved comfort and energy efficiency. Researchers have conducted studies to better understand glazed window (SW) performance. One investigation utilized Energy Plus (7.1) software to analyze energy consumption in a double-glazed facade, focusing on factors like glazing type, position, and layers. The findings highlighted the importance of glazing selection in energy-efficient building designs (Rempel et al. 2013).

A study utilized mechanical ventilation to channel air through a double-glazed facade, exploring various glazing materials and shading louvers to highlight passive heating potential. Experiments showed how different glazing choices significantly impact temperature control. Another study employed CFD to analyze thermal performance, examining diverse glazing types, air cavities, and shading components, deepening the understanding of glazing and building design interactions (Baldinelli 2009).

Multi-glazed facades offer architectural innovation but require careful fire safety considerations. One approach simulated thermal properties of a ventilated double-glazed facade with Venetian blinds, pointing to energy-efficient solutions. Further investigations assessed the effects of air-flow rates and blade angles on heat transfer performance, along with simulations of a multi-story building with a ventilated facade and light-colored horizontal blinds, contributing to the architectural knowledge base (Lai and Hokoi 2015).

Table 6. Results from studies on glazing with SWs.

Focus	Key Findings
Energy Plus models	• Balcomb’s method, by disregarding tilted glazing and overlooking the thermal advantages of sunspaces, provides a lower estimation of roof solar gain. The study revealed that the actual roof solar gain in the two spaces with the highest gains was 1/3 to 1/2 greater than Balcomb’s predictions. • The Gates sunspace, oriented 45◦ east of south, gained only 4–7% less solar energy compared to the south-facing

	Shaw space, challenging the conventional importance of strict due-south orientation, and highlighting the significance of diffuse solar resources in the Pacific Northwest.
Double-skin facade	• Comparisons with traditional enclosures in a central-Italy office room revealed that the proposed facade significantly improved the building's energy behavior throughout the year, with a potential energy saving of up to 60 kWh per year per square meter, particularly notable in a forced convection configuration in winter.
Different climate zones (Amman, Aqaba, and Berlin)	• From a financial standpoint, opting for low-emissivity double-glazed windows resulted in the lowest life cycle cost (LCC) in both Amman and Aqaba climate zones, while high-emissivity double-glazed windows proved to be the most cost-effective choice for Berlin's climate zone. • Considering local conditions, it is advised to maintain a 26 ◦C room temperature during summer, leading to additional energy savings.
Ventilated double-skin facade in winter	• - Increasing the blind size from 30 mm to 320 mm raises the average outlet temperature of DSF by 53% during peak sun hours. - Positioning blinds closer to the outer glazing moderately increases the outlet temperature and improves the average mass flow rate by over 10%, highlighting the importance of blind placement for winter performance. - Optimizing blind size to 240 mm boosts dynamic efficiency by 139% at 11 a.m., maximizing heat extraction to the Air Handling Unit (AHU), while closer placement can double winter dynamic efficiency.

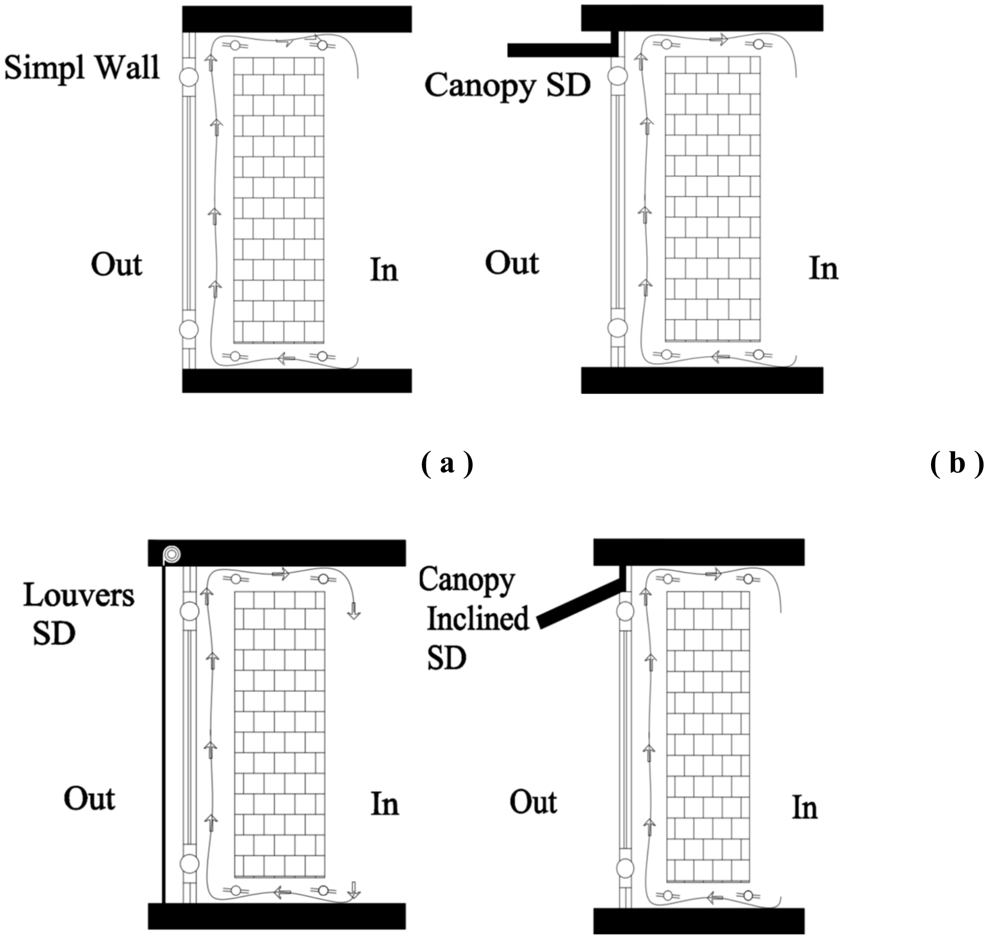
3.3. Shading Devices

SDs are essential in SWs, especially for highly glazed facades commonly found in modern buildings. While these facades enhance architectural appeal and allow natural light and views, they can also result in high heating and cooling loads. SDs help mitigate this by managing solar irradiation, reducing summer overheating, and optimizing daylight in winter (Konstantoglou and Tsangrassoulis 2016a).

Building surfaces have evolved into versatile platforms for integrating PV modules, resulting in four primary BIPV categories (Konstantoglou and Tsangrassoulis 2016b):

- PV Facades: These encompass curtain wall products, spandrel panels, glazing, and other vertical surfaces.
- PV Roofs: This category includes tiles, shingles, standing seam products, skylights, and other roof-related components.
- PVWindows and Overhead Glazing: This involves glass–glass laminated products, laser-etched thin films, transparent thin films, and similar technologies•.
- PV Sunshades: These encompass panels, louvers, blinds, and other shading elements designed to integrate PV technology.

Figure 9 presents various types of SDs used in architectural design. It provides visual representations of these shading options, including (a) a simple window, (b) a canopy, (c) louvers, and (d) an inclined canopy.



(a) (b)

(c) **(d)**

Figure 9. Type of SDs: (a) Simple Wall; (b) canopy; (c) Louvers; (d) canopy Inclined [124].

Researchers have studied the performance of glazed shading devices (SDs) through experimental and numerical methods, revealing insights into energy consumption patterns. Fixed SDs are essential in architectural design, especially in hot climates, where slight design adjustments can significantly improve energy performance. This study evaluated 1485 scenarios with fixed external SDs, considering factors like direction, glazing type, window-to-wall ratio (WWR), SD depth, and slope. Results indicated that SDs notably reduce cooling energy consumption, achieving reductions of 37% to 49% with high-performance glazing and 73% to 78% with low-performance glazing compared to no shading. The findings emphasize the need to consider multiple parameters in SD system design. Future research can explore different climates and additional factors such as glare and daylight quality (Koç and Maçka Kalfa 2021).

Shading devices (SDs) regulate sunlight and solar radiation to reduce glare and overheating, which lowers cooling loads and enhances indoor visual comfort. Using colored and partially translucent PV materials, SDs also improve the aesthetic appeal and architectural features of buildings traditionally associated with standard elements (Nagy et al. 2016).

3.4. Solar Radiation and Orientation of TWs

Passive solar heating systems (SWs) rely on solar radiation and orientation for efficiency. Research by Li and Liu shows a direct relationship between thermal wall (TW) efficiency and solar radiation levels, highlighting solar energy's role in heat storage for space heating.

An experimental study in Yazd, Iran, introduced a unique TW design that captures sunlight from three directions—East, South, and West—adapted for its desert climate. This design kept indoor temperatures between 15 ◦C and 30 ◦C during cold winter days, thanks to effective energy storage and innovative channel design, allowing the absorber to reach 47 ◦C even in extreme conditions.

Hourly analysis indicated that higher solar intensity led to maximum energy absorption of 5800 kJ/h in February. This TW design shows promise in improving thermal comfort, cost-effectiveness, and space efficiency, with options for additional insulation on cloudy days. In subtropical climates, research evaluated TW systems for heating and cooling, comparing a naturally ventilated TW to a reference cell without it (Y. Li and Liu 2014).

Indoor temperature measurements from 2011 and summer 2012 showed that the TW system outperformed the reference cell, especially in colder conditions. The study identified improvements like wall insulation and automated ventilation for efficiency in three subtropical locations. In the northern hemisphere, the best orientations for TW systems are south, southeast, and southwest, while in the southern hemisphere, they are due north, northeast, and northwest. A case study on a solar-cooled office building in Tunisia, using TRNSYS software, found energy savings of 46% in winter and 80% in summer through wall insulation and a cool roof. TWs reduced heating needs by 21%, and features like internal curtains and movable solar overhangs decreased the cooling load from 14.09 kW to 8.68 kW. Recommendations included adding a cooling storage system for better solar cooling efficiency (Soussi et al. 2013).

3.5. Insulation Effect

The integration of thermal insulation in solar walls (SWs) is crucial for enhancing performance and addressing issues like reverse heat transfer and overheating. Research shows that insulation significantly impacts solar wall efficiency across different climates and building contexts. A review of insulation materials includes traditional, state-of-the-art, and new conceptual options, each varying in thermal conductivity, mechanical strength, and environmental impact. This highlights the need for selecting appropriate insulation tailored to specific building requirements (Jelle 2011).

Li et al.'s study proposed an anisotropic insulation design that addresses varying solar irradiation orientations to reduce indoor radiant thermal discomfort. It introduced a simplified calculation method for insulation thickness based on equal heat flux, accounting for factors like exterior surface, brick wall thickness, and orientation differential insulation (ODI). ODI proved effective in high solar radiation areas, reducing material costs in Lhasa by 24.6% and increasing average heating energy consumption by only 6.1% compared to isotropic insulation. When using the same insulation material, heating energy consumption decreased by 9.0%. ODI showed significant advantages in thermal balance and energy efficiency for northward and southward rooms. While SWs harness solar energy for heating, they have low thermal resistance, leading to heat loss at night and potential overheating in well-insulated buildings during hot weather (Kundakci and Yilmaz 2007).

Insulating solar windows (SWs) is crucial for optimizing their performance. Research shows that well-insulated composite SWs, which may include components like glass panels and ventilated mass walls, can outperform traditional SWs, especially in cold, overcast conditions, leading to improved energy conservation. A study in Italy using Energy Plus software found that while insulation significantly reduces seasonal heating energy demand—from 58.33 kWh/m² for regular SWs to just 16.21 kWh/m² for super-insulated versions—it increases cooling energy requirements from 9.19 kWh/m² to 23.31 kWh/m². Overall, insulated SWs demonstrate considerably higher efficiency, highlighting the complex effects of insulation on SW performance (Szyszka 2022).

3.6. Ventilation Techniques

Ventilation systems are crucial for optimizing the thermal performance of walls (SWs) by regulating heating and cooling in buildings. Research has highlighted the importance of installing thermo-circulation vents at the upper and lower portions of vented SWs to minimize heat loss occurring in the air gap between glazing and the wall, driven by convection, conduction, and radiation. Strategically placed vents help reduce this heat loss: warm air rises through the upper vent while cooler external air enters through the lower vent. The operation of these vents significantly affects heat-transfer coefficients, which are essential for optimizing system performance (Elsaid et al. 2023).

The experimental work on natural convective heat transfer in a Trombe-type assembly showed improved performance with thin vertical transparent partitions. Proposed correlations effectively optimized the thermal sizing of Trombe walls. Another study developed a sizing approach considering energy consumption, economics, and thermal comfort, highlighting that constructing a Trombe wall (TW) is economically viable for thermally insulated new buildings used in winter. For uninsulated existing buildings, a TW is feasible only if its area exceeds 9 m^2, emphasizing insulation's role and the importance of personalized comfort parameters (Elsaid et al. 2023).

An analysis of the Trombe wall heat transfer process in Yazd, Iran, examined variations in the Rayleigh number, convective heat transfer coefficient, and heat transfer rates. The study found significant temperature decreases in the early hours, with conduction leading in early and late periods, while convection prevailed at midday. The new channel design improved radiation heat transfer.

In Abha, Saudi Arabia, an experimental study assessed the Trombe wall's performance, revealing that radiative exchanges were more significant than convective ones. The wall could fulfill varying heating needs based on conditions, providing 80% heating on sunny days with low wind, 42% with strong winds, and 37% under scattered clouds. Even in heavy cloud cover, it offered 14% of heating needs, demonstrating its effectiveness as a passive solar system (Elsaid et al. 2023).

The vent size is a key parameter in solar water (SW) designs, influencing the solar saving fraction. This study introduces a small-scale solar chimney (SC) integrated with Photocatalytic Reactors (PCRs) for indoor ventilation and methane degradation. Numerical simulations reveal that SCs with High-performance PCRs (HPCR) achieve 3.57 times greater methane removal than Photocatalytic Painted PCRs (PPCR) under 900 W/m^2 solar radiation. Increasing the reaction zone length boosts photocatalytic efficiency. The optimal purification rate of 57.27 μg/s occurs at $\gamma = 0.85$ and $L = 1.5$ m under 500 W/m^2. Backflow from airflow resistance can be addressed by adding a small porous material near the chimney outlet. Additionally, external vents on SWs improve air circulation, enhancing ventilation and cooling in the air gap during summer (Elsaid et al. 2023).

Vents play a crucial role in controlling heating and cooling in ventilated solid walls (SWs), highlighting the effectiveness of ventilated versus non-ventilated systems in passive energy research. A study on SWs with thermo-circulation vents across various U.S. climates identified a challenge: these vents can cause reverse airflow at night, reducing efficiency. Researchers recommended using dampers to prevent this issue.

Additionally, ventilation technology has shifted focus to enhancing the performance of thermal walls (TW). A study investigated how air velocity affects natural ventilation and indoor temperature regulation. By using mathematical modeling, researchers found a direct correlation between air velocity, the temperature difference between the massive and glass walls, and wall height. They adjusted the boundary line to prevent backflow, offering valuable insights for optimizing TW systems (Elsaid et al. 2023).

The ultraviolet (UV) part of solar radiation triggers photocatalytic reactions on the TiO2 membrane of PV panels, while the visible light is converted into electricity for indoor use or storage. The remaining infrared radiation generates thermal energy, heating the panels. Cold air enters the TW chamber, where solar energy heats it, creating airflow. The integration of PV and aluminum panels in a baffle configuration enhances contact between pollutants and the catalytic materials, leading to effective decomposition of airborne pollutants. Clean air then exits through the upper outlet, warming the room.

Incorporating photocatalytic and thermal catalytic techniques in the TW system significantly improves air quality and sterilization, particularly using TiO2, which can sterilize bacteria and decompose endotoxins with minimal side effects. This is crucial for controlling respiratory infectious diseases in buildings. Enhancing TW performance involves optimizing energy harvesting through special coatings on the panels. The photo/thermal catalytic TW system utilizes solar energy and catalytic oxidation to simultaneously heat and purify indoor air, generating electricity and improving air quality. Experimental results show it can produce heat between 6.25 and 17.74 kJ/mol and generate 0.075 to 0.372 kWh of electricity daily between 9:00 and 16:00. It also achieves bacterial aerosol sterilization efficiency rates of 0.204 to 0.347. An optimal component spacing of 25 cm balances sterilization, heating, and electricity generation, while strategically placed UV light strips boost efficiency. This system is particularly effective in cold regions during winter but requires further evaluation across different climates and seasons (Elsaid et al. 2023).

The TW system merges solar heating and air purification to improve indoor air quality during passive solar heating. It utilizes a photo-thermal composite catalyst (MnOx CeO2/TiO2) that excels in solar heating and catalytic oxidation. Research on formaldehyde degradation shows a synergistic effect between photo-thermal catalysis and reduced activation energy compared to pure thermal catalysts.

To enhance this system, photocatalytic reactions are employed to lower airborne formaldehyde levels. Unlike traditional solar TWs, the new version features composite crawler-type modules (SiO2/TiO2) placed between the outer glass and inner wall. These modules contain circular ducts, with one area focused on adsorbing water and formaldehyde and the other on degrading formaldehyde.

As the adsorption modules rotate, humid air filled with formaldehyde is drawn into the ducts, where water vapor and formaldehyde are adsorbed. Elevated temperatures facilitate the desorption of these substances. Then, solar radiation prompts TiO2 to decompose formaldehyde into CO2 and H2O (Szyszka 2022).

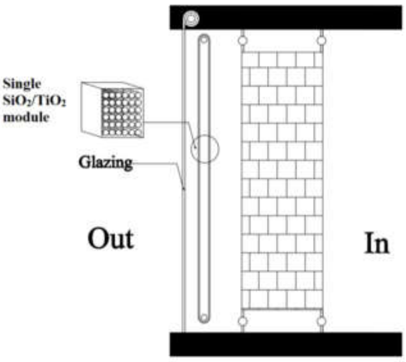


Figure 10. A photocatalytic SW.

Innovative studies have shown the promise of combining photocatalytic oxidation with solar water (SW) systems, utilizing UV light to initiate air purification reactions. Yu et al. further advanced this by integrating space heating and indoor air purification, achieving impressive air heating efficiency and substantial fresh air generation.

Thermal catalytic technology provides effective sterilization without secondary pollution, as solar irradiation in the chamber raises air temperatures to disrupt bacterial self-repair and destroy DNA and RNA. While the hybrid wall system achieves a thermal efficiency of 36.5%, it only sees a minor 1% reduction compared to conventional thermal systems, but notably increases daily clean air production by 45.15 m^3. This research highlights the potential of photo-thermal catalytic technology to enhance thermal efficiency and indoor air quality, emphasizing the need for structural optimization for greater benefits (N. Li et al. 2023).

4. THE EVALUATION OF THE ENERGY AND ENVIRONMENTAL PERFORMANCE

4.1. Solar Heat Gain

Solar heat gain is essential for assessing the performance of thermal walls (TW) as passive solar heating systems. These walls are designed to utilize solar energy effectively, necessitating an evaluation of their capability to capture and store heat during the day. A parametric study in Portugal found that thicker walls (around 35 cm) gained more heat in winter, while thinner walls showed increased gains in summer, though at lower levels. The study also highlighted the importance of thermo-circulation linked to direct solar radiation. Both solid brick and granite walls displayed similar behaviors, allowing them to maintain temperatures above 20 °C without HVAC support (L. Zhu et al. 2009).

Estimating solar heat gain is crucial, and a new experimental method using large-scale model fenestration systems was introduced. This method employs a fenestration radiometer that effectively measures shortwave and longwave radiation, making it ideal for evaluating various daylighting technologies in real non-uniform sky conditions. The solar heat gain and shading coefficients obtained aligned well with different methods. However, concerns about overheating in passive solar buildings, especially during summer and mid-season, remain. Research in Ancona, Italy, emphasized the need to address these issues, investigating the effects of exterior overhangs and Venetian blinds in high thermal mass scenarios. It also highlighted the importance of thermo-circulation related to direct solar radiation in enhancing heat gain and stabilizing temperatures. Accurate assessment of solar heat gain is essential for optimizing performance, with ISO 13790:2008(E) providing valuable equations for calculating heat transfer and solar gains in special elements (Hassanain et al. 2011).

4.2. Thermal Efficiency

One challenge with solar walls (SW) is heat loss during nighttime and on shaded winter days, leading to higher energy consumption. Researchers, like Bajc et al., have developed numerical models to enhance thermal efficiency, particularly in moderate continental climates. Simulations using Belgrade weather data showed that in winter, the SW maintained a room temperature of 14.7 ◦C, while in summer, it increased temperatures to 29.8 ◦C, necessitating cooling to reach 26 ◦C. The integration of photovoltaic (PV) strips was significant, providing about 60% of the electricity needed for cooling devices, taking into account PV efficiency, insulation, and energy consumption (Bajc et al. 2015).

Comparative studies of solar walls (SWs) reveal that traditional SWs achieve high outlet temperatures but have reduced air flow rates, impacting heating efficiency. Water solar walls (WSWs) exhibit better performance due to lower natural convection. A CFD simulation of a composite Trombe wall, which combines a water wall with traditional design, examines factors such as solar radiation, ambient temperature, and water flow rates. The study finds that WSWs outperform traditional structures in daytime thermal performance by 3.3%, achieve the highest exergy efficiency, and reduce nighttime heat loss by 31%. The optimal mass flow rate for WSW thermal performance is 0.06 kg/s (Zhou et al. 2020).

Research on integrating PCMs into wall systems shows that PCM-enhanced walls can reduce peak heat flux, delay heating and cooling loads, and minimize indoor temperature fluctuations.

The placement of PCMs within walls significantly affects thermal performance and efficiency, suggesting that optimal positioning could improve passive solar heating systems.

In terms of environmental impact, studies have assessed CO2 emissions and energy consumption throughout the life cycle of SWs. An integrated approach by Stazi et al. emphasized holistic evaluations to optimize energy and environmental performance. A life cycle assessment (LCA) in Ancona revealed that aluminum and concrete production adds burdens during the pre-use phase, while energy consumption for summer cooling leads to high CO2 emissions during use.

Optimizing through level factorial plans reduced CO2 emissions and energy demand by up to 55%, highlighting the impact of tailored design choices like glazing type on environmental performance. The final SW design can focus on specific objectives, with an intermediate configuration effectively reducing summer energy needs while ensuring high performance. Future work will expand the analysis to include the disposal and recycling of facade components in the post-use phase (Zhou et al. 2020).

The integration of passive solar systems, such as the Trombe wall, enhances sustainable building design. A study on a novel building utilizing phase-change materials, a ventilated Trombe wall, and photovoltaic panels conducted a life cycle cost and discomfort degree hour optimization. Using a Monte Carlo approach, artificial neural network (ANN) models achieved high accuracy (R-squares of 0.997 and 0.972), outperforming stepwise linear regression. When coupled with the Strength Pareto Evolutionary Algorithm II (SPEA-II), the models identified optimal heating and cooling setpoints, PCM types, and window-to-wall ratios. Compared to a reference building, the design saw a 33.30% average improvement in thermal comfort and a 22.35% average reduction in life cycle costs.

Additionally, research by Boji´c et al. highlighted the environmental benefits of selecting low-density core materials for solar walls, potentially saving up to 5% in primary energy. An analysis of a solar-powered building in Lyon showed that Trombe walls could reduce heating energy use by 20%, with more significant benefits for electrical heating (15% savings) compared to natural gas (11%). The optimal core thickness for electrical heating was 0.35 m, while for natural gas, it was 0.25 m, emphasizing careful consideration of material thickness based on heating type (Zhou et al. 2020). The study also highlighted how low-density core materials positively impacted heat accumulation and nighttime energy loss, offering insights for optimizing energy-efficient Trombe wall designs.

The integration of passive solar systems like solar water heaters (SWHs) in building designs supports sustainable development by significantly reducing energy consumption for heating, which lowers CO2 emissions. SWHs can cut a building's heating energy use by up to 30%. They offer greater environmental benefits when paired with electrical heating compared to natural gas, resulting in more primary energy savings and a shorter energy payback time (Hassanain et al. 2011).

5. Discussion And Conclusions

Transitioning to zero-energy buildings is crucial for reducing waste and greenhouse gas emissions. Energy-efficient building envelopes, particularly passive solar systems (SWs), are essential in this effort. SWs enhance thermal storage and maximize solar gains, leading to significant reductions in energy consumption and carbon footprints while improving indoor comfort.

Solar water walls (WSWs) and innovative systems like double-skin SWs effectively capture and store solar heat through thermo-circulation. Integrating photovoltaic solar cells into SWs optimizes electricity generation, while phase change materials (PCMs) help reduce peak thermal loads. These systems adapt to various climates and can significantly lower a building's energy usage, contributing to sustainability and environmental responsibility.

Key factors for optimizing SW performance include climate conditions, glazing materials, orientation, insulation, and ventilation techniques. SWs demonstrate impressive energy-saving potential in diverse environments, making them versatile solutions for harnessing solar energy for heating and cooling in modern architecture.

- **Glazing**: The choice and placement of glazing materials greatly affect solar water (SW) performance. Key properties include U-value, solar heat gain coefficient, and visible transmittance, which help balance lighting, thermal comfort, and energy efficiency. Multi-layered facades can enhance both comfort and efficiency.
- **Shading Devices (SD)**: Properly designed SDs prevent overheating in glazed facades by optimizing solar irradiation, allowing for adequate daylight in winter while minimizing heat gain in summer.
- **Solar Radiation and Orientation**: Accurate alignment with the sun’s path is vital for SW efficiency, with optimal orientations varying by hemisphere.
- **Insulation**: Effective insulation is essential for minimizing heat loss and maximizing SW efficiency, especially in composite systems.
- **Ventilation Techniques**: Efficient ventilation systems help regulate heating and cooling, enhancing overall energy efficiency and thermal comfort.
- **Photo and Thermal Catalytic Techniques**: Integrating these methods improves indoor air quality while generating electricity and heat, offering dual benefits.

In summary, understanding these interrelated factors is crucial for optimizing SW design, reducing energy consumption, and promoting sustainable building practices. Future research should focus on innovative technologies to enhance SW efficiency across various climates.

In terms of energy performance, solar walls (SW) effectively harness solar heat, with wall thickness and material influencing heat gain. Thicker walls (about 35 cm) enhance heat capture in winter, while thinner ones do better in summer. Thermo-circulation, linked to direct solar exposure, boosts heat gain, and the use of large-scale fenestration systems aids in estimating this gain under various conditions. To combat overheating, shading devices like overhangs and Venetian blinds are explored, especially with high thermal mass. Standardized methods, such as ISO 13790:2008(E), provide equations for assessing solar heat gains. Regarding thermal efficiency, SWs encounter heat loss during cold nights, resulting in higher energy use. Proposed solutions include numerical modeling and integrating phase change materials (PCMs) into walls, which help reduce heat flux and improve temperature control. The placement of PCMs is crucial for optimal performance. For environmental performance, thermal walls (TW) significantly lower heating energy consumption, thus reducing CO2 emissions and supporting sustainability. Material choices, like lower-density options, are key to minimizing environmental impact. Overall, TWs align with sustainable goals by promoting energy-efficient and eco-friendly building practices, particularly compared to other heating methods.

6. FUTURE DIRECTIONS

In the future, sustainable buildings (SWs) will evolve through advanced materials research, focusing on novel glazing, insulation, and adaptive smart designs. The integration of smart technologies will enable real-time optimization and tailored climate-specific guidelines for different regions. Multifunctional systems will increasingly incorporate features like rainwater harvesting and air purification. Comprehensive life cycle analyses will guide responsible design, while user behavior studies will ensure comfort and user-centered designs. The integration of renewable energy will create hybrid systems for maximum efficiency. Support from policies, public awareness, and collaborative research will drive the adoption of SW technologies, leading to a sustainable built environment.

The future of SWs will blend innovation, sustainability, and collaboration, addressing climate challenges and enhancing occupant well-being, ultimately aligning with global climate goals and fostering a new era of sustainable architecture.

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