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Review

Solar Wall Technology and Its Impact on Building Performance

Mehrdad Ghamari and Senthilarasu Sundaram *

School of Computing, Engineering and Digital Technologies, Teesside University, Tees Valley,
Middlesbrough TS1 3BX, UK; mehrdad.ghamari.9.7@gmail.com
* Correspondence: s.sundaram@tees.ac.uk

Abstract: Solar walls provide transformative solutions by harnessing solar energy to generate electricity, improve thermal comfort, and reduce energy consumption and emissions, contributing to zero-energy buildings and mitigating climate change. In hot and humid regions, solar walls can reduce indoor temperatures by 30% to 50%, significantly improving energy efficiency. Optimizing the performance of solar walls includes factors such as glazing, shading, solar orientation, ventilation, and catalytic techniques, allowing them to be adapted to different climates. Innovative solar wall variants that include photovoltaic panels, water storage, and phase-change materials offer multifunctionality and sustainability in building design and are in line with global energy efficiency and environmentally conscious goals. In addition, innovative solar wall variants that combine photovoltaic panels, water storage, and phase-change materials promise even more sustainability in building design. These multifunctional solar wall systems can efficiently heat, cool, and generate energy, further reducing a building's environmental impact. Solar walls have the potential to significantly reduce heating energy consumption; align with global goals for energy-efficient, environmentally conscious, and climate-responsive building design; and offer dynamic and adaptable solutions for sustainable architecture.

Keywords: solar walls; Trombe walls; zero-energy buildings; energy efficiency; sustainable construction; glazing and shading; ventilation techniques

1. Introduction

In an era characterized by escalating global concerns regarding climate change and environmental sustainability, the imperative to address energy waste has taken center stage. This urgency is amplified by the far-reaching consequences of climate change, as emphasized by the Sustainable Development Goals (SDGs) [1], the assessments of the Intergovernmental Panel on Climate Change (IPCC) [2], and the steadfast commitments made at the United Nations Climate Change Conferences (COPs). Now, more than ever, the world is united in recognizing the pressing need for swift and resolute action [3]. Amidst this collective realization, the building and construction sector has emerged as a pivotal battleground in the fight against climate change and environmental degradation. This sector, by its very nature, consumes vast quantities of resources and energy, exerting significant stress on natural ecosystems and finite resources. Its environmental footprint extends across multiple dimensions, encompassing resource consumption, waste generation, and greenhouse gas (GHG) emissions [4]. The global consensus, echoed through a multitude of international roadmaps, underscores the critical urgency of transitioning away from energy-intensive buildings towards structures that operate at zero-energy or net-zero energy levels [5]. This imperative necessitates a fundamental shift in our approach to energy generation, namely, away from conventional fossil fuels and towards sustainable, renewable sources [6]. It represents a shared resolve among nations and stakeholders worldwide to confront the profound challenges posed by climate change and to curtail the deleterious environmental impact stemming from the construction and

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operation of the built environment. There is an undeniable emphasis on the vital necessity for a significant overhaul in our approach to both construction practices and the utilization of energy resources. This sense of urgency is deeply rooted in a profound awareness that structures characterized by high energy consumption not only deplete Earth's finite resources but also wield considerable influence in the emission of GHG. Consequently, this exacerbates the overarching global climate predicament, as highlighted by reference [7].

Furthermore, the building and construction sector is a significant contributor to waste generation, accounting for over 35% of the total waste produced in the European Union (EU). This staggering statistic not only underscores the magnitude of the challenge at hand but also emphasizes the pressing need for innovative solutions that reduce waste and promote sustainability throughout the construction lifecycle [8]. The GHG emissions associated with this sector are perhaps even more alarming. These emissions are the result of a range of activities, including material extraction, construction product manufacturing, and building construction and renovation. These activities contribute an estimated 5–12% of national GHG emissions. Mitigating climate change is imperative, and this substantial source of emissions must be effectively addressed [9]. Within this context, there is untapped potential for immense progress. The prospect of reducing up to 80% of these emissions through heightened material efficiency and sustainable building practices exists; however, this potential remains largely untapped, primarily due to the vast number of existing buildings requiring retrofitting and renovation [10]. A glaring disparity emerges as we acknowledge that approximately 35% of the EU's building stock exceeds half a century in age, necessitating extensive renovation, repair, and strengthening. Astonishingly, three-fourths of these structures grapple with energy inefficiency, leading to increased energy consumption and carbon emissions [11]. Despite the pressing need for transformation, the current rate of annual building stock renovation in the EU is languishing at a mere 1%. This slow pace of renovation underscores the urgent and significant growth required to achieve net-zero emissions goals and ensure the longevity of the built environment [12]. In the United States, ambitious targets have been established for both residential and commercial construction, emphasizing the need for energy-efficient practices. By 2020, new residential construction projects were expected to attain zero-energy status, with a parallel aim for all new commercial buildings to achieve this milestone by 2030 [13]. This commitment underscores the critical role that energy efficiency and sustainability play in the evolution of the building and construction sector. With a forward-thinking approach, the EU has introduced a groundbreaking proposal in December 2021, transitioning from the current Nearly Zero-Energy Building (NZEB) standard to Zero-Emission Buildings (ZEBs). This visionary shift aligns energy performance requirements for new constructions with the EU's long-term climate neutrality goals and the prioritized "energy efficiency first principle." The proposed Zero-Emission Buildings are defined by exceptional energy performance, fully relying on renewable sources, and devoid of on-site carbon emissions from fossil fuels. The directive mandates the fulfilment of ZEB requirements starting on 1 January 2030 for all new buildings and starting 1 January 2027 for those owned or occupied by public authorities. Additionally, the proposal includes lifecycle Global Warming Potential (GWP) calculations, fostering a transparent approach toward sustainability and emission reduction. This bold initiative represents a significant leap toward a sustainable, zero-emission built environment in the EU [14].

The distribution of solar energy potential across the globe is an indispensable consideration in the quest for sustainable and renewable energy sources. The practical solar PV output (PVOUT) reveals an unexpected pattern in consistency worldwide. Contrary to expectations, PVOUT values exhibit a relatively consistent range worldwide, underpinned by the intricate interplay of factors like air temperature and solar irradiance. Furthermore, the revelation that 93% of the global population resides in countries with an average daily PV potential ranging between 3.0 and 5.0 kWh/kWp underscores the widespread feasibility of leveraging solar energy as a sustainable and readily accessible energy source [15,16]. Unlike the theoretical potential, PVOUT factors in various real-world scenarios, including air temperature, terrain horizon, albedo, module tilt, configuration, shading, soiling, and more, influence system performance. [17].

The results of this comprehensive analysis unveil a remarkable trend in PVOUT distribution. Contrary to initial assumptions, the variability in PVOUT across the globe is not as extensive as anticipated. The influence of air temperature often offsets the impact of Global Horizontal Irradiance (GHI), representing the theoretical potential. As a result, regions with below-average solar radiation, benefiting from cooler year-round temperatures, can match the PV power output of regions with higher solar resources. This equilibrium is further highlighted by the fact that the difference between countries with the highest (Namibia) and lowest (Ireland) average practical potential is only slightly more than a factor of two [18,19]. These findings underscore the universal potential of solar energy as an accessible and reliable renewable energy source, irrespective of geographic location [20].

A cornerstone in the realization of these ambitious targets is the adoption of energy-efficient building envelopes [21,22], encompassing elements such as insulation [23,24], windows [25,26], roofing [27–29], solar chimneys, and exterior walls [30–32]. These components play a pivotal role in regulating energy flow within structures, making the enhancement of their energy efficiency paramount in the reduction in primary energy consumption in buildings [33]. In order to holistically strive for improved energy performance, net-zero GHG emissions, and the extension of the service life of the built environment, an unequivocal call is made to embrace novel materials and technologies capable of simultaneously fulfilling multiple pivotal objectives [34].

Passive solar systems, like solar walls (SWs), represent significant technological strides in bolstering the thermal storage capacity of materials and optimizing heat transfer processes [35]. These advancements extend beyond conventional energy efficiency measures and GHG reduction strategies. Regions with abundant sunlight hold substantial potential to harness solar energy as a renewable building resource. The incorporation of SW into building envelopes stands out as a particularly promising approach for maximizing solar gains while curbing energy consumption. As a result, the integration of passive solar systems into building envelopes, coupled with enhancements in energy storage materials, promises to elevate solar energy as a sustainable alternative, ultimately elevating energy efficiency standards [36–38].

The central aim of this research is to evaluate the transformative impact of SWs in addressing challenges inherent in the building and construction sector. The research framework will encompass an exhaustive review of the pertinent literature, focusing on the operational principles of SWs and previous research endeavors in this domain.

Through the examination of practical applications and a comprehensive analysis of the latest developments in SW technology, this research endeavor seeks to shed light on how these groundbreaking solutions can play a pivotal role in establishing a sustainable and energy-efficient built environment. In doing so, they contribute significantly to global initiatives geared towards mitigating climate change and alleviating the adverse consequences of environmental degradation [39–43]. This research holds promise for revolutionizing the way we approach energy-efficient building design and construction [44–48].

SWs not only contribute to energy efficiency but also enhance the thermal comfort of buildings [49]. By absorbing and storing solar energy during the day and gradually releasing it at night, SWs play a pivotal role in regulating indoor temperatures [50]. This dual functionality makes them a compelling choice for sustainable construction and renovation projects worldwide, contributing to reduced energy consumption and GHG emissions. The innovative SW concept has garnered attention as a sustainable and multifaceted solution, renowned for its ability to tap into the sun's abundant energy to generate electricity and fulfill heating or cooling functions within buildings. This eco-friendly technology enhances the energy efficiency and overall performance of structures while contributing to a more sustainable future. By capturing solar radiation during the day and releasing the stored energy into the building's interior during nighttime hours, SWs optimize energy utilization [51]. This absorbed solar energy serves various purposes within the building, including ventilation, heating, and cooling, effectively reducing the reliance on conventional energy sources, resulting in significant energy savings, and a diminished carbon footprint. Furthermore, the inherent multifunctionality of SWs, which not only generate clean electricity but also regulate indoor temperatures, positions them as a compelling choice for sustainable construction and renovation projects worldwide [52].

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 [53,54].

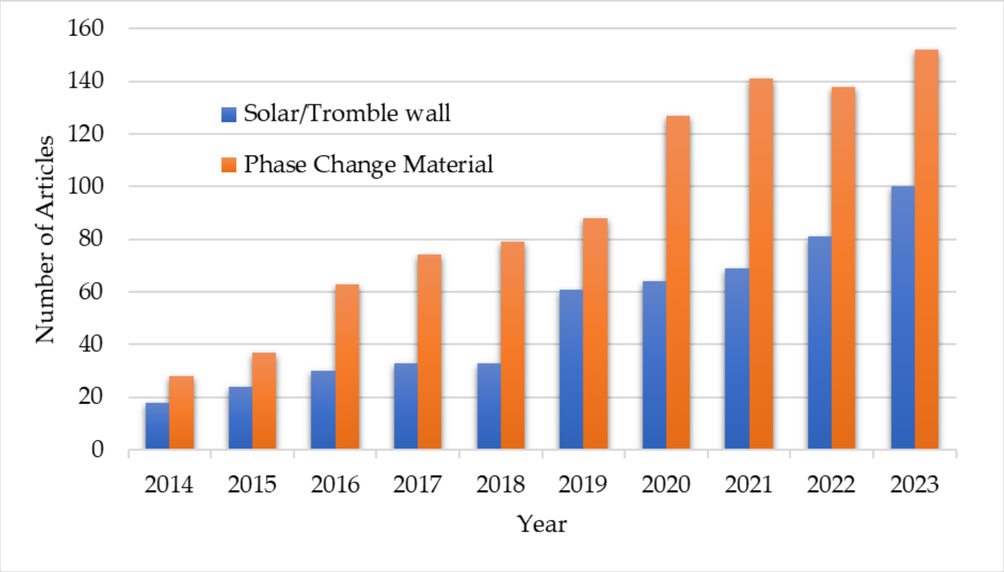


Figure 1. Trends in published articles by year on Trombe walls and phase-change materials from 2014 to 2023 [53,54].

2. Overview of SWs

A remarkable innovation in solar energy utilization, SWs are a carefully engineered system designed to harness the sun's radiant power. This cutting-edge technology is dedicated to optimizing the greenhouse effect by creating a glazed enclosure that efficiently captures and stores solar heat within a substantial wall [55]. At its core, SWs typically feature a sturdy, south-facing structure constructed from materials like masonry or concrete, complemented by an intermediate air layer and an outer glazing layer [56,57].

One particularly intriguing variation of this concept is the Trombe wall (TW), which introduces a clever twist by incorporating vents strategically positioned at both the upper and lower sections of the wall. This ingenious design promotes controlled airflow between the interstitial space within the wall and the interior of the building. Within TWs, the exchange of heat unfolds through a unique synergy of thermal transmission across the wall's structure and the controlled ventilation facilitated by these strategically placed vents [58].

SWs, originally popularized by French engineer Felix and architect Jacque Michel in the late 1950s and 1960s, have evolved, with modern variations referred to as TWs (Figure 2) [59]. 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% [60].

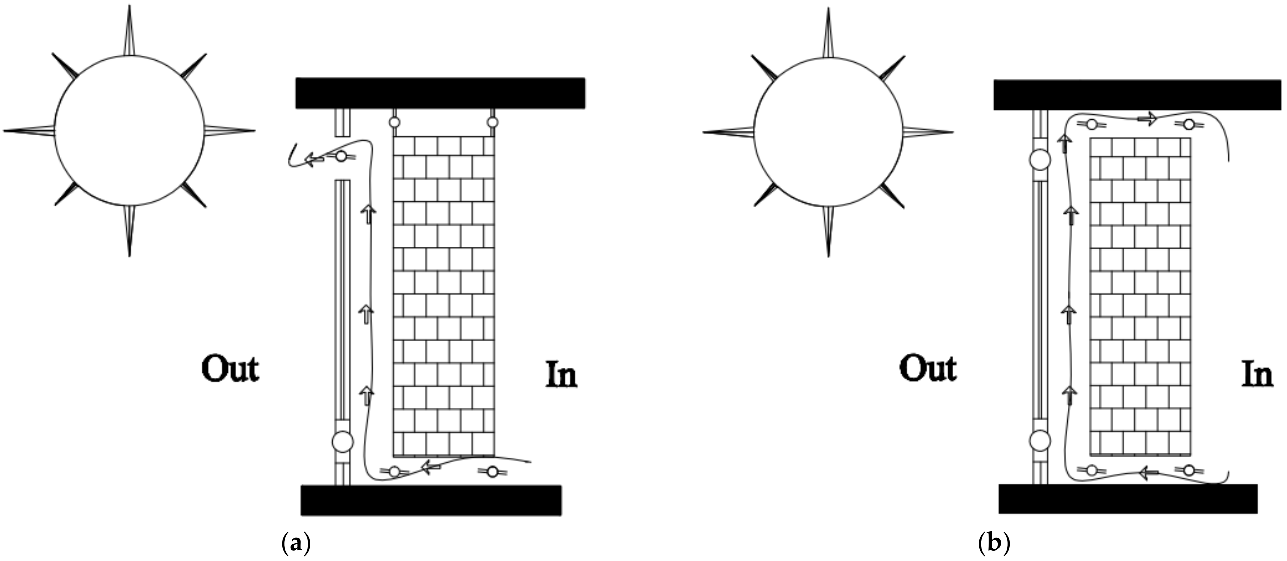


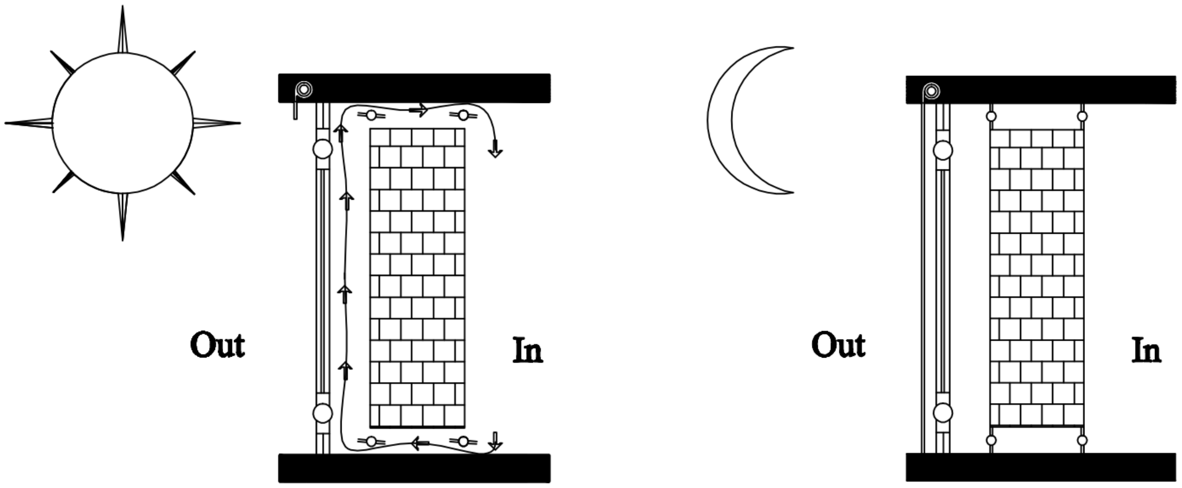
Figure 2. TW (daytime periods): (**a**) summer; (**b**) winter.

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 [61]. 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, an inverse thermo-siphon phenomenon can occur, leading to cooling of the interior [62]. To address this, innovative solutions like supple plastic films have been introduced to control airflow through the orifices, allowing for precise temperature regulation [63].

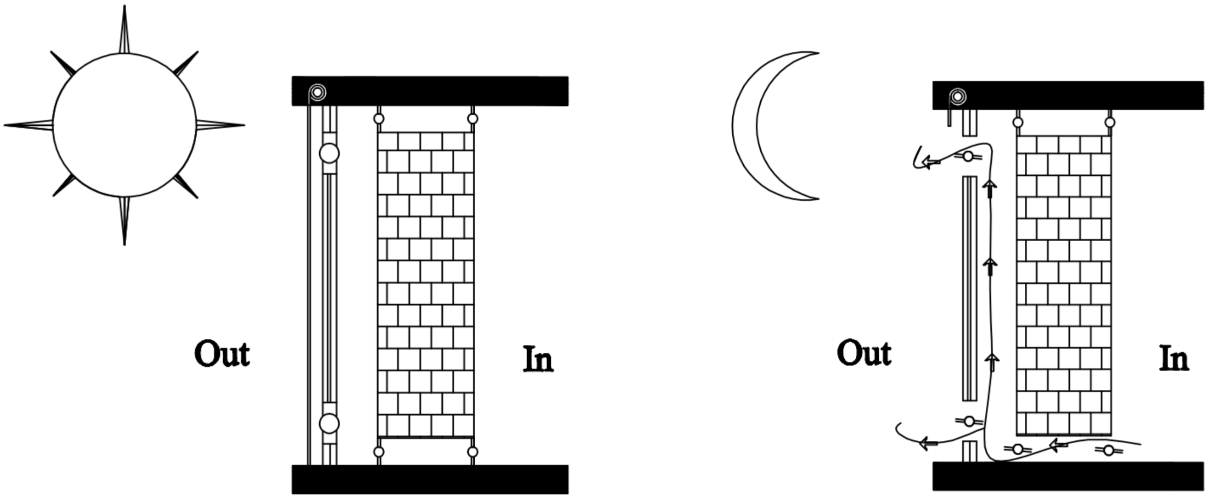
In contrast, composite TWs build upon the classical design while addressing heat loss issues during colder periods. It incorporates an insulating wall behind the massive wall. Initially, solar energy is conducted through the massive wall and then transferred through convection via the thermo-circulation phenomenon that occurs between the massive wall and the insulating wall. During periods of reduced sunlight, the orifices in the insulating wall can be closed to minimize heat loss [64,65].

TWs operate by absorbing direct and diffused solar radiation when the sun is shining [66]. This absorbed heat energy is then transferred to a thick storage mass interior wall, primarily through convection or conduction as the sun sets. The air space between the sun-facing wall and the glazing, typically ranging from 3 to 6 cm, plays a pivotal role in gradually releasing and storing this absorbed heat energy as thermal mass. The core mechanisms of heat transfer involve radiation and convection, ultimately enhancing the thermal comfort of building occupants [67].

The effectiveness of TWs is further enhanced by strategically placed air vents [68]. These vents, located at both the base and the top of the massive wall, serve to reduce heat loss to the external environment. They facilitate air movement through thermos-circulation, eliminating the need for mechanical ventilation [69]. Warmer air rises and enters the interior space through upper openings, while cooler air exits through lower openings, creating efficient air circulation. However, in cases where air layer temperatures rise significantly, there can be increased heat loss through the glazing. To counteract this, the management of air vents should be adjusted based on local weather conditions and desired indoor temperatures [70]. Considering TWs' primary role in passive heating, precautions are necessary to prevent overheating in the summer [71]. External shading or occlusion devices can help, and the use of air vents in both the massive wall and glazed surface, as seen in the Double-ventilated TW (DVTW) (Figure 3), can aid in cooling the air layer. Achieving the desired indoor temperature involves optimizing the TW design and effectively managing air vents and shading devices (SDs) [63]. During winter daytime periods when ample solar radiation is present, it is advisable to have the air vents located on the glazing surface and to keep the massive wall closed. This closure results in the establishment of an air layer greenhouse effect, leading to increased indoor temperatures. The use of shading devices during this time is not recommended to maximize the absorption of solar heat. The activation of the ventilation system within the massive wall should only occur when the temperature in the air layer exceeds that inside the room and there is a need for space heating, as illustrated in Figure 3a. During nighttime in the winter, keeping the air vents and shading devices closed is the preferred course of action to prevent heat loss from the interior to the outside environment, as shown in Figure 3b. In the summer, during daylight hours, it is essential to have the ventilation system closed and make use of shading devices. It is worth noting that the effectiveness of solar gains decreases as the shading device becomes opaque, and using a lighter-colored shading device enhances the reflection of incident solar radiation, as depicted in Figure 3c. During nighttime in the summer, it is advantageous to have the air vents on the glazing surface and to keep the shading devices open to facilitate the cooling of the air layer. In this scenario, a DVTW can contribute to cross-ventilation within the building. By opening the vents at the bottom of the massive wall and those at the top of the glazing, hot air circulates within the building. Openings on the opposite north-oriented facade allow for cross-ventilation, effectively cooling the internal spaces, as illustrated in Figure 3d. During winter days with abundant solar radiation, it is advisable to close the air vents on both the glazing and the massive wall to create a greenhouse effect in the air layer, raising temperature levels [72]. SDs should not be used to maximize solar gains [73]. The massive wall's ventilation system should only be activated when the air layer's temperature exceeds that of the interior and heating is required [74]. During nighttime, closing the air vents and the use of SDs prevent heat loss from inside to the exterior [64].



(**a**) (**b**)



(**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) [63].

In the following, various types of SWs are examined and classified into five distinct groups based on their fundamental technologies and design features, as illustrated in Figure 4. The first category encompasses PV solar cells, where photovoltaic cells are integrated into the wall to directly convert solar energy into electricity. The second group consists of solar water walls, where water is utilized as a heat absorbent to capture and convey solar energy. The third category includes PCMs, incorporating materials capable of storing and releasing energy during phase transitions. The fourth group comprises double-skin facades, featuring an outer layer that shields against environmental elements while facilitating controlled ventilation. Lastly, the fifth category encompasses Fluid Walls, incorporating fluid-based systems for the absorption and distribution of solar heat, providing a versatile approach to solar energy utilization in building design.

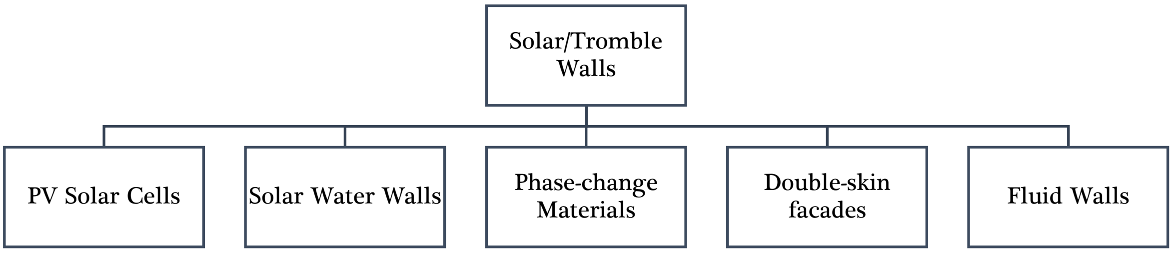


Figure 4. Classification of SW Technologies.

2.1. PV Solar Cells and the SW

Managing high temperatures presents a significant challenge for SW systems, especially in hot and sunny climates. Traditionally, SWs have been utilized for passive heating, involving the absorption of solar radiation and the transfer of heat into buildings through natural convection. However, in extremely hot conditions, this approach can lead to overheating, resulting in reduced comfort and energy efficiency. To tackle these challenges, the integration of PV solar cells into SW designs has been explored (Figure 5). This integration seeks not only to utilize SWs for passive heating but also to generate electricity from solar energy. This strategy optimizes resource utilization and significantly enhances overall system efficiency [75,76]. The incorporation of PV solar cells into SWs has spurred innovative research efforts aimed at improving energy generation and thermal performance.

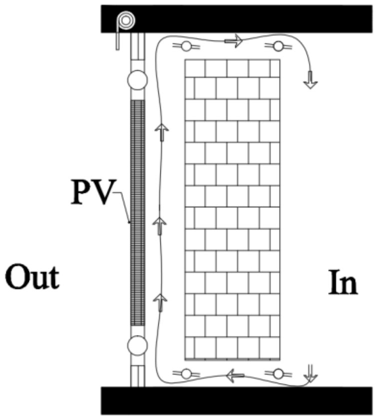


Figure 5. SW integrated with PV solar cells.

Traditionally, TWs have predominantly served passive heating functions. Nevertheless, with the introduction of PV solar cells, their capabilities have expanded to encompass active energy generation. A novel system has been proposed, combining photocatalytic, PV, and TW technologies, enabling the simultaneous generation of electricity, heat, and fresh air. This innovative approach underscores the multifaceted advantages of PV-TW, effectively transforming them into holistic energy solutions. This study also investigated the effects of channel dimensions on both electrical and thermal performance. The research findings highlighted that the combination of photocatalytic and PV technologies with TWs allows for the concurrent production of electricity and thermal energy. Notably, the dimensions of the channels, both in terms of width and height, exert a substantial influence on system efficiency, emphasizing the need to optimize these parameters for enhanced performance [77].

Indoor air quality represents another critical aspect of building design. Researchers have undertaken a study focused on degrading gaseous formaldehyde throughout the year while simultaneously generating sustainable electrical energy using PV/T-TW. The study aimed to explore the potential of PV-TW in contributing to indoor air purification alongside electricity generation [78].

Yaxin Su et al. conducted a study employing computational fluid dynamics (CFD) to simulate heat transfer and airflow in a PV-TW system. Their specific focus was on investigating the impact of the gap distance between the PV panel and the TW. The research findings indicated that an optimal gap distance led to the highest airflow rate and improved heat transfer efficiency. This discovery holds critical importance for the design of PV-TW systems, allowing for the effective harnessing of solar energy while maintaining indoor thermal comfort [79].

PV-TW systems are noteworthy for their ability to address energy efficiency and sustainability challenges. This is particularly crucial in the arid climate of Saudi Arabia, where maintaining comfortable indoor temperatures is of paramount importance. To effectively manage shading and airflow, these systems incorporate Venetian blinds. The successful integration of these blinds demonstrates their effectiveness in regulating temperatures and enhancing overall indoor comfort conditions [80].

Significant economic and environmental advantages are offered by PV-TW systems. In a comprehensive study conducted by Kashif Irshad et al., energy consumption, cost savings, and carbon emission reduction associated with the integration of PV-TW into building designs were assessed. Their research, carried out in Malaysia’s climate context, revealed substantial cost savings and a significant reduction in carbon dioxide emissions. By utilizing solar energy for both heating and electricity generation, PV-TW systems reduce reliance on traditional heating and cooling methods, resulting in both economic and environmental benefits [81].

Table 1 summarizes the key findings from various studies focusing on the impact of PV solar cells on TWs.

Table 1. Impact of PV solar cells on TWs.

Ref.	Focus	Key Findings
[77]	TW with Air Purification, Photovoltaic, Heating, and Ventilation	• When increasing channel height to 1.4 m at 800 W/m^2, 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.
[78]	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 m^3/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.
[79]	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, achieving 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.
[80]	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.
[81]	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.

2.2. Solar Water Wall

Solar energy utilization for building heating and cooling has witnessed a groundbreaking advancement with the introduction of solar water walls, marking a notable departure from conventional SW systems. These innovative structures replace traditional masonry with water-storage reservoirs to store and distribute heat, offering an appealing solution for passive heating strategies [82]. The use of water as a heat storage medium brings distinct advantages, capitalizing on water's exceptional heat retention properties, surpassing the heat retention capabilities of air, which is commonly used in traditional SW. This innovation facilitates improved heat reflection onto glazed surfaces, aligning seamlessly with the principles of environmentally responsive building design to enhance thermal comfort [83].

The water-blind-based TW system introduces a novel approach comprising key components: a glass cover, water blinds equipped with parallel microchannels, an air gap, a massive wall, and a water tank. Within this system, each slat of the water blind serves as a highly efficient heat exchanger. It facilitates the absorption of solar radiation by circulating cold water from the tank, which, in turn, returns as heated water after the heat exchange process. This innovative design maximizes the utilization of solar energy for space heating and offers improved thermal performance for the building [84].

According to Figure 6, the remarkable specific heat of water, more than four times that of masonry, is very valuable for heat storage. However, its use is cumbersome because waterproof containers are required. Transparent glass containers filled with colored water and biocides act as translucent barriers. Absorbent glass and semi-transparent components provide structural support and regulate sunlight transmission. This is addressed by employing protective measures, including the use of glazing and shading devices, to regulate solar radiation and prevent excessive heat absorption. These components act as barriers to control the entry of sunlight, ensuring a balanced thermal environment within the system.

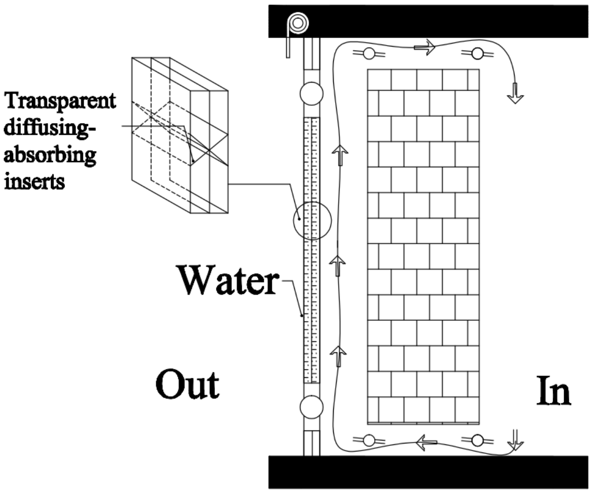


Figure 6. Operation principle of water TWs.

Additionally, the sunward surface of these slats is optimized for maximum solar energy absorption. To provide space heating, a radiator is integrated with the water tank, allowing for versatility in the operation of the system. Solar water walls offer numerous advantages, primarily their exceptional heat retention capabilities attributable to water's high specific heat capacity (C) which surpasses that of traditional building materials like concrete and bricks. Furthermore, these systems expedite heat transfer to interior spaces, as water proves to be a more efficient medium compared to the commonly used air in conventional SWs.

In the pursuit of overcoming challenges and optimizing this technology, endeavors have been undertaken by researchers to enhance solar water walls. Additionally, experts have explored the integration of water sprayer systems into TW solar systems to enhance their efficiency. This innovative approach has yielded promising results, incorporating a water sprayer system in an arid climate in Yazd, Iran. This innovative design featured transparent walls in multiple orientations, resulting in improved natural air ventilation and lower room temperatures compared to traditional systems [85]. Similarly, experiments conducted by Agurto et al. evaluated a low-cost TW solar system equipped with vertical water sprayers, offering valuable insights into its thermal performance across different climatic seasons [86].

In the pursuit of overcoming limitations and enhancing efficiency, the integration of water sprayers into TW solar systems has been explored, resulting in substantial benefits. The water TW system achieved superior thermal performance, with an impressive 3.3% increase in efficiency compared to traditional TW solar systems. Moreover, combining water sprayers with the TW system significantly reduced heat loss by approximately 31% during nighttime operation, as validated through meticulous numerical modeling [64,87]. These advancements hold great promise for the field of energy-efficient and environmentally responsive building design, as solar water walls and optimized TW systems pave the way for effective solar energy utilization in heating and cooling applications. Table 2 highlights some of the key studies that have analyzed different forms of solar water walls.

Table 2. Results from studies on solar water walls.

Ref.	Focus	Key Findings
[82]	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.
[84]	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.
[85]	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.
[86]	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.
[87]	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/(m^2·K), outperforming TW (1.4 W/(m^2·K)) and CW (1.5 W/(m^2·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 inevitably results in the production of excess heat, giving rise to challenges concerning both the efficiency of the panel and the comfort of the associated building. Issues such as uncontrolled temperature fluctuations, moisture accumulation, and varying humidity levels can emerge, emphasizing the critical necessity for the precise regulation of temperature and humidity. Passive Thermal Energy Storage (TES) utilizing PCMs is emerging as a promising solution, making use of the latent heat properties inherent to PCMs (Figure 7). These versatile materials, available in various forms, including inorganic, organic, and eutectic variants, serve as effective agents for TES. PCMs undergo phase shifts at specific temperatures, proficiently storing and releasing latent heat during these transitions. The incorporation of PCMs into building materials presents a practical approach to reduce energy consumption, especially in heating, ventilation, and air conditioning (HVAC) systems, potentially resulting in energy savings of up to 35%.

Moreover, the integration of PCM enhances the porosity of these materials and mitigates thermal spikes and fluctuations, contributing to more precise temperature control. Notably, it has been demonstrated that the inclusion of PCM of up to 20% by weight in mortars enhances thermal properties while preserving essential thermal–mechanical characteristics for repair and reinforcement purposes [60]. Comprehensive testing protocols are imperative to confirm the effectiveness of this innovative technique and ensure no PCM leakage could compromise its performance.

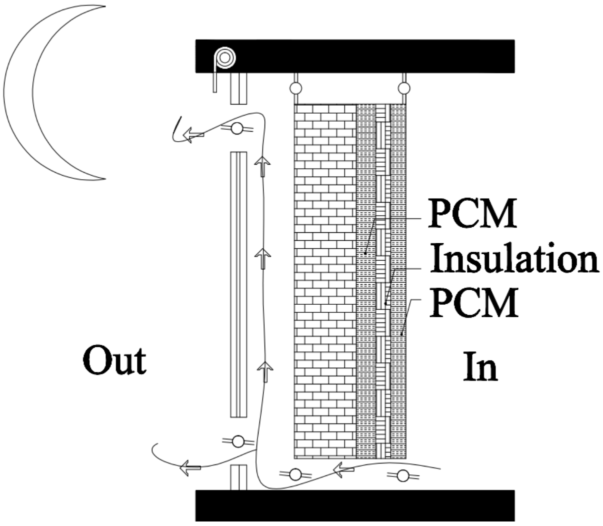


Figure 7. TW with PCM operation modes.

The strategic incorporation of PCMs within the porous structure of a material layer holds the potential to conserve significant amounts of heat through phase transitions during the day. This stored heat can be released during the night when temperatures are lower, preventing rooms from overheating. Research indicates an average nighttime temperature increase of approximately 20.2% in a room heated by PCM-filled porous structure layers compared to rooms without PCM-coated granular capsules in an integrative thermal wall–PCM system, achieving an impressive 76.2% thermal storage efficiency [88].

Extensive studies have been conducted by researchers to assess the feasibility and effectiveness of PCM-enhanced SW systems, yielding noteworthy findings. Simulations of TW systems equipped with PCM layers and insulation, conducted by Zhu et al., demonstrated their effectiveness in reducing peak thermal loads during both summer and winter [89]. This reduction has significant implications for energy-efficient building designs, minimizing reliance on active heating and cooling systems. The integration of double layers of PCMs in SW systems, as explored by Shanshan Li et al., showcased their capacity to mitigate interior overheating in summer and reduce temperature fluctuations in winter. This improvement in thermal comfort enhances the overall livability of spaces while concurrently reducing the energy demand for HVAC operations [90]. Enghok Leang et al. investigated the performance of a composite concrete storage TW with microencapsulated PCMs, finding that this modification led to enhanced thermal performance compared to traditional TW systems. This approach holds promise for enhancing year-round thermal comfort in buildings, particularly in regions with significant temperature variations [91].

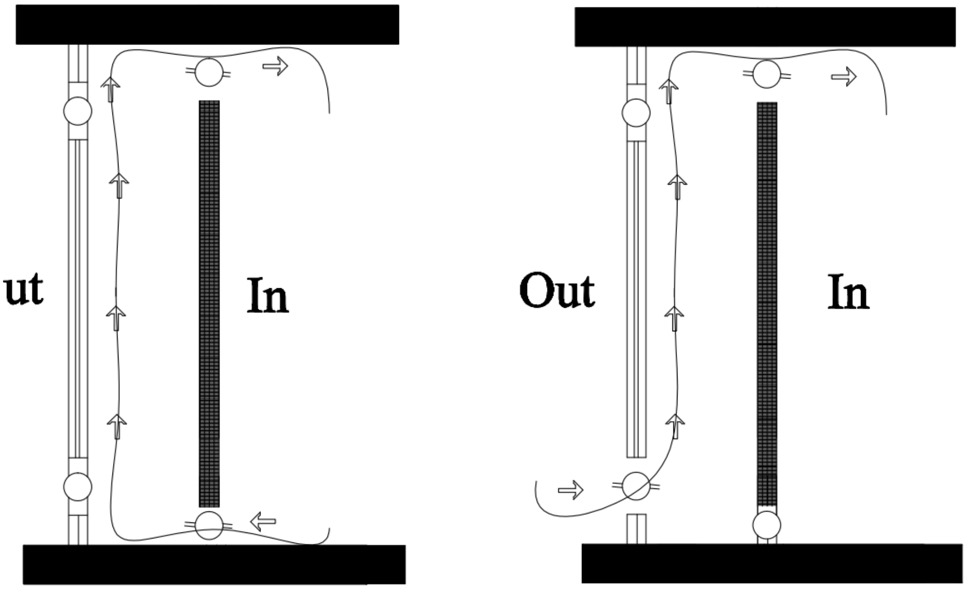
Table 3 presents diverse research findings on SWs integrated with PCMs.

Table 3. Results from studies on SWs integrated with PCMs.

Ref.	Focus	Key Findings
[60]	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.
[88]	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.
[89]	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 m^2; 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.
[90]	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.
[91]	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

SWs exhibit a remarkable versatility in their design and applications, offering a range of combinations tailored to specific purposes and adapted to diverse architectural and environmental contexts. These innovative combinations underscore the adaptability and compatibility of SW technology in enhancing energy efficiency and promoting sustainable building practices. Among the notable variations are the double-skin SW, fluid SW systems, and custom SW. Double-skin SWs represent a sophisticated integration of solar technology within the building envelope. This design involves the creation of a dual-layered wall system, typically comprising an outer layer of transparent or translucent materials, such as glass, and an inner layer that incorporates solar components like PV panels or solar thermal collectors [92]. Figure 8 illustrates the operational modes of a double-skin facade system. Panel (a) depicts the mechanically ventilated airflow window, while panel (b) showcases the naturally ventilated double-skin facade [93]. This configuration allows for the capture of solar energy through the transparent outer layer while providing insulation and weather protection. Double-skin SWs excel in improving thermal comfort, reducing energy consumption, and enhancing indoor air quality. Their adaptability to different climates and architectural styles makes them a valuable addition to sustainable building strategies [93–97]. Table 4 showcases the outcomes of multiple investigations scrutinizing the double-skin SW.



(**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 [93].

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

Ref.	Focus	Key Findings
[94]	Double-skin facade for a clustered housing unit	• Increased heating loads occurred with greater cavity depth, while cooling loads decreased. The optimal cavity depth for all scenarios was determined to be 1.00 m. • The Conventional DF system exhibited increased energy needs with deeper cavities, with 1.00 m being the optimal depth for minimizing primary energy needs and ensuring usability as a veranda space. For BIPV and BIPV/T DF systems, the integration of PVs and PV/Ts positively impacted the reduction in energy needs, with an optimal cavity depth of 0.97 m. • The incorporation of a Conventional DF system did not lead to a reduction in energy needs, whereas both BIPV and BIPV/T DF systems played a pivotal role in achieving nearly-zero-energy buildings (nZEBs) with high energy performance. The integration of BIPV and BIPV/T systems into the building envelope aligns with prior studies, affirming their potential for contributing to nZEBs.
[95]	Semi-transparent PV double-skin facades	• Ventilation in the STPV-DSF system substantially reduces cavity overheating, lowering temperatures by 1.35 °C to 2.21 °C compared to natural ventilation in June, October, and December. Additionally, the net electricity demand for cooling and heating decreases by 4.08%, 9.86%, and 14.05% under forced ventilation.
[97]	Solar chimney double-skin facade	• Larger opening areas between the occupant space and double-skin space yield higher ventilation rates, but exceeding 16 m^2 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.

Fluid SWs are a dynamic innovation in SW technology, employing a network of fluid-filled channels or pipes integrated into the building envelope. During daylight hours, solar radiation heats the fluid within these channels, enabling the collection and storage of thermal energy, which can be efficiently utilized for space-heating purposes. A notable feature of fluid SWs is their adaptability to varying climatic conditions, making them particularly advantageous in regions with fluctuating weather patterns. They excel at facilitating heat exchange processes during nighttime or when cooling is required, contributing to controlled temperature regulation within the building interior. By harnessing solar energy and effectively managing thermal resources, fluid SW significantly reduce the dependency on traditional heating and cooling systems, making them a promising technology for enhancing energy efficiency and sustainability in buildings [98–101].

The adaptability and versatility of these SW combinations highlight their potential to enhance energy efficiency and sustainability across diverse architectural and environmental contexts. As the demand for sustainable building solutions continues to grow, these variations of SWs serve as valuable tools for architects, designers, and builders to achieve energy-efficient and environmentally responsible building designs.

3. Optimizing SW Performance Factors

SWs are a testament to sustainable architectural innovation, offering a dynamic solution for harnessing solar energy to heat and cool buildings; however, assessing the performance of SWs involves a complex interplay of factors. Firstly, the climate conditions of a specific region are paramount. The availability of consistent sunlight and solar radiation significantly influences the efficiency of these systems. In sunnier climates, SWs thrive, making them a natural choice for energy-conscious building design. Secondly, the selection of glazing materials is crucial. The right glazing can enhance heat absorption and retention, ensuring that captured solar energy is utilized optimally. Proper SD are also vital, as they regulate solar radiation, preventing overheating during peak hours.

Additionally, the orientation of the SW concerning the sun's path plays a pivotal role. Correct alignment ensures that the wall receives maximum sunlight exposure throughout the day, boosting its energy capture capabilities. Effective insulation within the system minimizes heat loss, enhancing overall performance. Ventilation techniques are equally important, as they facilitate the movement of heated air, maintaining thermal comfort within the building. Furthermore, the integration of photo and thermal catalytic techniques can optimize energy conversion and storage, pushing the boundaries of SW efficiency. The consideration of these multifaceted factors is paramount for successfully designing and implementing energy-efficient, climate-responsive SW systems that align with sustainable building practices and environmental goals.

3.1. Climate Condition

Research findings emphasize the energy-saving potential of SWs across diverse climates as outlined in Table 5. In hot and arid regions like Yazd, Iran, classic SWs with water-spraying systems yielded an impressive 8 °C indoor temperature reduction [102]. PV-SWs in composite climates like Hefei, China, demonstrated adaptability, achieving a temperature drop of 2.47 °C with insulation and an additional 2 °C with shading curtains [39]. Mediterranean climates, exemplified in Ancona, Italy, showcased SWs and PV-SWs with roller shutters, achieving temperature reductions from 63% to 72.9% [47,71]. In Malaysia's hot–humid climate, poly-crystalline solar modules proved superior, aligning with solar radiation levels [103]. A new ventilated Trombe wall (VTW) with double PCM wallboards (PCM-VTW) showed promise year-round. PCM-VTW reduced the cooling load (14.8%) and heating load (12.7%) with specific fusion temperatures. Compared to a shading device, PCM-VTW reduced the total energy consumption by 5.83 kWh in summer and 23.54 kWh in winter, thus enhancing indoor thermal comfort [104]. For cold climates, a redesigned Trombe wall mitigated heat loss through glazing, maintaining sufficient heat storage capacity. Effective in latitudes from 40° to 50°, the new design reduced the annual energy consumption by 59%, cutting CO_2 emissions by 18% compared to the classical Trombe wall [105].

Table 5. Investigation of climatic changes.

Ref.	Climate Condition	Key Findings
[39]	Composite Climates (Hefei, China)	• Thermal insulation raises temperatures in winter by 2.36 °C and lowers temperatures in summer by 2.47 °C, with a <2% electrical efficiency decrease. • Adding a shading curtain reduces the indoor temperature by 2.00 °C in summer and increases electrical efficiency by ~1%. • Adopting thermal insulation in both winter and summer and adding a shading curtain in summer, especially for diurnal use, is recommended.
[47,71]	Mediterranean (Ancona, Italy)	• Experimental summer monitoring of Trombe wall with closed shutters and cross ventilation maintained the internal temperature (27.4 °C) close to room air (27.2 °C), ensuring comfort. • In summer, an unscreened SW caused excessive heat gains, but strategies like cross ventilation enhanced their performance. • Screening with roller shutters reduced the surface temperature by 1.4 °C, lowering daily heat gains by 0.5 MJ/m2. Combining overhangs, roller shutters, and cross ventilation improved thermal comfort, decreasing cooling energy needs by 72.9% and 63.0% for low or highly insulated building envelopes compared to an unvented Trombe wall without solar protections.
[102]	Hot and Arid (Yazd, Iran)	• The innovative channel design increased solar irradiance by around 16%, raising the maximum room and Trombe wall temperatures by 3–6 °C. • The weekly results indicated low temperature fluctuation in the test room, meeting air conditioning standards. • The Trombe wall stored energy efficiently, reaching a maximum of 5800 kJ/h in February. • The innovative design demonstrated cost-effectiveness, occupying only 50% of the southern building's wall area, while further insulation improvements were suggested for cloudy days in winter.
[103]	Hot–Humid (Malaysia)	• Malaysia's predictable climate, offering 6 h of daily sunlight with solar radiation between 800 W/m^2 to 1000 W/m^2, favors renewable energy development. • Poly-crystalline solar cells exhibit superior performance in high solar radiation, while amorphous cells show higher efficiency in low-intensity conditions. • Poly-crystalline solar modules, when paired with a single-axis time/date solar tracker under Malaysian climate, demonstrate the highest performance ratio, making them suitable for sustainable building designs with a reduced PV panel quantity.
[104]	Cold (Changsha, China)	• The optimal transition temperatures for exterior and interior PCM wallboards were determined to be 26 °C and 22 °C, resulting in a 14.8% cooling load reduction and 12.7% heating load reduction. • Coatings on the exterior PCM wallboard outperformed shading devices, reducing total energy consumption by 5.83 kWh in summer and 23.54 kWh in winter.
[105]	Cold (Kursk, Belgorod, Khabarovsk, Russia)	• The Trombe wall's molten material for heat storage ranges from 100 to 300 kg, with calculations varying based on the day in January or February. • The newly designed Trombe wall in Harbin reduces annual external energy consumption and CO_2 emissions by 59%, with a 7-year payback period compared to the classical Trombe wall.

3.2. Glazing

Glazing plays a pivotal role in the performance and sustainability of SW systems, significantly influencing diverse aspects of a building's performance. This impact encompasses indoor illumination, thermal comfort, and the efficient utilization of solar energy which is summarized in Table 6. The careful selection of glazing types and their associated properties is crucial within passive heating and cooling systems, especially with SWs emerging as an innovative sustainable solution. Building glazing fulfills a dual role in architectural design, encompassing aesthetic and functional dimensions, as it shapes indoor illumination, creates visually appealing spaces, and regulates the indoor thermal environment, thereby affecting temperature control and occupant comfort. Furthermore, it contributes to the efficient utilization and control of solar energy within buildings [106].

Computational models were utilized to optimize energy consumption in diverse Asian climates, emphasizing the importance of glazing properties like U-value, solar heat gain coefficient, and visible transmittance for achieving a balance between lighting, thermal comfort, and energy efficiency. Key findings include the need to minimize window size in most cases, varying optimal window placement by climate zone, the efficiency of specific window types, and the impact of the U-value on the heating and cooling energy. The study underscores the necessity of tailoring window properties to specific climates when designing energy-efficient buildings [107].

Multi-layered facades, featuring transparent elements, achieve a harmonious blend of visual appeal and practicality [108]. The selection of glazing components in these structures is pivotal in determining their overall effectiveness. Factors such as the type of glazing material (clear, absorptive, or reflective glass), glazing placement (internal or external), and the number of layers all hold significant importance [22]. A comparative assessment of various glazing options within open-plan office environments across different urban areas underscored the critical significance of thoughtful glazing decisions to enhance both comfort and energy efficiency [109].

Researchers have conducted comprehensive studies, both experimental and numerical, to gain a deeper understanding of the performance of glazed SWs. For instance, one study harnessed the power of Energy Plus (7.1) software to meticulously examine energy consumption patterns within a double-glazed facade. This investigation encompassed variables such as the type of glazing used, its position within the facade, and the number of glazing layers. The research underscored the central role of glazing selection in the creation of energy-efficient building designs [110].

Similarly, another study adopted mechanical ventilation to direct air into the air-flow channel of a double-glazed facade [111]. Various glazing materials and shading louvers were explored, shedding light on the potential of passive heating solutions [112]. An empirical approach was taken in another study, which conducted experiments to assess the preheating effects of double-glazed facades on outdoor air [113]. The findings vividly demonstrated how glazing choices can exert a significant influence on temperature control. Additionally, another research leveraged CFD to delve into the thermal performance of double-glazed facades. This study considered a wide array of glazing materials, air cavities, and shading louvers, revealing the intricate dynamics between different glazing types and architectural components. These collective efforts contribute to a deeper comprehension of the intricate interplay between glazing and building design [114].

Multi-glazed facades, spanning across several floors, function as a canvas for architectural innovation; however, they necessitate meticulous attention to fire safety considerations during their design [115]. One study introduced a method to simulate the thermal properties of a ventilated double-glazed facade incorporating a Venetian blind, offering potential avenues for energy-efficient architectural solutions [116]. Similarly, another investigation delved into the impact of varying air-flow rates and blade angles on the heat-transfer performance of a ventilated double-glazed facade with a Venetian blind, providing insights into optimizing such systems [117]. Additionally, another study conducted simulations to assess the thermal performance of a multi-story building featuring a ventilated double-glazed facade with a light-colored horizontal blind, contributing to the growing body of knowledge in this architectural domain [118].

Table 6. Results from studies on glazing with SWs.

Ref.	Focus	Key Findings
[110]	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.
[114]	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.
[115]	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.
[117]	Ventilated double-skin facade in winter	• Increasing the blind size from 30 mm to 320 mm raises the average outlet temperature of DSF by about 53% during peak sun hours. • When blinds are positioned closer to the outer glazing, the outlet temperature of DSF moderately rises, and the average mass flow rate during peak sun hours improves by over 10%, demonstrating the importance of blind placement for enhancing winter performance. • Optimizing the blind size at 240 mm enhances dynamic efficiency by 139% at 11 a.m., maximizing the extracted heat rate to the Air Handling Unit (AHU). Meanwhile, positioning blinds closer to the outer glazing doubles the dynamic efficiency of DSF in winter.

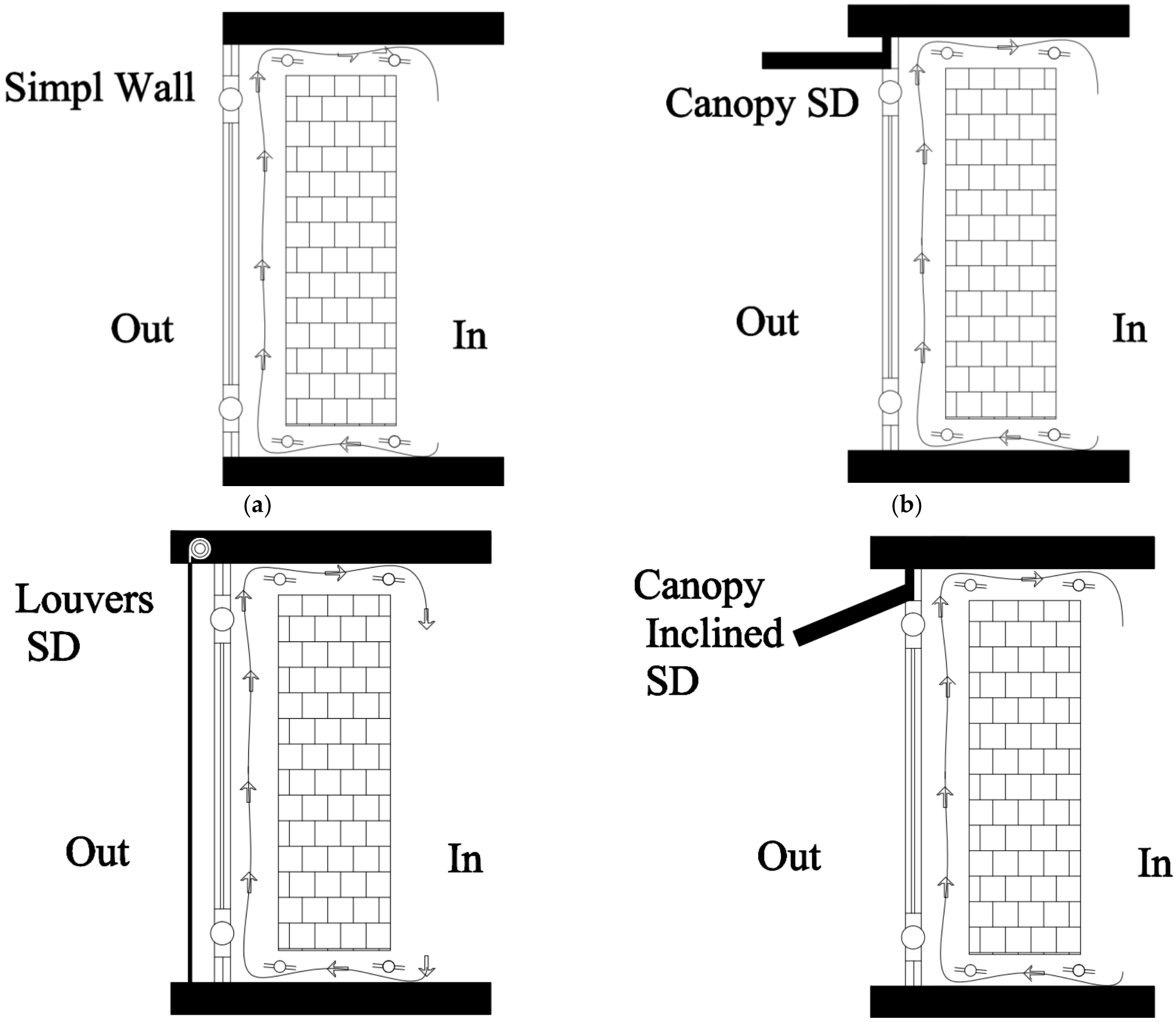
3.3. Shading Devices

SDs play a crucial role in SWs, particularly in the context of highly glazed facades widely used in contemporary buildings. The preference for such facades brings both advantages and challenges. On one hand, they offer architectural suitability and the potential to provide natural light and external views, but on the other hand, they can lead to high heating and cooling loads [119]. In contemporary building design, highly glazed facades are favored for their architectural suitability and ability to provide natural light and external views; however, this preference can lead to elevated heating and cooling loads. SDs play a pivotal role in rectifying this by controlling solar irradiation, preventing overheating in summer and optimizing daylight entry in winter [120].

Building surfaces have evolved into versatile platforms for integrating PV modules, resulting in four primary BIPV categories [121–124]:

- 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.
- PV Windows 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. This figure serves as a reference to help readers understand the different shading techniques discussed in reference [124].



(**a**) (**b**) (**c**) (**d**)

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

Researchers have conducted comprehensive studies to understand the performance of glazed SWs, utilizing both experimental and numerical methods. These investigations have led to valuable insights into energy consumption patterns. Additionally, fixed SDs have been recognized as crucial elements in architectural design, particularly in hot climate regions, where even minor adjustments in the SD design can significantly enhance building energy performance. This study, unlike previous ones that focused on isolated parameters, conducted a holistic evaluation of 1485 scenarios involving fixed external SDs, considering factors such as direction, glazing type, window-to-wall ratio (WWR), SD depth, and slope. The results showed that SDs have a substantial impact on building energy performance, particularly in reducing cooling energy consumption, with the best scenarios achieving reductions of 37% to 49% compared to no shading with high-performance glazing and 73% to 78% with low-performance glazing. This study's findings underline the importance of considering multiple parameters when designing SD systems, and the results are applicable to Mediterranean climate regions and similar areas. Future research could extend this approach to different climatic zones and explore additional factors like glare, view, and daylight quality [125]. By regulating sunlight and solar radiation, SDs mitigate glare and overheating, resulting in reduced cooling loads and improved indoor visual comfort [126,127]. By employing colored and partially translucent

PV materials, SDs enhance the visual attractiveness and distinctive architectural characteristics of structures and assembly elements usually linked with traditional building elements [128,129]. Table 7 presents the results of various studies examining shading devices with SW.

Table 7. Results from studies on shading devices with SW.

Ref.	Focus	Key Findings
[112]	Exterior shading device	• The external device is significantly more effective than internal devices, with the experimental results reporting an 11% cooling energy saving even in the worst-case scenario with a 60° slat angle. • Among shading devices equipped with slats, declining slats outperformed upward slats in energy efficiency, with the optimal energy consumption at a slat angle of 0° and a maximum at 60° due to increasing direct sunlight.
[124]	SDs for integrating PV	• Optimal southern-oriented SWs in office buildings were assessed using a multi-criteria analysis involving diverse stakeholder groups. “Brise soleil full façade” consistently ranked highest across all groups, while traditional SDs like “Louvers horizontal inwards” ranked lowest, suggesting a need for innovation in building-integrated photovoltaic (BIPV) technology.
[125]	1485 scenarios with fixed external SD	• The best results for the eastern and western directions were obtained with ECL_50%DSL_15◦_0.5, showing a 23% and 26% increase in energy consumption compared to the best scenario in the southern direction. • Horizontal Louvers (HLs) and External Canopy Louvers (ECLs) were effective in reducing cooling energy consumption, with HL performing better than vertical louvers.
[126]	Building-integrated Photovoltaic Blinds	• The shading effect from the blind’s slats can have a nonlinear impact on the BIPB’s technical performance, especially in relation to design variables such as orientation, PV panel width, and season. An increase in the width of the PV panel resulted in a nonlinear decrease in the Average Electricity Generation per unit (AEGunit). • Economic analysis: Feasibility linked to investment changes. Shading effect nonlinearly influences NPV25 and SIR25, emphasizing careful real-world implementation.
[129]	Adaptive Solar Facade (ASF)	• Highlighting a modular design for seamless integration, the research prototype of the Adaptive Solar Facade achieved 25% energy savings in simulations. Incorporating soft pneumatic actuators and thin-film photovoltaic modules establishes a foundation for economically optimized and versatile systems.

3.4. Solar Radiation and Orientation of TWs

SWs, passive solar heating systems, rely heavily on solar radiation levels and their orientation to achieve peak efficiency. Extensive research, as demonstrated by Li and Liu, has revealed a direct relationship between TW efficiency and increasing solar radiation levels. This underscores the importance of solar energy input in enhancing a TW’s capacity to capture and store heat for space-heating purposes [130].

An experimental study conducted in Yazd, Iran, focused on a unique TW design tailored for its desert climate. Unlike traditional models that primarily capture sunlight from one direction, this innovation harnessed solar radiation from three angles: East, South, and West. The results showcased the TW’s ability to maintain indoor temperatures between 15 °C and 30 °C, even during Yazd’s coldest winter days. This achievement was attributed to increased stored energy, narrowing the temperature difference between maximum and minimum levels. An innovative channel design further contributed to efficient solar energy absorption, allowing the absorber to reach around 47 °C on the coldest winter days. The hourly analysis revealed higher solar intensity correlated with increased energy absorption, peaking at 5800 kJ/h in February. This TW design offers the potential to enhance thermal comfort, cost-effectiveness, and space efficiency, with options for additional insulation on cloudy winter days [102]. In the evaluation of a TW system in a subtropical location, researchers investigated the effectiveness of TW systems for both heating and cooling in subtropical climates. They conducted experiments using two test cells: one incorporated a naturally ventilated TW, while the other served as a reference without the TW. Indoor temperature measurements were taken during cold periods in 2011 and the summer of 2012. The results indicated that the TW system outperformed the reference cell, especially in colder conditions. Additionally, the study evaluated the year-round advantages of the system in three subtropical locations, showing consistent performance. The research identified potential improvements, including insulating the remaining walls and the backside of the storage wall, and implementing automated ventilation control to enhance overall system efficiency [131].

In the northern hemisphere, the most advantageous orientations are due south, southeast, and southwest. These orientations are strategically chosen to ensure maximum exposure to direct sunlight, particularly during the winter months when the sun's path is lower in the sky. Conversely, in the southern hemisphere, TWs perform optimally when oriented due north, northeast, or northwest, again aligning with the path of the sun for maximum solar energy absorption [62]. In a notable case study, the energy efficiency of a solar-cooled office building in Tunisia was meticulously examined through TRNSYS software (Version 16) simulations. The primary objective was to evaluate how architectural elements and passive techniques impacted the building's overall energy consumption. The investigation delved into the effectiveness of existing passive heating strategies during winter and their potential for causing overheating issues in the summer. Furthermore, the study proposed and assessed passive cooling strategies to curtail the building's cooling requirements. The findings were remarkable, indicating substantial energy savings of 46% during winter and an impressive 80% reduction in summer compared to a standard building when implementing wall insulation and a cool roof. Notably, TWs played a vital role in reducing heating needs by approximately 21%. The incorporation of internal curtains, movable solar overhangs, and low-emissive Argon coatings led to significant reductions in overall energy demands. The cooling load dropped from 14.09 kW to 8.68 kW, prompting suggestions for further enhancements, such as a cooling storage system, to optimize solar cooling efficiency [132]. Duan's study investigated two types of TWs: one with an absorber plate on the thermal storage wall and one with an absorber plate between the glass cover and the thermal storage wall. Type II showed higher energy and exergy efficiencies due to reduced convection and radiation heat losses, resulting in greater air temperature rise and airflow rate. The solar radiation intensity and glass cover emissivity significantly influenced system performance. While both types exhibited high energy efficiency, exergy efficiency remained low. Increasing the absorber plate temperature was an effective method to decrease exergy destruction and enhance energy and exergy efficiencies [133].

3.5. Insulation Effect

The integration of thermal insulation in SWs has emerged as a crucial aspect of enhancing their performance and mitigating potential issues such as reverse heat transfer and overheating. Various studies have explored the impact of insulation on solar wall efficiency, highlighting its significance in different climatic conditions and building contexts. A comprehensive overview of thermal insulation materials and solutions reveals a diverse range, categorized into three main groups: traditional, state-of-the-art, and new conceptual materials. These materials vary in properties such as thermal conductivity, mechanical strength, and environmental impact. This classification underscores the importance of choosing the right insulation materials tailored to specific building contexts [134].

Li et al.'s study introduced an anisotropic insulation design, accounting for varying solar irradiation orientations to mitigate indoor radiant thermal discomfort. It established a simplified calculation method for insulation thickness based on equal heat flux on the envelope, considering factors like exterior surface, brick wall thickness, and material influence orientation differential insulation (ODI) thickness. ODI was found to be suitable for regions with high solar radiation intensity. In Lhasa, ODI reduced material costs by 24.6%, with only a 6.1% increase in the average heating energy consumption compared to isotropic insulation. When using the same insulation material, the heating energy consumption decreased by 9.0%. ODI demonstrated substantial advantages in thermal balance, material savings, and reduced energy consumption for northward and southward rooms [135].

SWs, a passive solar heating technology, harness solar energy for space heating. However, classic SWs exhibit low thermal resistance, resulting in significant heat loss at night [136]. Moreover, in well-insulated buildings and hot weather conditions, SWs can inadvertently contribute to overheating due to reverse heat transfer [71]. These challenges necessitate the proper insulation of SWs to maximize their performance.

Numerous research investigations have explored the efficiency of insulation within composite SW, which integrate components such as glass panels, mass walls, and insulated walls equipped with ventilation systems. The findings indicate that adequately insulated composite SWs have the capacity to surpass the performance of conventional SWs, particularly in cold and overcast conditions, thus presenting promising opportunities for energy conservation [137–139].

In Italy, an empirical investigation using Energy Plus software to assess how insulation affects the performance of SW. Their research reveals that insulation has a notable effect: it reduces the seasonal demand for heating energy but increases the cooling energy requirements. Despite this trade-off, the study underscores that insulated SWs exhibit significantly higher overall efficiency. Specifically, they observed that a regular SW had a seasonal heating-energy demand of 58.33 kWh/m^2, whereas a super-insulated SW lowered this demand to 16.21 kWh/m^2, representing just 28% of the former's consumption. In contrast, for cooling, a typical SW consumed around 9.19 kWh/m^2, whereas a super-insulated version required approximately 23.31 kWh/m^2. These findings highlight the complex impact of insulation on SW performance, with a clear emphasis on the substantial efficiency improvements gained through insulation [47].

Addressing the issues of excessive heat and reverse heat flow, it becomes evident that the importance of adequate insulation for SW cannot be overstated. This understanding is pivotal when aiming to optimize airflow rates within buildings with incorporated SWs, especially in the summertime [140].

The process of enhancing passive solar design techniques and making informed insulation decisions are interconnected in the pursuit of reducing overall lifecycle expenses. This collaboration involves fine-tuning insulation thicknesses, selecting appropriate window styles, and integrating heat recovery systems. Their research underscores the importance of adopting a comprehensive approach to energy-efficient building design. It emphasizes that insulation selections should align with the overarching objective of minimizing energy usage while preserving indoor thermal comfort [141,142].

3.6. Ventilation Techniques

Ventilation systems are integral components in optimizing the thermal performance of SWs and play a pivotal role in regulating heating and cooling processes within buildings. Numerous studies have been conducted to assess the impact of ventilation on the efficiency of SWs, shedding light on the design and operation of these systems.

In the context of vented SWs, the installation of thermo-circulation vents at both the upper and lower portions of the wall holds significant importance. Heat loss primarily occurs within the air gap positioned between the glazing and the wall, driven by mechanisms like convection, conduction, and radiation. Table 8 reviews the studies in the heat transfer types area and provides a condensed overview of their findings. Placing vents strategically at the wall's extremities contributes to reducing this heat loss. During operation, as the air within the gap warms and becomes lighter, it rises and enters the interior through the upper vent. Concurrently, cooler external air enters through the lower vent, replacing the rising warm air. The control of these vents, whether opened or closed, directly impacts heat-transfer coefficients, a critical parameter for optimizing the system's performance [88].

The results of the experimental work on natural convective heat transfer in a Trombe-type assembly revealed significant improvements in performance by utilizing thin vertical and transparent partitions. The proposed correlations offered an effective strategy for optimizing the thermal sizing of a Trombe wall's assembly [143]. Another study aimed to develop an approach for TW sizing by considering energy consumption, economics, and thermal comfort. The research filled gaps in existing studies by separately assessing energy and economic life cycle costs based on building conditions. The results indicated that, for a thermally insulated new building used only in winter, constructing a TW is economically viable. However, in uninsulated existing buildings, a TW is only feasible if its area is greater than 9 m^2. The study emphasized the impact of insulation, the economic viability of TWs with increasing area, and the consideration of personalized comfort parameters [144]. An analysis of the heat transfer process in the Trombe wall system with a new channel design in Yazd, Iran, was conducted. The study investigated the variations in the Rayleigh number; convective heat transfer coefficient; and rates of convection, conduction, and radiation heat transfer. The results highlighted noticeable decreases in temperature differences during the early hours and the dominance of conduction in the early and late hours, with convection dominating at midday. The new channel design maximized radiation heat transfer. The heat transfer was more significant on the coldest day due to higher temperature differences within the Trombe wall system [145]. An experimental study in the Abha region of Saudi Arabia assessed a Trombe wall's performance under real climatic conditions. The results indicated that radiative exchanges were more important than convective ones, and that the Trombe wall could meet varying percentages of heating needs based on climatic conditions. For instance, it could meet 80% of the heating needs on a sunny day with low wind, 42% on a sunny day with strong wind, and 37% on a day with scattered or low-density clouds. Even in heavy cloud cover, the Trombe wall could provide 14% of heating needs, showcasing its effectiveness as a passive solar system [61].

Table 8. Results from studies on heat transfer types with SWs.

Ref.	Heat Transfer Types	Key Findings
[143]	Natural convection	• A 10.0% to 14.4% increase in natural convective heat transfer in Trombe-type assemblies with thin vertical partitions was observed. • Elevating the aspect ratio between 0.1 and 0.2 leads to a 13% enhancement in natural convective heat transfer within the active cavity. • The proposed correlations enable the effective calculation of the average natural convective heat transfer, aiding in optimizing Trombe wall assembly thermal sizing.
[144]	Convection	• For newly built, thermally insulated houses, TWs are economically viable, irrespective of size. In existing uninsulated buildings, a TW becomes feasible only if constructed larger than 9 m^2, emphasizing the impact of insulation on economic viability. • Optimal TW sizing is determined by analyzing the cumulative distribution frequencies of room temperatures, relative humidity, and CO$_2$ concentrations. For occupants preferring temperatures below 23 °C, a 3.8 m × 3 m TW outperforms a larger counterpart, highlighting personalized comfort considerations in TW design.
[145]	Radiation Conduction Convection	• Radiation stands out as the primary method of heat transfer from the Trombe wall. Both convection and conduction contribute to the heat transfer process, but their roles are minor compared to radiation. • Conduction is the sole means of heat transfer into the room during non-sunny periods, and in the early hours, it exhibits a reverse process due to a significant decrease in absorber temperature. • Convection delivers heat only when vents are open, with the highest occurrence during sunny periods. Overall, heat transfer is more pronounced on the coldest day due to higher temperature differences within the Trombe wall system. • Early hours saw a notable drop in the Rayleigh number and air temperature difference between the absorber and channel. Increased solar intensity boosted the Rayleigh number, which was especially noticeable on colder days.

		• During overcast periods, the rising Rayleigh number resulted from the reduced air temperature in the channel, increasing the temperature difference.
[61]	Radiation Conduction	• Thermo-circulation in Trombe walls correlates with sunshine hours and radiation intensity. The wall effectively stores and releases heat, fulfilling heating needs, specifically 80% on sunny days with low wind, 42% on windy sunny days, 37% on days with scattered clouds, and 14% even in heavy cloud cover.

Various ventilation techniques improve TW efficiency by analyzing the impact of air channel thickness and vent positioning on heating characteristics. This study findings demonstrated that optimized TW configurations resulted in higher air temperatures, increased average airflow rates, enhanced heating capacity, and improved thermal efficiency when compared to conventional TW designs. These results underscore the substantial potential for performance enhancement through the implementation of advanced ventilation strategies in TW systems [146].

The vent size emerges as a crucial parameter in SW designs, withs its significance being contingent upon the desired solar saving fraction. In this study, we propose a small-scale solar chimney (SC) integrated with Photocatalytic Reactors (PCRs) for indoor ventilation and atmospheric methane degradation. Numerical simulations analyze factors influencing the system's indoor ventilation and methane removal performance, leading to the following conclusions: (1) SCs with High-performance PCRs (HPCR) exhibit 3.57-times-higher methane removal compared to Photocatalytic Painted PCRs (PPCR) under 900 W/m^2 solar radiation. Increasing the reaction zone length enhances methane photocatalytic efficiency. (2) Enhanced methane removal and ventilation in SCs with HPCR result from the increased air gap width and solar radiation. The optimal purification rate of 57.27 μg/s is achieved at $\gamma = 0.85$ and $L = 1.5$ m under 500 W/m^2 solar radiation. (3) Backflow, caused by increased airflow resistance, can be mitigated by placing a small porous material near the chimney outlet, ensuring efficient methane degradation [147]. Moreover, the inclusion of external vents, which can be positioned on the outer surface of SWs, was identified as an effective means to bolster air circulation, thereby enhancing ventilation and cooling within the air gap positioned between the glazing and the primary wall structure, especially during the scorching summer months [148].

A study evaluated the energy performance of a building in Japan that featured a ventilated TW solar system specifically designed for winter use. This unique system integrated fans within the TW structure to regulate thermal circulation and enhance ventilation rates. The research outcomes highlighted that a composite TW with well-controlled ventilation could yield significant energy savings, potentially reducing annual costs by up to 3.7% when compared to a non-ventilated wall. This outcome underscores the promising benefits of incorporating ventilation into TW systems [149].

The essential function of vents as a fundamental control system within ventilated SWs is emphasized, as they significantly influence both heating and cooling processes within buildings. The comparison between the effectiveness of ventilated and non-ventilated SWs remains a central aspect of research in the field of passive energy systems [150].

A comprehensive evaluation of SW with thermo-circulation vents in various U.S. climates revealed a challenge associated with these vents. They occasionally induced a reverse airflow during nighttime, causing a significant decrease in efficiency in certain situations. To address this problem, the researchers suggested the use of dampers to control the vents and prevent a reverse airflow [69].

Ventilation technology has expanded its applications beyond traditional SWs and have begun focusing on improving TW performance. A detailed investigation explored the impact of air velocity on natural ventilation and its role in regulating indoor temperatures for both heating and cooling purposes. Using mathematical modeling and simulations, researchers analyzed how air velocity behaves under various conditions. They discovered a direct relationship between air velocity, the temperature difference between the massive wall and the glass wall, and the wall's height. To prevent unwanted backflow, they adjusted the boundary line to align with the massive wall's width. The study provides valuable insights for optimizing TW systems by considering air velocity as a crucial parameter [151].

3.7. Photo- and Thermal Catalytic Techniques

When sunlight reaches the PV and aluminum panels, several processes are initiated. The ultraviolet (UV) part of the solar radiation triggers photocatalytic reactions on the TiO2 membrane of the PV panels. Simultaneously, the visible part of the solar radiation is converted into electricity, which can power various indoor appliances or be stored for later use. The remaining infrared radiation is converted into thermal energy, increasing the temperature of the panels. Cold air from the room enters the TW chamber through the lower air inlet. Solar irradiation heats the air within the chamber, creating thermal pressure and causing the air to flow upwards. The integration of PV panels with aluminum panels in a baffle-like configuration extends the airflow path, enhancing contact between pollutants and catalytic materials. Within the TW chamber, catalytic reactions take place due to the high temperature, effectively decomposing airborne pollutants. This process results in clean air leaving the chamber through the upper air outlet, simultaneously heating the room [152,153].

The incorporation of photocatalytic and thermal catalytic techniques into TW system offers significant benefits in terms of air quality improvement and sterilization. Photocatalysis, especially using TiO_2 as a catalyst, has been proven effective in sterilizing pathogenic bacteria and decomposing endotoxins with minimal side effects. This characteristic is particularly valuable for controlling respiratory infectious diseases within buildings. The improvement of TW functionality and performance involves integrating PV panels and aluminum panels into the TW chamber. These panels are coated with materials that enhance both photocatalytic and thermal properties to optimize energy harvesting. The resultant photo/thermal catalytic TW system harnesses solar energy and catalytic oxidation to warm and purify the air within the chamber, offering the dual benefit of generating electricity and providing heating while enhancing indoor air quality. The experimental outcomes demonstrate that this innovative TW system can yield heat ranging from 6.25 to 17.74 kJ/mol and generate electricity in the range of 0.075 to 0.372 kWh daily between 9:00 and 16:00. Furthermore, it achieves a one-way sterilization efficiency for bacterial aerosols, with rates ranging from 0.204 to 0.347. The optimal spacing between system components is determined to be 25 cm, ensuring a balance between sterilization efficiency and heating and electricity generation. The strategic arrangement of UV light strips at the top and bottom of the system enhances sterilization efficiency. This approach offers a versatile solution for addressing energy generation and enhancing indoor air quality in building designs and is particularly well-suited for severe cold regions during the winter. Nevertheless, it is advisable for future studies to evaluate its performance under varying seasons, climates, and environmental conditions [152].

The innovative TW system combines solar heating and air purification to address concerns about indoor air quality during passive solar heating with TW. This system relies on a photo-thermal composite catalyst ($MnOx\ CeO_2/TiO_2$) with remarkable performance in both solar heating and catalytic oxidation. Experimental investigations into formaldehyde degradation have revealed a synergistic effect between photo-thermal catalysis and a reduction in activation energy when compared to pure thermal catalysts. To enhance the TW system's functionality, solutions were proposed to improve hygiene and sanitation. One such solution is the catalytic TW, utilizing photocatalytic reactions to efficiently reduce airborne formaldehyde concentrations. In contrast to traditional solar TWs, the new photocatalytic version incorporates composite crawler-type modules (SiO_2/TiO_2) between the outer glass unit and the inner wall. Each module features circular ducts, as depicted in Figure 10, comprising areas with composite SiO_2/TiO_2 material and areas with TiO_2 alone. The former is primarily responsible for adsorbing and desorbing water molecules and formaldehyde, while the latter focuses on photo-catalytically degrading formaldehyde. As the adsorption modules rotate inward, humid air laden with formaldehyde particles is drawn into the circular ducts. Here, water vapor and formaldehyde are adsorbed and later released by SiO_2/TiO_2 upon desorption. Externally, elevated temperatures prompt the desorption of water and formaldehyde, facilitated by the growth in temperature of the adsorption modules. The resulting desorbed water vapor exits, while TiO_2, under the influence of solar radiation, decomposes formaldehyde into CO_2 and H_2O [137].

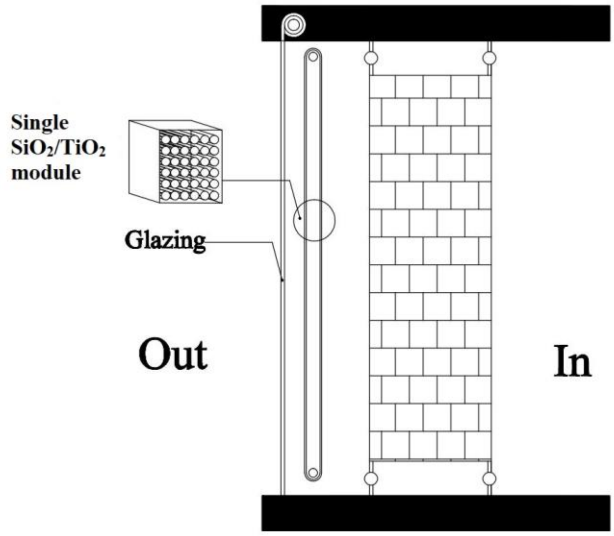


Figure 10. A photocatalytic SW [137].

Innovative studies have demonstrated the potential of combining photocatalytic oxidation with SW systems. They utilized UV light from solar radiation to initiate photocatalytic purification reactions. Yu et al. took this a step further by achieving simultaneous space heating and indoor air purification. Their system demonstrated impressive daily air heating efficiency and a substantial volume of fresh air generation [154].

Thermal catalytic technology, on the other hand, offers efficient sterilization with high removal efficiency and no secondary pollution. Solar irradiation from SWs can raise the air temperature within the chamber to levels that inhibit bacterial self-repair mechanisms and efficiently destroy bacterial Deoxyribonucleic acid (DNA) and Ribonucleic acid (RNA) [155,156].

While the hybrid wall system achieves a commendable thermal efficiency of 36.5%, it only experiences a minor 1% reduction compared to conventional thermal catalytic TW; however, it significantly boosts daily clean air production by 45.15 m^3. This research underscores the potential of photo-thermal catalytic technology to improve both thermal efficiency and indoor air quality in building systems, underscoring the importance of further optimizing its structural design for maximum benefits [157].

4. The Evaluation of the Energy and Environmental Performance

4.1. Solar Heat Gain

Solar heat gain plays a pivotal role in evaluating the performance of TW as passive solar heating systems. These walls are specifically designed to harness and effectively utilize solar energy, making it imperative to assess their ability to capture and store solar heat during daylight hours. In a parametric study conducted in Portugal, the impact of factors such as wall thickness and materiality on heat gain was investigated, revealing intriguing insights [61]. Thicker walls, particularly around 35 cm, exhibited increased heat gains during winter, although not in a linear proportion, while thinner walls demonstrated rising heat gains during summer but within lower value ranges. Additionally, the study emphasized the role of thermo-circulation, closely associated with direct solar radiation, in enhancing heat gain. Both solid brick and granite storage walls exhibited similar behavior patterns, ensuring that both SWs and TWs maintained temperatures above 20 °C without the need for HVAC input [158].

Efficiently estimating solar heat gain is essential, and an experimental method for this purpose involving large-scale model fenestration systems was introduced. This method, utilizing a fenestration radiometer, is sensitive to shortwave and longwave radiation, making it suitable for assessing various daylighting technologies under real non-uniform sky conditions. The values obtained for solar heat gain and shading coefficients were notably consistent with those obtained using different methods [159]. Nevertheless, concerns about overheating in passive solar buildings, particularly during summer and mid-season, have persisted. Experimental studies in Ancona, Italy, highlighted the importance of addressing overheating concerns in SW systems. To mitigate this issue, the studies explored the influence of SD like exterior overhangs and Venetian blinds, focusing on scenarios with high thermal mass. Additionally, it reinforced the role of thermo-circulation, linked to direct solar radiation, in boosting heat gain and maintaining stable temperature patterns in high-thermal-mass rooms [160]. These insights emphasize the significance of accurately assessing solar heat gain to optimize SW performance. Furthermore, ISO 13790:2008(E) provides valuable equations to calculate heat transfer and solar heat gains in special elements, offering a foundation for defining calculation methodologies for SW thermal performance [161].

4.2. Thermal Efficiency

However, one of the challenges with SW is heat loss during nighttime and shaded winter days, leading to increased energy consumption. Researchers have sought to overcome this issue through various improvements. For instance, Bajc et al.'s numerical model focused on SW temperature fields in a moderate continental climate, emphasizing the need for optimized SW designs for enhanced thermal efficiency. Simulations using Belgrade weather data revealed a significant winter impact, maintaining a room temperature of 14.7 °C. In summer, the SW contributed to heat loads, and incorporating PV stripes increased the room's temperature to 29.8 °C, requiring additional cooling to reach 26 °C. The PV strips played a crucial role, contributing approximately 60% of electricity needed for cooling devices on summer days, with considerations for PV efficiency, Trombe glazing area, insolation, and energy consumption [162].

Comparative studies of SWs show variations in thermal performance, with traditional SWs achieving high outlet temperatures but suffering from reduced air flow rates, impacting heating efficiency. Water SWs (WSWs) have enhanced performance due to a reduction in natural convection. A proposed composite Trombe wall, integrating a water wall with the traditional design, is studied through a CFD simulation. Examining solar radiation, ambient temperature, inlet water flow rate, and inlet water temperature, the analysis focuses on energy efficiency, exergy efficiency, and heat loss. The study concludes that the composite structure excels in utilizing low-temperature water, reducing building heat loss at night. Key findings include WSWs outperforming traditional structures in daytime thermal performance by 3.3%, achieving the highest exergy efficiency and significantly reducing heat loss by 31% compared to traditional Trombe walls at night. The mass flow rate of water has a minor impact on the WSW's thermal performance, with an optimal mass flow rate of 0.06 kg/s based on the simulation results [64].

Furthermore, research on incorporating PCMs into wall systems has shown promising results. PCM-enhanced walls exhibit reduced peak heat flux, delayed peak space cooling and heating loads, and decreased indoor temperature fluctuations. The location of PCMs within walls is crucial for optimizing thermal performance, as it affects temperature profiles and overall efficiency. Studying the effects of PCM location within walls can lead to more efficient passive solar heating systems [163].

4.3. Carbon Emissions Reduction, Life Cycle Assessment (LCA), and Indoor Air Quality

In the environmental domain, comprehensive assessments of SWs have incorporated factors like CO_2 emissions and energy consumption across their life cycle. Stazi et al. introduced an integrated approach considering CO_2 emissions and energy consumption to optimize SW energy and environmental performance, emphasizing the importance of holistic evaluations. Additionally, a life cycle assessment (LCA) methodology, combined with a factorial plan technique, effectively optimized energy and environmental performances for a SW system in Ancona's climate conditions. This study revealed significant environmental impacts in the pre-use and use phases, with aluminum and concrete production contributing to pre-use burdens, and energy use for summer cooling leading to high CO_2 emissions. Through level factorial plan optimization, CO_2 emissions and energy demand were reduced by up to 55%, underscoring the potential for tailored design choices. Context-specific considerations and the influence of design parameters, like glazing type, were highlighted for environmental and energy performance. The final SW design could be based on specific objectives, with an intermediate configuration showing potential for limiting summer energy needs while maintaining high environmental performance. Future developments aim to extend the analysis to the post-use phase, incorporating considerations for the disposal and recycling of facade components [164].

The integration of passive solar systems like the Trombe wall into building designs supports sustainable development goals. In a study featuring a novel building design incorporating phase-change materials, a ventilated Trombe wall, and a photovoltaic panel, optimization based on the life cycle cost and discomfort degree hour was conducted. Utilizing a Monte Carlo approach for sampling, artificial neural network (ANN) models exhibited high accuracy with R-squares of 0.997 and 0.972 for life cycle cost and discomfort degree hour, outperforming stepwise linear regression. Coupling ANN models with optimization algorithms, the Strength Pareto Evolutionary Algorithm II (SPEA-II) demonstrated superior performance, yielding Pareto solutions indicating optimal heating and cooling temperature setpoints, PCM type, and window-to-wall ratios. Compared to a reference building, the integrated design achieved impressive results, including a 33.30% average thermal comfort improvement rate (U), 43.81% maximum thermal comfort improvement rate (U_{max}), 22.35% average life cycle cost reduction (S), and 45.51% maximum life cycle cost reduction (Smax) [165].

Various materials and configurations of SW have been studied to determine their environmental impact. For instance, Bojić et al.'s study explored the environmental impact of SW finding that selecting core materials with lower density and embodied energy could yield up to 5% primary energy savings. Analyzing a solar-powered building in Lyon, France, with Trombe walls, the study revealed a potential 20% reduction in operating energy during heating compared to a structure without Trombe walls. The study underscored Trombe walls' significance, showing greater benefits for electrical heating (up to 15% more energy savings) than natural gas heating (up to 11%). Optimal core layer thickness varied with heating type (0.35 m for electrical and 0.25 m for natural gas), emphasizing trade-offs and cautioning against excessive thickness for specific heating methods. 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 [166].

The integration of passive solar systems like SWs into building designs aligns with sustainable development goals. These systems can substantially reduce a building's energy consumption for heating, resulting in lower CO_2 emissions and a more environmentally friendly design. For example, using SWs can reduce a building's energy consumption for heating by up to 30% [166]. The environmental benefits are even more pronounced when considering different heating methods, such as electrical heating or natural gas heating. SWs used with electrical heating save more primary energy and yield a higher environmental benefit compared to natural gas heating, with a shorter energy payback time [159].

5. Discussion and Conclusions

Transitioning to zero-energy buildings is essential for reducing waste and GHG emissions. Energy-efficient building envelopes, particularly passive solar systems like SWs, play a vital role. SWs enhance thermal storage, maximize solar gains, and reduce energy consumption, contributing significantly to global climate initiatives. They improve indoor comfort, reduce carbon footprints, and offer compelling solutions for sustainable construction and renovation projects.

SWs, especially WSWs, efficiently capture and store solar heat. SWs operate based on thermo-circulation, transferring solar heat into living spaces. Integrating PV solar cells into SW optimizes resource utilization and electricity generation. Solar water walls enhance thermal comfort by replacing traditional masonry with water-storage reservoirs. PCMs in SWs reduce the peak thermal loads, and innovative variations like double-skin and fluid SW offer diverse applications for energy efficiency and sustainability.

These SW innovations emphasize their adaptability and compatibility with various contexts, serving as valuable tools for achieving energy-efficient and environmentally responsible building designs. They address the increasing demand for sustainable solutions in the face of climate change.

SWs represent sustainable architectural innovation, offering dynamic solutions for harnessing solar energy. Their adaptability to diverse climates and optimization through factors like glazing, shading, insulation, ventilation, and advanced techniques align with global goals for a greener, energy-efficient future. SWs, as passive solar heating systems, demonstrate effective solar heat capture and can significantly reduce a building's energy consumption, contributing to sustainability and environmental responsibility through lower CO_2 emissions and efficient energy use. Material choices further impact their environmental performance, making SW integration a valuable addition to sustainable architecture.

Optimizing the performance of SWs involves considering several critical factors. These factors include climate conditions, glazing materials, SD, orientation, insulation, ventilation techniques, and the integration of photo and thermal catalytic techniques. SWs are versatile solutions for harnessing solar energy for heating and cooling buildings, but their effectiveness depends on various parameters, including the following:

- Climate Conditions: SWs exhibit remarkable energy-saving potential across diverse climatic conditions. They prove highly effective in hot and humid regions, reducing indoor temperatures by 30% to 50%. In hot and arid areas, SWs with water-spraying systems can lower indoor temperatures by 8 °C, a significant achievement for energy-efficient buildings. In composite climates, PV-SWs with insulation and shading curtains offer adaptable solutions for fluctuating weather conditions.
- Glazing: Glazing material and placement significantly impact SW performance. Studies highlight the importance of glazing properties like the U-value, solar heat gain coefficient, and visible transmittance in balancing lighting, thermal comfort, and energy efficiency. Multi-layered facades and thoughtful glazing decisions enhance both comfort and efficiency.
- SD: SDs are crucial in preventing overheating in highly glazed facades. Properly designed SDs control solar irradiation, optimizing daylight entry in winters and preventing excessive heat gain in summers.
- Solar Radiation and Orientation: SWs rely on solar radiation and orientation to achieve peak efficiency. Proper alignment with the sun's path is essential for maximum solar energy absorption, with orientations varying based on the hemisphere.
- Insulation: Insulation minimizes heat loss and enhances SW efficiency. It is especially crucial in composite SWs and well-insulated buildings. Proper insulation can reduce the heating energy demand significantly.

- Ventilation Techniques: Ventilation systems are integral to SWs, regulating heating and cooling processes within buildings. Well-controlled ventilation enhances SWs' efficiency, reducing energy consumption and improving thermal comfort.
- Photo and Thermal Catalytic Techniques: The integration of photocatalytic and thermal catalytic techniques in SWs improve indoor air quality while generating electricity and providing heating. These techniques offer promising dual benefits.

Optimizing SWs' performance require a comprehensive understanding of these factors and their interplay. SWs have the potential to significantly reduce energy consumption, enhance indoor comfort, and contribute to sustainable building practices when designed and implemented effectively. Future research should continue to explore innovative technologies and strategies to further improve SW efficiency and applicability in diverse climates and building contexts.

In terms of energy performance, SW are designed to harness and utilize solar heat effectively. Research indicates that wall thickness and materiality significantly impact solar heat gain. Thicker walls, approximately 35 cm, show increased heat gains during winter, while thinner walls exhibit higher heat gains during summer. Thermo-circulation, linked to direct solar radiation, plays a crucial role in enhancing heat gain. Efficient methods, such as large-scale model fenestration systems, are employed to accurately estimate the solar heat gain, even under non-uniform sky conditions. To address potential overheating concerns, studies have explored the influence of SDs, like exterior overhangs and Venetian blinds, particularly in scenarios with high thermal mass. These insights highlight the importance of precise solar heat gain assessment for optimizing SW performance. Additionally, standardized methodologies, such as ISO 13790:2008(E), provide valuable equations for calculating heat transfer and solar heat gains, laying the foundation for assessing SW thermal performance.

Regarding thermal efficiency, SWs face challenges related to heat loss during nighttime and shaded winter days, leading to increased energy consumption. Researchers have proposed solutions, including numerical modeling and the incorporation of PCMs into wall systems. WTWs have demonstrated improved thermal performance by reducing natural convection and enhancing efficiency. PCM-enhanced walls show a reduced peak heat flux and improved temperature regulation. The location of PCMs within walls is critical for optimizing thermal performance.

In terms of environmental performance, TWs contribute significantly to reducing a building's energy consumption for heating, resulting in lower CO_2 emissions and promoting sustainability. Integrated approaches consider CO_2 emissions and energy consumption over the entire life cycle of TW systems, emphasizing the importance of environmental factors alongside energy performance. Material selection, such as lower-density and lower-embodied-energy materials, plays a vital role in minimizing the environmental impact of TWs. These findings demonstrate that TWs align with sustainable development goals by significantly reducing energy consumption for heating and promoting environmentally friendly building design. The environmental benefits are particularly pronounced when compared to different heating methods, making TWs a compelling choice for energy-efficient and eco-conscious building designs.

6. Future Directions

In the future, SWs will continue to evolve and shape the landscape of sustainable building practices. Advanced materials research will be a focus, driving the development of novel glazing materials, insulation solutions, and smart SDs that adapt to environmental conditions. The integration of smart technologies will improve the performance of SWs through real-time optimization, while climate-specific design guidelines will ensure that SW are tailored to different geographical regions. Multifunctional SW systems of will become increasingly common and include functions such as rainwater harvesting and air purification to improve sustainability. A comprehensive life cycle analysis will provide a deeper understanding of environmental impacts and lead to responsible design decisions. User behavior and comfort studies will provide user-centered SW designs, and the integration of renewable energy sources will create hybrid systems for maximum energy efficiency. Adaptation to changing climate conditions, policy and regulatory support, public awareness and education, and collaborative research initiatives will together drive the adoption of SW technologies and contribute to a greener and more sustainable built environment.

The future of SWs promises a convergence of innovation, sustainability and collaboration. By addressing climate-specific challenges, using cutting-edge materials and technologies, and considering the entire life cycle and user experience, SWs will play a crucial role in achieving energy-efficient and environmentally friendly buildings. This commitment is not only in line with global climate goals but also enhances the well-being of building occupants and heralds a new era of sustainable architecture.

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