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A Systematic Review on the Research and Development of Adaptive Buildings

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Abstract: Rapid urbanization and industrialization have led to great changes to the climate, such as global warming, urban heat islands, and frequent fluctuations in ambient temperature, and also a large amount of building energy consumption. Adaptive building provides an appropriate solution to maintain low energy consumption under various indoor and outdoor conditions and therefore has increasingly gained attention recently. Yet there is no clear definition on adaptive buildings and the current literature often focuses on the building envelope and overlooks buildings' mechanical system, which is also an important part of the building system for responding to the indoor requirements and outdoor conditions. This article presents a systematic review on the research and development of adaptive buildings to address the identified research gaps. Firstly, it introduces and discusses the definition and evolution of the concept of adaptive building. Secondly, it reviews the adaptive building envelope technologies of roof, wall and window. Thirdly, it investigates the research progress on the adaptive mechanical system, especially lighting and air-conditioning systems. Lastly, it demonstrates practical applications of adaptive buildings and provides recommendations on future research directions on adaptive buildings.

Keywords: adaptive building; building envelope; mechanical system; practical applications



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1. Introduction

Rapid urbanization demands a large amount of building energy needs. According to statistics, buildings consume 36% of global energy [1]. In particular, buildings consume 27.6% of the total energy in the USA [2,3] and 22% in China [4], respectively. Building envelopes and mechanical systems should be paid special attention to relieve the building energy burden [5]. The former determines the heat flux from outdoors to indoors, and the latter consumes energy to maintain the desired indoor thermal environment. However, the requirements on the indoor environment, i.e., air quality, thermal comfort, etc., are becoming stricter [6], and hence, building energy consumption is increasing. How to improve building energy performance while satisfying the occupants' needs under various ambient conditions is of particular importance. Adaptive buildings provide effective solutions to this challenge. They can detect the changes in the outdoor environment and make corresponding adjustments to achieve high energy efficiency and occupant satisfaction [7].

The advancement of adaptive buildings involves multidisciplinary research and innovations, such as materials science, architectural engineering, and intelligent control. For

example, the design of adaptive building envelopes requires integrally taking into account energy, economics, the environment and indoor comfort [8]. Advanced materials technologies, such as phase change materials (PCMs) [9,10], color-changing windows [11,12], and photovoltaic technology [13,14], are adopted to achieve dynamic control of lighting and temperature. For mechanical systems, the intelligent control of lighting [15] and air conditioning systems [16] is also an important part of adaptive building. They can automatically adjust their settings according to changes in the indoor and outdoor environments to achieve energy savings and optimize the indoor environment by integrating sensors and intelligent control algorithms [17]. As multidisciplinary science and technologies are involved, it is of particular importance to perform a comprehensive and in-depth review on the research and development of adaptive buildings and provide recommendations for future research directions.

A few review papers have been published and provided valuable insights into research on adaptive buildings. Some consider the building envelope as a whole. For example, Mohtashami et al. [8] discussed the general aspects of adaptive building envelope design, which mainly focused on photovoltaic (PV) technology. Wang et al. [18] reviewed the adaptive dynamic building envelope combined with PCMs, which were classified as transparent and opaque envelopes. Xu et al. [19] reviewed building envelopes with variable thermal physical properties. Others focused on a specific part of the building envelope. For example, Tällberg et al. [20] reviewed adaptive controllable smart windows by comparing the thermochromic, electrochromic and photochromic technologies. Yu et al. [21] reviewed the power generation and optical properties of building-integrated photovoltaic (BIPV) windows and their thermal performance. Gu et al. [22] reviewed Trombe walls and summarized different evaluation indicators from four perspectives, i.e., energy, exergy, economics and environment (4E). These studies mostly focus on one aspect of the building envelope, and few papers consider the whole picture of the adaptive building that integrates the building envelope with mechanical systems.

The above review shows that current studies primarily concentrate on the building envelope, with few relevant studies addressing the mechanical system. However, as an integrated part of adaptive buildings, the mechanical system should not be overlooked. Meanwhile, they typically focus on certain technologies, rather than looking at adaptive buildings as a whole. In addition, there is no review on the definition of adaptive buildings. To address these research gaps, this article aims at providing an in-depth comprehensive review to explore the research and development of adaptive building technologies, which expands the scope of review from just the building envelope to include the mechanical system as well, considering both as important elements in the context of adaptive buildings. In addition, it clarifies the definition of adaptive buildings to enhance understanding of the concept and presents practical cases of adaptive buildings.

This paper first conducts a review on the definition and evolution of adaptive buildings and its potential connections with recent regulatory frameworks, then focuses on the adaptive technologies of various components of building envelopes, including roofs, windows and walls, covering the technologies mentioned in the latest ENISO 52016-3 [23] standard, and with additional components. Thirdly, the adaptive control technologies of mechanical systems, especially lighting and air-conditioning systems, are reviewed to show how they respond to environmental changes, which was not covered by previous literature surveys. Finally, the applications of adaptive buildings in the real world are demonstrated, and recommendations on the future research and development of adaptive buildings are provided.

2. Method

To gain a full picture of the research progress and development trends of adaptive buildings, a systematic literature survey following the PRISMA process framework has been conducted (Figure 1). Firstly, a composite search strategy is constructed, and databases such as ScienceDirect, Google Scholar, Web of Science, and China National Knowledge Infrastructure (CNKI) are selected. Keyword combinations such as “adaptive building”, “adaptive architecture”, “climate responsive building”, “climate resilient building” are used for cross-library search, focusing on the cross-research of the two major technical paths of building envelope (roof, exterior window, wall) and mechanical system (air conditioning, lighting). The initial search obtained a total of 331 documents, which entered the screening process after deduplication. At the same time, 15 references of related building cases were queried and added to the screening process. As can be observed from Figure 2, the increasing number of publications year by year reflects the increasing attention of the academic community to the research on adaptive buildings and the increasing relevance of adaptive buildings in modern society.

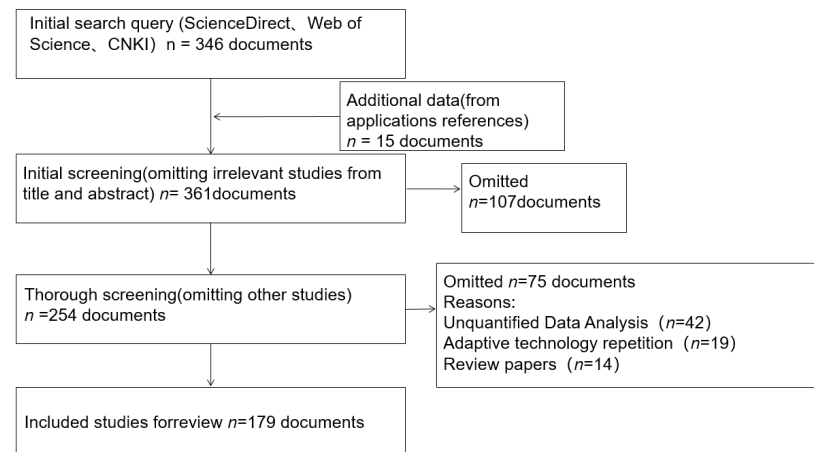


Figure 1. The PRISMA framework.

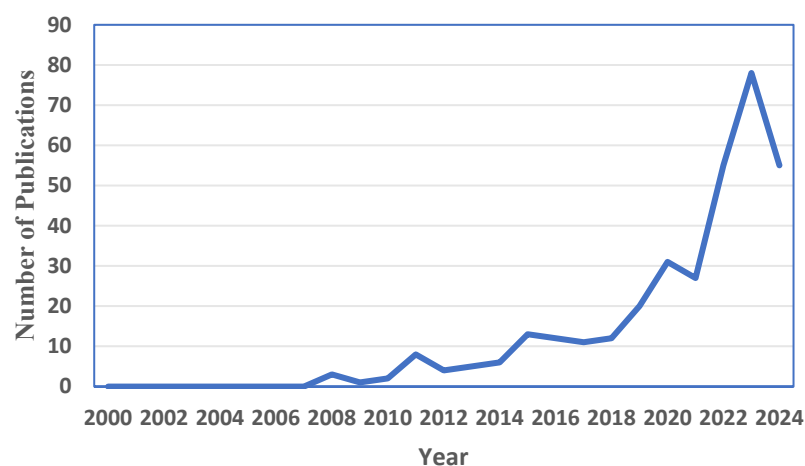


Figure 2. Variation trends of publications on adaptive buildings.

Secondly, a preliminary screening process was conducted to screen the titles and abstracts, and literature that was not related to adaptive building construction, performance optimization, etc., was eliminated. As a result, 346 documents were left for stricter screening. By carefully reading the full text, a total of 167 documents that lacked quantitative data analysis, repeated technical content, and review papers were excluded. In the end, 179 high-quality articles and electronic documents from official websites were retained,

covering various adaptive technologies, building components, and optimization methods on building envelop and mechanical systems, as well as adaptive building definitions. Figure 3 shows the distribution of the number of papers on different building components, with research on walls ranking the highest, followed by windows, roof, lighting, and heating, ventilation and air-conditioning (HVAC) systems.

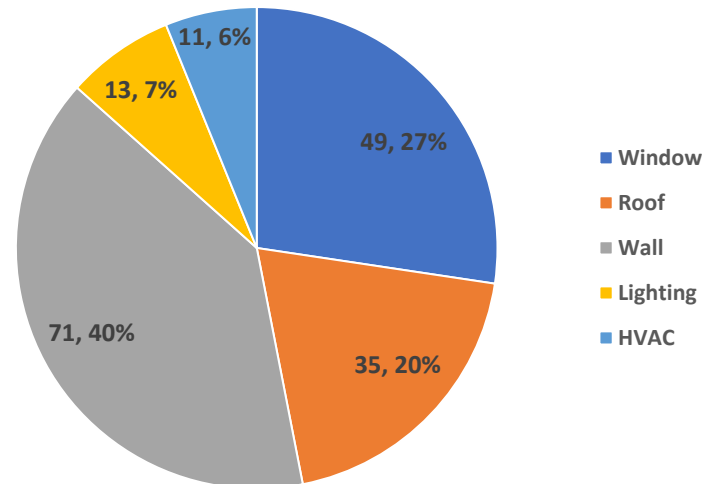


Figure 3. Distributions of the publications by different building components.

3. Definition of Adaptive Building

The climate changes and increase in building energy demand call for designing buildings that adapt to ambient climate with high energy performance. Various terms have been used to refer to such types of buildings, such as “adaptive building”, “adaptive architecture”, “climate responsive building”, and “climate resilient building”. Therefore, there are different viewpoints on the definition and scope of adaptive buildings. For example, Loonen et al. [24] classified 44 climate adaptive building shells and excluded some active, advanced, or interactive shell technologies that do not effectively affect the indoor climate or do not actively respond to the variable conditions.

A few regulatory frameworks have been proposed to evaluate the smartness, sustainability, or greenness of the building, such as Smart Readiness Indicator (SRI) [25], Leadership in Energy and Environmental Design (LEED) [26], and Building Research Establishment Environmental Assessment Method (BREEAM) [27]. In particular, the SRI aims to qualitatively assess the level of smartness of buildings, focusing on their ability to operate more energy-efficiently, interact effectively with occupants, and integrate with the power grid [25]. The dynamic envelope, lighting, and heating are included in the nine areas of the indicator, and they are closely related to adaptive buildings. SRI aims to assess the ability of buildings to effectively utilize intelligent technologies [28]. Through the quantitative assessment of SRI, the performance of adaptive buildings in terms of smartness and energy efficiency can be more comprehensively measured.

Smart buildings and adaptive buildings differ in technical perspective. Smart buildings usually involve data collection, processing and intelligent decision making, while adaptive buildings respond to the external environment in terms of physical or operational status through the building itself or its structural components. However, smart buildings and adaptive buildings are highly consistent in many core aspects, such as adaptability: the ability to learn, predict and meet user needs and external environmental pressures; interactivity: the ability to allow interaction between users; and efficiency: the ability to provide energy efficiency and save time and cost [29]. They constitute a closed-loop control

system of “perception-analysis-response” to realize the dynamic adaptation of buildings to environmental changes and improve building energy performance.

Table 1 lists the relevant definitions of adaptive buildings. Most studies focus on key features such as “versatility and adaptability”, “environmental responsive”, “user interaction”, and “repeated reversible changes”. However, there are some slight differences. For example, Loonen et al. [30] emphasized the changes in “reversibility” and “performance requirements”, while López et al. [7] focused on “predicting changes in the external environment” and “interactions between internal activities and residents”. At the same time, they both stressed the need to take into account user behavior and internal activities.

Table 1. Definitions of adaptive building.

Author	Year	Concept	Ref.
de Boer et al.	2011	A climate-adaptive building shell (CABS) is able to adapt to occupants’ needs and ambient climate variations, with minimized energy usage to maintain the desired comfort. It mainly focuses on building facade, also called “intelligent facade”, “active facade”, “dynamic facade” or “smart facade”.	[31]
Loonen et al.	2011	A CABS can repeatedly and reversibly change parts of its function, characteristics, or continuously respond to variations in performance demands and boundary conditions to enhance total building performance.	[30]
Loonen et al.	2015	Adaptive façade is able to perform responsive function to achieve certain goal (goals) to enhance the building performance, reacting to transient variations in performance demands and boundary conditions. The façade (or building envelope) consists of a versatile and highly adaptable system in which the physical separation (i.e., the building envelope) between the interior and exterior environments is able to change its function, properties, and behavior over time in response to changes in instantaneous performance demands and boundary conditions to improve overall building performance.	[32]
López et al.	2015	An adaptive building envelope (ABE) is one that responds to indoor and outdoor environmental condition variations while managing the interior environment. It should have adaptive schemes to expected external environmental changes, internal activities and their interactions with residents.	[7]
Aelenei et al.	2016	Adaptive facades should fully respond to changes in the external and internal environment to ensure or improve the envelope structure’s requirements in terms of heat, airflow, water vapor flow, rainwater infiltration, solar radiation, noise, fire protection, strength and stability, and aesthetics. Multifunctional adaptive facades can respond reversibly and repeatedly to variations in performance demands and boundary conditions over time.	[33]
Mols et al.	2017	The unique adaptive behaviors of smart building shells can be divided into four parts: climate, human, time frame, and mechanism. The climate part includes CABSs that can respond to the environment. The human part is a subdivision of CABS based on human behavior, and each type is designed to change its characteristics according to human activities. Technologies suitable for the time frame part have seasonal or shorter adaptation capabilities. Mechanisms are divided into two subsections: microscopic mechanisms in which materials change their structure and thermophysical or optical properties by changing their internal energy, and macroscopic mechanisms of energy changes that do not change material properties.	[34]
Zarzycki et al.	2019	Climate-resilient buildings react to varying and usually unexpected weather patterns while reducing building carbon footprint. Dynamically responsive properties in the building sector are expected to help regulate the indoor climate of the built environment and reduce the energy consumption of modern heating, ventilation, and air conditioning (HVAC) systems.	[35]
Xu et al.	2020	Building envelopes can adjust their thermal performance in response to temperature changes. Such buildings can take full advantage of climate resources, such as solar energy and changes in ambient air temperature, to create comfortable indoor environments. Climate responsiveness refers to the building envelope’s ability to adjust itself in response to climatic and seasonal changes. If necessary, heating, ventilation and air conditioning (HVAC) systems can be supplemented to ensure thermal comfort.	[19]

Table 1. *Cont.*

Author	Year	Concept	Ref.
Kim et al.	2020	A Climate Adaptive Building Envelope (CABE) refers to a dynamic facade that is able to change its geometry, color, transparency levels, or thermal properties, responding to time-varying weather stimuli. Unlike a static building envelope, CABE performance analysis must account for time-varying geometric transformations and material properties.	[36]
Dakheel et al.	2020	A smart building is a nearly zero energy building (nZEB) that can manage the amount of renewable energy in the building and the smart grid through advanced control systems, smart meters, energy storage and demand-side flexibility. In addition, it can respond to the needs of users and occupants and can diagnose faults in the operation of the building.	[29]
Tabadkani et al.	2021	The system's ability to vary its physical properties in a timely manner, responding to unexpected environmental conditions so as to provide multiple objective comfort criteria, is called adaptability.	[37]

It can be observed from Table 1 that the definition of adaptive buildings can be summarized as “adaptive buildings can adjust themselves to respond to indoor and outdoor environmental conditions to satisfy occupants’ indoor environmental conditions while maintaining high energy performance”. However, it is worth noting that the definitions listed only focus on the building envelope and not the mechanical systems such as lighting and HVAC systems. As the mechanical systems are the ones that consume energy, their reactions to the outdoor environment are critical to improving building energy performance. In fact, with intelligent control, the mechanical system can actively react to indoor and outdoor environmental condition variations and therefore should be part of the adaptive building. With the rapid evolution of AI and big data technologies, the building envelope and mechanical systems can work together to achieve the highest performance through the building’s adaptive behaviors.

4. Adaptive Building Envelope (ABE)

The ABE can modify its physical properties in response to indoor and outdoor environmental condition variations, which includes elements like adaptive roofs, windows, and walls. The recent EN ISO 52016-3 standard [23] classifies adaptive components of building envelopes into three categories: the ones with dynamic shading functions; the ones with tinted glass; and the ones with active ventilation cavities [23]. It provides clear technical directions and normative guidance for the adaptive design of building envelopes. The adaptive technologies reviewed in this article not only cover the adaptive component requirements mentioned in the EN ISO 52016-3 standard, but also further expand the scope and depth of application of related technologies.

4.1. Adaptive Roof

The roof is a main component of an adaptive building envelope, especially for low-rise buildings, where heat transfer rate through the roof represents a big part of the overall heat gain/loss. Adaptive roofs mainly include cool roofs, photovoltaic roofs, roofs with phase change material, etc., according to the different adaptive methods adopted.

4.1.1. Cool Roof

A cool roof refers to a roof with thermal emittance and solar reflectivity higher than an ordinary roof, e.g., thermal emittance of 0.9 and solar reflectivity of 0.2 [38]. Cool roofs can generally be classified as traditional cool roofs (solar reflectivity in the range of 0.7~0.94 and thermal emittance in the range of 0.75~1), ultra-cool roofs (solar reflectivity ≥ 0.95 and thermal emittance ≥ 0.95), and temperature adaptive roofs [39].

Compared with traditional dark roofs, cool roofs can reduce roof temperatures by reflecting solar energy [40]. Antonaia et al. [41] studied the application of three materials in the automotive field (traffic white varnish, neutral pure white paint, and white acrylic paint) in cool roofs. Through laboratory measurements of different substrates and configurations, white acrylic paint was found to have satisfactory thermal emittance (92%) and spectral reflectance (77–80%), and can maintain the roof temperature below 40 °C. Although cool roof technology can be used to effectively reduce the roof temperature, roof coating material performance is affected by external environmental factors, especially solar radiation. To overcome this problem, Jiang et al. [42] attempted to combine phase change materials with cool (PCMC) roofs, which can not only solve the problem of unstable performance under variable solar radiation, but also enrich the selection of melting points of PCMs that are usually restricted by regional climate. Compared with ordinary roofs, PCMC roofs can reduce the exterior and interior roof surface temperatures by 33.3 °C and 6.4 °C, and the heat flux through the interior roof surface by 33.3–66.7%, respectively. However, it can be concluded that in wintertime or when there is a heating load, the use of a cool roof will lead to an increase in building energy consumption, and therefore, how to optimize the performance of a cool roof is very important.

A temperature-adaptive roof is defined as one with temperature-based variable roof color, solar reflectance or thermal emittance [39]. Its thermal emittance or solar reflectance increases/decreases when above/below the transition temperature with the use of thermochromic (TC) materials, or temperature-adaptive materials [39]. Simulation under the EnergyPlus environment demonstrated that compared with ordinary roofs and traditional cool roofs, TC roofs can achieve a reduction in total energy needs, carbon emissions, and energy costs in different geographic locations in the United States [43]. TC materials combined with PCMs can be used to intelligently control solar energy reflection/absorption and heat energy transfer in buildings and achieve energy savings. Building simulation revealed that compared with PCM roofs, TC roof, and traditional asphalt roofs, TC/PCM roofs reduced total energy consumption by up to 17%, 15%, and 13%, respectively, under five climate zones in China [44].

The above literature survey shows that cool roofs can effectively reduce roof surface temperature, thereby reducing its heat gain and thus lowering the air conditioning energy consumption, which is important to achieve energy savings. However, it may lead to an increase in heating energy needs. Therefore, careful attention should be paid to evaluate its yearly performance before the implementation of cool roof technology. Additionally, cool roof technology can be coupled with phase change energy storage technology and other methods to become temperature-adaptive, so that it can respond to the outdoor climate and improve the roof's thermal performance. It is critical to conduct research on the optimization of the temperature-adaptive rules between roof properties and the outdoor environment.

4.1.2. Photovoltaic Roof

A photovoltaic (PV) roof is an important branch of BIPV technologies. PV roofs can receive more solar radiation than vertical PV facades per unit area with clear surroundings, thus easily meeting the building design requirements [45]. Energy savings of PV roofs are mainly achieved through power supply and shading [46]. Yang et al. [47] estimated the potential available roof area of Västerås city and the whole country of Sweden for PV installation to be 5.74 km² and 504 km², with peak installation capacity of 956 MW and 84 GW, respectively. Aiman et al. [46] evaluated the impact of rooftop PV shading on building thermal loads in a medium-dry warm climate region and found that the roof heating load increased by 10.3% in winter and cooling load decreased by 8.10% in summer.

As a PV roof has different impacts on power generation, heating and cooling demand, they should all be taken into account for overall PV roof performance analysis.

PV modules can be divided into monofacial and bifacial PV modules according to the solar radiation receiving direction. Monofacial PV modules only receive frontside solar radiation to generate electricity. A transparent backside cover is attached to bifacial solar cells to be used in the bifacial PV module, enabling it to not only receive radiation from the front, but also from the back for power generation. Ground reflectivity (albedo), module height, inclination, row length, row distance, and other optical-related parameters mainly affect the backside radiation gains [13]. Table 2 compares the performance of the two PV modules. Both PV modules can effectively achieve indoor temperature drops and energy savings. Bifacial PV modules yield higher power outputs than single-sided PV modules and can be installed on the east–west façade instead of the south façade. Higher yield also means higher operating temperature. Additionally, in combination with green roofs and cool roofs, bifacial PV modules can achieve high PV yield and reduce the cooling building energy needs. High reflectivity of the plant also leads to high system yields.

Table 2. Performance comparison of monofacial and bifacial PV modules.

Item	Performance	Ref.
Monofacial PV panels	Buildings energy needs are reduced by better floor temperature control. The PV system raised the normal floor temperature by 0.9 °C in winter and lowered it by 5 °C in summer compared to no PV system.	[13]
Bifacial PV panels	Compared with monofacial PV panels, bifacial modules generate 4.3% more energy with 0.6 °C higher temperature during operation. PV modules with higher bifaciality have higher yields. There is uneven irradiance at the back sides of the bifacial modules.	[13,48]
Vertical bifacial PV panels combined with green roofs	East–west-oriented vertical bifacial PV systems can achieve comparable specific energy yields to south-oriented monofacial installations on flat roofs. In addition, the yields of vertical panels depend largely on albedo and ground coverage. Compared with standard green roofs, silver-leaved plants can increase system yields because of higher reflectivity and albedo. PV yield can be significantly increased (+8.6%) compared to ordinary	[49]
Bifacial PV panels combined with cool roofs	single-sided photovoltaic panels; the operating temperature is 1.6 °C higher than ordinary bifacial PV panels; cool roof coatings can decrease unshaded floor temperatures, resulting in a big proportion of cooling energy savings.	[13]

Three generations of PV technologies have been developed so far, among which the first- and second-generation technologies have been widely adopted in practical application. The first-generation technology mainly used crystalline silicon photovoltaic technology, and the second-generation technology mainly used cadmium telluride, amorphous silicon thin film, and copper indium gallium selenide sulfide [50]. The difference between the second generation and the first-generation technologies depends on whether the PV materials are transparent in the application. Wang et al. [51] designed a curved air-based photovoltaic/thermal (PV/T) roof integrated with copper indium gallium selenide (CIGS) solar cells. They found that when glass covering materials are added to the roof, roof thermal performance can be enhanced and hot air can be provided to the connected rooms; meanwhile, the power output is affected by the transmittance of the cover. Table 3 makes a comparison between opaque and transparent/semi-transparent PV roofs. It can be found that opaque PV roofs have lower electricity efficiency, however, with higher thermal efficiency. This phenomenon could be explained by the difference in thermal properties and transmittance that affect the absorption of solar radiation, convection and heat conduction. In the meantime, the use of transparent BIPV can reduce excessive daylighting time. Ad-

ditionally, opaque BIPV leads to a higher reduction in energy balance (38.3%), compared with transparent BIPV (21%).

Table 3. Comparison between opaque and transparent/semi-transparent PV roofs.

Type	Feature	BIPV *	Roof Type PV/T Roof	Ref.
Opaque	Low cost, mature technology, long term	An energy balance of 38.3% is achieved.	Average electrical efficiency of 5.05%, average thermal efficiency of 70.88%	[50–52]
Semi-transparent or transparent	Low temperature coefficient, low solar energy to electricity conversion rate	Reduced energy demand by 6.9%, reduced total energy balance by 21%, and reduced over-lighting time.	Average electrical efficiency of 5.73%, average thermal efficiency of 39.58%	[50–52]

* Building integrated PV.

Based on the above literature survey, applying PV technology to building roofs effectively saves energy and can achieve the adaptation of the roof to the environment. The difference between PV roofs and other adaptive roofs is that they can not only maintain indoor comfort, but also generate power to achieve additional energy saving. Different application methods have been studied, and PV technology has also become mature with research advancement in materials, especially for the first- and second-generation technologies. However, PV technology is still worth studying, for example, to find mature application methods for organic materials in the third-generation PV technology and optimize PV roof performance by taking into account power generation, heating, and cooling energy needs. At the same time, the investigations on the combinations of PV roof technology with other technologies such as cool roof and green roof are of importance to improve its energy performance. Decarbonization of the disposal of PV panels might be of particular importance in future research.

4.1.3. Phase Change Material

Integrating PCMs into building roofs can effectively reduce building energy consumption and improve indoor comfort through energy storage. The melting process occurs in the daytime to absorb excessive heat, delay the heat waves, and reduce the peak indoor temperature. The stored heat is released at night to maintain a suitable room temperature, which helps to reduce the cooling energy needs [53]. Jayalath et al. [54] examined the effect of PCM roofs on building thermal performance in Melbourne and Sydney and found that adding PCMs as a roof layer can improve the indoor thermal comfort and reduce the building thermal loads.

Various ways of PCM application have been explored, for example, double-layer PCM roofs [55], shape-stable PCMs [56], and shape-stable PCMs with variable transparency [57,58]. Double-layer PCMs can be superimposed on the roof. Yu et al. [59] conducted experimental studies on roofs with no PCMs, single-layer, and double-layer PCMs with different melting points. They found that a double-layer PCM roof can effectively suppress fluctuations of indoor air temperature (IAT) and can be used in all seasons. Zhang et al. [55] placed two pieces of PCMs, which differ in melting points, on both sides of the roof layer composed of Low-E glass and aerogel, and switched their position in different seasons to improve thermal resistance in summer and receive heat in winter. This type of glass roof was found to achieve energy saving rates of up to 14.08% and 33.74% in summer and winter, respectively.

Shape-stable PCMs are usually composed of PCMs with carrier material or supporting matrix. The matrix is embedded with PCM to prevent its direct exposure to the surrounding

environment, thus enhancing its stability. As a containment, the supporting matrix functions as shape to prevent flowing or leaking of PCM during melting and solidification [60]. The studies on shape-stable PCMs have evolved from opaque to transparent materials. Wang et al. [58] proposed an adaptive roof combined with a variable transparency shape-stable PCM, and found the yearly thermal load was reduced by 9.57–31.25%, compared with a normal roof.

In addition, other technologies can be integrated with PCM roofs to improve the building performance. For example, ventilation technology can be used to remove part of the phase change heat storage at night, thereby reducing the heat gain in the room [56]; dynamic insulation materials or structures have variable thermal resistance that help to control the building heat flux [61]. Table 4 lists the different kinds of PCM integration technologies. Building energy performance was found to be significantly enhanced by integrating PCMs with multiple technologies. For example, the combination of phase change materials with ventilated roofs can achieve 37.5% energy savings [56]. When multiple phase change materials are integrated, as high as 97.1% energy savings can be achieved [62]. When phase change materials are combined with dynamic thermal insulation roofs, high energy saving performance can be achieved in all climate zones [61].

Table 4. Different PCM integration technologies.

Author	Integration Method	Description	Ref.
Li et al.	Glass roof combined with PCMs	The PCM-filled glazing roof energy demands are significantly lower than that of air-filled glazing (up to 47.5%).	[9]
Shi et al.	Combination of phase change energy storage technology, ventilation technology, and reflective coating	The PCM-filled glass roof has better thermal performance than the PCM roof, in terms of maximum temperature reduction (MTR), damping factor (DF), time lag (TL) and heat flow reduction (HFR). The PCM-filled glass roof energy saving rate can reach 59.4%, which is 10% higher than that of PCM roof. Significant energy demand reduction can be achieved by PCM integrated with night ventilation (NV). A 30 mm PCM helps reduce the peak IAT, internal surface temperature, and accumulative building cooling load by 2.9 °C, 5.5 °C, and 19.2%, respectively. The use of NV with $v = 3$ m/s enhances the average latent heat utilization rate and reduces cumulative building cooling load by 37.5% and 22.9%, respectively, compared with the reference roof and PCM roof.	[63]
Yu et al.	Ventilated roof combined with stable PCMs	Compared with conventional ventilated roofs (CVRs), multi-phase change material ventilated roofs can reduce 16.9–18.8% peak indoor temperatures and delay their occurrence by 30–50 min. In addition, the energy saving rate can reach 97.1%.	[56]
Li et al.	Ventilated roof with multi-phase change materials	Compared with ordinary roofs, PCM cool roofs reduce the real-time exterior and interior roof temperatures, and heat flux on the interior roof surface by up to 30.0 °C, 6.4 °C, and 33.3–66.7%, respectively. Significantly higher cooling effects and energy saving were achieved, compared with related roof studies.	[62]
Jiang et al.	Cool roof with PCMs	Compared with ordinary insulated roofs, the total annual thermal loads in hot summer and warm winter regions, cold regions, and hot summer and cold winter regions are reduced by 24.8%, 16.4%, and 35.4%, respectively.	[42]
Yu et al.	Combination of PCMs and dynamic insulation roof		[61]

An adaptive building can adjust itself in response to the outdoor environment and achieve high energy performance. For example, a building with a glass roof integrated with phase change materials can achieve 47.5% energy saving [9]; a building with a ventilated

roof combined with multi-phase change materials can save 97.1% of energy. Compared with the general code for energy efficiency and renewable energy application in buildings, GB55015-2021 [64], the required average energy saving rates for residential buildings in cold and severe cold regions, other regions, and public buildings are 75%, 65%, and 72%, respectively. Adaptive technologies can help to achieve or even exceed the requirements of building energy efficiency standards.

Based on the above literature survey, current studies focus on the effectiveness of PCMs in reducing building energy needs and combinations of PCMs with other energy-saving technologies or materials to achieve better energy-saving effects. However, most studies have obtained the energy-saving effects of PCMs through simulation under certain climatic conditions. Therefore, the effects of the actual application of PCMs need to be explored. In addition, how to achieve self-adaptation under different climate environments is also worth investigation.

4.2. Adaptive Window

An adaptive window can adjust itself according to the outdoor environmental conditions. Adaptive window technologies can be divided depending on whether they are switchable or not. Switchable technologies include electrochromic windows, thermochromic windows, photochromic windows, and suspended particle device (SPD) glass windows, and non-switchable technologies include aerogels, vacuum glass, photovoltaic glass, etc. [65].

4.2.1. Single Response Color-Changing Windows

Color-changing windows adjust their optical properties according to climate conditions and user requirements, e.g., photochromic windows change their color to meet the comfort needs of residents. Based on different adaptive technologies, they can be divided into photochromic (PC) windows, thermochromic (TC) windows and electrochromic (EC) windows [20]. Compared with ordinary window glazing, PC windows are significantly more energy-efficient. Li et al. [11] found that EC glazing increases the average illuminance in rooms by 42%, compared with the base case (BC) rooms with ordinary glass during nighttime lighting. EC glazing increases the daily heat supply by 4.4–21.9% in winter and reduces heat gain by 19.1–41.8% in summer. TC windows have better thermal performance than ordinary glass windows, e.g., in hot areas, the energy saving rate can reach 50% [66]. Nicoletti et al. [67] compared PC windows with Low-E glazing and clear double-glazing windows. They found that when the window area is small, PC windows are not suitable, but when the window area is large, PC windows have a good energy-saving effect of 4.1% and 9.3%, respectively, compared with Low-E glazing and clear double-glazing windows.

Many studies have been focused on color-changing windows. By using different color-changing components or integrating with other adaptive technologies, excellent thermal and optical properties of the glazing can be achieved, including high stability, high response speed, excellent visible light transmittance (T_{lum}), high solar modulation (ΔT_{sol}), and low critical solution temperature (LCST). Table 5 lists different methods for improving the performance of color-changing windows. It can be seen that changing the color-changing components used in smart windows is the main way to improve their performance. As high as 87.37% and 69.65% can be achieved for T_{lum} and ΔT_{sol} [68], respectively. It means that by improving glazing, reversible properties can be achieved through technology optimization.

Based on the above literature survey, existing investigations focus on the evaluation of the energy performance of color-changing windows and improving their optical properties and thermal performance by using suitable and high-quality color-changing devices and integrating them with other technologies. The practical application of these windows to

buildings has not been fully explored. Future studies should focus on how to optimize the properties of color-changing windows that can respond to the outdoor climatic conditions more effectively and their energy saving potential on an annual basis.

Table 5. Different color-changing windows.

Type	Technology	Method	Description	Ref.
EC	Novel photovoltaic (PV) cell-powered EC energy storage smart window	Nickel-cobalt bimetallic oxide EC window combined with $\text{Cu}_2\text{ZnSn}(\text{S},\text{Se})_4$ (CZTSSe) PV cells	The NiCoO_2 EC film exhibits large light modulation (up to 60.0% at 550 nm), fast switching speed (11.4 s and 7.6 s in the bleaching (tb) and coloring (tc) processes), excellent EC stability (61.7% maximum light modulation at 550 nm can still be maintained after 1000 cycles), and excellent magnification capability. It exhibits excellent EC and energy storage performance. Under natural environments, light-based solar radiation be can intelligently adjusted through neutral tones.	[12]
	ITO-free self-regulating EC window	Flexible transparent electrode (FTE) was prepared with an Ag@Au NW network by a facile electrodeposition method. A high redox potential (1.5 V), ethyl viologen-based all-in-one flexible EC device was fabricated. Commercial solar cells (SCs) power FECD to become self-regulated.	FECDs outperform commercial ITO. They have excellent CE ($106 \text{ cm}^2/\text{C}$), high optical contrast (41% at 605 nm), and excellent cycling stability (optical contrast drops by about 20% after 4000 cycles). Meanwhile, energy storage performance of 6.02 mF^{-2} can be achieved. It enables spontaneous bleaching without consuming energy. Therefore, when the SC is used to power the Ag@Au FTE-based FECD, solar intensity and transmittance can be intelligently adjusted. Independent regulation performance of “bright”, “cold” and “dark” was presented. Large light modulation: 74.9% and 79.1% at 700 nm and 2000 nm; short coloration/bleaching time: 7.6/2.7 and 6.7/3.9 s at 700 nm and 1200 nm; good stability and reversibility: capacity decreases by 4.3% after 1000 cycles, and Coulombic efficiency is stable at 99.2%.	[69]
	Semi-solid, multi-color dual-band EC smart window.	Organic assembly of polyaniline (PANI), AlCl_3 -polyvinyl alcohol (PVA), and monoclinic WO_3 -x nanowires (m- WO_3 -x NWs).		[70]
	Self-powered EC window based on hydrogel	Preparation of polyethylene terephthalate (PET) electrodes modified with nitrogen-doped graphene quantum dots (N-GQDs) protected silver nanowires (AgNWs) as flexible transparent conductive electrodes (f-TCE) (N-GQDs/AgNWs/PET), followed by the fabrication of flexible electrochromic devices (ECDs).	The N-GQDs/AgNWs/PET-based flexible ECDs show excellent optical contrast of 45.4% and coloration efficiency (η_{CE}) of $42.7 \text{ cm}^2\text{C}^{-1}$. In addition, rapid bleaching and coloring times of 5.7 s and 6.9 s were exhibited.	[68]
TC	TC smart window based on $\text{KCA}/\text{Na}_2\text{SiO}_3/\text{PNIPAm}$ hydrogel	A novel composite hydrogel doped with Na_2SiO_3 and carrageenan (KCA) was used. Na_2SiO_3 content was controlled to accurately adjust lower LCST of PNIPAm between 25°C and 28°C . KCA enhanced Tlum and ΔTsol while reducing agglomeration in the gel system. By adding antifreeze agent ethylene glycol, poly (N-isopropylacrylamide-co-N, N-dimethylacrylamide)/ethylene glycol (PNDE) hydrogel with adjustable and outstanding antifreeze property (below -100°C) was prepared, and PNDE hydrogel, polyvinylidene fluoride and polymethyl methacrylate-silver nanowires were assembled into antifreeze smart window with solar and thermal radiation regulation (STR).	The composite hydrogel material exhibited high atmospheric window emissivity (0.962), low LCST (27.2°C), and high Tlum (87.37%), ΔTsol (69.65%). Under direct sunlight, a temperature drop of 12.3°C was achieved. It was durable under low/high temperature and highly stable even after 100 cycle tests.	[71]
	TC window based on frost-resistant poly (N-isopropylacrylamide) hydrogel	Free electrons were released during phase transition of VO_2 to metallic state to support high temperature (above $\sim 65^\circ\text{C}$) plasma resonance, which distinguishes the absorption in near-infrared (NIR) region. Temperature-dependent and geometric transition localized surface plasmon resonance (LSPR) dominate in UV-visible and NIR ranges, respectively.	The assembled STR window exhibited high Tlum (68.2%), high ΔTsol (62.6%), suitable $\tau_c \sim 30^\circ\text{C}$, and low temperature resistance at -27°C . In addition, different thermal emissivities (0.68 and 0.94) on both sides enable it to keep warm under cold weather conditions and radiate cooling under hot weather conditions.	[72]
	TC window based on elastic plasma		Compared with the best reported passive transparent VO_2 TC system modulation, the proposed smart window can achieve higher solar modulation (37.7%)	[73]

Table 5. Cont.

Type	Technology	Method	Description	Ref.
	Smart window integrating radiation cooling technology and TC technology	Visible-NIR were effectively regulated at 20.12%, with regulation by TRSW on solar energy through automated modulation on the emissivity (ϵ) ($\epsilon_{\text{LWIR-L}} = 0.35$ at low temperature, $\epsilon_{\text{LWIR-H}} = 0.68$ at high temperature).	TRSW has Tlum of 21.42% and 0.02% at 20 °C and 60 °C, ΔT_{sol} of 20.12% and $\Delta \epsilon$ of 0.34. Compared with normal glazing, at a power density of 1 kW/m ² , a cooling effect of 4.6 °C can be produced by TRSW.	[74]
	PC window based on AgCl-AgPO ₃ composite glass	Incorporation of PC AgCl thin layers into silver metaphosphate (AgPO ₃) glazing.	Higher AgCl salt concentration leads to enhanced PC performance, but lower reversibility. Better reversibility characteristics were observed from samples with lower salt concentration, reaching 100% within 5 min after UV-induced PC response.	[75]
PC	PC window based on organic/inorganic nanocomposites	Combination of silica-coated lanthanide-activated strontium aluminum oxide nanoparticles (LSAO NPs) with recycled polycarbonate plastic (RPC) to create an organic/inorganic nanocomposite.	After UV irradiation, the fluorescent sheet becomes bright and exhibits a vivid green color. This fluorescent window glazing exhibits long-lasting and reversible luminescence properties.	[76]
	PC window based on sol-gel	Sol-gel-based organic-inorganic mesoporous coating matrix embedded with organic PC dye 1,2-b-naphthopyran to prepare the coating material. Bleaching speed and visible light transmittance are deeply affected by the type of organic groups and the cross-linking degree of the coating matrix.	The reduction in visible light transmittance in the colored state is in the range of 30~60%. A U-value of 1.58 and a G-value of 0.26 are achieved with double-glazed design.	[77]

4.2.2. Dual Response Color-Changing Windows

Single-response windows have their own disadvantages. For example, most EC materials are limited in adjusting solar transmittance, and EC windows require additional energy and manpower consumption [78,79]. In addition, EC and PC devices are even more limited as passive modulators. TC materials are mostly limited in their response to temperature, and the low solar modulation efficiency of VO₂ limits their use in window applications [80]. PC windows have limited transmittance modulation, and slow and irreversible light response [79]. By combination with two different types of color-changing windows, the dual-response windows exhibit better performance. For example, the photoelectric dual-response window can simultaneously meet the requirements of high solar transmittance, good reversibility and fast response speed. Table 6 summarizes the performance of different dual-response windows. As can be seen from the table, after the combination of two color-changing windows, the new smart window exhibits better performance, with many advantages such as high transmittance, high solar modulation, fast response, stable reversibility, etc. In addition, the room temperature is also greatly improved after using the dual-response color-changing window. For example, the indoor temperature inside the house model with T-ECD window glazing is 13.3 °C lower than the one with traditional window glazing [78].

Table 6. Comparison of different dual-response windows.

Type	Materials	Description	Ref.
PC and EC dual response	Extended viologen derivatives, EV-1 and EV-2.	It has four modes: EC, PC, OFF, and photoelectrochromic modes, which can perform different light and heat adjustments.	[81]
	Inorganic all-solid-state E/PC devices (E/PCDs) respond simultaneously to electricity and light. They are constructed using zinc oxide-functionalized oxygen vacancy tungsten oxide (OV-WO _{3-x} /ZnO) composite films.	Excellent electrochromic properties: high dual-band light modulation (74.5% at 1000 nm, 85.9% at 633 nm); fast response speed (tb/tc = 3.1/5.5 s); high optical modulation (86.1%); good reversibility (return to initial state within 15 s). They can autonomously change their transmittance according to the incident light intensity and actively adjust the transmittance through electric field stimulation. Additionally, their smart window prototype provides outstanding temperature regulation of 4.7 °C and 5.3 °C via photochromism and electrochromism, respectively.	[79]

Table 6. Cont.

Type	Materials	Description	Ref.
TC and EC dual response	The devices are fabricated on highly durable transparent indium tin oxide (ITO)/graphene/polyethylene terephthalate (PET) electrodes, where amorphous WO ₃ film and crystalline VO ₂ film are used as EC and TC materials, respectively.	By changing the optical transmittance in four different modes responding to temperature changes and applied electric fields, the Tlum and Tsol values of the hybrid device in the initial bleached state dropped dramatically from 52.44% and 49.17% to 2.42% and 2.32%.	[82]
	The modified asymmetric viologen group was synthesized onto the triazole group of a phase change monomer (poly(NIPAmn-TEG)). The dual-responsive material (poly(NIPAmn-TEG-BPV)) was prepared by quaternization.	When heated from 25 °C to 32 °C, it changes from clear to opaque, achieving an optical contrast (ΔT) of >84.7% in the visible light range (650 nm). When a potential of about 2.5 V is applied, it changes from clear to purple state with $\Delta T > 89.6\%$ (550 nm). Poly(NIPAmn-TEG-BPV) helps to achieve bleaching and coloring speeds of 26.1 s and 8.1 s, respectively. The coloring efficiency and cycling stability were found to be 346 cm ² C ⁻¹ and >500 cycles. High optical contrast (ΔT) of >91.05% exhibits a transition from transparent to cloudy blue state.	[83]
	Combining TC polypyrrole (Ppy) and poly(N-isopropylacrylamide) (PNIPAm)	PNIPAm/Ppy window lowered water temperature by 3.5 °C compared with blank glazing under simulated light irradiation for 20 min. In addition, the T-ECD based on PNIPAm/Ppy can shorten the phase change time to 90 s, increase solar modulation efficiency to 63.0%, and reduce the transmittance to 0.2%.	[80]
	Combination of photothermal EC polyaniline (PANI) film with TC hydroxypropyl cellulose/potassium chloride (HPC/KCl) hydrogel electrolyte	The thermoelectrochromic device (T-ECD) can switch from light yellow to purple state. It has visible light transmittance (15.70–75.53%). It has high solar modulation efficiency (60.89%). It reduces the phase change time from 3 min to 30 s, compared with the conventional TCD. A model house with T-ECD installed could reduce the IAT by 13.3 °C compared with conventional window glazing.	[78]

Based on the above literature survey, current studies focus on the evaluation of the modulation performance improvement of the dual-response windows, compared with single-response windows. Few studies have been found on the application of dual-response windows in actual practice and evaluating their annual energy performance. Future research could focus on the practical implementation of dual-response windows and evaluate their energy saving potential as well as design optimization based on energy performance and cost-effectiveness.

4.2.3. AC-Powered Windows

Switchable electrically driven windows can be divided into DC-driven and AC-driven. The EC windows mentioned in the previous section are driven by DC. The liquid crystal (LC) and suspended particle device (SPD) window glazing introduced in this section both operate under AC, with the SPD film and LC layer sandwiched between two conductive plate glazings [84]. For AC power sources, the particles between the two conductive glass plates allow sunlight to pass through in an organized direction, and the glass window becomes transparent (ON state); when there is no power source, the particles are oriented in random directions to prevent or absorb sunlight, and the glass window becomes opaque or translucent (OFF state) [84] (see Figure 4).

Polymer dispersed liquid crystal (PDLC) glass and SPD glass are commonly used in active control switchable smart windows. They have been proven to be advantageous in energy saving and are good substitutes for ordinary glass. Table 7 presents the performance of the two types of glazing under the same or different climatic conditions. It can be seen that both types of glazing exhibit good performance under multiple climatic conditions. Moreover, switchable smart windows are more advantageous in hot climate conditions, which can achieve net energy consumption reduction of up to 58% [85]. In addition, both types of glazing can be combined with vacuum glass to improve the window performance.

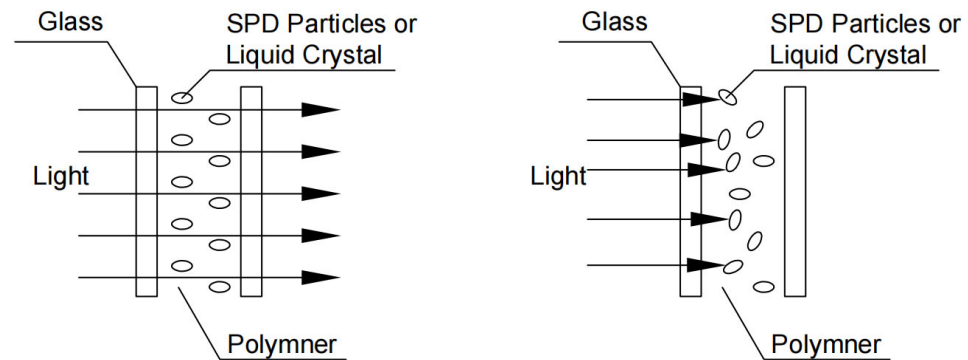


Figure 4. Schematic diagram of the AC-driven glass window ON/OFF status.

Table 7. Performance of the SPD and PDLC glazing.

Condition	SPD Glazing	PDLC Glazing	Ref.
Subtropical climate	The power consumption for cooling was reduced by 29.1%, while that for heating was increased by 15.8%. The annual power consumption was reduced by 4.1%.		[86]
Temperate climate		The best energy performance can be achieved under solar radiation intensity of 500 W/m ² with reduction in heating load by up to 4.9%; the annual heating load is reduced by 4.2% at the window temperature of 20 °C; at 100 W/m ² , the annual daylight glare index (DGI) reaches 63.06%; the proportion of DGI greater than 22 under 4 °C conditions in the areas with low solar radiation intensity is 55.09%.	[85]
Hot and arid climate	Net energy consumption is reduced by 58% in the OFF and automatic control state; in the ON and automatic control state, daylight illuminance (UDI100lux–2000lux) and daylight autonomy (DA300lux) are acceptable; significant daylight glare probability (DGP) reduction is achieved.	The best annual energy performance can be achieved under solar radiation of 100 W/m ² ; cooling load reduction of up to 12.7% can be achieved; annual cooling load reduction can reach 12.8% when temperature is as low as 4 °C; annual daylight glare index (DGI) reaches 75.8% at 100 W/m ² ; the proportion of DGI greater than 22 under 4 °C conditions in areas with low solar radiation intensity is 68.52%.	[85,87]
Combination with vacuum glass	With 110 VAC power supply, the state range of SPD vacuum glass is between 2% and 38%, the solar heat gain coefficient (SHGC) is between 0.31 and 0.58, and the color analysis results are CCT of 5786.18 K and CRI of 94.83.	The U-values produced in both the OFF and ON states are less than 1.10 W/m ² ·K; the maximum solar transmittance in the ON state is 37%; and the SHGC is 0.45.	[88,89]

PDLC glazing structure can be changed to enhance its performance, e.g., through combination with vacuum glazing [88,89]. For example, Qahtan et al. [90] combined PDLC and Low-E glazing to form Smart Double Insulated Glazing (SDIG), which can switch between colored, transparent and dynamic states. The SDIG was found to enhance indoor thermal performance by 21% and 25.5%, respectively, when placed towards south and west orientations. Additionally, changing the liquid crystal particles between the two conductive glasses is also a way to enhance the glazing thermal performance. For example, Katariya-Jain et al. [91] doped 0–0.1% carbon nanoparticles (CNPs) into liquid crystal materials to evaluate the effects of voltage and temperature on the composite film. They found that different colors can be displayed under different voltages. The electro-optical behavior is almost independent of temperature at the optimal doping level. Polymer-LC composite film with a CNP concentration of 0.01–0.05% was found to be the best choice. Malik et al. [92] doped different concentrations of aluminum oxide nanowires (ANWs) into PDLC and found that when the doping amount of ANWs in PDLC was 1.0 and 0.25 wt.%, its threshold voltage and saturation voltage were reduced by 62.5% (1.5 V) and 56.57% (16.5 V), respectively. Improved transparency can be achieved at a low voltage (19.5 V).

Based on the above literature survey, current research focuses on the evaluation of switchable active control smart windows, SPD and LC windows on improving indoor

thermal environment and reducing energy consumption, as well as enhancing smart window performance by adjusting the window structure and changing the type of liquid crystal particles between the two conductive plates. Future research could focus on the combinations of different types of windows to improve building energy performance as well as optimization on the adaptive control strategies in response to ambient weather conditions.

4.2.4. Photovoltaic Glass Windows

BIPV windows are an excellent alternative to traditional windows. They retain the performance of traditional windows and have extra advantages, such as achieving heat insulation and generating electricity through solar cells embedded in the structure. BIPV windows can also help reduce glare on windows [21,93]. BIPV windows can be divided into single-layer PV windows, double-layer PV windows, and vacuum windows. Double-layer PV windows can also be divided into closed air layer double-layer PV windows and ventilated air layer double-layer PV windows according to whether the air in the cavity layer is circulated [21]. Most of the studies focus on semi-transparent photovoltaic (STPV) windows. Compared with transparent windows, semi-transparent photovoltaic windows effectively increase the absorption rate of solar radiation with solar cells [94]. Sun et al. [95] investigated semi-transparent cadmium telluride PV window glazing performance of office buildings under different climatic conditions. They found that compared with traditional windows, PV windows lead to a large amount of energy savings with window-to-wall ratio $\geq 45\%$. The use of STPV windows helps to reduce energy consumption by up to 73% with better daylight performance, and effectively reduces glare possibility. Hu et al. [96] evaluated CdTe PV window performance through survey and experimental measurement. They found that the illumination of rooms with CdTe PV windows met the visual comfort requirements, which were lower than that with transparent windows. Zhang et al. [14] further evaluated the performance of a combination of CdTe PV double-layer ventilation window (VPV-DSV) with vacuum glazing and found it outperforms double-layer insulated glass windows and two other photovoltaic ventilation windows, using single transparent glass and insulating glass as back glass, respectively.

However, semi-transparent photovoltaic windows are non-switchable windows. They present a tradeoff between transmittance and power conversion efficiency [97]. Therefore, many scholars have turned their attention to switchable glass by combining PV glazing with switchable technology. Liu et al. [98] evaluated BIPV window system performance with variable visible light and solar transmittance through simulation, and found it has better energy and lighting performance than traditional BIPV glass and Low-E double-glazing, which can achieve 36.6% annual energy saving.

Based on the above literature survey, current studies mostly focus on the evaluation of the performance of STPV windows and the integration of switchable technology into PV glazing to improve their energy performance. Future research could focus on the optimization of PV glazing design considering visual, thermal comfort and the balance between power generation, heating and cooling energy needs.

4.2.5. Other Types of Window Glazing

There are some other types of window glazing, which can also be adaptive to the outdoor conditions, such as aerogel glass, vacuum glass, etc.

Aerogel is an advanced building thermal insulation material, usually applied to the envelope as aerogel glazing, where silica aerogel glazing received the widest attention due to its high solar transmittance, low thermal conductivity, and high cost-effectiveness [99]. Compared with traditional glazing or Low-E glazing, aerogel glass has obvious advantages

in lowering indoor temperature and reducing heat loss [100]. Mohammad et al. [101] found that aerogel windows can reduce heating requirements by 15.5% compared with conventional double-glazed windows if applied under British climatic conditions. Ma et al. [102] coupled aerogel glazing with solid-solid PCMs and investigated their performance under cold climates and found energy saving could reach 18.22%, compared with traditional glazing. However, as pure aerogel windows have low thermal resistance and high solar transmittance, building cooling load tends to increase in hot climates. Jin et al. [100] doped core-shell nanospheres into a silica aerogel matrix to form a dynamic aerogel window and found it exhibited excellent solar energy control and transmission performance.

Vacuum glazing can help reduce convection and conduction heat transfer using vacuum gap. It has similar transmittance compared with double-layer glass; however, it has a lower heat loss rate [103]. As high transmittance can make people feel dizzy, it is often combined with other technologies to improve indoor visual comfort. Ma et al. [104] applied vacuum glazing to water flow windows. Compared with traditional double-layer water flow windows, vacuum water flow windows reduced indoor heat gain by 6–38% in cold seasons; in heating seasons, they helped reduce environmental heat loss and improve heat utilization efficiency. Combining vacuum glass with PV windows is an effective method to achieve daylight control, insulation improvement, and solar heat gain reduction [103]. Qiu et al. [105] evaluated the thermal, lighting and energy performance of a proposed vacuum PV window glazing and found it provides enough daylight in the front half, thus balancing the availability of lighting and visual comfort and minimizing sunlight glare. Its energy-saving potential is in the range of 35.0~66.0%.

Based on the above literature survey, current studies focus on aerogel glass and vacuum glass, which have advantages in heat insulation compared with traditional glass. Future research could focus on combinations of window glazing with other adaptive technologies to improve their thermal performance.

4.3. Adaptive Wall

The application of adaptive wall technology is an effective approach to meet the indoor comfort requirements and achieve energy savings. Adaptive walls mainly include PCM wall, dynamic insulation wall, Trombe wall, and photovoltaic wall.

4.3.1. PCM Wall

PCM walls integrate PCMs with energy storage and release properties into walls [106]. The use of PCM walls can effectively achieve energy saving and regulate the indoor thermal environment by significantly reducing indoor temperature fluctuations and heat transfer rate, thereby keeping a cool indoor environment in summer and warm environment in winter, thus improving indoor thermal comfort. Anter et al. [10] found that PCM walls can significantly reduce indoor heat gain/loss and help the inner walls reach ideal temperatures in summer. For office buildings, Wang et al. [107] found exterior walls with PCMs to be more energy-efficient than interior walls with PCM, with a maximum energy saving of 10.5% in the cold season. There have been many investigations on the integration of PCMs into different wall structures, including concrete walls [108], brick walls [109], hollow walls [110] and lightweight walls [111]. The integration methods include absorption, direct incorporation, shape-stable phase change materials, microencapsulation and macroencapsulation [110], where microencapsulation and macroencapsulation methods are favored by researchers. Erlbeck et al. [108] encapsulated PCMs in concrete walls and investigated their thermal performance with different encapsulation methods. They found that the block temperature rises slowly, thus reducing the heat flux into the inner room. The change of PCM encapsulation design leads to thermal behavior adjustment without

mass alteration. The optimal design solution involves the setting positions of many thin encapsulations with surface area for heat transfer. Saxena et al. [109] incorporated PCMs into brick walls and found that the temperature fluctuations were significantly reduced. Compared with traditional bricks, the peak internal temperature was decreased by 4.5 °C to 6 °C. Abbas et al. [110] integrated PCM capsules in hollow bricks that help reduce the IAT and temperature fluctuation by 4.7 °C and 23.84%, respectively. Liu et al. [111] investigated lightweight PCM wall performance under different directions and found that the effect and parameter settings of PCMs vary under different directions. Under appropriate PCM parameter settings, the thermal performance of the east and west walls was significantly improved, and the average and peak heat flux reduction could reach 28.2–29.5% and 62.8–66.4%, respectively, compared with the base case. The delay time is increased by 5–5.34 h.

However, there are many limitations with PCMs, e.g., the performances of PCMs are significantly affected by outdoor conditions. PCMs may fail under extreme weather conditions. In addition, phase change temperature is optimized according to the specific ambient temperature [112]. Therefore, many studies focus on the optimization of the operation of PCMs by superimposing or modifying the PCM parameters or coupling the PCM with other adaptive methods (see Table 8). While traditional PCMs are usually only suitable for one season between winter and summer, most of the optimized walls can be used in both cooling and heating seasons. The optimized walls can better regulate indoor temperature and effectively reduce building energy consumption. The ventilation and sunlight regulation wall combined with variable transparency and shape-stable phase change materials has the best performance, with an annual energy saving rate of 43.49% [113].

Table 8. Research on the optimization of PCM walls.

Method	Description	Ref.
Double-layer PCM wall	It has high seasonal adaptability, with an average delay time of 4.65 h. An average reduction in attenuation coefficient by about 80% is achieved.	[114]
Radiative cooling coupled with PCM wall	External temperature fluctuation is suppressed by thermal storage, and the internal temperature approaches the target temperature faster.	[115]
PCM coupled with TC coating wall	It has an excellent ability to reduce cooling and heating loads. The optimal switching temperature for Shanghai is 26 °C; maximum energy saving of 10% is achieved in Guangxi.	[112]
Dynamic PCM wall	It performs well in winter and summer, with monthly heat gain reduced by 135.53% to 535.73%, and heat loss reduced by 2.92% to 58.76%.	[116]
Combination of variable transparency shape-stable PCM with ventilation and sunlight regulation wall	This wall passively reduces solar absorption in summer and increases solar absorption in winter. Compared with a large wall structure, yearly energy saving reaches 43.49%.	[113]

Based on the above literature survey, current studies focus on PCM applications in different types of walls, the effects of PCM thickness and other properties on wall performance, and methods to improve PCM wall performance to address their application limitations under different outdoor environmental conditions. Future research should continue to focus on the optimization of PCM material properties to satisfy the needs of different climatic regions.

4.3.2. Dynamic Insulation Wall

Dynamic insulation walls can adjust their transmittance or thermal resistance according to variations in outdoor environmental conditions to achieve efficient energy utilization

and maintain indoor comfort [117,118]. There are two main ways to implement dynamic thermal insulation walls. One is to change the thermal resistance by changing the airflow through the wall, that is, ventilated walls; the other is to use dynamic thermal insulation materials, which can switch the R-value between insulating and conductive states [5].

There are two different types of ventilated walls according to the airflow direction to the wall, namely, permeodynamic walls (perpendicular) and parietodynamic walls (parallel) [5,117] (see Figure 5). In addition to changing the thermal resistance, ventilated walls have the additional advantage of improving indoor air quality (IAQ) by introducing fresh air [5]. Karanafti et al. [119] investigated opaque ventilated wall performance by combination with dynamic insulation technology with different materials and structures. Compared with traditional opaque ventilated facades, heat removing efficiency was improved by 210–260% under Mediterranean summer conditions. The maximum efficiency was reached with thermal mass evenly distributed to the cavities on both sides. Li et al. [120] proposed a ventilated wall, which consists of photovoltaic panels, air ducts and curtain walls. Numerical results show that after adding the air duct, the reduction in the interior surface and average PV panel temperatures reaches 7.12% and 2.12%, respectively.

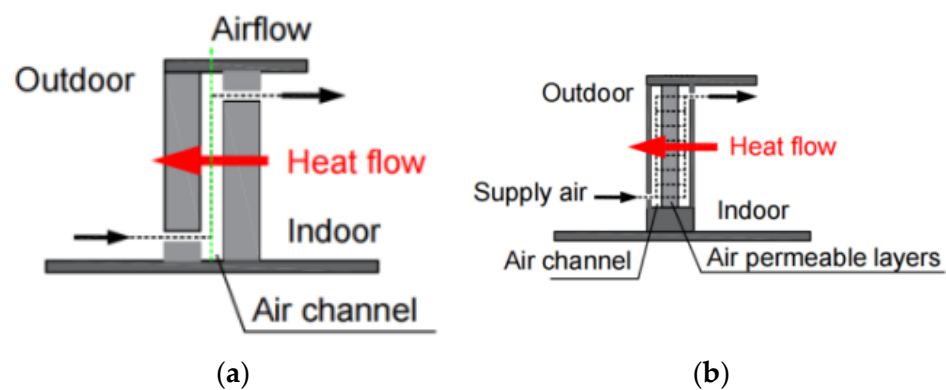


Figure 5. Ventilated wall schematic diagram: (a) parietodynamic wall; (b) permeodynamic wall.

Dynamic insulation materials (DIMs) can change their thermal resistances through a controlled exchange of liquid or gas media. Park et al. [121] found that DIMs help reduce the annual residential cooling energy consumption by an average of 15% under American climate conditions, and up to 39% in mild climates in the United States, and 10% annual heating energy reduction on average. It is worth noting that most scholars now conduct research on coupling PCMs with DIMs to achieve better wall thermal adaptability, which can not only adjust the R-value according to weather conditions, but also effectively shift the peak load of the building in a timely manner and improve indoor comfort [5]. Kishore et al. [122] found that the integrated wall (PCM + DIM) has high energy-saving potential. Compared with individual DIM and PCM walls, the reduction in annual heat loss and heat gain can reach 7–38% and 15–72%, respectively. Zhang et al. [123] found that forced turbulence can change the thermal resistance of air to the lowest value and proposed a new type of forced turbulent air dynamic insulation system–PCM system (DIS-PCM system). The DIS-PCM system was found to greatly improve multi-layer hollow wall system thermal performance based on simulation results. Under variable ambient temperature, the stable indoor heat dissipation rate maintained a small inner wall temperature fluctuation range of 27–28.69 °C. The air flow rate helped to precisely adjust the indoor thermal comfort temperature.

Based on the above literature survey, current studies mainly focus on ventilative walls and DIMs. Ventilative walls optimize the indoor thermal environment, and at the same time improve IAQ by introducing fresh air. However, the performance of dynamic thermal insulation walls is affected by the outdoor environment and deserves further investigation.

Future research could focus on the optimization of variation rules of dynamic insulation walls to improve the building thermal performance.

4.3.3. Trombe Wall

As an efficient passive solar heating technology, the Trombe wall has attracted widespread attention for its simple structure, high efficiency and low operating cost [124]. The Trombe wall provides an effective energy conservation solution through indoor thermal environment improvement and thermal load reduction. The investigations on the Trombe wall have covered many aspects such as performance evaluation, evaluation indices, design and optimization [22, 124]. According to structural and functional differences, they can be divided into different types, such as classical, composite, zigzag, PCM, PV, water, fluidized, air purification, EC, and translucent insulating (TIM) Trombe walls [125,126]. The classic Trombe Wall System (TWS) is composed mainly of a glazing layer, an air layer and a large heat capacity wall. This wall system effectively reduces the energy requirements of the building through daytime solar energy absorption and storage, and nighttime energy release to the indoor space, and it can achieve building energy savings of up to 30% [127]. However, there are some drawbacks to the application of classic Trombe walls, such as low thermal resistance, proneness to overheating due to the absence of insulation [127], and susceptibility to outdoor environmental influences, which results in large amounts of heat loss [128]. Therefore, efforts have been made to investigate Trombe wall performance improvement, e.g., the proposed zigzag Trombe wall leads to a reduction in excessive daytime heat gain and glare [124]; PCM walls lead to increased heat storage capacity; and water walls effectively maintain building thermal comfort and achieve a reduction in energy needs [128]. Table 9 lists the investigations on the different types of Trombe walls and shows that great efforts have been made to improve their performance and enlarge the scope of applications. As can be seen from the table, compared with ordinary Trombe walls, the optimized walls can effectively improve their performance. PCM Trombe walls and water Trombe walls perform well in maintaining thermal stability and indoor thermal comfort. Fluidized Trombe walls have significant advantages even in cold areas or high altitudes, where they can help quickly increase the indoor air temperature.

Based on the above literature survey, current studies focus on the evaluation of different types of Trombe walls on indoor thermal environment improvement, and building load and energy need reduction. The adaptiveness of a Trombe wall to outside weather conditions still requires further investigation. Future research should focus on improving Trombe wall performance through wall structure and medium optimization to become adaptive to different weather conditions.

Table 9. Research on different types of Trombe walls.

Type	Feature	Improvement Measures	Results	Ref.
Classical Trombe Wall	The Trombe wall consists mainly of a glass cover and an endothermic surface. The convective heat transfer between the airflow and the endothermic surface in the cavity is caused by buoyancy, which can reduce the heat transfer from indoors to outdoors in winter and function oppositely in summer.	Optimized Trombe walls with built-in fins	Compared with finless Trombe wall, the thermoelectric efficiency and building energy saving rate can be improved by 68.50% and 53.57%, respectively.	[129]
Zigzag Trombe Wall	It can reduce excessive heat gain and glare during the day	Zigzag Trombe Wall	Compared to classic Trombe wall, it enables effective whole day heat distribution, in particular in the morning.	[124]
Composite Trombe Wall	Add insulation materials behind the wall to prevent heat from escaping outward	Low-E glazing + temperature-controlled ventilation	When used in combination with HVAC system, heating requirements were reduced by 61.4%, and 11.1% compared with typical walls and classic TWS, respectively.	[127]

Table 9. Cont.

Type	Feature	Improvement Measures	Results	Ref.
PCM Trombe Wall	Incorporating PCM into the wall as a heat storage medium can increase heat storage capacity	Double-layer PCM Trombe wall	Compared with optimized reference Trombe wall and traditional wall, reduction in annual thermal load can reach 13.52% and 7.56%, respectively.	[130]
		PCM Trombe wall with insulated outside cavity	External insulation of the chamber can greatly reduce nighttime heat loss.	[131]
		New Trombe wall system based on phase change slurry (DPTW) direct absorption solar collector	The DPTW system has a high indoor thermal comfort level. Indoor occupied area temperature stayed at 18.5~24 °C for 148.4 h (67% longer than with traditional Trombe wall). PMV values of −0.5~0.5 lasted for 119.2 h (21% higher than traditional TW). The heating load was reduced by 39% in winter.	[132]
		Dynamic Trombe wall combining a PCM layer and an insulating layer	Compared with static walls, the dynamic walls with and without PCMs can increase the energy efficiency by 25.3% and 17.5% higher, respectively. Similarly, they can increase the thermal efficiencies by 79.8% and 35.4%, respectively.	[133]
Water Trombe Wall	Placing the water container inside the wall as a heat storage medium can help achieve thermal comfort and effectively reduce energy needs	Water Trombe Wall	Water Trombe walls are designed for optimal thermal performance, which increases operational efficiency during the day. The Water Trombe wall is 3.3% more thermally efficient than a conventional Trombe wall under certain conditions. Heat loss can be reduced by 31% at night and efficiency increased by 7.2% under low irradiation conditions. An average thermal efficiency of 52.8% can be achieved under hot water mode, and the thermal comfort enhancement coefficient of this room is 0.744 under air-water heating mode (higher than under independent air heating mode).	[128]
		Trombe wall combining water flow channels and Venetian shutters		[134]
Fluidized Trombe Wall	Highly absorbent fluidized particles are placed in the gap between the wall and the exterior glass to improve wall system thermal performance	Trombe wall with porous media	In the high Andes region, the average PMV reaches +0.10. With acrylic particles, the internal temperature can be increased by up to 155% compared to non-Trome wall systems.	[135]

4.3.4. PV Walls

BIPV technology is primarily used on building roofs. However, in high-rise buildings, the wall area is significantly larger than the roof area and can receive a substantial amount of solar radiation. Therefore, PV walls have received more and more attention [136]. Great efforts have been made to optimize and improve their thermal performance by introducing different PV wall types, such as PV double-skin façades (PV-DSF), Bifacial PV Wall (BPV), and PV thermoelectric wall (see Table 10). Compared with single-layer PV glass, double-layer PV walls have stronger thermal insulation performance [137], and can achieve the functions of power generation, thermal insulation, and natural lighting at the same time. Meanwhile, the airflow between the double-layer walls can help cool photovoltaic panels and improve power conversion efficiency [136]. To further improve the performance of the wall, its structure can be modified, e.g., to become a double-layer photovoltaic wall with a folding structure. Ahmadi et al. [138] studied the performance of a double-layer PV wall with a folded structure. They found that it captures 250% of solar radiation compared with the traditional vertical layer DSF. Net heat gain through the outer layer is 33% higher than under the base case condition with an increase in the fold depth. Double-sided PV walls can generate electricity using radiation from both sides simultaneously [139]. High backside wall reflectivity helps enhance power generation through indoor ventilation and achieve heating load reduction [140]. As can be observed from Table 10, double-sided photovoltaic walls can also be combined with reflective films, thermochromic materials, etc., to achieve better energy-saving effects. The PV thermoelectric walls can use local electricity in a timely manner to reduce the interior surface temperature of enclosure structure and instantaneous heat flux entering the indoor space to achieve energy saving. Table 10 summarizes the

investigations on different PV walls. As can be seen from the table, these three types of walls have their own advantages and are suitable for different climatic conditions and building requirements. PV-DSF performs well in insulation and power generation, especially in cold and humid subtropical climates, with significant energy-saving effects; BPV improves solar energy utilization efficiency and building energy-saving effects through double-sided power generation and ventilation optimization, and is suitable for areas with good daylighting conditions; photovoltaic thermoelectric walls achieve the highest proportion of energy saving, especially in cold areas and scenarios with high cooling needs.

Table 10. Investigations on different types of PV walls.

Type	Advantages	Focus	Description	Ref.
PV-DSF	It can simultaneously achieve power generation, heat insulation and natural lighting. The economic performance is improved for solar power conversion. The airflow can help cool the PV panels and improve the power conversion efficiency.	PV-DSF performance in winter	On a sunny day in a cold climate, the inner circle mode performs 10.9% better than the thermal buffer mode; fan activation further increases total energy saving potential by 12.6%	[136]
		Performance of crystalline silicon PV-DSF in humid subtropical climate	Compared with single-layer semi-transparent photovoltaics, heat loss and heat gain reduction by PV-DSF can reach 50.3% and 30.4%, respectively	[137]
		Thermal performance analysis of BIPV-DSF with folded structure	250% more solar radiation is captured, compared with conventional vertical layer DSF; 33% more net heat gain through the exterior layer can be achieved with the increase in pleat depth compared with base case	[138]
BPV	Electricity can be generated by utilizing solar radiation simultaneously from both sides; high wall reflectivity and back-side power generation enhancement through indoor ventilation can help achieve thermal load reduction	Experimental and numerical study of double-sided PV walls	On sunny days, the overall solar energy utilization efficiency can reach 40%. In addition, 21.2% energy saving can be achieved through ventilation	[140]
		Innovative BPV wall combining BPV with reflective film	Compared with single-sided photovoltaic, 24% average power generation increase can be achieved	[139]
		Experimental study of double-sided photovoltaic wall combined with thermochromic materials	In summer, the system can achieve a solar energy utilization rate and thermal efficiency by 38.8% and 83%, respectively	[141]
		Thermoelectric performance of innovative double-sided photovoltaic ventilative wall	The average temperature of the bifacial PV modules reached 68.3 °C in the warm season. The annual cumulative electrical energy of the wall, performance ratio, and annual average efficiency were 63.8 kWh/m ² , 0.7, and 6.3%, respectively; the total energy reduction reached 92% in winter	[142]
PV thermo-electric wall	Use localized power in a timely manner to reduce the interior envelope surface temperature and transient heat flux into the interior space	PV-thermoelectric-battery wall	The energy savings achieved by the system in cold, mixed, and cooling advantage areas are 72–92%, 88–100%, and 100%, respectively	[143]

Based on the above literature survey, current studies focus on the optimization of the PV walls for multiple functions such as power generation, thermal insulation, and natural lighting through different designs and technologies. Future research should focus on the integration of PV walls, mechanical systems and lighting control to improve the building performance under different weather conditions while taking into account the power generation, heating and cooling energy needs.

4.3.5. Adaptive Solar Shading Systems

Adaptive solar shading systems can effectively reduce solar heat gain to reduce building cooling energy needs in summer while allowing enough solar radiation to enter the building in winter. Therefore, shading systems are crucial for energy saving, especially for large glass facades [144]. At the same time, adaptive shading systems dynamically change their configuration to respond to the outdoor environment and the needs of residents to balance natural light and reduce glare to meet the visual comfort needs of residents [145]. Roller blinds, shutters, and internal shading are typical types of shadings [144], which have

been investigated by a number of researchers. For example, Kunwar et al. [146] evaluated the performance of two dynamic roller blinds in different directions using two different control strategies under different weather conditions. They found a calculated average cooling energy saving of 26% for the HVAC system with an acceptable glare level at over 90% of the time in all directions. Some researchers investigated the impact of blind shapes and control strategies on the building performance. For example, Uribe et al. [147] conduct research on the performance of porous curved louvers under different control strategies. Ibrahim et al. [148] evaluated the performance of trapezoidal louver shading panels under different directions and shading configurations and found they have great potential in improving the energy efficiency and daylight performance of prefabricated buildings.

In addition, there are other adaptive shading systems, such as adaptive bionic facades and multi-layer adjustable semi-shading systems. Bionic adaptive solar building envelope (Bio-ASBE) is defined as a building facade or skin (including vertical and horizontal enclosure structures) that is designed to regulate and/or collect solar radiation by borrowing relevant strategies from nature [149]. The basic module of the facade consists of four shading devices that can be folded along the horizontal and vertical axes and imitates the ability of Oxalis to track the path of the sun and change its angle accordingly [150]. Studies have shown that after the facade design is modified, 32% of building energy saving can be achieved while ensuring indoor visual comfort. Zheng et al. [151] proposed a complex multi-layer adjustable semi-shading system and demonstrated that the optimized design helped reduce glare by 49–53% and annual energy consumption by 100 kWh in a typical office space.

In summary, the adaptive shading system can effectively reduce building energy consumption, improve visual comfort by dynamically adjusting solar radiation and natural lighting. In future research, more shading methods and more intelligent control methods can be investigated.

5. Adaptive Mechanical System

Even though the adaptive building envelope can adapt to ambient environmental conditions, it cannot guarantee indoor thermal and visual comfort all year round. The mechanical system is able to provide extra cooling, heating and lighting to fulfill these comfort requirements. With the advancement in control and artificial intelligence, the mechanical system can also be adaptive to the indoor and ambient environment while minimizing energy consumption. The adaptive mechanical system primarily includes lighting and the HVAC system.

5.1. Lighting

Smart lighting reduces building energy needs while satisfying indoor lighting comfort by dynamically adjusting the artificial lighting level to meet the changes in occupancy and daylight conditions [152]. A smart lighting system is mainly composed of dimmable light-emitting diodes (LEDs), occupancy sensors, photodetectors, and controller units [15]. Table 11 lists the investigations on intelligent lighting systems in recent years based on different response methods, which mainly include daylight response, occupancy response and sound response. The studies used effective control methods or optimized algorithms to achieve rapid response and reduce energy consumption. For example, Seyedolhosseini et al. [15] developed an ANN model on the dimming level of the lamp and the illumination of each area, and used it to adjust the dimming level of a luminaire to provide a given required level of illumination for each area, then optimized and reduced the number of photodetectors without significantly affecting the lighting quality [153]. Optimized lighting control can lead to high building energy-saving ratio of over 40%, even

reaching 93%. These intelligent lighting control systems have significantly improved the energy performance and user experience of lighting systems through different response modes and control methods. The selection of a suitable system should be determined according to specific application scenarios and needs to achieve the best energy-saving and comfort effects.

Table 11. Research on lighting control systems with different response methods.

Feature	Response Method	Description	Results	Ref.
Daylight adaptive closed-loop lighting control method based on artificial neural network	Daylight	The target output of the photodetector is calculated through linear optimization of the preprocessor unit. Based on the target illuminance provided by the preprocessor module, the decision unit determines the dimming level of the luminaire. Artificial neural network is used to study the relationship between luminaire and zone illuminance for dimming level adjustment. Unstable changes in daylight are monitored by placing a number of auxiliary photodetectors in the environment.	The average mean square error between the required illuminance and the sensed illuminance values is 1.2.	[15]
Lighting control system with limited amount of photodetectors without significantly reducing control accuracy	Daylight	Combination of K-means clustering algorithms with linear optimization is used to determine the number and location of these detectors. Detector data are analyzed using a feedforward neural network to identify how to adjust the auxiliary photodetectors to cope with daylight changes and ensure that the lighting conditions in different areas meet the requirements, that is, to maintain consistent brightness (illuminance) and uniformity of brightness distribution (illuminance uniformity).	Photodetectors could be removed by 82% with a calculated holding illuminance of zero. Furthermore, the mean absolute error is <23.6 lx without photodetectors on the surface of the area.	[153]
Intelligent self-calibrating lighting control system	Daylight	Workstation illuminance and occupancy were measured. Bulb dimming and level workstation illuminance relationship was estimated using an unobtrusive self-calibration process. Comfort dimming levels were adaptively adjusted periodically while achieving energy saving.	Responding quickly to changes in user preferences, daylight, and occupancy; reduce energy needs by approximately 40% compared with traditional LED lighting systems.	[154]
sound level based lighting control	Sound	Using sound sensors to determine the activity level of the environment. Light and energy consumption of the LED light source is limited in situations without or with limited activity.	This approach can reduce energy consumption by more than 40% when environmental activities are reduced.	[155]
WiFi-based smart building occupancy-driven lighting control system	Occupancy	Uses existing WiFi networks to obtain detailed occupancy information in a non-invasive way; calculates appropriate dimming instructions for each lamp through an innovative algorithm. distributes instructions to regional gateways by the central control system, and brightness adjustment is performed by the built-in local controller of each lamp to achieve lighting control based on occupancy; allows users to customize brightness settings according to their preferences and remotely control lighting through their mobile devices.	Compared with the static scheduling lighting control solution and the passive infrared (PIR) sensor-based lighting control solution, it achieves energy savings of 93.09% and 80.27%, respectively, while ensuring individual lighting comfort.	[156]
Received signal strength indicator (RSSI) based real-time device-free human detection (DFHD) intelligent lighting control	Occupancy	System components: ZigBee 2.4 GHz wireless network; RSSI filter with moving average (MA) and exponentially weighted moving average (EWMA) techniques; adaptive DFHD algorithm; hardware set and lighting control method.	100% accuracy in moving people detection. When a woman is walking (home scene), the cumulative lighting power needs are reduced by (72.12% and 29.31%), and when a woman is walking and a man is riding a motorcycle (parking scene), the cumulative power consumption is reduced by (86.19% and 54.84%).	[157]
Intelligent lighting control system integrating multi-target detection and monocular depth estimation	Occupancy	Automatic detection of the personnel position and lights through video for light control. Combination of AdaBins technology and Scaled-YOLOv4 to perform target detection and depth estimation simultaneously, as well as personnel position and light level. By using a proprietary image dataset and deep transfer learning methods, target detection accuracy is improved. Based on the detection results, the system uses the K-Means algorithm for intelligent lighting control and verification.	Average control error is less than 1 m. At the same time, the system can be easily deployed without recalibration.	[158]

Based on the above literature survey, current studies focus on developing intelligent lighting systems for indoor lighting comfort enhancement and building energy needs

reduction by automatically adjusting artificial lighting to adapt to changes in occupancy and daylight level. Future research could focus on the integration of lighting control and HVAC system control to achieve better energy performance. In the meantime, daylighting control should also be taken into account for further improvement of the building energy performance.

5.2. HVAC System Control

Adaptive HVAC systems respond to the outdoor and indoor environmental conditions by adjusting air conditioning systems and ventilation systems [159] to maintain indoor temperature, humidity [160], etc., while achieving high energy performance and indoor comfort. Adaptive air conditioning systems are mostly used in large buildings, such as subways. Table 12 lists the investigations on adaptive air conditioning systems in recent years. The adaptiveness of the HVAC system was demonstrated through simulation and building energy modeling (BEM) [16], electrochromic-induced adaptive fresh air pretreatment systems with different operating modes [161], demand-based monitoring and control methods [162], etc., and proved to effectively achieve energy savings while ensuring the comfort and health of the indoor environment. Adaptive HVAC system control can also be applied to cultural relic protection. For example, a multi-index adaptive ventilation control system was developed, which achieved 30% building energy saving, reduced a variety of air pollutants and adjusted IAQ parameters to protect cultural relic buildings with minimal structural and visual impact. By comparing and analyzing these studies, it can be found that the application of adaptive technology in HVAC systems has significant energy-saving and comfort improvement potential. Through introducing advanced control methods and technologies such as electrochromic glass, hybrid modeling, digital twin technology, and demand-based control strategies, HVAC system operating efficiency was optimized, energy waste was reduced, and indoor environmental quality was improved.

Table 12. Investigations on adaptive HVAC systems.

Feature	Inputs	Object	Description	Results	Ref.
Electrochromic-induced adaptive fresh air pretreatment system with different operation modes	Solar radiation, outdoor ambient temperature, indoor temperature set point, humidity	Fresh air pretreatment system	EC glass embedded in a flat switchable panel enables switching between heating and cooling modes to process fresh air.	Fresh air pre-treatment system was effective up to 55.4% of the time annually. Maximum energy savings for medium-sized offices, warehouses, and single-family homes were 11.52%, 26.62%, and 18.29%, respectively.	[161]
Use hybrid modeling technique for multi-zone adaptive temperature and humidity control	Indoor temperature and humidity	Air flow volume	Integration of first-principle model with data-driven model based on full-form dynamic linearization (FFDL) multi-zone climate dynamic model. Compared with the existing first-principle model, it takes into account the unknown multi-zone nonlinearities and uncertainties of hygrothermal dynamics with online measured data. A model-free adaptive control (MFAC) scheme is applied to achieve desired multi-zone climate control performance.	The MFAC solution based on the hybrid model can achieve an average energy saving of 4%.	[160]
Dynamic occupancy adaptive HVAC control	Zoning parameters for thermal zones, time interval, and occupancy-based set point rules.	HVAC systems in subway stations	Integration of BEM with passenger flow simulation for subway station dynamic occupancy-based HVAC control evaluation. Integration of agent-based modeling (ABM) with BEM is implemented to simulate and evaluate occupancy-based HVAC control strategies.	Adaptive control using ceiling diffusers can save 1.8% to 24.4% of cooling energy while not significantly affecting thermal comfort.	[16]
Multi-index adaptive HVAC ventilation control system	IAQ parameters including CO ₂ , humidity, temperature, SO ₂ and NO ₂ concentrations	Air flow rate or temperature	This system uses digital twin technology for IAQ management, which consists of triggers and feedback. A heritage building information model (HBIM) with sensors is used for ventilation adjustments. Computational fluid dynamics (CFD) is used to set sensor placement rules and response graph generation.	Up to 30% of energy saving can be achieved. Multiple air pollutants are reduced in a timely manner and IAQ parameters are adjusted to protect the heritage building with minimal structural and visual impact.	[159]

Table 12. Cont.

Feature	Inputs	Object	Description	Results	Ref.
An integrated framework for real-time optimization of HVAC setpoints	Occupied condition	HVAC system temperature settings	The system consists of several key components: first, visual monitoring using cameras to capture occupant activities and equipment usage; second, a predictive HVAC energy and thermal comfort model, which combines a shallow neural network-based model to predict internal heat changes caused by occupant activities as well as HVAC load and thermal dissatisfaction percentage; and finally, an HVAC temperature set point optimizer that determines the optimal temperature set point based on optimization rules. The entire system works together through these components to achieve optimization of energy efficiency and indoor comfort. Large rooms are divided into multiple zones; the temperature of each zone each is controlled independently. In the breathing layer of each zone, wireless temperature sensors are installed to meet target temperature setpoints. This demand-based monitoring control system only provides temperature adjustment for areas where people are present and takes into account the heat exchange between occupied and unoccupied areas.	The framework could achieve a reduction in heating energy and thermal dissatisfaction by 36.8% and 5.26%, respectively. Reduction in cooling energy needs and thermal dissatisfaction ranged from 3.5 to 33.9% and from 0.17 to 2.89%, respectively.	[163]
Demand-based temperature control method for large air-conditioned rooms	Occupied condition	Temperature	Adaptive cooling technology automatically adjusts based on time of day (occupied or unoccupied) and indoor and outdoor environmental conditions to balance energy saving optimization and indoor comfort.	Compared with conventional control, it can save about 20–30% of the supply air flow and reduce the energy consumption by more than 10% in both full and half occupied conditions.	[162]
Adaptive Cooling Technology	Indoor temperature and humidity and occupied conditions	HVAC system	Adaptive cooling technology automatically adjusts based on time of day (occupied or unoccupied) and indoor and outdoor environmental conditions to balance energy saving optimization and indoor comfort.	Compared with conventional technologies, adaptive cooling technology enables the teaching building to achieve an annual energy saving potential of 305,150 kWh.	[164]

Based on the above literature survey, current studies focus on developing intelligent control methods to enhance HVAC system energy performance and achieve energy reduction. These methods usually involve real-time monitoring of indoor and outdoor environmental parameters, occupancy detection, and model-based prediction and optimization to improve indoor thermal comfortable energy efficiency. Future investigations can focus on further exploration of the practicality, economy, and sustainability of these technologies, their applicability in different climate regions and different building types, as well as integration with adaptive building envelope technologies. Integration of sensing technology, AI and big data technologies with the physical laws of HVAC operation is another important future research direction.

6. Adaptive Building Applications

Adaptive building technologies have been adopted in practical applications, e.g., the Crystal Hotel (Figure 6), the Edge (Figure 7), and the New York Times Building (Figure 7). The Crystal Hotel is located in London. It has window facades that can dynamically adjust transparency. Through suspended particle devices, they can instantly transition from transparent to opaque to provide privacy and glare control.

The Edge building is located in Amsterdam. It has electrochromic windows that can dynamically adjust their color according to external conditions, thus optimizing daylighting control and reducing dependence on artificial lighting and mechanical cooling.

The Al Bahr Towers are located in Abu Dhabi, United Arab Emirates (Figure 8). The tower's facade consists of mechanized structures that adapt to the movement of the sun, providing protection from solar beams while optimizing the entry of natural diffuse light. Figures 8a and 8b demonstrate the front view of the building before and after the mechanical structure is open, respectively.

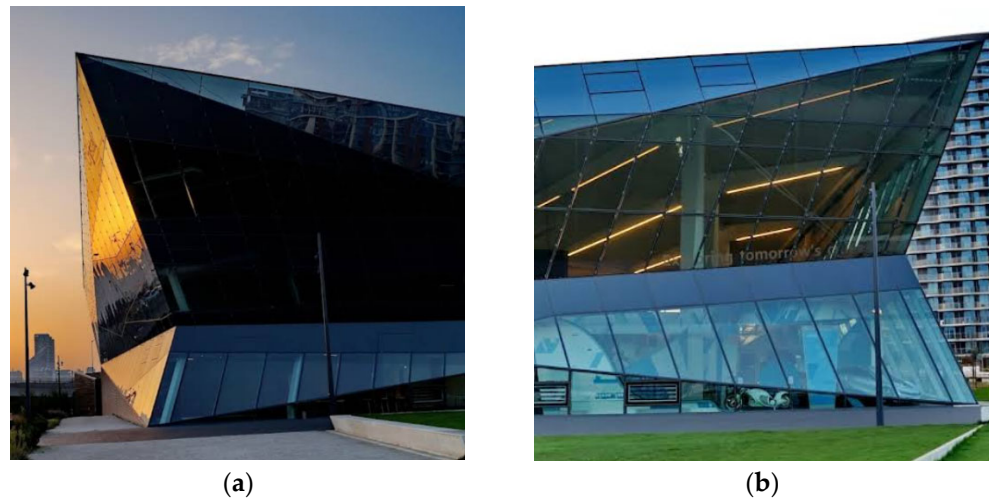


Figure 6. The Crystal Hotel (source: Google map). (a) Opaque; (b) transparent.

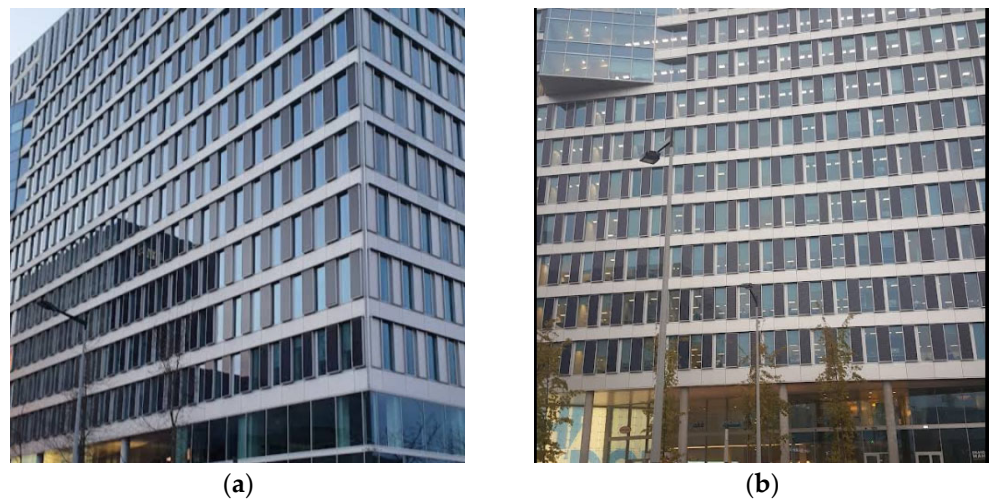


Figure 7. The Edge (source: Google map). (a) State 1; (b) state 2.

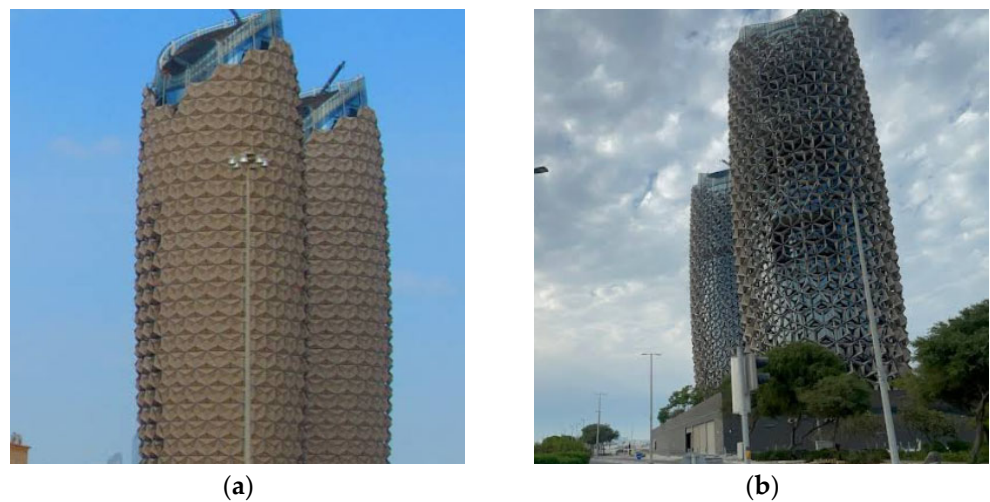


Figure 8. Al Bahr Towers (source: Google map). (a) Mechanical structure is closed; (b) mechanical structure is open.

Table 13 lists adaptive building cases in different countries, showing how adaptive building technologies respond to environmental changes through intelligent control and materials, demonstrating the diversity and innovation of adaptive building technologies,

leading to energy performance improvement, and creating a more sustainable and comfortable building environment. From PV roofs to smart windows, to dynamic shading systems and Trombe walls, they can be used to achieve building energy demand reduction, and enhance the aesthetics and functionality of buildings through innovative designs. These technologies optimize building energy performance and indoor environmental quality by dynamically responding to environmental changes and user needs. Case studies in different climatic regions demonstrate their applicability to a wide variety of building types and climate conditions. With technological advancements and growing demand for sustainable development, these smart building solutions are expected to be more widely used in the future.

Table 13. Practical applications of adaptive buildings.

Type	Solution	Location	Building Name	Description	Ref.
Roof	PV roof	South Korea	Ur-Ban-Chan Farmers Market	The building features BIPV colored glass (with integral PV) and gardens to form the roof and bring dynamic lighting to the inner space.	[165]
	PV roof	Santa Cruz West Cliff, Argentina	West Cliff Drive	The house has built-in PV panels installed on the roof to convert solar energy into electricity, and can achieve natural daylighting and reduce artificial lighting energy needs.	[166]
	PCM roof	U.K.	Crossway Residence	The combination of a locally handmade clay tile arched roof with PCM thermal storage panels and a heat stream PCM thermal storage system enables automatic regulation of indoor temperature.	[167]
Window	Electric glass shutters	France	École Daniel Pennac	The control facade is composed of tempered glass slats, which are motorized to form an adjustable shading system to provide solar protection to the interior.	[168]
	EC windows	Amsterdam, Netherlands	The Edge, an energy-efficient skyscraper	The windows utilize electrochromic technology to dynamically adjust their tint based on exterior conditions, optimizing daylighting and minimizing the use of HVAC systems and artificial lighting.	[169]
	Smart Window with Suspended Particle Device (SPD)	London	The Crystal Hotel	The Crystal Hotel's facade features windows with dynamically adjustable transparency, which instantly transition from transparent to opaque through a suspended particle device, providing privacy and glare control.	[170]
	TC windows	New York, United States	New York Times Building	Thermochromic glass adjusts color based on temperature changes, limiting solar heat gain at high temperature and allowing more sunlight in at low temperature, improving energy efficiency.	[171]
Wall	PV facade	Canada	The Edge Building	The building's 560 photovoltaic panels on its facade can meet 80% of the building's electricity needs. At the same time, the building is also connected to the local city grid to transfer its excess electricity.	[172]
	Dynamic shading system	Abu Dhabi, United Arab Emirates	Al Bahr Towers	The tower's facade consists of mechanized structures that adapt to the movement of the sun, providing protection from solar beams while optimizing the entry of diffuse solar radiation.	[173]
	Dynamic shading system	Austria	Kieffertechnik Architecture Showroom	The facade consists of several layers—aluminum columns and beams wrapped with a white plastered EIFS. The perforated aluminum panels are electronically operated to transform the building's appearance from a solid monolithic volume to an interesting combination of transparent and closed surfaces.	[174]
	Bionic dynamic facade	South Korea	One Ocean Pavilion	The pavilion's dynamic facade mimics the baleen filters used by whales and is composed of 108 sheets of glass fiber-reinforced plastic controlled by 216 coordinated servo motors.	[175]
	Trombe Wall	Chile	OutsideIN House	The OutsideIN residence uses Trombe walls as an adaptive solar control strategy to achieve passive heating and automatic regulation of indoor temperature.	[176]
	Trombe Wall	Amsterdam, Netherlands	Nature and environmental learning center	The Nature and Environment Learning Center (NME) uses Trombe walls as a passive solar heating solution. The Trombe walls are made of dark concrete panels that absorb solar energy, with small adjustable gaps between the panels and the glass controlling the fresh air heating.	[177]
Lighting	Occupancy Control Lighting Systems	Los Angeles, U.S.A.	NoMad Hotel	Integrated lighting control systems adjust lighting automatically based on time of day or manually by staff to meet space needs or guest requests. Room occupancy sensors turn off lights when rooms are unoccupied and allow temperatures to drift a few degrees to save energy. Blinds and curtains close automatically to prevent sunlight from warming empty rooms.	[178]
	Occupancy Control Lighting Systems	Beijing	Capital Museum	The lighting control system uses infrared sensors for human flow detection and automatically turns the lighting on and off. The lights will be turned on when visitors approach and dimmed when they move away. This not only greatly reduces the wear and tear of exhibits, but also saves energy.	[179]

Based on the above building cases, it can be observed that the application of adaptive building technologies mostly focuses only on one technology, e.g., building envelope or lighting control. Meanwhile, there is no information on building energy saving rate. Compared with the outcomes from the research in recent years, the application of adaptive

methods lags behind. Future investigations should focus on the application of multiple adaptive technologies and their actual savings.

7. Conclusions

A comprehensive discussion on the advancement of research on adaptive buildings is presented, from the aspects of definition, building envelope, mechanical system, and practical applications. The novelty and contribution of this paper lie in expanding the scope of review from just the building envelope to include the mechanical system as well, considering both as important elements in the context of adaptive buildings. In addition, it clarifies the definition of adaptive buildings to enhance understanding of the concept and presents practical cases of adaptive buildings.

The following conclusions can be drawn:

1. The definition of adaptive buildings emphasizes key features such as “versatility and adaptability”, “environmental response”, “user interaction”, and “repeated reversible changes”. The definition can be summarized as “Adaptive buildings respond to environmental changes by changing the building’s own conditions to achieve comfort and energy saving”. Recent regulatory frameworks, especially Smart Readiness Indicator, have been proposed to stress the importance of utilizing intelligent technologies to improve the smartness and adaptation of the buildings. Therefore, although earlier concepts of adaptive buildings typically focus on the building envelope, the mechanical system also deserve wide attention with the rapid evolution of AI and big data technologies that can be applied to improve the control algorithm of HVAC and lighting systems.
2. Building envelopes can enhance building adaptiveness by adopting a variety of technologies or integrating advanced materials to lower building energy consumption. In particular, some adaptive technologies, such as PCMs, BIPV, etc., can be applied to all envelope structures. In actual practice, the outside weather conditions, occupants’ requirements and behaviors could vary all the time, resulting in requirements of variation in building envelope properties. Therefore, modulation of variable physical properties of an opaque envelope, and window transmittance and shading control to achieve optimal building energy performance and its impact on adaptive thermal comfort deserve special attention.
3. From the mechanical system perspective, lighting and air conditioning systems in adaptive buildings can achieve great energy performance enhancement and provide a better indoor environment by integrating sensors and artificial intelligence algorithms into system control. Future research should focus on the integration of AI and big data technologies to achieve adaptive optimal control on HVAC and lighting systems. The building envelope, sensors and intelligent control of the mechanical system work together to form a closed-loop control system of “perception-analysis-response” to realize the dynamic adaptation of buildings to environmental changes and improve building energy performance.

With the growing global demand for sustainable and intelligent buildings, adaptive buildings will undoubtedly become a key direction for future research development. This paper puts forward several suggestions for future research:

1. Judging from the practical cases, many adaptive technologies remain largely in the theoretical research phase. Therefore, future research should focus more on converting laboratory research results into implementable solutions.
2. More consideration can be given to integrating renewable energy based on adaptive technology, which would not only lower operational energy consumption but also reduce reliance on traditional energy sources and mitigate environmental impacts.

Many studies focus on simplistic environmental conditions, such as only summer or winter, or a single climate zone. Future research should evaluate adaptive building performance under various climate conditions. The economic benefits of adaptive buildings should be studied, considering the initial investment, operation, maintenance costs, potential energy savings, as well as carbon emissions.

Although this paper provides an extensive review of adaptive buildings, there are still some limitations that need to be explored in future studies. (a) The absence of quantitative data on energy performance. Current researchers typically obtained the building energy saving ratio through simulation. However, there is little information about the actual energy saving through data collection and measurement. (b) The technological readiness level of the systems reviewed. It can be observed from the practical applications that there is a time lag when applying adaptive technology to actual architecture, as the required materials are difficult to use on a large scale due to cost restriction, performance stability, etc., and some dynamic technologies or combination of multi-technologies are difficult to realize in practice. (c) How well these solutions perform across different climate zones. Many researchers consider only one or two climatic zones when evaluating the performance of the adaptive technologies. Therefore, there is a need to determine whether adaptive technologies are effective across all climatic zones. For example, the performance of phase change materials is highly affected by the outdoor temperature and they have bad performance in areas with extreme climates. (d) A comparative analysis of the advantages and disadvantages of each approach. While some studies mention the advantages of individual technologies, few studies have been carried out to systematically compare the advantages and disadvantages of different technologies. (e) Influence of occupancy (occupant behavior). Although occupants' behaviors have a significant impact on building energy performance, they are often neglected during the evaluation of adaptive building performance. The impact of occupants' preferences for temperature regulation, lighting habits, and acceptance of new technologies deserves further investigation.

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Abbreviations

The following abbreviations are used in this manuscript:

PV	Photovoltaic
BIPV	Building-integrated Photovoltaic
HVAC	Heating, ventilation and air-conditioning
4E	Energy, Exergy, Economic and Environment
CNKI	China National Knowledge Infrastructure
CABS	Climate-adaptive Building Shell
CABE	Climate Adaptive Building Envelope

ABE	Adaptive Building Envelope
PCM	Phase change materials
PCMC	Phase change materials with cool
TC	Thermochromic
EC	Electrochromic
PV/T	Photovoltaic/Thermal
CIGS	Copper indium gallium selenide
IAT	Indoor air temperature
MTR	Maximum temperature reduction
DF	Damping factor
TL	Time lag
HFR	Heat flow reduction
NV	Night ventilation
CVR	Conventional ventilated roofs
SPD	Suspended particle device
BC	The base case
Tlum	Excellent visible light transmittance
ΔT_{sol}	High solar modulation
LCST	Low critical solution temperature
FTE	Flexible transparent electrode
SCs	Solar cells
ECDs	Electrochromic devices
η_{CE}	Coloration efficiency
STR	Solar and thermal radiation regulation
NIR	Near-infrared region
LSPR	Localized surface plasmon resonance
ε	Emissivity
LSAO NPs	Lanthanide-activated strontium aluminum oxide nanoparticles
RPC	Recycled polycarbonate plastic
ITO	Indium tin oxide
PET	Polyethylene terephthalate
LC	The liquid crystal
PDLC	Polymer dispersed liquid crystal
DGI	The annual daylight glare index
DGP	Significant daylight glare probability
SHGC	The solar heat gain coefficient
SDIG	Smart Double Insulated Glazing
CNP	Carbon nanoparticles
ANWs	Aluminum oxide nanowires
STPV	Semi-transparent photovoltaic
VPV-DSV	A combination of CdTe PV double-layer ventilation window
IAQ	Indoor air quality
DIMs	Dynamic insulation materials
DIS-PCM system	Dynamic insulation system-PCM system
TIM	Translucent insulating
TWS	Trombe Wall System
DPTW	Direct absorption solar collector based on phase change slurry Trombe wall
PV-DSF	PV double-skin façades
BPV	Bifacial PV Wall
LEDs	Light-emitting diodes
PIR	The passive infrared
RSSI	Received signal strength indicator
DFHD	Device-free human detection
MA	Moving average

EWMA	Exponentially weighted moving average
BEM	Building energy modeling
FFDL	Full-form dynamic linearization
MFAC	Model-free adaptive control
ABM	Agent-based modeling
HBIM	Heritage building information model
CFD	Computational fluid dynamics

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