Active building envelope systems toward renewable and sustainable energy

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ABSTRACT

Although passive building envelope systems dominate contemporary building design, active building envelope (ABE) research, development, and deployment are rapidly growing and present many new ways to address building energy efficiency at the façade level. This paper presents a comprehensive review on the state-of-art research on ABEs for improving building energy efficiency. First, a clarified concept of ABE is put forward based on two conditions: The ability of lowering cooling/heating loads in buildings, and performing energy transformation as the key judging factors. Second, four major categories of ABEs, namely air-based, water-based, solid-based and kinetic façades, are discussed in terms of their system structural and functional features as well as system performance. In addition, a statistical analysis is performed for a better understanding of current research focus, general trends, as well as research methods. It is found that technical research on ABEs has dramatically increased but the ratio of ABE to general façade studies remains stable. In terms of research methods and approaches, numerical simulations are dominant. Some specific comments on limitations of current ABE studies and general suggestions for the future studies are discussed. Future work suggests the need for contributions from a wide range of scientists, engineers, and architects in the building industry and beyond to push forward building energy efficiency.

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1. Introduction

1.1. Background and motivations

Buildings are responsible for about 30–40% of the primary energy consumption, and up to one third of the worldwide greenhouse gas emissions (GHG) [1], and the International Energy Agency anticipates an additional 30% increase of GHG by 2040 [2]. At present, numerous researchers and engineers are pushing forward new technologies, and governments proactively promote the implementation of building energy codes to ensure energy efficiency over the entire life span of buildings. Numerous research studies in the area of building energy confirm that to reduce energy consumption in buildings, it is necessary to enhance the performance of building envelopes [3–5].

The building envelope may be seen as the totality of components which separate the indoor from outdoor environment [6]. According to its function and location, building envelope is the generic term for building wall, window, roof, etc. The indoor man-made environment can be maintained according to occupant's requirements for thermal comfort. This is achieved through the operation of heating, ventilation and air conditioning (HVAC) systems to create cool or warm air and surfaces, while maintaining humidity levels and acceptable air conditions.
velocities. Building envelope plays a major role as it keeps the produced thermal energy from escaping to the outer environment. No matter how the envelope is designed and optimized, undesirable heat losses or gains are inevitable due to potential gradients between the indoor and outdoor environments. This drives heat conduction through envelopes, radiative heat exchange with outdoor surfaces, or direct losses from air exchanges (leakage, ventilation).

In a previous research [7], it was estimated that between 20% and 50% reduction in total energy consumption could be achieved by implementing appropriate building envelope design. More precisely, appropriate design may include: Devised structures for improved thermal performance, such as the adoption of air layer in building envelopes [8], Trombe wall [9], phase-change materials (PCM) [10], Photovoltaic (PV) modules [11], thermoelectric modules [12] etc. Some of those examples are passive envelope systems, and others are active building envelopes (ABEs). A much higher energy efficiency was reported by studies on ABEs, which can largely demonstrate their application potential and contribution to building energy issues. For example, in the case of an active building integrated PV thermoelectric wall system [13], up to 170% of energy savings compared to a massive wall, was reported in hot-summer and cold-winter zones of China.

However, after a broad literature survey and analysis, we have identified the following three major research thrusts:

1. Although ABEs are the subject of intense research, an effective definition of its concept and characteristics is still missing. To the best of our knowledge, there is only one ABE definition in the literature. In 2003, Wachenfeldt and Bell [14] published a study on the development of both passive and active building envelopes. In that study, the definition of ABEs was given as “utilizing the environment to either produce power or operating in conjunction with some mechanical devices to utilize renewable energy to provide heating and cooling”. Since then, engineers and researchers have further developed ABE systems, with a focus on wider varieties of active building systems. It should be noted that this original definition restricts ABEs to use renewable energy from natural environment to produce power or thermal energy. Consequently, this definition may exclude certain building envelope systems from ABEs, such as thermoelectric embedded envelopes which use electric power from grid [15], or air-based heating envelope systems using man-made fire and fume [16]. In addition, thermoelectric cooling/heating needs no mechanical component which does not satisfy the previous definition.

2. The concept of ABE is often implicitly hidden in various studies without a unified description and sometimes it is even misused. Currently, different researchers put forward various concepts such as adaptive envelope [17,18], responsive envelope [19,20], carbon negative building façade [21], smart façades [22], etc. The functions and concepts of those systems are overlapped. One single façade system could be labeled with different names. For example, the adaptive building envelope described in Sjarifudin’s research [23] and the responsive envelope conducted by Foged et al. [19] are actually using similar transformable mechanical components to change the shape of external envelope. And the carbon negative building façades [21], smart façades [22] both are electrochromatic glazing façades. Another big concern is that without a universal ABE definition, in some situations “active façade” could be misused. For example, the system entitled “Ventilated Active Façades with PCM” [24] actually is a passive envelope, because it can only passively react to dynamic thermal circumstances and it even does not fit to the old ABE definition. Another example is the concept given by Khire et al. [25], in which the definition of ABE is limited to thermal control technology that actively uses solar energy to compensate for passive heat losses or gains in building envelopes or other enclosures.

3. There is no state-of-the-art review on ABEs available in the literature, and the studies of ABEs are insufficient and incomplete. There are many original reviews on passive envelope systems, and at the same time there are some technical studies targeted at discussing a few specific types of ABEs. There are many new advancements made to ABEs although they did not claim an active envelope system in their studies. Many different types of ABEs are scattered among a large number of studies mixed with passive building envelopes. The development of ABEs can hardly be captured by other researchers, and the future outlook for ABEs are not identified without a comprehensive review. Although Wang et al. [26] recently carried out a review study on ABEs, their study is only focused on the heat and mass transfer analysis of transpired solar collectors (TSC).

In addition, the relevant studies on ABEs are insufficient and incomplete. Although several studies present some potentially promising technologies and new concepts, only little detailed investigations are available in the literature. For example, most of the kinetic envelopes [27] are innovative building elements with appealing appearance and energy saving potentials. They can be deformed or transformed to meet certain specific purposes. However, this important type of ABE is frequently optimized by architects but rarely evaluated by engineers from the perspective of building energy issue. There is an obvious research gap here that needs to be bridged.

1.2. Aim and contributions

- In order to address the research challenges 1 and 2, the first task of this study is to give a clear definition for ABEs (Section 2) below. This will help classifying different envelope concepts and serve for a better building design.
- Then, based on the clarified concept and definition of ABEs, relevant literature about ABEs are collected for initial data analysis (Section 3). The developing trends, research distribution in countries and institutions, as well as research approaches for ABEs are presented. This will deliver a big picture about ABEs and thus help researchers identify current status.
- The main body of this review is going to address the research challenge 3, by providing a comprehensive review on recent development of ABEs and a technical analysis to better design building envelopes (Section 4). In addition, this review can trigger inspirations among researchers and engineers to develop new and efficient building envelope systems.
- Last, a discussion is put forward to further help identifying research outlook and recommendations to develop ABEs (Section 5). This will provide researchers and engineers with future directions, which might accelerate the development of ABEs and building energy solutions.

2. Active building envelope concept

2.1. Concept

Within the scope of this research, the basic definition for ABEs is expanded to two specific categories. At least one of the following two conditions must be fulfilled, a building envelope system can be clarified as an ABE.

- **Condition 1**: A building envelope system actively utilizes energy input to manage the cooling/heating load of envelope or indoor artificial daylighting load, directly reducing the demand on central HVAC systems, and often supplanting their function with the ABE through mechanical, electrical or chemical actions.
- **Condition 2**: A building envelope system acts as an energy converter that transforms renewable energy (solar energy, wind energy, etc) into conventional energy (specifically electrical, mechanical or...
chemical energy) for a certain means of improving building performance.

It is possible for a building envelope system to meet the conditions above, and it should be noted that a standalone ABE system can hardly realize its functionality without the contribution of passive envelope technologies. If one system satisfies one or both conditions, it should be considered an ABE even if there are some passive technologies also applied in this envelope system. Nevertheless, the most important feature of ABE is its dependency on extra energy input to enhance building performance. A high performance and successful design of ABE must ensure that the energy saving range is larger than the energy input during operation.

2.2. Proposed definition

Currently, ABEs are less developed than passive building envelopes and have numerous unsolved issues such as system operation control, simulation optimization, etc. The old definition of ABEs by Wachenfeldt and Bell [14] does not specifically differentiate the role of active energy utilization and renewable energy generation. By proposing the above definition with two explicit judging conditions, the ABE systems can be strictly distinguished from passive envelope systems, leaving no ambiguous and vague evaluation. More importantly, the designers and engineers can have a clear goal for which type of ABE they are going to fabricate and optimize.

According to the selection criteria 1 and 2, it is clear that ABEs realize their unique features and functions in a totally different way than other passive envelope systems, which needs further clarifications:

(1) The Condition-1 type ABEs require extra energy input to improve building performance by directly eradicating part of HVAC and indoor lighting loads. The energy input mentioned in Condition 1 can be either conventional energy sources, like fossil fuels or renewable energy like solar energy. And this concept emphasizes the purpose of lowering HVAC and lighting loads, which are the major components in building energy scenario. More specifically, those energy inputs are used to proactively shield, eliminate or reduce thermal influence from ambient environment. The channels to this end are expanded to mechanical, electrical or chemical actions to control energy and mass flow through envelope. The operation of Condition-1 type ABE is an energy-trade-off. The cost is energy input and benefits are reduced HVAC and lighting loads. Optimized design and management should be performed to ensure profitable characteristics for ABEs.

(2) The Condition-2 type ABEs also require extra energy input but it is performed as an energy transformer in the form of building envelope. The energy input mentioned in Condition 2 is limited to renewable energy sources like solar or wind energy. The purpose of this type of ABEs is to make the renewable energy usable for building systems and emphasizes that the transformed energy flow does not have to be utilized immediately and the final usage is not limited to HVAC or lighting devices. This means Condition-2 type ABEs can also be helpful to improve energy efficiency of other building energy systems like electronic devices. The key for Condition-2 type ABEs is the environment conditions, because the renewable energy supply usually is unstable and hard to predict. The design of this type of ABEs should fully consider the local climate, geographical features, and building types.

After quite abstract explanations on the concept of ABEs, several illustrative examples are to be showcased to deepen the understanding. Limited by the content, analysis and discussion are confined to the ability of reducing the cooling load of the envelope in summer condition. In order to distinguish the concept of ABEs from passive envelope systems, comparisons are shown in the following examples.

1) Concept comparison is to be made between evaporative cooling envelope [28], water wall [29] and water pipe-embedded wall [30]. First, the envelope using passive cooling technology does not imply it is a passive system. For example, the passive evaporation is a common passive cooling technology, but the spraying of water on the evaporative roof [31], or external wall [28] needs operational energy input and this fits into the definition of an ABE. The water wall [29] is a passive system containing a water layer in the envelope which is sandwiched by external and internal board. The water layer is used as short-term thermal energy storage system, which requires no extra energy input and it can passively control heat flux. The water pipe-embedded wall [30] is a widely researched ABE system, because the indoor heat gain can be largely reduced by the circulating low temperature water in the summer from low-grade energy sources. This active wall can ensure higher efficiency than water wall, but extra pumping power is indispensable.

2) Concept comparison is to be made between Trombe wall [9] and PV façade [32]. Both traditional Trombe wall and PV façade are traditional solar façades. In a Trombe wall, the solar energy is utilized to warm up the air duct. This is a typical of passive envelope system, because this system neither utilizes extra energy input to control cooling/heat load of envelope (Condition 1) nor transforms solar energy into electrical, mechanical or chemical energy (Condition 2). But the PV façade is an ABE system using renewable energy source for power generation which can indirectly offset HVAC load. The air channel is used for thermal dissipation of PV module in daytime. Moreover, after part of solar radiation is transformed into electric power and part of thermal energy is dissipated from air duct, the heat gain through the envelope is considerably reduced.

3. Status analysis

In order to get a clear overview of the current studies on ABEs, a simple statistical analysis was conducted based on reviewed studies and extended data from ISI Web of Science database. There are all together 140 articles or conference papers satisfying the definition of ABEs in this study. However, this is an incomplete record of all ABE-related publications. The data of two major kinds of ABEs from Web of Science, namely PV wall or roof systems and PV glazing or façades, was used to make a complete statistical analysis besides the 140 articles about ABEs. The time scale covered in our study is from 1960 to 2016, and the literature is only referencing journal articles and conference proceedings. For PV wall or roof systems, we used Boolean operation TS (Topic Searching) = (Building envelope and (PV or photovoltaic or solar cell) and (wall or roof or shell)) in advanced searching. For PV glazing, window or façades, the searching topics are TS = (Building envelope and (PV or photovoltaic or solar cell) and (glaze or glazing or facade or window or blind or shading)).

3.1. Research tendency

Fig. 1a shows the publication trend of active opaque envelopes, translucent envelopes, and overall ABEs from 1960 to 2016. There is an obviously slow development from 1960 to 1990, but a rapid growth since 2005. The growth rate of active opaque envelopes and translucent façades are similar. If we take into account the overall ABEs publications before 2005, the number of publications reaches a maximum of 6. But this number raised to 61 in 2016. Nevertheless, this figure does not tell the real situation of ABE because the increasing publication number is a general trend in science and engineering field. To provide a more accurate representation of the evolution of research in the area of ABEs, we took the publications of general building envelope as a benchmark and calculated the ratio of specific type ABEs. For example, we used the topic searching TS = (building envelope and
(wall or roof or shell)) for common opaque envelope in Web of Science and 1730 results were found which may include both active and passive envelope publications. Those 1730 publications are classified in terms of publication year. Then, the ratio of active opaque envelope publications to general opaque envelope publication can be calculated for each year since 1960. Likewise, topic searching TS = (Building envelope and (glaze or glazing or façade or window)) for general translucent envelope, resulted in 1065 publications. The normalized analysis for the period 1990–2016 is presented in Fig. 1b. The ratio for active opaque and translucent envelopes stabilizes around 9% and 15% using averaged data from 2012 to 2016. The ratio for overall ABE tends to be about 18% of research on a broad range of building envelopes.

3.2. Research distribution

By looking at the country distribution of ABE research, we found that China has become the largest contributor to this field (Fig. 2a), followed by USA, Italy, Spain, France and Germany and others. Nearly 1/3 of the papers are coming from China and most of them are within the last 10 years. This analysis can clearly reflect the fact that China is making a big contribution to ABE systems. This is attributed to the increasing support from central government of China to science and engineering research, and the necessity to solve building energy issues.

We further analyzed the top research institutes involved in publications on ABEs, but only 140 papers reviewed in this study are represented (Fig. 2b). The researchers from Rensselaer Polytechnic Institute, NY, USA conducted a series of studies on both active opaque and translucent building envelopes. Their research are mainly on TE module-based windows and walls. Other research institutes are all from China, and these are Hunan University, Huazhong University of Science and Technology, City University of Hong Kong, Tsinghua University. It should be noted that these results excluded the institutes that published research on PV wall or roof systems, and PV glazing or façade systems, since there are too many studies on PV systems to make a complete statistical analysis.

3.3. Research methods

For a certain type of ABE or common building envelope, simulation, experiment, theoretical design and review study are four approaches to...
explore the system performance, structure features, operation control and evaluation. Analytical models are so strict and difficult to obtain which make them the least favorite modeling tools. In all the reviewed papers conducting simulations, only 11.71% of study is based analytical method (Fig. 3b). It requires strict conditions such as simplifications on solving domain, system geometry, and boundary conditions. For example, by deriving the analytical model of water-pipe embedded solar-thermal collector wall, D’Antoni and Saro [33] made five assumptions for modeling the heat transfer problem and 4 further assumptions for system model solving. Then, Laplace transformation and Z-transform theory can be applied to solve the Fourier partial differential equations. Usually the knowledge of partial differential equation (PDE) theory, algebra equations, probability theory as well as matrix theory is needed for analytical solutions. This can facilitate the understanding of researched systems, but sometimes it is not approachable.

For some complicated ABE systems in structure and functionality, numerical simulations could be a better choice especially due to the fast development of algorithms in numerical methods and computer hardware. For all the reviewed simulation-based studies, numerical methods take up the largest percentage of 68%. The numerical approaches can be finite difference methods, finite element methods, finite volume methods, control volume methods, and boundary element methods. Those methods in common are going to derive and solve discrete algebra equations from governing PDEs. For example, when Luo et al. [34] were modeling the PV-TE wall system, the heat conduction in the PV panel and insulation as well as the convection in an air duct are represented by a set of ordinary differential equations (ODE) using control volume methods which can be later solved by state-space method [35,36]. To provide a standard, validated, and convenient simulation platform, some laboratories or companies developed energy simulation programs available for researchers, engineers and students. The frequently used softwares for building simulation include EnergyPlus, Ecotect, TRNSYS, DOE2, DeST, etc. The detailed introduction, comparison, function analysis and discussion can be found in some review studies [37–39]. Although nowadays so many different software simulation programs are available, the statistical data showed that only 20% of publications adopted energy simulation programs, because the existing simulation programs can hardly cover all types of systems especially for some novel ABEs. With the advancement of ABE design and simulation programs, more attention should be focused on adding new and flexible simulation modules into existing programs to better model building performance and evaluate building energy efficiency.

For most situations, conducting simulation is not sufficient and experimental testing is necessary to directly explore system performance and validate numerical models. In this review, about 20% of references adopted complete experimental investigations either in lab or in outdoor test chambers [40]. And this percentage does not include 14% of studies doing both experiments and simulations. In all the experimental studies, only 22% of them were in laboratory and the rest were outside in the field. It should be mentioned that some lab experiments are full sized and under such circumstances, the experiment designer can create an ideal testing environment for ABE. However, some experimental setups like ground heat exchangers related ABEs [41] are too expensive to implement.

Besides conducting simulation and experiments, review studies are also important for the discussion of system structure, function, features and projected system performance. For example, Hanoor and Levy [42] focused discussion on kinetic façades; Dhiman et al. [43] gave a summary for water-based roof; Skandalos and Karamanis [44] review the PV glazing systems; Xu et al. [45] reviewed studies on air-based slabs, etc. Those reviews help reorganize previous studies and point out future directions. Theoretical or conceptual design is another kind of method which proposes some quite novel and new ideas and concepts for ABEs, but those studies only discuss system feasibility of structure, operation and control without in depth calculation or field testing.

4. Structure and performance analysis of active building envelopes

Previously, Wachenfeldt and Bell [14] mentioned in their review the difficulty in categorizing active building systems. In this section, all the ABE studies are categorized into four classes, namely air-based, water-based, solid-based and kinetic active façades. The physical structure of air-based, water-based and solid-based active envelopes cannot be transformed to realize specific demands, while kinetic active façades can adjust its physical structure to meet certain purposes. In each subsection, the recent developments and applications on both opaque and translucent external façades will be discussed. There are basically two reasons for choosing this kind of classification. First, it is inspired by a recent review work on building integrated photovoltaic/thermal (BIPV/T) systems by Yang and Athienitis [46], in which they present different BIPV/T systems as air-based and water-based systems. Second, comparing with other ways of classifications such as energy sources or transparency of envelope, current categories can evenly include all selected literatures such that, designers and engineers can easily decide which kind of ABEs could be chosen to achieve specific purposes.

4.1. Air-based active building envelopes

An air layer-based envelope has higher thermal resistance while the movability of air facilitates the removal of excess thermal energy. These features make the air layer structure gain considerable attention for modern building design and construction, in terms of enclosed and non-closed type [8]. Nevertheless, active building wall and roof in a further step, will use air layer to achieve higher building performance. This is
made possible by using thermal energy from either natural cooling/heating sources or man-made equipment.

From a technical point of view, heating energy is easier to obtain than cooling energy. In this respect, the Roman pioneered air based active heating building envelope system [16]. The hot fumes of fire were passed naturally through the air layer in building envelopes which can effectively increase the indoor thermal comfort in winter and prevent heat loss. It was called the Roman thermo-causten and muro-causten system [47] shown in Fig. 4a. This system is like a smaller scale modern centralized heating system. The “hypocaust” system means underground conditioning, particularly for system allowing hot air to circulate under the floor and within envelope [48]. Later engineers realized that solar energy is a perfect natural heating source which can be incorporated into the design of air-based heating wall system. Hastings and Mørk [49] introduced the system transferring the heated air on a building roof to the air layer within building walls (Fig. 4b).

The adoption of natural sources can save building energy for cooling/heating energy generation, but usually energy for delivery is needed. The active air based solar heating wall can achieve higher energy efficiency for buildings in winter, than passive solar façade like Trombe wall. Because the passive solar façade can only be beneficial to the building shell that can receive solar energy, the northern external wall still suffers from huge heat loss in winter, while the solar energy received by conventional building roof is not well used.

As for the air-based active cooling envelope systems, the natural cold sources from relatively low air temperature at night and underground are effective channels. Barton et al. [50] studied a prototype of TermoDeck hollow core slab system which can supply air at night bringing in cool air into the hollow slabs to cool the building and the warm air is cooled during daytime in summer conditions. The operation of this TermoDeck system is limited to locations where the temperature difference between daytime and night in summer should be large. Otherwise, its thermal performance cannot be ensured. This shortcoming can be overcome by using underground geothermal energy which is relatively stable and independent of climate conditions. Zeiler and Bozem [47,51] (Fig. 5) proposed a geothermal active envelope system in which a “thermo-labyrinth” system is adopted to generate cool fresh air in summer. The “thermo-labyrinth” is an earth-air heat exchanger, which is also called as ground tube, or ground-coupled air heat exchanger [52]. The supplied cool air has two purposes. One stream is used for ventilation and the other one for air conditioning. The air for the conditioning purpose is used to cool or heat the total building envelope.

Besides natural cold sources, the thermolectric (TE) cooling device is suitable to be integrated into cooling façade, due to its compact tiny size, features of requiring no refrigerant and moving parts, silence operation, easier control and fast cooling speed [53,54]. Ibáñez-Puy et al. [15,55] proposed an air based thermolectric active wall to provide a cooled internal wall surface as well as cool circulating air for indoor space, which can simultaneously shield inward heat flow and offset part of indoor HVAC load. As shown in Fig. 6, internal and external side of TE module is attached to heat sink and heat pipe respectively. There is an internal and external side air gap in this system separated by an insulation layer preventing heat loss from cooled air. The TE module is working as a solid heat pump to absorb heat from internal air gap and dissipate heat into the external gap for higher system performance in summer. At the top and bottom of internal air gap, the louvered air inlet and outlet is installed. This system is powered by the electricity power from grid. The authors later developed the system using PV panel as the power source [56]. At daytime, the solar energy can power this PV-TE wall system, but at night, the grid power is used because no battery system is available. Irshad et al. [57–59] and Yusoff et al. [60] studied another kind of air based active wall system using a similar structure and working mechanism as Ibáñez-Puy et al. did in research [15]. There are also two designed air channels for the cold and hot side of the TE module. The difference is that the cooled air is supplied from the outdoor environment instead of indoor, which can ensure a higher quality of fresh air supply but seems to be lower of performance.

The above air based active wall systems mainly tackle with indoor sensible load, and only few of them can effectively deal with indoor latent load. Recently, a new desiccant channel integrated building wall system was proposed and evaluated [61] (Fig. 7). The vertical air gap involved wall system is divided into the upper section desiccant channel and lower section solar collector. As indicated in Fig. 7, in working mode, the solar collector section is sealed, and the desiccant channel is used to dry the air and then supplied to a dedicated fresh air system. During the winter season, solar collectors preheat the outside air before entering the Air Handling Unit (AHU). While in regeneration mode, the air flow is heated up by solar collectors and then absorbs the humidity from the desiccant material. Fan power is required to circulate the moving air into interior environment. The flowing air in the channel is also conducive to lower the heat gain from the external wall.

Similar to air-based building wall systems, the air-based active glazing system require an integrated cooling/heating device to produce cool/heated air to withstand heat gain/loss through glazing, or to provide cool/heated fresh air directly to indoor space.

Currently, no publication is found for active glazing system using natural cooling/heating sources to eradicate or offset heat gain or heat loss. In terms of man-made thermal energy sources, the conventional centralized HVAC system can naturally provide cool or heated air for glazing façade. The exhaust air from an air-conditioned indoor environment is cool in summer and warm in winter, which can be re-used in active façade systems. Goia et al. [62] introduced three different kinds of double skin façades that served as an exhaust component for the ventilation air of centralized HVAC system, which are Climate Façade [63,64], Highly Integrated Façade [65], and Hybrid Ventilated Façade (Fig. 8). Those three façades can effectively take advantage of exhaust air from HVAC to reduce cooling/heating loads of glazing façade. The unique feature of the Climate Façade is that it can further increase exhausted air temperature by absorbing solar energy in winter.
in the double skin façade (DSF) cavity. Then, the exhaust air will be used to pre-heat fresh air which is beneficial to HVAC systems. The unique feature of Highly Integrated Façade is that it can activate an underground heat exchanger using well water for air cooling in summer. The Hybrid Ventilated Façade can be operated in three modes (heat dissipation, heat storage and fresh air source). In the experimental studies, a single glazed façade and DSF were chosen as reference system to be compared with these three active façades. However, there are no detailed numerical simulations and specific energy evaluations for these active glazing systems.

Other conventional HVAC techniques like absorption cooling and evaporative cooling can also be integrated into glazing façades. An example of such technology has been discussed in the literature [66] and [67], where a triple state air-based absorption module worked with a Sydney type vacuum tubes solar collector for desorption at daytime using solar thermal energy was designed. The absorption module and solar collector are installed in the lower region of the façade. A mechanical fan and folding shading blinds are placed in the upper area of the façade. The cooled fresh air in the absorption module is then pushed into indoor environment. This configuration can use solar energy for regeneration process. In addition, all the components can be pre-fabricated which offers a “plug and play” solution. Tanuharja [68] first introduced the concept for an integrated façade consisting of dehumidification stage and indirect evaporative cooling stage. The warm and humid ambient air will be processed first through a desiccant material (Calcium Chloride (CaCl₂)) and then pass the evaporative cooling unit along with the vertical direction of glazing façade. Finally, the dry, cool and fresh air flows into indoor space. The regeneration of the desiccant material is conducted in a solar thermal collector.

Except for the applications in opaque walls, thermoelectric module (TEM) is an ideal option to provide cooling/heating energy source for
active glazing façades. Depending on the location of the TEMs, within air-based transparent/semi-transparent façades, TEMs can be attached to the center surface of the façade [69] (Fig. 9a), in the side frame [70–72] (Fig. 9b), or on the top [73] (Fig. 9c) to cool the air in the cavity of the façade. Fig. 9a shows an Active Thermal Manifold Skin using solar powered TEM cooling/heating for the experimental chamber. This façade is self-supported for functioning, where indoor air will be cooled or heated in the cavity with TEMs. And the side-channel designed TEM window in Fig. 9b, and the top-installed TEM window in Fig. 9c use convective and conductive heat transfer, respectively, to regulate the air temperature in the gap.

Various kinds of air-based ABEs are researched for building energy efficiency, but they are satisfying Conditions 1 or Condition 2 with diversified research methods, energy inputs, contributions, as well as restrictions. Glazing façades and windows are usually less energy-efficient compared to opaque wall systems. The incident sun light though fenestration and high U-value of glass result in huge energy consumption in buildings. From a case study on a two-story residential building with 30% of the walls covered by windows, about 60% of the total energy loss through the building envelope was observed [74]. Due to energy constraint, people’s attitude towards building façade has changed from aesthetics-oriented to energy-sensitive [75]. For Condition-1 type translucent external envelope, properly incorporated extra thermal energy source is a vital part. Table 1 presents a summary of existing air-based ABEs with their features and performances.

### 4.2. Water-based active building envelopes

Air and water are commonly used fluids for thermal storage and transfer. In some cases, due to the higher heat transfer capability and larger thermal capacity, water can improve system efficiency. According to a literature survey, there are more studies on water-based ABEs than air-based ABEs, which directly reflects the preference. For opaque envelopes, two water-based ABE prototypes prevail currently. One is active water pipe-embedded wall [30,77] and the other is water evaporative cooling wall [78].

The basic component of active pipe-embedded wall is water pipe, which must be extraordinary durable and allow heat to pass through efficiently. In addition, the pipe installation must be reliable and leak resistant, and require minimal maintenance over time. The most commonly used pipe material is high-density polyethylene or polybutylene [30]. The copper pipe and steal pipe may also be used but adequate treatments must be undertaken for corrosion prevention. When the active pipe-embedded building wall is constructed, coiled water pipe is installed within the interior layer of multi-layered wall, which is shown in Fig. 10a [79]. Different layouts for the embedded pipes are possible.
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<td>Condition 1</td>
<td>Review</td>
<td>Natural thermal energy is utilized to lower building HVAC load, but extra energy is need for thermal energy transportation, and no quantitative result was reported.</td>
</tr>
<tr>
<td>Barton, [50]</td>
<td>Cool air at night; opaque wall</td>
<td>Condition 1</td>
<td>Numerical simulation</td>
<td>Obvious thermal attenuation is observed by adopting five-core in the slab, and no experimental results are provided.</td>
</tr>
<tr>
<td>Zeiler [47,51]</td>
<td>Geothermal energy; opaque wall</td>
<td>Condition 1</td>
<td>Theoretical design</td>
<td>Promising concept to lower heat gain/loss through envelope was proposed, but experiments, simulations on energy saving potential were not reported.</td>
</tr>
<tr>
<td>Ibáñez-Puy [15,55,56,76]</td>
<td>Electric grid and thermoelectric modules; opaque wall</td>
<td>Condition 1</td>
<td>Theoretical design and experiment test</td>
<td>The system has better performance in winter conditions. System simulation model, energy evaluation is not available, and the thermal bridge problem should be addressed.</td>
</tr>
<tr>
<td>Irshad [57–59], Yusoff [60]</td>
<td>Electric grid and thermoelectric modules; opaque wall</td>
<td>Condition 1</td>
<td>Experiments and numerical simulations</td>
<td>Thermoelectric cooling/heating is used to provide cool or heated and fresh air through the envelope. System can save about 1007 kWh/year.</td>
</tr>
<tr>
<td>Fernández-Hernández [61]</td>
<td>Solar energy, and grid electric power; opaque wall</td>
<td>Condition 1</td>
<td>Numerical simulation</td>
<td>Desiccant cooling is used. In a Mediterranean climate, the maximum latent load that can be removed by the system reaches 30 W per linear meter of façade. The efficiencies range between 0.02 and 0.12 depending on the solar radiation level. There is no experimental test and model validations.</td>
</tr>
<tr>
<td>Corgnati [63], Serra [64,65]</td>
<td>Exhaust air of HVAC system and grid electric power; glazing façade</td>
<td>Condition 1</td>
<td>Experimental tests</td>
<td>Waste thermal energy is used. HVAC load reduction varies from 37% to 58% compared with a single-skin façade. System numerical model and optimizations are not available.</td>
</tr>
<tr>
<td>Avesani [66], Hallstrom [67]</td>
<td>Grid electric power and solar thermal energy; glazing façade</td>
<td>Condition 1</td>
<td>Experiment and commercial simulation program</td>
<td>Absorption cooling is used. Cooling production could reach its maximum value about 50kWh/m2 in July and EER is between 3 and 8 with its maximum in April and its minimum in December in Rome. The system optical and thermal efficiency should be improved.</td>
</tr>
<tr>
<td>Tanuhrarja [68]</td>
<td>Grid electric power and solar thermal energy; glazing façade</td>
<td>Condition 1</td>
<td>Numerical simulation</td>
<td>Evaporative cooling is used. The indoor space of an office building in hot and humid climates can be controlled to comfort temperature of 26.7 °C and relative humidity of 60%.</td>
</tr>
<tr>
<td>Gibson [69], Harren-Lewis and Zhang [70–72], Liu [73]</td>
<td>Grid electric power and thermoelectric modules; glazing façade</td>
<td>Condition 1</td>
<td>Experiments and numerical simulations</td>
<td>Thermoelectric cooling/heating is used to control glazing surface temperature. Annual performance evaluation revealed that for Maui and Hawaii climate, monthly cooling load reduction can be 45%, when compared to double pane window.</td>
</tr>
</tbody>
</table>
It can be horizontal [80] or vertical [33] (see Fig. 10b) coiled within the wall structure. For most studies, the vertical orientation received more attention. Despite the layout, the position of the pipe layer is also of importance for the system thermal performance, as shown by Niu and Yu [81].

In this pipe-embedded envelope system, high temperature cool water and low temperature hot water is used respectively in summer and winter to offset and eradicate part of cooling/heating load of the building envelope. As demonstrated in Fig. 11, the cooling or heating energy sources can be cooling tower [82–84], air source heat pump [85], solar thermal energy [33], ground water [86] and ground heat sources [87,88]. In those active pipe-embedded wall systems, only energy input for water pumps or fan power is needed for delivery of cool or heated water.

In the cooling tower involved systems [84], water is either cooled through total heat exchange in open system or through sensible heat exchange in a closed system. The efficiency of the former type depends on the wet-bulb temperature of the ambient air and the latter one is on dry-bulb temperature of air. This distinctive difference determines that open cooling tower involved active wall can be more efficient. However, the cooling tower, heat pump or solar collector integrated active wall systems are confronted with the limitation of application and operation in the cooling season to provide usable cool water. This problem can be solved by using geothermal energy [41,89]. Because the temperature of ground soil and water usually can be maintained around a stable level which is a natural cooling source in summer and heating source in winter. This can safely ensure the operation of pipe-embedded wall throughout the year. It should be noted that underground water source is not permitted to be used in HVAC systems due to environmental regulations. The issue of energy balance in annual operation for the underground soil heat source based systems must be considered [30]. The system discharge thermal energy from indoor space into ground through running water in the pipe and this part of thermal energy is then extracted from ground for usage in the winter season. The released and extracted energy should keep a balance for long term operation, without changing and damaging underground environment, as well as system efficiency. Besides the active pipe-embedded wall system using ground thermal energy (Fig. 11), there is another type of thermo-active diaphragm wall in which both the concrete elements and embedded pipes are extended into ground [90]. This is called “energy geo-structures”, which provide thermal conditioning to buildings and spaces and also to large infrastructures [91].
Based on the central idea that the system takes away or supplements excess thermal energy for building external wall, the pipe-embedded structure is also employed for minimizing heat loss from external wall independently of its orientation. Ibrahim et al. [92,93] conducted both experimental and numerical studies on a new pipe-embedded wall design by transferring solar thermal energy collected by south external wall to north wall using closed water pipe loop (Fig. 12). This system is suitable for cold or Mediterranean climate regions when northern external wall suffers numerous heat losses. Except for applications in building sector, pipe-embedded structures were also employed for graphitization furnace for the purpose of decreasing the cooling period and recovering the heat in the furnace [94,95].

The pipe-embedded wall system brings difficulties to post-installation maintenance and repair work. Moreover, it is hard to detect which part of water pipe should be replaced once water leakage occurs. This work becomes even more troublesome if this system is applied for high rise buildings. It was reported that those problems can be solved by designing an active pipe-integrated wall system in which the coiled pipe is attached onto the outer surface of the external wall [88,96] or external surface of the roof [97], or the internal surface for temperature control [98]. In a pipe-integrated wall system, the panels are connected to the outer walls of the building through a steel frame. The water pipe in this system is evacuated tube which is enclosed by curved mirrors for solar energy collection, as indicated in Fig. 13. In summer, the working principle of this wall system acts similarly to active pipe-embedded wall by using flowing water to minimize inward heat gain. In winter, the hot water is produced by solar collectors on the walls. Caponetto et al. [96] also pointed out that PV module is possible to be incorporated into this novel system for higher system performance.

Previously mentioned pipe-embedded walls utilize the sensible heat exchanges for extra heat gain or heat loss reduction. While another type of water-based ABE is named as evaporative cooling wall [99], and the latent thermal energy of water is used in this configuration to curtail indoor HVAC load in summer. The evaporative cooling wall uses water flow and water evaporation around the external surface of the building wall without support and guide for pipes. It is classified as ABE because conventional energy should be consumed to sustain system operation and water supply. In the literature, two kinds of active evaporative cooling wall are summarized.

The first type structure is a ventilated air channel combined with water sprinkling system. As indicated in Fig. 14a, the water sprinkling system can keep the wet insulation layer full of water and the natural ventilation in Fig. 14b accelerates water evaporation and cooling effect is achieved by removing the warm wet air. This process could be an effective protection against solar heat, while ensuring good insulation performance in the winter when the system is switched off [78,99–101]. In addition, the air channel can also provide cool air for indoor space [102,103] (Fig. 14b). Chan et al. [104] further proposed a combined wall system which can both cut cooling load and deliver cool and fresh air for indoor space.

The second type of active evaporative cooling wall uses an engine to drive moving wet film which covers the building roof and walls [105–107]. Usually a water tank should be available to wet the moving film. For evaporative cooling wall and roof [31,43] system, the waterproofing layer must be ensured and the water volume usage should be matched with cooling load of envelope.

As for active glazing façades, the water-based systems can be more efficient than air-based ones. This has been verified by Chow et al.
With continuous heat absorption by the flowing water in the channel formulated by external and internal glass pane, the indoor heat gain can be largely reduced [109]. The water-flow glazing window (Fig. 15a) is extensively studied by Chow et al. [108–114]. Gonzalo later integrated the water-flow window with a ground source heat pump [115,116] and showed 40% savings of cooling consumption in the summer.

The previous studies [117–119] proved that the water-flow glazing façade is simply effective and energy efficient in reducing building cooling load. Recently, another type of water-flow glazing façade was proposed by Shen and Li [120,121], who designed a new DSF with water flowing in the pipe-embedded shading blinds (Fig. 15b). The low-grade thermal energy sources can be adopted in this pipe-embedded DSF to mitigate heat flux through glazing façades.

Water-based active opaque external envelopes and glazing façades received much attention, especially for the water pipe-embedded wall system. The circulation of running water in the building envelope can effectively take away the absorbed thermal energy from sun light and ambient air. Many experiments and simulations justified the energy saving potential of this type of ABE under different climate conditions.

Since there is no study reported to incorporate energy production modules into water-based building envelope systems, all the water-based ABEs are Condition 1 type. Table 2 presents a summary of existing water-based ABEs concerning their features and performances.

4.3. Solid-based active building envelopes

Generally, three major categories are summarized for solid-based active opaque envelopes: photovoltaic (PV) [46], thermoelectric (TE) [76], and PV-TE wall or roof [12,13,25]. The PV module can change the building envelope from an energy consumer to an energy producer. Therefore, it is defined as an active system according to Condition 2 of ABE in Section 2. The TE envelope needs conventional energy electricity input for building envelope load reduction and energy saving, which satisfies Condition 1 of ABE. And the integrated PV-TE wall satisfies both Conditions 1 and 2. The relevant studies and reviews about PV wall (solar façade) [11,46,123–128] are abundant. The review of this section only focuses on the less studied TE wall and PV-TE wall.

Prieto et al. [129] concluded in their study that TE module is suitable to be integrated in building façades for cooling/heating. TE

![Fig. 14. (a) Active evaporative cooling wall [78] (b) ventilated wall cavities with spray evaporative cooling system [103].](image1)

![Fig. 15. (a) Water-flow façade [108], and (b) water pipe-embedded double-skin façade (DSF) [121].](image2)
## Table 2

### Features and Performance Analysis of Water-Based ABEs

<table>
<thead>
<tr>
<th>First Author and Ref</th>
<th>Energy Sources and Typology</th>
<th>Condition</th>
<th>Research Methods</th>
<th>Features, Performance and Restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xie [80]</td>
<td>Unspecified low-grade energy source; opaque wall</td>
<td>Condition 1</td>
<td>Numerical simulation</td>
<td>Running water in the pipe is used to reduce heat gain/loss. When pipes spacing reduced by 50 mm, inward heat flux can be reduced by 2.3 W/m². No experimental validation is reported.</td>
</tr>
<tr>
<td>D'Antoni [33]</td>
<td>Solar thermal energy; opaque wall</td>
<td>Condition 1</td>
<td>Numerical simulation</td>
<td>Embedded water pipe is used as solar collector in envelope. It reached an energy yield of 460.77 kWh/m² y and an average heat flux of 93.07 W/m² for the reference climate of Stuttgart. No experimental validation is reported.</td>
</tr>
<tr>
<td>Ibrahim [92, 93]</td>
<td>Solar thermal energy; opaque wall</td>
<td>Condition 1</td>
<td>Experiment and numerical simulation</td>
<td>It can transfer south wall absorbed energy to north wall. Annual energy saving for new house in Mediterranean climate reaches 28–43% and 15–20% for old houses.</td>
</tr>
<tr>
<td>Shen [84]</td>
<td>Cooling tower; opaque wall</td>
<td>Condition 1</td>
<td>Numerical simulation</td>
<td>Running water in the pipe is used to reduce heat gain/loss. The heat gain in Beijing can be reduced by 17.4 kWh/m². Total electricity reduction rate in Shanghai and Guangzhou are 51.9% and 58.9%.</td>
</tr>
<tr>
<td>Shen [85]</td>
<td>Air source heat pump; opaque wall</td>
<td>Condition 1</td>
<td>Numerical simulation</td>
<td>Running water in the pipe is used to reduce heat gain/loss. 84% of the heat transfer on the internal surface can be reduced, whereas the heat dissipation on the external surface increased by only 18% in Beijing.</td>
</tr>
<tr>
<td>Snijders [86]</td>
<td>Groundwater; opaque wall</td>
<td>Condition 1</td>
<td>Analytical analysis</td>
<td>Seasonal thermal energy storage in aquifers is adopted. No detailed energy performance is specified.</td>
</tr>
<tr>
<td>Li [87]</td>
<td>Ground heat sources; opaque wall</td>
<td>Condition 1</td>
<td>Numerical simulation</td>
<td>Ground thermal energy is used to cool or heat wall. Peak cooling load reductions in 4 cities in China (Tianjin, Shenyang, Kunming and Wuhan) range from 9% to 45% as the number of GSHEs varied from 1 to 12. Lack of experiments.</td>
</tr>
<tr>
<td>Meggers [88]</td>
<td>Ground heat sources; opaque wall</td>
<td>Condition 1</td>
<td>Experiment and numerical simulation</td>
<td>Ground thermal energy is used to cool or heat wall. Total electricity consumption can be reduced by 15% compared to static insulation.</td>
</tr>
<tr>
<td>Romaní [41, 89]</td>
<td>Ground heat sources; opaque wall</td>
<td>Condition 1</td>
<td>Experiment</td>
<td>Ground thermal energy is used to cool or heat wall. The energy saving ratio reaches 54–82% in cooling season and 20–41% in heating season. Lack of numerical modeling.</td>
</tr>
<tr>
<td>Caponetto [96]</td>
<td>Solar thermal energy; opaque wall</td>
<td>Condition 1</td>
<td>Numerical simulation</td>
<td>A water pipe is used on the external side of envelope to produce hot water and reduce HVAC load. This system can reduce heating and cooling load by 45% and 25% respectively. Lack of experimental validation.</td>
</tr>
<tr>
<td>Sodha [97]</td>
<td>Unspecified thermal energy sources; roof</td>
<td>Condition 1</td>
<td>Analytical simulation</td>
<td>Running water is used to reduce heat gain in summer. The heat flux is reduced, and heat collection area increases.</td>
</tr>
<tr>
<td>Craig [98]</td>
<td>Unspecified thermal energy sources; opaque wall</td>
<td>Condition 1</td>
<td>Experiment and analytical calculation</td>
<td>A water circuit is integrated at internal surface to remove heat. No concrete conclusion is reported for energy saving potential.</td>
</tr>
<tr>
<td>Naticchia [99], He [101]</td>
<td>Unspecified thermal energy sources; opaque wall</td>
<td>Condition 1</td>
<td>Experiment and numerical simulation</td>
<td>Water sprinkling and evaporation is used to cool the surface of wall. The wall temperature can be 10 degrees lower than the reference system; daily building cooling load was reduced by 30–40%.</td>
</tr>
<tr>
<td>Ghosal [105], Butera [106], Sodha [107]</td>
<td>Water tank; opaque wall or roof</td>
<td>Condition 1</td>
<td>Experiment and numerical simulation</td>
<td>Moving wet film is used to cool building surface. Room air temperature is reduced by 2–6°C in shaded condition in comparison to un-shaded condition.</td>
</tr>
<tr>
<td>Chow [108–111, 113, 114], Lyu [122]</td>
<td>Water tank; glazing façade</td>
<td>Condition 1</td>
<td>Experiment and numerical simulation</td>
<td>Running water goes through gap of glazing to reduce thermal load. It can reduce up to 22–35% of HVAC load annually for a range of feedwater flow rates.</td>
</tr>
<tr>
<td>Gonzalo [115, 116]</td>
<td>Geothermal energy source; glazing façade</td>
<td>Condition 1</td>
<td>Experiment and numerical simulation</td>
<td>Window and ground heat exchanger is coupled. The cooling in summer can save 10%.</td>
</tr>
<tr>
<td>Shen [120, 121]</td>
<td>Cooling tower; glazing façade</td>
<td>Condition 1</td>
<td>Numerical simulation</td>
<td>Pipe embedded blinds are used to reduce heat gain. Cooling water averagely takes away about 50% of the solar radiation directly and the average solar energy transmittance is only 13%.</td>
</tr>
</tbody>
</table>
module can be viewed as a compact solid heat pump transporting thermal energy between indoor and outdoor environments with inputting direct electric power. The early configuration of TE wall can be traced back to 1995 in a US Patent named “Superinsulation Panel with Thermoelectric Device and Method” [130]. As shown in Fig. 16a, the TE module #54 is sandwiched between heat sink #50 and #70 for heat dissipation and cool energy delivery. The element #80 is called cold finger connecting TE module and heat sink for heat conduction. The remaining parts of the wall are insulated to prevent heat losses. This system was later revised and redesigned by Ibáñez-Puy et al. [76], as shown in Fig. 16b in which an air duct is designed for heat dissipation in summer and heat collection in winter.

The TE wall still needs electric power to control the surface temperature of the building wall and the PV module can transform solar energy into electricity. The early fabrication of PV-TE wall is depicted in a 2003 US Patent named “Composite thermal system” [131]. And this system is further investigated by the research group led by Steven Van Dessel in terms of heat transfer [25], design optimization [132], economic analysis [133], system control [134] and life cycle assessment [135]. In this PV-TE system (Fig. 16c), a PV panel is installed vertically on the external wall leaving a channel for heat dissipation from heat sink in summer. The TE effect can also be used to generate electric power from temperature differences between the two end sides. This technology is more suitable to be deployed on roof top [136–138].

Furthermore, the PV-TE wall system can be integrated with wind mills [139] to provide extra fresh cool air or use water-cooled methods to dissipate heat in a compact new design [140]. In order to transfer cool or heat energy for indoor space, a new terminate device for TE radiant cooling/heating is proposed by Liu et al. in a newly designed active PV-TE wall [141,142]. An array of TE modules are attached to the back surface of a radiant panel [143,144], which can provide extra radiant cooling in summer, and heating in winter (Fig. 13d) [12,13,34,145].

Currently, only the small-sized heat pump TEM is suitable to provide cooling/heating energy for solid-based active glazing façades. Usually an array of TEMs is attached to the surface of window frames [146] or window glass panes [147]. There are mostly two types cited in the literature: 1) Steven and Benjamin [147] adopted the structure that TEMs are located within the gap of double-glass windows, and closely attached to the surfaces of both external and internal glass panes; 2) [148,149] directly embedded TEMs in the window frame and install heat sink at the cold and hot side of TEMs. Xu and Steven [150,151] further added a water-pipe as a thermal storage tank for TEMs. The above mentioned TEM-embedded windows are operated by inputting

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Fig. 16. (a) TE wall system in US patent [131]; (b) TE wall system in winter (left) and summer (right) [76]; (c) Active PV-TE wall system [25]; (d) Building integrated photovoltaic thermoelectric wall [34].
Different from PV cells, thermoelectric generator (TEG) façade is not included but can be found in other literature outside the scope of present review study, the discussion on performance of PV window/translucent façades includes electrochromic (EC) glazing, TE windows, and solar heat gains by a low voltage control [162]. Unlike EC windows, TE windows can control the heat gain/loss with little influence and solar heat gains by a low voltage control [162]. Unlike EC windows, TE windows can control the heat gain/loss with little influence and solar heat gains by a low voltage control [162].

As shown in Table 3, the Condition-1 type solid-based opaque ABEs are nearly all realized by adopting thermoelectric cooling/heating. It is either powered by the grid or connected to PV modules. The solid-based translucent façades include electrochromic (EC) glazing, TE windows, and PV-TE windows. Those three technologies all need electric power input, and EC coatings can simply modulate the transmitted light, glare, and solar heat gains by a low voltage control [162]. Unlike EC windows, TE windows can control the heat gain/loss with little influence on glazing transmittance.

As for Condition-2 type opaque ABE, PV façade prevails in the built environment, acting as an energy producer. Limited by the content and scope of present review study, the discussion on performance of PV façade is not included but can be found in other literature [11,124–126]. Different from PV cells, thermoelectric generator (TEG) can take advantages of waste heat and recycle it to usable electric power without mechanically moving components. As for translucent façades, the popular semi-transparent PV glazing and the emerging TEG windows are two major prototypes. PV glazing can harvest solar energy in site, and curtail indoor solar heat gain at the same time, and its thermal and electrical performances can be found in extensive published literature [44]. Meanwhile, power generation by TEG is dependent on temperature difference. The on-going materials science research is going to push the boundaries, and offer better solutions for energy related engineering problems.

4.4. Kinetic active building envelopes

There is another group of ABEs which does not need working medium, but they can proactively change, adjust, and transform the building shell to control solar heat/light penetration, natural ventilation or even generate power. Within the scope of current study, it is called kinetic active envelope although it also known as adaptive [164], responsive façade, dynamic envelope, intelligent building, reconfigurable architectural structure [165], retractable and dismountable configurations, or smart envelope [42] in some other literatures. Therefore, façades can now sense the environment and make their own adjustments in order to achieve the targeted goals [166].

The fundamental concept of kinetic architecture can be traced back to the 1970s work “Kinetic Architecture”, by Zuk and Clark [167]. They defined this genre of architecture as being adaptable to the changing environmental conditions (not only to climate) and pragmatic needs. In some other literatures, kinetic structures in architecture can be defined as buildings and/or building components with variable mobility, location and/or geometry [168], i.e. portable buildings like caravans, tents and prefabricated barracks [169]. The kinetic façade can be operated in the ways of folding, sliding, expanding, and transforming in both size and shape. The means may be, among others, pneumatic, chemical, magnetic, natural or mechanical actuation systems [168]. Typical examples are revolving restaurants on tops of buildings, sliding roofs of soccer stadiums, and artistic monuments [165].

Hanaor and Levy [42] made a comprehensive review on kinetically deployable envelope structures. In their study, kinetic structures are classified into lattice or skeletal structures, and continuous or stressed-skin structures. In addition, kinetic structures can also be classified into four groups in respect to their structural forms: spatial bar structures consisting of hinged bars, foldable plate structures consisting of hinged plates, strut-cable and membrane structures [42]. While in terms of major function, kinetic active walls are designed for (1) decreasing or increasing solar heat and light penetration, (2) utilizing natural ventilation, and (3) power generation [170], which are within the scope of ABE concept in this study.

Foged et al. [19] proposed and designed a kinetic wall prototype, primarily based on a ‘shape morphing hinged truss structure’...
Table 3
Features and performances analysis of solid-based ABEs.

<table>
<thead>
<tr>
<th>First author and Ref</th>
<th>Energy sources and typology</th>
<th>Definition type</th>
<th>Research methods</th>
<th>Features, performance and restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ibáñez-Puy [76]</td>
<td>Grid electric power; opaque wall</td>
<td>Condition 1</td>
<td>Theoretical design</td>
<td>Thermolectric modules are used to cool surface temperature through conduction. No experiments nor simulations are reported.</td>
</tr>
<tr>
<td>Khire [25,132]</td>
<td>Solar energy; opaque wall</td>
<td>Condition 1 and 2</td>
<td>Analytical simulation</td>
<td>PV cells are used to produce electricity power for TE modules. Configuration involving 20 TE coolers of CP1.0-17-05L type was found to be optimal for the generic enclosure.</td>
</tr>
<tr>
<td>Maneewan [136,137]</td>
<td>Solar thermal energy; roof</td>
<td>Condition 2</td>
<td>Experiment and commercial software simulation</td>
<td>Thermoelectric is used for power generation. The system can generate up to 9 W with area of 0.0525 m² and annular energy saving is 3623 Wh. Energy payback time is 4.36 years.</td>
</tr>
<tr>
<td>Tsai [139]</td>
<td>Solar energy; opaque wall</td>
<td>Condition 1 and 2</td>
<td>Experiment and numerical</td>
<td>PV cells are used to produce electricity power for TE modules and using wind mills to provide fresh air. Internal surface temperature of wall can be reduced by 4-5 °C.</td>
</tr>
<tr>
<td>Liu [141,142,163], Luo [13,34,145]</td>
<td>Solar energy; opaque wall</td>
<td>Condition 1 and 2</td>
<td>Experiment and numerical simulation</td>
<td>Semi-transparent PV cells are used to power TE modules. Overall system can provide 35–45 W effective energy to condition the temperature of the room. Overall efficiency is 5% in cooling mode and 13% in heating mode.</td>
</tr>
<tr>
<td>Xu [146,150,151], Harren-Lewis [152]</td>
<td>Solar energy; glazing façade</td>
<td>Condition 1 and 2</td>
<td>Experiment and numerical simulation</td>
<td>The opaque PV cells are sparsely distributed to make glazing semi-transparent. Power decreased about 0.48% (in standard test conditions with the exception of the temperature condition) and 0.52% (in outdoor conditions, under 500 W/m²) per 1 °C increase of the PV module temperature. The PV cell is semi-transparent. Energy saving potential of the optimized PV glazing was 25.3% and 10.7%, respectively, compared to the single clear glass window and the Low-E glass window.</td>
</tr>
<tr>
<td>Dessel [147]</td>
<td>Grid electric power; glazing façade</td>
<td>Condition 1</td>
<td>Experiment</td>
<td>TE modules are used to cool/heat glazing pane. The system COP is around 0.5–1.0. Energy saving potential should be carried out.</td>
</tr>
<tr>
<td>Park [153]</td>
<td>Solar energy; glazing façade</td>
<td>Condition 2</td>
<td>Experiment</td>
<td>PV cells are attached on the blinds. Ventilation can reduce PV cell temperature by 20 °C and reach better efficiency at 11.7%. Power generation and electrical energy savings in the test room were about 32% more and 35% less, respectively, than those in reference room.</td>
</tr>
<tr>
<td>Wang [154]</td>
<td>Solar energy; glazing façade</td>
<td>Condition 2</td>
<td>Experiment and commercial software simulation</td>
<td>PV cells are used as shading blinds in glazing façade. This system can save about 12.16% and 25.57% of energy in summer compared with conventional DSF with and without shading blinds.</td>
</tr>
<tr>
<td>Kang [158], Kim [159]</td>
<td>Solar energy; glazing façade</td>
<td>Condition 2</td>
<td>Experiment and commercial software simulation</td>
<td></td>
</tr>
<tr>
<td>Luo [160,161]</td>
<td>Solar energy; glazing façade</td>
<td>Condition 2</td>
<td>Experiment and commercial software simulation</td>
<td></td>
</tr>
</tbody>
</table>
functioning with local shape changing linear actuations driven by electricity. The open-closed elements shown in Fig. 18a in the façade structure can control the solar heat and light intake according to occupancy demands and thermal environment conditions. Solar energy is beneficial to indoor environment in winter but not desired in summer. The reconfigurable kinetic façade can better absorb solar energy in winter and serves as a shield in summer, which is totally different from previously mentioned air-based or solid-based active walls to cool or heat envelope in different seasons. New materials like electro active polymers can be applied in kinetic structures because the shape of this material can be controlled by electricity [171], which was also designed to realize dynamic and controlled ventilation [172]. Additional kinetic façades can be found in [170,173].

Instead of changing the shape and structure of external façade, the orientation of the Rolf Disch’s rotating Heliotrop in Freiburg, Germany [3,18] (Fig. 18b) can be altered via a powerful engine. One-half of the building is highly glazed and the other side is well insulated. The building orientation is therefore controlled in response to the sun. Similar to PV walls, small scale wind turbines integrated into buildings can also be defined as kinetic active walls [174] because they can transform buildings into energy producers. One case is the COR Building in Miami, the Greenway Selfpark Garage in Chicago (Fig. 18c).

In order to optimize the kinetic active wall system response to thermal environment and to achieve the best building performance and energy saving of indoor HVAC devices, it is indispensable to use adaptive control, systems of sensors, actuators, signal processors, etc. As for wind power integrated buildings, the economics and regulatory issues, severe noise issues and the ability to match the structural and aesthetic integrity of buildings should all be seriously considered in system design [170].

Kinetic glazing façades require a transformative, controllable glazing shell which can adapt to changing external environment conditions. Except for large-area glazing façades, most of glass windows are kinetic because they can be opened according to people’s need for natural ventilation. The collapsible shading blinds device is commonly used as auxiliary glazing façades. The radical design for transformative glazed components is rare and not necessary to improve envelope performance, but the multilayer glazing with shading louver is a convenient adaptive system to external environments. Within the study by Tzempelikos et al. [176], shading devices are highly influential for optimized energy performance of buildings. These shading devices, once integrated into the design of façades, could reduce the solar heat gains, block undesirable direct sunlight and mitigate glare.

New technologies and better integration strategies provide the impetus to continually change the perception of glass façades from “energy losers” to “energy managers” and ultimately to “energy suppliers” [177]. The previously reviewed air-based, water-based and solid-based active glazing façades can function as “energy suppliers”, while the kinetic glazing systems are more likely to act as “energy managers”. The motorized shades integrated glazing façades [178] can improve the amount of available daylight compared to fixed solar shading devices and can dynamically manage direct solar gain. This will result in the reduction of artificial daylighting energy use and potentially improve thermal comfort. This was verified by the investigation conducted by the Lawrence Berkeley National Laboratory (LBNL), in a post-occupancy monitored evaluation of Automated Shading in the New York Times Building [179]. In the research implemented by Liu et al. [180], simulation and experimental results indicated that about 60% energy savings can be made by controlling shutters and blinds compared to static façades. Additionally, motorized shading blinds can be coupled with electrochromic windows under a central control network [181], and allow a balanced control and management for both indoor daylighting requirements and cooling load reduction.

In Table 4, numerous innovative concepts were introduced for kinetic façades, but the relevant detailed energy performance related experiments and simulations are not available. Most of them are still in the conceptual stage. Some studies provided investigations of kinetic façades in depth which are only limited to shadings and overhangs, mostly on Automated Venetian Blinds [22,178,179]. There is still an important knowledge gap to understand kinetic façades in terms of engineering perspective.

According to the concept of ABE, the kinetic translucent envelope also refers to a controllable, transformative building shell which can adapt itself to dynamic thermal and lighting environments. Currently, motorized shading blinds or roller shade devices are popular and widely researched kinetic translucent envelopes. The central concern is the
problem of energy performance, occupant comfort and satisfaction with the indoor environment, and impacts on maintenance and operations.

5. Outlook and recommendations

In this sub-section, some limitations for the current state-of-the-art research on ABEs and suggestions for future development in this field are given.

- Specific limitations for current ABEs:
  1) Except for the TE air-based opaque envelope systems [57–59], research on other types of air-based opaque and translucent envelope systems requires further investigations. Geothermal active building envelopes [47,51] can effectively utilize low-grade energy source but no supporting field experiments or simulations are available. Active façades with Peltier cells were implemented in theoretical designs [56], but no detailed energy model or experimental investigations are currently available. In the literature, research on new desiccant channel integrated façades [61] and sorption collector integrated glazing façades [66] are studied by numerical simulations but experimental validation and further energy efficiency analysis remains to be done [182].

  2) Water pipe-embedded walls, water film roof and water flow window systems have been extensively studied experimentally and numerically in terms of thermal performance evaluation, parametric and sensitivity analysis, optimization etc. Nevertheless, future work in this area should focus on engineering challenging that will support real applications of these ABEs. The system performance of ventilated wall cavities with spray evaporative cooling system [99,103] should be further explored by considering system application region and the corresponding system efficiency.

  3) The TE and PV modules are the main components for design either as a thermally active controlled envelope, or as a power generation envelope. This type of ABE has shown its energy saving potential in different studies, and there is an increasing interest on building integrated TE and PV envelopes [12,13,183]. However, the critical need for these systems is the optimization of system performance [184–186] to lower costs and provide higher outputs. The pioneering research and recent advances in materials science may address these needs through close collaboration with civil engineers.

- General suggestions for future ABEs:
  1) To achieve high-performance building envelopes, the redesign and optimization of current ABEs should be further investigated. It is possible to design and build new types of ABEs upon relatively mature active building technologies, such as the water-pipe embedded venetian blinds system, which originates from water pipe-embedded active wall systems.

  2) A holistic study and development on integrated ABE design is suggested because the majority of publications in the literature only focus on one single type of building envelope (either active building wall or window), without taking into account the entire building by using different sorts of ABEs. The latter may provide solutions toward “Positive-Energy” buildings which is a concept that can achieve higher energy performance and go beyond “Zero-Energy” buildings.

  3) High-performance simulation tools for newly emerging ABEs should be developed to efficiently address energy issues in buildings. The highly flexible and compatible simulation modules and codes may provide big contributions to the field by...
upgrading commercially available simulation packages.

4) One critical question is the actual energy performance and efficiency of different ABEs comparing with existing passive systems. Although certain ABEs can be claimed as highly efficient nowadays, they still need to be confirmed by theoretical analyses, and compared to some passive systems (used as benchmark). There is currently a huge knowledge gap in this area.

5) It should be noted that both active and passive envelope systems are crucial to the energetic, structural, and architectural aspects of buildings. It is highly suggested to research hybrid technologies and solutions by combining both active and passive strategies in the specific building design, control and optimization.

6. Conclusions

In this review, ABE technologies are presented and discussed to improve building energy performance. This review contributes to the general knowledge on ABEs, and the major valuable results are as follows:

1) One of the most important contributions of this study is the effective definition for ABEs based on two conditions: The ability of lowering cooling/heating loads in buildings, and performing energy transformation as the key judging factors. This description provides an up-to-date and precise definition that covers new advancements in ABEs, as well as offering a unified concept to eliminate the mis-interpreted criteria of a class of similar building envelope systems such as adaptive façade, smart façade, advanced building envelope, etc. By proposing the definition with two explicit judging conditions, the ABE systems can be strictly distinguished from passive envelope systems, leaving no ambiguous and vague evaluation. More importantly, designers and engineers can have a clear goal for which type of ABE they intend to fabricate and optimize based on those two conditions.

2) Based on the proposed definition, a preliminary statistical analysis on publications related to ABEs was carried out. The results show that the number of publications on ABEs has drastically increased since 2000. But using the publications of general building envelopes as benchmark, the ratio of ABEs over general building envelopes tend to be about 18%. In addition, it is found that nearly half of the studies are from China and USA, and most of them are within the last 10 years. Considering the research method for ABEs, about 50% of researchers adopted numerical simulation tools, which confirmed the importance of building simulation techniques.

3) This study reviewed four general types of ABEs, namely air-based, water-based, solid-based and kinetic façades. The proposed classification can better cover all types of ABEs following the new definition, which entirely covers the features of different ABEs. This review gives a complete and state-of-the-art summary of existing ABE technologies based on their working mechanisms. In addition, the performances of ABE systems are discussed in detail to provide not only a basic understanding but also their evaluation.

Furthermore, the limitations of present studies on ABEs, and some general suggestions for future developments are presented for the consideration of a broad range of scientists, engineers and researchers in the building sector and beyond. This can be largely beneficial for further development of ABEs and support energy savings in buildings.

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