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Review

Building Applications, Opportunities and Challenges of Active Shading Systems: A State-Of-The-Art Review

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Abstract: Active shading systems in buildings have emerged as a high performing shading solution that selectively and optimally controls daylight and heat gains. Active shading systems are increasingly used in buildings, due to their ability to mainly improve the building environment, reduce energy consumption and in some cases generate energy. They may be categorized into three classes: smart glazing, kinetic shading and integrated renewable energy shading. This paper reviews the current status of the different types in terms of design principle and working mechanism of the systems, performance, control strategies and building applications. Challenges, limitations and future opportunities of the systems are then discussed. The review highlights that despite its high initial cost, the electrochromic (EC) glazing is the most applied smart glazing due to the extensive use of glass in buildings under all climatic conditions. In terms of external shadings, the rotating shading type is the predominantly used one in buildings due to its low initial cost. Algae façades and folding shading systems are still emerging types, with high initial and maintenance costs and requiring specialist installers. The algae façade systems and PV integrated shading systems are a promising solution due to their dual benefits of providing shading and generating electricity. Active shading systems were found to save 12 to 50% of the building cooling electricity consumption.

Keywords: active shading systems; kinetic shading devices; smart glazing; rotating shading systems; folding shading systems; photovoltaic (PV); solar collector; algae façade system; controls

1. Introduction

Daylighting in buildings provides multidimensional benefits that have been widely reviewed in the specialized literature [1]. The provision of daylight through building openings permits views to the outdoors [2], which concurrently contributes to visual [3], psychological comforts [4], health [5], and productivity [6]. Additionally, optimum daylighting design strategies reduce reliance on artificial lighting and lessen energy consumption [7,8]. Although daylighting has many benefits, it has however undesirable side effects such as heat gain and glare [9]. Therefore, successful daylighting designs will consider the use of shading devices to reduce glare and excess heat gain in buildings [10]. Shading devices are used in buildings to provide a healthy balance by reducing the excessive glare and heat gain and providing privacy [11].

1.1. Passive versus Active Shading Systems in Buildings

Fixed shading devices are a prominent feature in vernacular architecture. They are often designed in response to environmental conditions using locally available materials such as clay, tree branches, concrete, wood planks, bamboo and others to shade the buildings from direct sunlight [12–15]. The modern architectural movement dismissed these strategies until the 1970 energy crisis, which triggered a renewed interest in passive design strategies as well as pressing for advanced solutions [16].

Conventional static passive shading devices are often categorized first as internal or external based on location of the system [11]. The performance of shading devices including overhangs [17], external roller shades [18], Venetian blinds [19] and internal shadings [20] were investigated in several studies. Furthermore, fixed external shading devices have been widely known as an effective way of controlling heat gain and glare in buildings and reducing cooling energy and cost reductions in different climatic conditions [21–23]. By comparison, external shading devices are more effective than internal shading devices since they are more efficient in decreasing the cooling loads of buildings in hot climate regions [11]. Fixed shading devices have, however, their limitations, the most important of which is their inability to adapt to the external conditions variations as well as blocking the view to the outside [24].

At the other end of the spectrum, active shading strategies try to achieve a balance between sufficient daylighting levels, providing solar protection, energy balance and enabling the occupants with the flexibility to control the shading devices according to their evolving needs [25]. Active shading devices are systems that tend to change their properties in response to exterior climate and interior requirements [26]. The use of active shading systems decreases the undesirable solar heat gain, increase daylight, provide control for the users, may generate on-site energy and increase the use of natural ventilation [25,27,28]. The active systems can be within the glazing of the openings or as an exterior shading system. This is usually achieved through the use of smart glazing technologies [29–31], sensors and control systems [32,33], or through the application of smart dynamic shading devices [34,35].

1.2. Aim of the Review Paper and Objective

The main objective of this paper is to establish the extent of knowledge acquired on the subject through a review of the different emerging types of active shading systems and their applications in buildings. The three major types of active shading systems are reviewed; smart glazing systems, automated active (or kinetic) shading systems and shading systems that incorporate renewable energy. The types of control systems and mechanism used in active shading systems were then reviewed, as they are different and have implications on performance. Finally, the review assesses their potential, limitations and opportunities for further development and improvement.

The search process consisted of identifying studies with a search strategy across Science-Direct database and Google Scholar. The initial search keywords used were active shading systems, smart glazing, kinetic shading systems, integrated renewable energy and shading systems and it yielded more than 500 papers. However, the papers that were eligible after pre-selection focused on electrochromic (EC) glazing, suspended particle devices (SPDs), liquid crystal devices (LCDs), rotating shading systems, folding shading systems, PV integrated shading systems, algae façade systems and solar collector integrated shading systems. Further focused search considered the types of shading systems along the following related keywords; design principles, types, working mechanism, performances and application in buildings and resulted in a 165 direct relevant papers investigated in this review.

2. Active Shading Systems

Active or responsive shading systems, also called dynamic or kinetic shading systems, are often designed to respond to one or multiple environmental situations including: daylighting control [36], solar thermal control, ventilation control, and in addition sometimes energy generation [37,38].

The application of active shading systems is an important step towards improving the energy efficiency in the built environment [39]. By using active shading systems, buildings tend to adapt to evolving external conditions [39,40]. These systems can allow or block solar radiation access into the interior space by adjusting a device installed either inside or on the building skin.

Active shading systems can be classified into three main categories: the first one comprises: (i) the glazing in the form of smart glazing or as (ii) kinetic external shading devices or as (iii) shading devices that incorporate renewable energy generation. These main systems are the target of this review. First, smart glazing devices include suspended particle devices (SPDs), electrochromic (EC) devices and liquid crystal devices (LCDs). The second type of active shading is the kinetic external shading systems. This review considers mechanically movable dynamic shading systems which include the rotating and folding shading systems. The third type is the integrated renewable energy shading systems. The integration of renewable energy can be achieved by using photovoltaic panels (PV) attached on shading devices [41], or by using algae façade systems which can generate electricity [42], or through solar collectors attached on shading systems [43]. The active shading systems types reviewed in this study are shown in Figure 1.

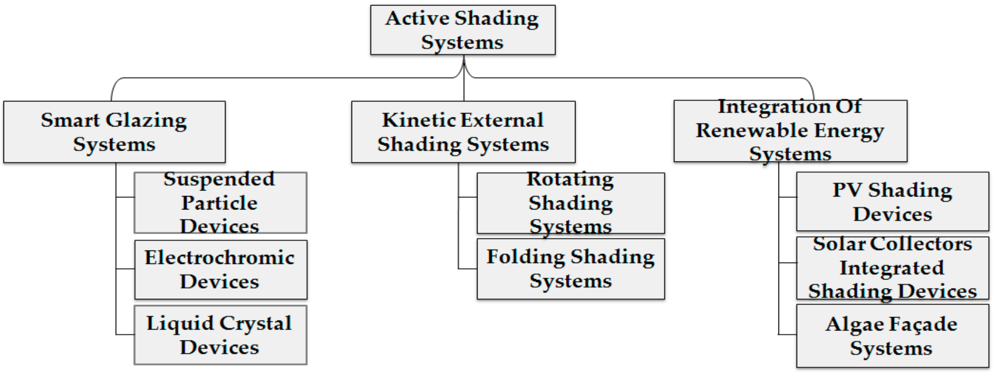


Figure 1. Active shading systems classification diagram.

2.1. Smart Glazing Systems

Windows with dynamic optical properties are a form of building shade. Smart glass, often called smart windows, is defined to be the glass whose light transmission properties are altered when voltage, light or heat is applied, by changing from translucent to transparent [44].

The function of a smart window is to control the transmission of light into and out of the glazing system, according to occupants' comfort. Smart windows can also regulate lighting and heating levels for energy load management. Smart glass technologies include SPDs, EC devices and LCDs [45]. Installing smart glass in buildings' envelope, is similar to creating climate adaptable building shells, in which costs for heating, cooling and lighting are reduced [46,47]. Additionally, smart glass prevents 99.4% of ultraviolet light, which reduces furniture and curtain fabric fading [44,45]. The three systems require transparent conductors as electrical contacts.

SPDs tend to rapidly switch from a dark bluish-black state to a clear greyish appearance when voltage is applied to control the amount of light, glare and heat passing through [48].

The EC devices use a technology that utilizes an electrical voltage to control the amount of light passing through the glass [49]. ECs offer dynamic and responsive control that responds to the external changing conditions and controls visible transmittance, reduce glare and improve indoor light environment when compared to regular and low-E glass. Additionally, when compared to the fixed shading devices, they offer a dynamic solar radiation and do not block the view [49,50].

LCDs use liquid crystals that dissolve into a liquid polymer they will, in turn, solidify. The liquid crystals are randomly arranged in the droplets, resulting in scattering of light as it passes through the smart window assembly and forming a translucent film [51].

The performance of smart glazing is first evaluated through the transmittance modulation range in the visible and whole solar spectrum. Secondly, the expected lifetime and number of achieved cycles is considered. Finally, its size as the larger the devices, the longer the switching time for coloration and bleaching of the glass [45]. Smart glazing acts differently during the transparent and opaque phases to control the transmitted solar radiation.

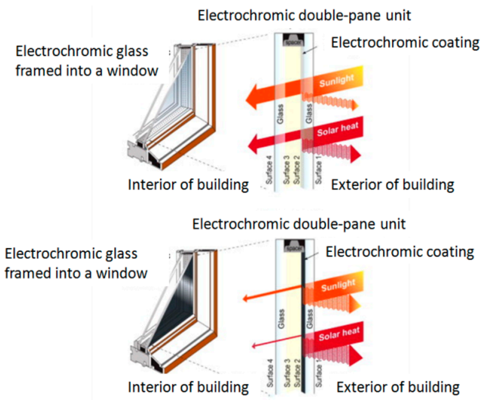
The design principle, types, working mechanism, diagrams, special features and benefits of the three types of smart glazing are summarized in Table 1.

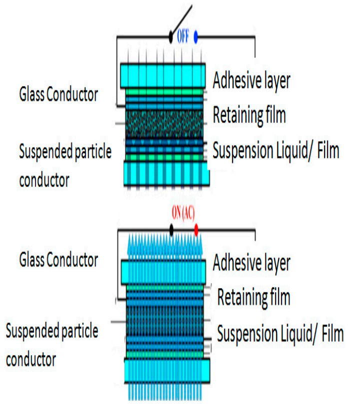
The performance of smart glazing devices is indicated by several factors, such as the electrical, optical and thermal properties that depend on the structural composition and configuration of the EC device itself. Typically, the required performance parameters include the specification of: (1) switching speed; (2) switching voltage; (3) optical reflectance; (4) color rendering; (5) solar heat gain coefficient; (6) optical memory coefficients; (7) thermal transmittance; (8) optical transmittance coefficients; (9) lifetime and (10) operating temperature [44,52]. The performance of the three types of smart glazing systems is summarized in Table 2 according to the climatic conditions while highlighting the main variables addressed in the studies.

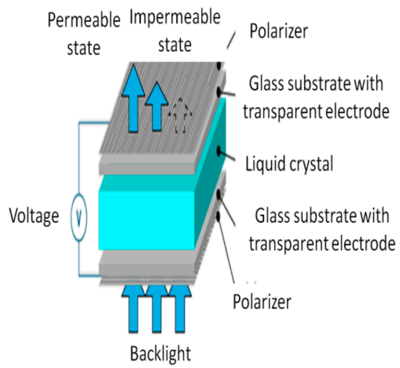
Table 1. Summary of smart glazing types.

System	Electrochromic Glazing (EC)	Suspended Particle Devices (SPDs)	Liquid Crystal Devices (LCDs)
Design Principle	• EC glazing is 1µm thick of purely ionic conductor placed between electrochromic and counter electrode layers that are placed between transparent electrical conductor layers [53]. • Change optical properties by switching between their oxidized and reduced forms [45].	• SPDs consist of 3–5 layers by which the active layer contains needle-shaped dipolar particles of polyiodides [54]. • Particles are less than 1 µm in linear size [55]. • The size of the particles is usually less than 200 nm to minimize light scattering and avoid non-desired haze [48].	• LCD consist of liquid crystal material positioned between two sheets of glass [56]. • LCD has field sequential color displays that uses red (R), green (G), and blue (B) light emitting diodes (LEDs) without noticeable color breakup [57].
Types and Materials	• Conventional Electrochromic (CEC) glazing [58]. • NIR switching electrochromic (NEC) glazing [59]. • "Dual-band" electrochromic (DBEC) [60].	• Evacuated vacuum SPD [61].	• Polymer-stabilized blue phase (PSBP) [62]. • Polymer-dispersed LC (PDLC) reported [63]. • Liquid crystal on silicon (LCoS) displays [64]. • Optically isotropic LC (OILC) [62]. • Gel dispersed liquid crystals (GDLC).
Working Mechanism	• EC glazing has a visible light transmission of 62% and allows 47% of the incident solar energy to the building interior in the clear state [52]. • Amount of incident solar energy going inside the building is reduced by 81% when a low DC voltage is applied [65]. • Solar irradiation is absorbed when the films are tinted. • Thermal energy is re-radiated based on the emissivity's of the films and the glass [65].	• During the "off" state, the SPDs are randomly oriented and absorb/scatter visible light [48]. • Then SPD shows a bluish-black dark color. • The scattering effect is due to the particles and is most prominent at short wavelengths. • During the "on" state the electric field is applied and the particles line up perpendicularly to the substrates. • Then, more light is allowed to pass through to increase the transmission [48].	• Liquid crystal molecules are aligned in parallel with the glass surface [56]. • When voltage is applied, the direction is changed and they become vertical to the glass surface. • Then light passes through the droplets with very little scattering and resulting in a transparent state. • The quantity of light transmission can be controlled by combining the motion of liquid crystal molecules and the direction of polarization of two polarizing plates attached to the both outer sides of the glass sheets [56].

Table 1. *Cont.*

<table>
<tr><th>System</th><th>Electrochromic Glazing (EC)</th><th>Suspended Particle Devices (SPDs)</th><th>Liquid Crystal Devices (LCDs)</th></tr>
<tr><td>Composition Diagram</td><td>

[52] Reproduced with permission from Elsevier and Copyright Clearance Center, 2017.</td><td>

SPD in "off" and "on" states [48] Reproduced with permission from Elsevier and Copyright Clearance Center, 2017.</td><td>

[56] Reproduced with the permission from Japan Display Inc, 2017.</td></tr>
<tr><td>Special Features</td><td>

- Applied on large-size glazing [66].
- Switching speed is influenced by environmental conditions and glazing area. The coloring takes longer time than bleaching [53,67].
- Electrically actuated EC glazing absorbs Infra-red spectrum of solar radiation [68].
- The higher the glazing surface temperature, the lower the power required to switch [69].
- A typical EC have visible transmission of $Tv = 0.65 - 0.50$ and fully colored transmittance of $Tv = 0.25 - 0.10$ [44].
- The shading coefficient (SC) is about $SC = 0.67 - 0.60$ for the bleached condition, and $SC = 0.30 - 0.18$ for the fully colored condition [70].

</td><td>

- There is no memory effect for the optical properties and the electric field must be maintained for keeping the SPD transparent [48].
- The light transmission of SPDs is controlled by the application of high amplitude alternating current voltage (AC) [48].
- Controls only the visible solar spectrum and transmit Infra-red (IR) spectrum [44].
- Over all heat transfer of 5.9 W/m^2 K [71].
- Solar heat gain coefficient change from 0.05 to 0.38 [72].

</td><td>

- At opaque state, LCD glazing scatters the light, become haze, and provides no control of Near-IR [44].
- Operating voltages are in the range of 20–100 Vrms to maintain the clear state of the device [73].
- This technology is used in interior and exterior settings for privacy control.
- The visible transmittance range is typically 50–80% and the solar heat gain coefficient (SHGC) is 0.55–0.69 [74].

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Table 1. *Cont.*

System	Electrochromic Glazing (EC)	Suspended Particle Devices (SPDs)	Liquid Crystal Devices (LCDs)
Benefits	• Requires power only during switching, where they consume a low voltage to switch usually 1–5 V. • Constant dimming and most designs have long-term memory usually 12–48 h [44,53]. • Has a low energy consumption, usually 8 W/m^2, and becomes almost zero when they are kept at constant conditions, due to their considerable open circuit memory [75]. • Coloration phases are virtually infinite and are capable of blocking both direct and diffuse solar radiation [52]. Improves the daylighting of buildings and offices, which leads to significant cost savings and improve labor productivity [50].	• SPD glazing is the most suitable among other types of glazing for building application. • Can connect directly with AC main power supply without the need for conversion system (EC glazing requires an AC to DC inverter to connect with mains) [76]. • Controls solar heat gain due to its variable transparency [72]. • Facilitates switchable single or double glazing systems [71]. Optical response times are around 1–3 s, which is the same range as for LCD devices and less than EC devices [48].	• Recent advances in next-generation LCDs with a fast response time [77]. • OILC use makes wide viewing angle without an alignment layer [77]. Optical response times are around 1–3 s, which is less than EC devices [48].

Table 2. Performance of smart glazing types according to climatic conditions.

Parameters	Performance of EC	Performance of SPDs	Performance of LCDs
Variable addressed	• Energy saving	• U-Value • Switching Power	• Response time • Material and optical transmittance • Haze coefficient
Cold climatic conditions	• Large-size EC windows facing south-east, used in a building in Oakland, California during winter was tested and the result showed that on a clear winter day, the average window luminance exceeded 850 cd/m^2 and the lighting energy was reduced by 6–24% in the 11% glazing, while the energy was 3% reduced when 13% glazing was used [53].	• Using a thermally insulated test cell yielded a U-value of 5.9 W/m^2 K in cold climate in Ireland [71]. While the use of low heat loss switchable SPD glazing offered a low overall U-value, which varied between 1.00 and 1.16 W/m^2 K in Ireland [61]. • Gosh et al. (2016) also tested the potential of powering SPD glazing from photovoltaic device and found that for a 1 m^2 of SPD glass under cold climatic conditions in Dublin the switching power consumption is 10.42 kWh which can be supplied by 1 W PV. Thus, there is a potential combination for SPD and PV for future low building annual energy consumption [76]. A 40 Wp PV device continuously powered a 0.07 W SPD glazing. Low sizing ratio of 1.12 between PV and inverter offered less power losses from inverter output [76].	• Glass gel-dispersed liquid crystal (GDLC) which has high quality electro-optical behavior was investigated in order to overcome the limitations of regular PDLC at cold climate in South Korea and showed a fast response time of ~0.5 and 3 ms which is 10 times shorter than that of PDLC, respectively for the on and off processes, high contrast and low haziness [78]. • The use of films of silver nanowires was investigated by Khaligh et al. (2015) in Ontario, Canada as an alternate electrode material to the PDLC [79]. It was found that the material and fabrication costs of silver nanowire films are lower than ITO and enable transparency of ΔTon – off = 57% versus ΔTon – off = 46% for the ITO-based devices and a lower voltage supply [79]. • A 20 µm commercial PDLC layer has been developed in South Korea between ITO coated polyester films to achieve a device with haze coefficient changing from 0.09 to 0.90. The device exhibits good temperature stability between 0 and 60 °C [80].
Variable addressed	• Power and energy consumption	• U-values and SHGC • Transmittance reflectance, color appearance and haze.	• Light transmittance
Warm and hot climatic conditions	• EC devices can lead to a 30% reduction in the annual power consumption and in peak demand by 23% in large area buildings in hot climatic conditions [81]. • Up to 50% of the primary energy consumed in air-conditioning is saved by the use of EC windows [82].	• It was claimed by Gosh et al. (2016) that high U-values and variable SHGC makes the SPD glazing to be suitable for summer. • (SHGC) varied between 0.05 (when opaque) and 0.38 (when transparent) and U-value varied between 5.02 W/m^2 K and 5.2 W/m^2 K for the two states and showed 6 kW h cooling load reduction [72]. • Total and diffuse components of transmittance and reflectance, along with color appearance and haze were used in model calculations to predict the thickness of the active layer during summer period and showed thicknesses of 200–300 µm as most optimum for SPD-based smart window applications [48].	• The light-controlled transmittance in a polymer-dispersed liquid crystals (PDLC) device was investigated by Cupelli et al. (2009) during warm climate in Calabria, Italy. It was claimed to self-increase scattering as a function of the light intensity and self-control the incident daylight and glare as a function of incident intensity both in building and automotive applications [83].

Table 2. *Cont.*

Parameters	Performance of EC	Performance of SPDs	Performance of LCDs
Variable addressed	• Energy consumption • Energy savings	-	-
Mixed climatic conditions	• The energy consumption of EC windows was tested in cold and hot climates in two prototype buildings in Chicago and Houston. The results suggested that the annual peak electric demand was reduced by 7–8% for moderate-area windows and by 14–16% for large-area windows in either climates [46]. • The performance of near-infrared switching electrochromic (NEC) window glazing was tested, using the COMFEN software to simulate a broad range of NEC performance levels, for commercial and residential buildings in 16 climatic variations-representative reference cities. The results showed an annual HVAC energy savings up to 11.6% with potential as high as 11 kWh/m^2 per year for commercial buildings, and up to 13% with 15 kWh/m^2 per year for residential over the highest performing static glazing [84]. • EnergyPlus software was used to simulate annual energy performance of the dual-band electrochromic (DBEC) glazing and indicated that DBEC is capable of achieving annual primary energy savings between 64.5 and 322.9 kWh/m^2 of window area from reduced heating, cooling, and lighting demand [58].	-	-

2.2. Kinetic External Shading Systems

Kinetic shading systems follow the same concept as dynamic facades and were introduced to satisfy some of the energy characteristics of the building envelope. The Lawrence Berkeley National Laboratory (LBNL) in the U.S. describes kinetic shading systems (dynamic façades) as systems that enable a building to reduce its lighting and cooling loads [85]. The development of these systems was a response to the growing awareness of energy reduction in buildings. Their adaptability offers the potential to achieve an energy-efficient environment, improve the comfort, balances indoor environmental quality (IEQ), such as, reduced glare, view to outside, privacy, thermal comfort and air quality and increase satisfaction and productivity of the occupants while minimizing the energy cost and environmental impact [86–88].

The systems move in response to mechanical, chemical or electrical stimuli by which folding, sliding, expanding, shrinking and transforming in the shading devices take place [89].

The development of kinetic facades presented in the literature are mainly concerned with the functional possibilities and enabling technology [37]. The mechanism in the kinetic shading depends on mechanical, chemical and electrical engineering where folding, sliding, expanding, shrinking and transforming in the shading devices takes place [89,90]. In this literature review the dominant types; rotating and folding shading systems have been explored.

2.2.1. Rotating Shading Systems

(a) Design Principle and Performance

As discussed earlier, rotating shading systems consist of a shading device made of either glass, metal, fabric or timber and is designed to rotate around either a horizontal or vertical axis depending on the position of its slates [91].

Glass lamella device have a better utilization of daylight over other systems [92]. The rotational movement of kinetic facades creates slow responses on every panel of the facade, which prevents any noise or distraction for the building's occupants throughout the day [88]. The influence of external dynamic louvers with light dimming strategies in an office building at hot and humid climate in Abu Dhabi, UAE was explored. The results showed that the dynamic louvers with inclination angle of -20° for the south had 30.31% energy savings, while with a 20° inclination angle for the east and west orientations the savings were 34.02% and 28.57%, respectively [93]. Similarly, a new double skin façade with movable integrated shading louvers was investigated and showed that during the entire year the proposed façade significantly improved the building energy behavior, especially when the winter configuration forced convection was considered [94].

The cooling and heating energy savings of four types of kinetic façade systems; the overhang, folding, horizontal louver, and vertical louver were investigated by Kensek and Hansanuwat (2011) at hot climate in California in U.S. It was found out that the most optimal shades are overhang and horizontal louvers and were able to rotate for 90 degrees, and decreased the energy consumption by 33% for cooling and 30% for heating [95].

(b) Material

The rotating shading devices are made of different materials, but predominantly use: (i) glass louvers, (ii) metal louvers and (iii) timber louvers. Examples of building applications with their performance are illustrated in Table 3.

(c) Carrier system of the shading device

The carrier system of the shading device may vary depending on the application type, the size of the louver and the span (Table 4).

Table 3. Application of materials of external shading systems.

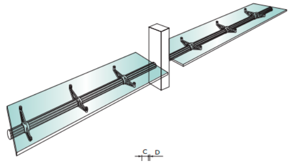
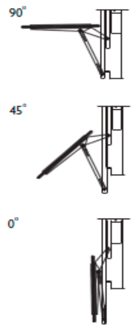
Material	**Glass Rotating Shading System [96,97] Reproduced with the Permission from COLT Company, 2017.**
Building application example	  European Commission Headquarters, Brussels
Shading system design description	The façade was renovated using glass rotating systems which respond to the changes in light intensity and temperature. It is a solar-controlled glass with high reflectance coatings.
Benefits	• Reduces solar heat gain and cooling loads. • Primary energy consumption of the building was reduced by 50% lower than a similar building as modeled. • Views are available when glass louvers are in use. • Can be used in residential buildings and mass housing.
Material	**Metal rotating shading device [97,98] Reproduced with the permission from COLT company, 2017.**
Building application example	  Zurich Airport, Switzerland
Shading system design description	• Perforated metal rotating shading system was used to reduce the extensive use of glass over the large area to avoid excessive heat gain within the building. • The system rotates in response to changing climate conditions and available daylight.
Benefits	• Reductions in cooling loads and glare. • Can be used in residential buildings and mass housing.

Table 3. *Cont.*

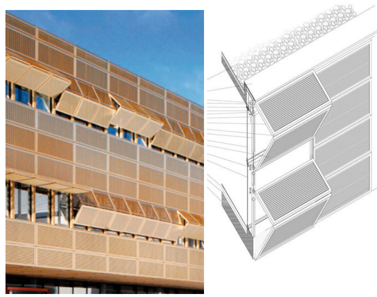
Material	**Anodized aluminum shading device [99] Reproduced with the permission from COLT company, 2017.**
Building application example	 University of Potsdam, Germany
Shading system design description	Vertically folding shutters which open and closed according to the position of the sun.
Benefits	• Dynamic and variable according to the weather situation. • Aesthetical kinetic appearance for the building. • Reduction in cooling energy and glare from direct sunlight.

Table 4. Carrier systems of shading device.

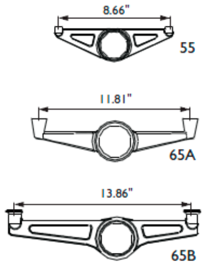
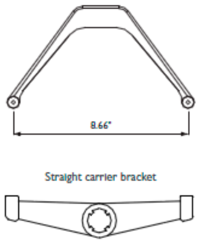
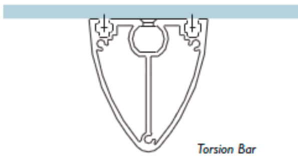
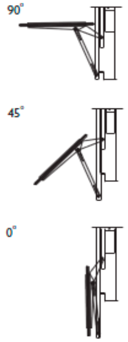
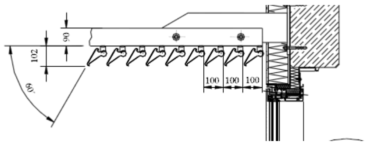
Carrier	Diagram	Description	Application
System 1: Straight carrier bracket [100]		Intended for wider spans, carrier system 1 incorporates a central aluminum torsion tube along the entire length of the louver, and is ideal for continuous facades, as well as for roofs.	Suitable for use with a variety of louver materials including glass, metal, fabric and timber wood. 
System 2: Bracket carrier [100]		Intended for shorter spans or where frequent anchor support points are available. It provides minimum obstruction from the louver so when used with glass louvers it maximizes the natural daylight and enhances the views to the outside.	Suitable for use with a variety of louver materials including glass, metal, fabric and timber wood. 
System 3: Torsion bar carrier [100]		Like carrier system 1, carrier system 3 is intended for wider spans and incorporates a discreet central aluminum torsion tube along the entire length of the louver. It is ideal for continuous facades as well as for roofs.	Suitable for use with a variety of louver materials including glass, metal, fabric and timber wood. 

Table 4. *Cont.*

Carrier	Diagram	Description	Application
System 4: Hung design carrier [100]		Carrier system 4 provides a back hung end pivoted solution with hidden control mechanisms integrated within the main vertical mullion supports. This allows for seamless continuous louvers with unobtrusive supports when viewed from the outside.	Suitable for use with a variety of louver materials including glass, metal, fabric and timber wood. 
System 5: Metal support clip [100]		The patented louver clip is adjustable in increments of 15 degrees. The plastic clip allows for thermal expansion of the blade and ensures that louver blades cannot rattle against the rafters.	Applied for metal louvers. 

2.2.2. Folding Shading Systems

(a) Design Principle and Performance

An effective type of shading systems is the shape morphing solar shading also called the folding shading system or the *Origami* shading device. This type of shading had been applied in several engineering fields, in adjustable and reconfigurable structures. Folding geometries have been used in biomedical devices [101], and in space and aircraft applications [102]. However, in architecture the use of folding Origami has only been recently experimented, especially as a shading device. When installed, they usually have different typologies of movement such as, translation, rotation and scaling, where external forces are required. Recent trends in shading device design have been trying to replace traditional mechanical systems with integrated multifunctional and smart actuators and are responsible for moving or controlling the mechanism [103].

Usually, sensors are able to analyze the variation of an external stimulus and transfer the information to the actuator, which provides the structure with a change in one of its properties [104,105]. The application of shape morphing solar shading in buildings depends on the following criteria that are considered to identify and analyze in detail the most suitable smart materials [106]:

- Corrosion resistance.
- Durability (life cycle of the smart movement/shape memory effect)
- Stimulus responsiveness (solar radiation, outside air temperature, electrical stimulus)
- Workability (process and adaptability)
- Achievable movements
- Impressing force

(b) Material

Recently, there are no solar shading devices that are entirely made of smart materials due to the material properties and costs. Therefore, smart materials are still used either as sensors or as actuators.

The types of smart materials of folding shading systems (either sensors or actuators) are illustrated in Figure 2 [106].

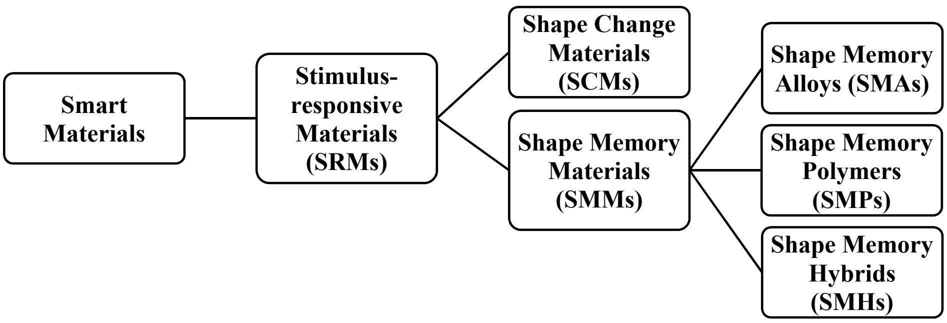


Figure 2. Smart materials types for folding shading systems.

Stimulus-responsive materials (SRMs) are the most suitable smart materials for shape morphing solar skins. This is due to their ability to respond to external stimulus through a change of their physical or chemical properties [107]. This type of smart materials is grouped into two main types as shown in Figure 2:

1. Shape change materials (SCMs) [106]: They are able to change their shape when right stimulus is present commonly a potential difference.
2. Shape memory materials (SMMs) [106]: "They are included in all the materials that are able to hold the modified shape until the appropriate stimulus is applied to activate the shape recovery cycle" [107,108]. Usually, those materials are activated by a difference in temperature.

A study compared, described and listed the properties of the three types of SMMs that are used either as sensors or actuators for solar shading devices [106]. The comparison showed that the SMPs is the most promising system, due to the fact that their global deformation is sensibly higher (800%) than Shape Memory Alloys (SMAs) (up to 10%) and Shape Memory Hybrids (SMHs) (up to 6–8%). However, in the time being, SMAs are the most durable shape memory materials since they are able to exceed 200,000 cycles, where SMPs have been tested only up to 200 cycles and SMHs have not undergone any tests [106].

(c) Building Applications

There are different types of shape morphing shading systems that can be applied in buildings. They usually move in response to variable external conditions, and they have the ability of minimizing energy required to perform adaptation. The movement of the folding shading systems has two main typologies [106]:

1. Translational movement which performs a bi-dimensional change of shape. It is linear and allows adjustment levels in the building skins by size-opening variation and by overlapping layers.
2. Rotational movement which performs a tri-dimensional change of shape; and performs swivel motion both in the same axis and/or around a different axis.

In both typologies an actuator is required, and it can be completely embedded into the device or strategically located to trigger a specific action. The different typologies of folding shading devices applied in buildings are shown in Table 5.

Table 5. Different types of folding shading systems.

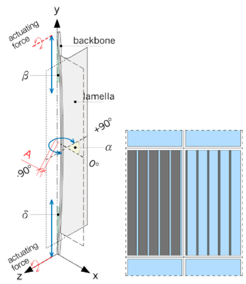
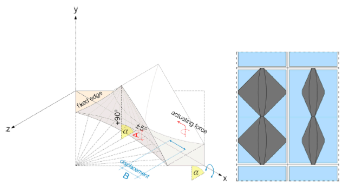
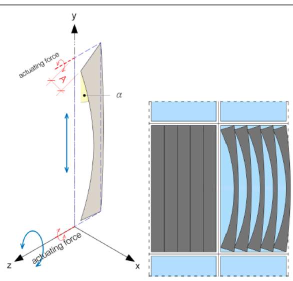
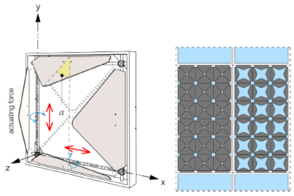
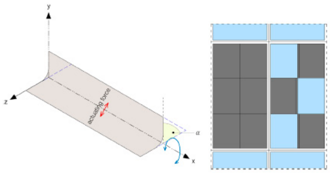
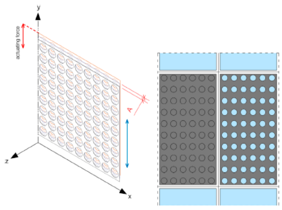
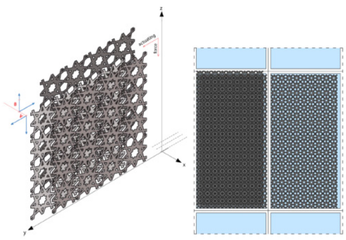
Reference Study	Shape	Motion	Smart Actuator
Flectofin [109]	 [106]	Three-dimensional movement (swivel motion—Both in the same axis).	-
Solar Kinetic [110]	 [106]	Three-dimensional movement (swivel motion—Both in the same axis).	Shape Memory Alloys (SMA)
Ocean Thematic Pavilion [111]	 [106]	Three-dimensional movement (swivel motion—around a different axis).	-

Table 5. *Cont.*

Reference Study	Shape	Motion	Smart Actuator
Air Flow [112]	 [106]	Three-dimensional movement (swivel motion—around a different axis).	Shape Memory Alloys (SMA)
Sun Shading [113]	 [106]	Three-dimensional movement (swivel motion—around a different axis)	Shape Memory Alloys/ Shape Memory Polymers (SMA/SMP)
Smart Screen [114]	 [106]	Bi-Dimensional Movement (Translational Movement by overlapping layers)	Shape Memory Alloys (SMA)
Shape Variable Mashrabiya [115]	 [106] Reproduced with permission from Elsevier and Copyright Clearance Center, 2017.	Bi-Dimensional Movement (Translational Movement by overlapping layers)	Not Available (N/A)

2.3. Integration of Renewable Energy Systems

2.3.1. PV Integrated Shading Device

(a) Design Principle and Performance

The integration of PV materials into shading systems was introduced in 1998 [116]. Integration of renewable energy generation can be applied in a very effective way in the shading devices, combining a dual benefit: shading and production of electricity. Integrated PV shadings could be used to provide energy controlling shape morphing devices.

Several studies were done on integrating PV panels as solar shadings and providing maximum PV performance. Researches were carried out different studies during 2002 and 2011 about integrating PV in the building as shading devices, the results showed that the use of BIPV as exterior solar shading devices produces on-site electricity and reduces cooling loads by 10% and 9.2% in building [117,118]. In another study, a prototype of a PV-integrated shading device on venetian blinds was built and monitored, where each blind consisted of a glazed static concentrator and of crystalline silicon bifacial solar cells. The result showed that the efficiency of PV cells was improved by 85% and represented a very good result for facades' applications [119].

Building integrated PV (BIPV) systems are used for generating electricity and as shading devices, they can be integrated into the building envelope, such as the roof, cladding, window shading, semi-transparent windows and façades. Additionally, they can reduce the use of building materials and electricity costs, reduction in use of fossil fuels and emission of ozone depleting gases [120].

Visual and the thermal performances of transparent BIPV on windows have been compared and revealed that in residential buildings in hot humid climate regions BIPV with slat angles of 60° and 68° provided good visual and thermal effect [121]. Mandalaki et al. also carried out several studies during 2012 and 2014 in hot climatic conditions on the visual and thermal comfort of PV-integrated with fixed shading devices. It was found out that shading devices with integrated south facing PV can produce electricity to be used for lighting and that the theoretical efficiency of 12% is satisfactory for simple geometries [41].

A prototype of a solar-powered automatic shading device was built and tested in Indonesian climatic conditions. The results showed a 3 °C decrease in the indoor air temperature due to the control of incoming solar radiation [122]. Kim et al. performed a study on a PV-integrated adjustable shading device combined with daylight responsive dimming system in Korea and results showed 32% increase of power production and a 35% reduction of energy consumed by lighting systems [123].

(b) Building applications

The design characteristics of shading devices (SDs) with integrated photovoltaic panels (PVs) for residential building facades were studied for cooling and heating weather conditions in Crete. The results defined the best position PV-integrated shading devices according to the best lighting levels for tasks [124]. Thirteen different forms of monocrystalline PV panels mounted on south-facing shading devices of office buildings in Mediterranean region were evaluated [125]. The results showed that the best form of shading device integrated with PV was the "Brise-soleil full façade" which had the best optimization in the heating, cooling and lighting loads [125]. Integration of PV panels on louvers is another alternative in which the blade is exposed to provide full ventilation and can be tilted to maximize the efficiency [126]. The integration of PV panels on several fixed shading systems was tested by Mandalaki et al. (2014) for cooling purposes in Crete and found that the Brise–Soleil systems is the most efficient system where it ensures visual comfort and sufficient energy production [126].

2.3.2. Solar Collectors Integrated Shading Devices

(a) Design Principle and Performance

Solar collectors are used in buildings to reduce energy consumption and carbon emissions [127]; they are usually installed on building facades, roofs, balconies, awnings and outdoor spaces, which are called building-integrated solar thermal (BIST) systems [128,129]. Integration of solar collectors with exterior shading devices can reduce solar radiation and at the same time generate heat.

Solar collector devices have been investigated in some researches, and research methods typically include heat output estimation, numerical model calculation [43,130] and simulation analysis [131].

A study integrated shading device with a solar thermal system for water heating and analyzed the system in buildings in temperate and Mediterranean climatic conditions of Portugal and Spain [132]. The two cases were compared; a real case that has a completely sunlit louver and two shaded louvers, and an ideal one with three completely sunlit louvers. For the real case, the shadings reduced transmitted energy by 7% for the 15° inclination on horizontal plane, 12% for the 30° inclination and 17% for the 45° inclination. For the ideal case, the optimum angle was 25° [132]. The payback period was 6.5 years and the CO_2 savings was 8.6 tons [132].

(b) Building applications

A full-size prototype of solar collector was installed on a shading louver and showed that when the solar radiation was enough, the systems did not require auxiliary heating equipment and the performance was 20% more than the performance of conventional solar collectors with natural circulation function [133].

The integration of solar collectors in buildings at hot and humid weather in Kuala Lumpur has been investigated by Saadatian et al. and the results highlighted that there are several ways of integration including mounting on a structure on the roof or window separated from the building or superimposed, where the collectors are mounted on a structure of the building envelope and are arranged in parallel [134].

Another study evaluated the heat pipe solar collector attached on a louver under a range of climatic conditions in the UK [133]. The indoor experimental results showed the performance of the new design to be very promising, even though the collector materials were not carefully selected. Increased collector efficiency can be achieved by increasing the number of heat pipes in the louver with only minimal increase in louver cost [131].

2.3.3. Algae Façade Systems

(a) Design principle

Algae façade systems grow micro-algae in order to generate heat and electricity and are used as external cladding elements and dynamic shading devices [42]. Double skin façades were developed for the purpose of protecting curtain walls from the sun. Several transparent façade technologies have been introduced in buildings, such as insulated glass unit (IGU) and shading device (such as stretched metal, frit, suspended film) [135]. The use of those technologies in buildings is to protect the building from excessive heat gain and improve the performance of the building. However, those technologies are not enough for achieving high performance building. In order to do that, energy generation must be achieved from the integration of those technologies; such as Photovoltaic and solar thermal systems. As an alternative for high performance facade, an algae facade system has been introduced.

Kim investigated the algae façade system, which consists mainly of an algae panel, aluminum framing and algae growing apparatus in the University of North Carolina in the U.S. as illustrated in (Figure 3) [42]. The size of the system is 1.5 m wide by 3.65 m tall or taller depending on building conditions, consisting of both vision zone and algae zone [42]. The purpose of the clear vision zone is for view, daylight and ventilation, while the algae zone is for growing algae. The algae growing apparatus is comprised of intake systems for supplying CO_2, and growing algae (e.g., algae, nutrients, medium etc.) and discharging systems for emitting O_2 and collecting grown algae [42]. The mechanism of work in this system is achieved first by water being filled in the vertical glass louvers that contains nutrients which convert daylight and CO_2 to algal biomass through the bio-chemical process of photosynthesis; at the same time the water is being heated up. Secondly, the biomass and the heat that is generated by the façade elements are transported by a closed loop system to the plant room, where both forms of energy are exchanged by a separator and a heat exchanger respectively. The temperature levels of the heat generated can be adjusted by using a hot water pump for the supply of hot water and for heating the building [136].

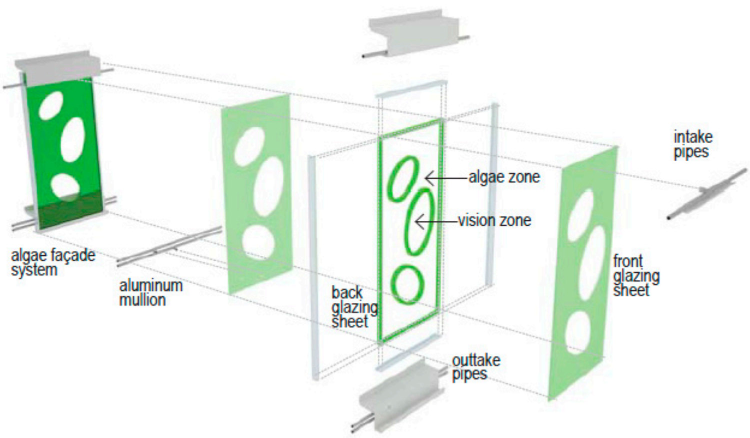


Figure 3. Algae façade system details [42]. Reproduced with the permission from author Kyoung-Hee Kim.

(b) System Performance

Kim has performed a few studies about the performance of algae façade systems. In one of the studies [42] the aim was to identify the feasibility of the algae façade system through schematic design and prototyping. The mechanism of algae facades was explained. Tests were conducted in a sunny winter noon in outdoor environment using a FLUKE (2006, SmartView (Version 3.2), NC, USA) thermography system with its software package. The result showed that the algae façade system has the future potential for sustainable façade alternatives and energy generation possibilities. The computer simulation on structural behaviors provided alternative design solutions to meet stress and stiffness criteria under various loadings, in addition to fabrication challenges associated with watertight interfaces between the vision zone and the algae zone [42]. Another study by Kim about bio-facades or algae façade systems showed a retrofitting case of a building [137]. The result showed that the algae facades reduces the energy consumption and CO_2 emissions, where the retrofitted building energy consumption was reduced by 30% compared to an existing building due to the thermal and daylighting performance improvements. Moreover, the retrofitted façade reduces the life cycle cost by $110,000 and reduces the life cycle by 200 tons, and CO_2 generation due to the photosynthesis process, which was 150 tons over the 30-year life cycle [136].

Usually, about 40 °C heat is obtained from the façade and is either used directly to heat water or stored in the ground to be used in a geothermal system. The efficiency of the conversion of light to biomass is 10% and to heat 38%. For comparison, photovoltaic systems have an efficiency of 12–15% and solar thermal systems 60–65% [136]. Therefore, algae façade is a competitive opportunity relative to these other technologies. Additionally, the algae façade helps improve the overall CO_2 balance by removing CO_2 from flue gas at quantities equivalent to the build-up of biomass [136].

(c) Building applications

The first algae façade integrated in a building was in the BIQ which is a part of the International Building Exhibition (IBA) 2013 in Hamburg, Germany [136]. The building used 129 "bioreactors" or algae façade, when sunlight hits the facade, photosynthesis process causes the microorganisms to multiply and causes the water to go about 40 °C , the heat then stored to be used for other uses [136]. Currently, the building reduces the overall energy needs by 50%, and the designer of the system says 100% is achievable by combining it with solar panels to power the pumps and heat exchangers [136].

Another application of the algae façade system was in the GSA Federal Building in Los Angeles that won first place scheme for the 2011 Ideas competition, where an "algae photo bioreactor tube" was attached to the top surface of the opaque building envelopes [136]. Similarly, the same company made a net energy zero Battery Park project in San Francisco that applied "algae photo bioreactor panels" to grow algae and reduce CO_2 [136].

3. Controls of Active Shading Systems

The control of the movement of dynamic shading can be either user manual control strategy or automatic control strategy.

3.1. User Control Shading Devices

Shading devices in buildings are linked to occupants' behavior. There are many studies that focused on the relationship between user comfort and shading operation.

Most of the researches done on user's response to these systems are related to the manual use of blinds [138]. A survey explored the factors that affect the occupants' comfort in Danish residential buildings [139]. The results suggested that most of the occupants preferred manually-controlled, especially for artificial light, windows opening and solar shading [139]. In another study, 800 building occupants were interviewed, and 90% preferred the use of automatic blinds because they thought they provided a better indoor quality [140]. The position of remotely controlled blinds in eight individual offices for 30 weeks was evaluated and showed that remotely controlled blinds were used three times more often than manually controlled ones [141].

Galasiu and Veitch pointed out that the results of the studies on manually operated blinds are helpful in favoring automated ones in Ontario, Canada [142]. Reinhart and Voss studied the reasons that trigger occupants' reaction to shading devices in Germany and found out that they tend to close their blinds to avoid direct sunlight above 50 W/m^2 on the work plane surface [143].

Wienold analyzed different shadings control strategies in Germany in order to design a shading system based on real user behaviors and the result showed that when a manual control is provided especially in summer, the shading device is rarely activated [144].

It was claimed that occupants had a positive experience when automated dynamic shading was applied [145]. It is concluded that automated control strategies of shading systems are preferred and are more beneficial in buildings.

3.2. Automatic Control Strategies

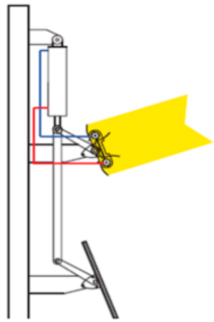
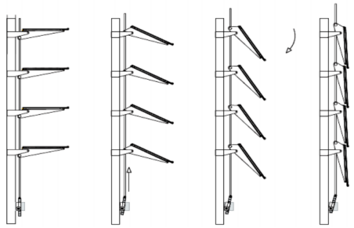
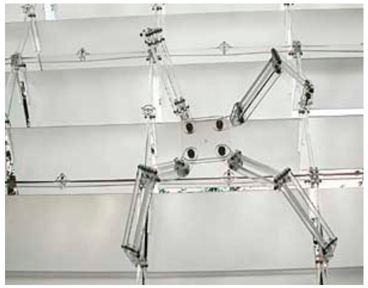
The use of sensors and actuators for controlling the movement of dynamic shading devices is more beneficial when it comes to adapting to various external environmental conditions. Control strategies and advanced control shading systems have positive impact on both the occupants' comfort and the energy performance of the building [146].

The operation of the façade components could be by occupancy, environmental variable, time or utility price signals. Two types of loop controls can be used in buildings; open and closed loop control systems [147,148]. The open loop motorized shading systems working mechanism depends on the pre-calculated angle of incidence of sun light [149–151], or the illuminance sensor measurements of the façade [143]. The control of the shading is based on three main types of control algorithms that depend on the performance criteria they address [30]:

1. Threshold controllers: where the shading device gets activated when an external solar illuminance or irradiance limit is exceeded.
2. Sun blocking controllers: moves the shading system or adjust the blind slat angle depending on the sun position.
3. Mode and scene controllers: use a variety of sensors and different control algorithms [30].

Three types of control of the external shading devices were analyzed [152]. The first type was based on external vertical irradiation level only; the second type was based on the interior temperature level only, while the third type was the most effective one which was a combination of both types. The external shadings are closed when both conditions are met and opened when at least one of the conditions is met. A scaled model was built to test two types of control strategies for external venetian blinds [153]. One strategy provided maximum slat openness, while the other one provided maximum work-plane illuminance. The results indicated that for the low ground reflectance the energy savings was 38.1%, while for the high ground reflectance, the energy savings was 55.3%. Bauer et al. developed a logic based control algorithm that minimized thermal and artificial lighting energy demand [154]. The result showed that the smart blind controller achieved saving of 11% for the artificial lighting and between 20% and 50% savings for heating/ cooling. A significant application of sensors application in buildings is the case of the "Arab World Institute" in Paris, which is the one of first buildings to apply sensor based automated response shading systems based on the environmental conditions. The lens opens or closes according to the light quality inside the building. The system consisted of photosensitive mechanical automated devices, 30,000 light sensitive diaphragms on 1600 elements, which function like, a lens of the camera and all the mechanical devices are connected to a central computer [155]. Examples of innovative controls of shading devices that depends on different strategies for their movement are discussed in Table 6 below.

Table 6. Innovative shading control systems.

Control Type	Description	Working Mechanism	Diagram
Non electrical thermo-hydraulic controlling system [156].	A self sun-tracking device designed to control the external shading louvers. Controls the louvers without the use of electrical power or digital electronic devices [156,157].	Consist of two fiber-reinforced polymer absorber tubes. The tubes are filled with special thermo-hydraulic fluid. When the sun moves, one tube is more irradiated to sun and heats up more than the other tube. This causes the hydraulic cylinder to move and rotate the louvers into optimal shading position throughout the day [156,157].	 [157] Reproduced with the permission from COLT company, 2017.
Electrical controlling system [157]	The electric control operation adjustment of motors could be manual switches or automatic. Automatic controlled system consists of various sensors and has a fully controlling over the internal climate.	When the sun is direct, the motor sends data to the holder of the gear which is retracted and pulls smoothly the rod of the louvers downwards to close the louvers and block the sun. The sensors control the shading by rotating the louvers following the sun rotation.	 [129] Reproduced with the permission from COLT company, 2017.
Built robotic controlling system [158] Reproduced with the permission from authors Stephen Gage and William Thorne, 2017.	Hypothetical fleet of small robots called “Edge monkeys”. To protect building facades, regulate energy usage and indoor conditions.	These small robots could detect building facade, and regulate energy usage and indoor conditions in order to close windows, check thermostats, and adjust blinds.	

4. Challenges, Limitations and Future Opportunities in Active Shading Systems

The application of dynamic smart shading has grown widely in order mitigate the building conditions against excessive heat gain and glare. However, there are some challenges inherent to these systems that should be considered in future research. Challenges, limitations and opportunities of active shading systems are discussed in Table 7.

Table 7. Challenges and future developments of dynamic shading systems.

Dynamic Shading Type	Challenges and Limitations	Opportunities and Development
Electrochromic Glazing	• High initial cost (between 100–1000 US $/m^2) and is more expensive than other smart glazing types [44]. • High labor and maintenance cost compared to other conventional glazing types [44]. • The optical properties that change the Near-infrared switching electrochromics (NIC) are still little known [68]. • The performance of the NIC glazing might be affected by the present climate changes [68]. • Low durability (sensitive to UV) [159] • High increased surface temperature and slow coloration process [160].	• Improve the Electrochromic glazing life time expectancy and durability to be similar to those of standard coated windows [44]. • Develop faster switching speeds (<5, 6 min) in order to promote better savings in energy and occupants' visual comfort [161]. • Develop higher visible transmittances in the bleached state ($\tau V > 0.6$) to allow more daylight [161].
SPDs	• Lower transparency in the SPDs' bleached state, compared with the EC glazing [48]. • Undesirable haze [48].	• Improve the properties of the SPD glazing and increase its transparency. • Remove haze from the SPD glazing. • Further research is required on the integration of SPD glazing in buildings.
LCD	• LCD glazing is hazy because it scatters rather than absorb light, so there is a fog factor even when the device is in transparent state [44,82]. • LC glazing is either transparent or opaque with no in-between states [44].	• Remove the haze from the LCD glazing. • Improve the properties of the LC glazing to have intermediate states between opaque and transparent states. • Investigate the application of the emerging (GDLC) which less haze and yellowing than conventional LCDs in different climate conditions [78]. • Carry out further researches on the integration of LCD glazing in buildings.
Folding shading systems	• Variable external conditions could limit the efficiency and the movement of the folding shading systems [106]. • The behavior of the SMPs is limited to one-dimensional deformation which limits their movement [162].	• Further studies should be undertaken on the use of shape memory actuators in the building industry; life cycle, solar activation, and resistance to external weather conditions [106]. • Further research on the use of smart materials with dynamic shading devices [106]. • Further research on the control of the folding shading systems in response to the climate variations.
PV mounted shading	• Higher temperatures will decrease the power production of the PV panels. • Dust accumulation and limited tolerance to overheating will restrict the expected performance and lower the efficiency. • Gap in PV shading systems in Mediterranean countries where the amount of solar radiation is high.	• Further research required on cost assumption of PV shading systems, particularly for movable PV shading devices. • To investigate materials that have long-term durability and can stand the various climate conditions (Snow, heat, dust, wind and air tightness) [163].
Algae Façade System	• High initial cost (approximately $2500 per square meter for the bioreactor system alone) [164]. • High maintenance cost.	• More research is required on working mechanism alternates of the algae façade systems in order to reduce their initial cost. • More research to test its performance under several climate conditions. • As relatively new, the Verde system was introduced in the market after the development of algae façade system. Its main function is to collect light and transfer it through fiber optic cables, then algae is grown within the bioreactor to generate energy. More research is necessary to establish its properties and part of the market [165].

5. Conclusions

This paper reviewed the current status of active shading systems in buildings, exploring their design principle, performance, working mechanism and building application. Six types of active shading systems including the electrochromic glazing, the automated shading systems consisting of the rotating and folding shading devices and the shading systems that integrated renewable energy generation such as the PV, algae façade and solar thermal collectors were discussed. The design principle, performance and application of each system were explored. Additionally, the control strategies of the systems including user control automated control were reviewed. In this literature review, 165 papers were examined to evaluate the different types of active shading systems. The significant conclusions inferred from the reviewed studies states that:

1. The use of electrochromic windows is increasing; however, its high cost is still a challenge.
2. The electrochromic windows have always progressed in their performance and there is always an emergence of new types such as the NIR and POMs which have better performance. However, they are hindered by their high initial costs.
3. The use of folding shading systems is still limited because of the need of expensive smart actuators and sensors.
4. Rotating shading system is the most applied and studied system among active shading systems. Its low initial cost and available resources and materials including glass, metal, timber and fabric make it attractive.
5. The use of automatic control strategies has been proven to be much more effective than the use of manual user controlled systems due to the benefits they provide including the adaptation to the external conditions.
6. The use of robotic controlling systems and the thermo-hydraulic controlling systems are emerging automatic control systems that requires further investigation as there are limited number of studies done on their performance, building application and use in varying climate conditions.
7. Additionally, more studies should be done on the integration of PV panels on this emerging type of shading devices.

Furthermore researches must be done on to develop faster switching speeds of electrochromic glazing to increase energy savings. Additionally the SPDs and LCDs suffer from haze in the glazing, thus, further research must be carried out in order to decrease the haze and test their integration in buildings. The movement of folding shading systems could be limited by the variable external conditions, therefore further investigation under different climatic conditions is required. Finally, the algae façade system is a promising immerging system that needs further exploration in terms of performance and building application.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

PV	Photovoltaic
SPDs	Suspended particle devices
EC	Electrochromic devices
LCD	Liquid crystal devices
LEDs	Light emitting diodes
CEC	Conventional electrochromic glazing
NEC	Near-infrared Switching Electrochromic
DBEC	Dual-band Electrochromic
PSBP	Polymer-stabilized Blue Phase
PDLC	Polymer-dispersed Liquid Crystal
LCoS	Liquid crystal on silicon displays
OILC	Optically isotropic LC
GDLC	Gel dispersed liquid crystals
AC	Alternating current
IR	Infra-red
SHGC	Solar heat gain coefficient
Tv	Visible transmission
SC	Shading coefficient
ITO	Indium tin oxide
IEQ	Indoor environmental quality
SRMs	Stimulus-responsive materials
SCMs	Shape change materials
SMMs	Shape memory materials
BIPV	Building integrated PV
BIST	Building-integrated solar thermal
IGU	Insulated glass unit

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