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Advances in switchable and highly insulating autonomous (self-powered) glazing systems for adaptive low energy buildings

Aritra Ghosh

University of Exeter, a.ghosh@exeter.ac.uk

Brian Norton

Technological University Dublin, brian.norton@tudublin.ie

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Review

Advances in switchable and highly insulating autonomous (self-powered) glazing systems for adaptive low energy buildings

Aritra Ghosh^{a, b, *}, Brian Norton^a^a Dublin Energy Lab, Dublin Institute Technology, Grangegorman, Dublin 7, Ireland^b Environmental and Sustainability Institute, University of Exeter, Penryn, Cornwall, TR10 9DF, UK

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ABSTRACT

Building energy reduction requires highly advanced low heat loss, heat gain and comfortable daylight allowing glazing. Presently available glazing systems are classified mainly in two categories, controlling solar heat gain and controlling low heat loss. Low heat loss through glazing systems can be achieved by (i) suppression of convection in the air between the outer panes by use of multiple glass panes or aerogels, (ii) having an inert gas or vacuum between the panes to reduce or eliminate respectively convective heat transfer. In all these systems, low emissivity coatings are also required to reduce the radiative heat transfer. Low heat glazing allows large areas of a building façade to be glazed without large attendant heat losses. However, they require the addition of an ability to switch from transparent to opaque to avoid excessive solar heat gain and to control glare. Electrically actuated electrochromic, liquid crystal and suspended particle device glazing systems and non-electrically-actuated thermochromic, thermotropic, and gasochromic glazing systems offer control of solar heat gain control and daylight. Recent relevant developments are reviewed with the contemporary status of each technology provided.

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* Corresponding author. Dublin Energy Lab, Dublin Institute Technology, Grangegorman, Dublin 7, Ireland.

E-mail addresses: a.ghosh@exeter.ac.uk, aritrighosh_9@yahoo.co.in (A. Ghosh).

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1. Introduction

Glazing visually connects interior spaces with the outdoor environment to offer daylight, conducive to good health and working or living conditions. However, a large glazed area can incur (i) high heat losses increasing a building heating load in cold conditions, and (ii) a large cooling load to remove solar gains in hot conditions. These attributes combined with the energy used to more generally ensure comfort conditions and artificial lighting head to buildings thus consuming 40% of global energy to meet heating, cooling and lighting energy demands, though this varies in different countries. For example 41% of energy in US and the EU but 25% in China [1]. In Japan, the building sector consumes 14.2% energy, which has doubled compared to 1970s [2]. Buildings generate one-third of global greenhouse gas emissions (GHG) being responsible for 32% of GHG emissions in Europe, 48% in USA and 33% in Australia [3–5]. In Australia commercial building emissions are projected to increase GHG emissions by 154% from 2005 to 2050 [3,4]. It was reported in 2003 that the CO₂ emissions in the residential sector of Japan of 50.5 million tonnes of carbon had increased by 43.5% in comparison with 1990 [6] [7]. Space heating, cooling and lighting are the main uses of energy in residential and commercial buildings. Building energy performance improvement is an important part of European Union (EU) 2020 and 2030 energy targets (EU Commission, 2011)[8] to meet EU Kyoto Protocol commitments for CO₂ emissions reduction [9]. In developing new Net Zero Energy Buildings (NZEB), renewable sources [10,11] placed near to the point of use [12] to reduce power transmission losses. In NZEB, glazing systems can play a vital role in ensuring low cooling, heating, and lighting loads [13,14]. The existing building stock lower energy consumption can be achieved by retrofitting windows as part of an overall refurbishment that may also include heating system upgrade, heat recovery, and thermal insulation [15–17]. Glazings are responsible for 20–40% of energy used in a building [18–20]. Insulation and retrofitting lower heat loss glazing can together reduce annual energy of a building by 47% [21].

Buildings glazing enhance cooling load demand due to excessive entering solar heat gain, heat loss from inside to outside via a glazing, which incurs a heating load demand and lack of daylight gives rise to an electric lighting energy demand and excess artificial lighting energy, can create glare issues. Fig. 1 shows a detail working principle of a window.

Solar heat gain coefficient (SHGC) is the fraction of incident solar radiation enters a room through a glazing in the form of transmitted radiation or as secondary heat gains due to the inward flowing fraction of thermal radiation from the window [22]. High SHGC of glazing increases the cooling load of building in summer and in hot climates, whereas a high SHGC is beneficial for winter

Fig. 1. Heat loss, heat gain and daylighting from a window.

and cold climates [23].

Overall heat loss coefficient (*U*-value) of a glazing depends on internal (*h_i*) and external (*h₀*) heat transfer coefficient and thermal conductance of a glazing as shown in Fig. 1.

Daylight in those wavelengths is sunlight that matches human spectral visual response [24–28]. Daylight through a window can provide an attractive visually pleasing environment. Daylight illuminances at a point in a building depend on (i) the total daylight from the sky (given, for example, by the horizontal external illuminance) (ii) the angular distribution of light over the sky vault, given by the sky luminance distribution [27] (iii) the size and locations of windows, size of reflectance and locations of internal surfaces. Use of daylight can reduce 50–80% lighting energy consumption while primary energy (heating + cooling + lighting)

Fig. 2. Taxonomy of available switchable and non-switchable glazing.

savings from daylight displacing artificial electric lighting can reach 40% [29]. For example, for cooling-dominated office buildings in Hong Kong, the peak cooling load and the annual electricity consumption were reduced by 11% and by 13%, respectively by use of daylighting [30]. Energy saving of 10% can be achieved by using daylighting strategies in Malaysian buildings [31]. Shading devices are used traditionally to control excessive heat gain and glare. Switchable (or so called smart, adaptive, responsive, dynamic, intelligent) glazings which modulate their thermo-optical properties in response to external stimuli, can also be used to modulate the entering solar spectrum [32].

Fig. 2 classify the different advanced switchable and non-switchable glazing based on their functionality. For adaptive or responsive building, constant or static transparency glazings are not suitable. Adaptation from second to seasonal, switchable glazings are attractive [33]. Recently review works on development and status of glazings have been performed by Refs. [34–38]. Jelle et al. gave an ample information about industry details of glazing which is interesting [34] as product details from industries are difficult to achieve. According to Baeteans et al. [37], electrochromic (EC) is preferable due to its higher visible spectrum compared to liquid crystal (LC) and suspended particle device (SPD) glazing. Glazing work between 1990 and 2000 was summarised by Seeboth et al. [38] which included electrochromic devices, thermotropic gels and polymer dispersed liquid crystalline systems. Gorgolis and Karamanis [36] discussed extensively about electrochromic, thermochromic, photovoltaic and other advanced glazings. Investigation on LC and SPD was excluded in that work. Rezaei et al. [35] concluded that an ideal glazing should possess self-powered, spectrally tunable and high visibly transmission properties. However, this review excluded combined glazings, LC and SPD glazing systems.

Further investigation on progress of material development and system integration had been performed after those aforementioned review works. This work covers present status of advanced glazing primarily performed by different research group and commercial availability of those glazing. Higher attention was given to switchable/smart/dynamic/adaptive glazing application particularly electrically activated switchable EC, SPD and LC type and their combined system works for low energy adaptive building application. The focus is on low U -values and solar heat gain coefficient (SHGC), daylight control. Mechanically operated blinds, shades, glazing frames, self-cleaning glazing are not part of this study.

First section of this paper will discuss about the constant transparency glazing, which includes both solar heat gain controlled double, low emissivity coating, prismatic, and photovoltaic type and low heat loss vacuum and aerogel. Detailed performance and recent developments of electrically and non-electrically actuated switchable glazing systems are discussed. At the end for the first time, recent development of combined glazing systems and their status have been thoroughly investigated.

2. Constant or static transparency low heat loss and heat gain glazings

This section aims to outline the research currently being undertaken to improve glazing technologies and product. First six glazing technologies such as solar control double glazing, low emissivity coated glazing, prismatic, water flow, air flow are mainly used to control solar factor or solar heat gain. Vacuum glazing and aerogel glazing contribute to control of low heat loss. Photovoltaic glazing has triple point advantages as it can control solar gain, admit comfortable daylight and generate clean electricity at the demand site. Thus, this section includes heat loss, heat gain control glazing which has single (constant/static) transparency.

2.1. Double glazing

The heat loss through double-glazing depends on the gap between two glass panes [39]. A photograph of double glazing is shown in Fig. 3. For ambient temperature ranging 19–49 °C, the optimal gap (optimal air layer thickness) was found to be in the range of 12–21 mm [40,41] to save energy losses through air-fitted double glazing in Turkey. Fig. 4 shows the variation of investment, heating and total cost with air layer thickness for Iskenderun city in Turkey. In the figure when insulation thickness increases, heating cost decreases. After a critical layer thickness, convective heat transfer dominates which increase the heating cost [39].

Air has a thermal conductivity of 0.026 W/mK compared with the lower thermal conductivity of the alternative gases such as Argon at 0.018 W/mK, Krypton at 0.0095 W/mK and Xenon at 0.0055 W/mK. Argon filled glazing has a low cost than use of Krypton or Xenon [34]. Infra-red absorbing gases composed of either difluoromethane (HFC-32), norflurane (HFC-134a), trifluoroethane (HFC-143a) and sulfur hexafluoride (SF6) in equal parts or dichlorodifluoromethane (CFC-12), CFC-13, CFC-14 and SF6 in equal parts [42–44] can be used to reduce the direct radiative

Fig. 3. Photographic view of an air-filled double-glazing.

Fig. 4. Effect of air layer thickness on the costs for Iskenderun. (taken from Ref. [39].

exchange between opposite glass surfaces in the window. The SHGC can also be varied by alternating the transmittance of the glass panes [45]. Due to higher visible transmission, daylight and glare control using double glazing is not possible. External or internal shading devices are required to obtain control over incoming daylight.

2.2. Low emissivity (low -e) coated double glazing

To reduce building cooling and heating load, reduction of entering solar radiation in summer and reduction of heat transfer from indoor to external environment in winter is essential. Incident solar radiation on a double-glazing transmits, reflects and absorbed by the glass surface. According to Kirchhoff law of thermal radiation, energy absorbed by an opaque material must be equal to emitted energy. Thus, emittance will be equal to absorbance. Higher emittance enhances the radiative heat transfer. Radiative heat from a material relative to a blackbody (emissivity 1) is categorised as emissivity and its value varies from 0 to 1 [46]. Inclusion of low emissivity (Low-e) coating reduces the thermal radiation from a glass surface. For double glazing, low-e coating applied on the internal surface of the inside glass pane reduces the heat loss from interior room to an exterior environment. While low-e coating applied on the internal surface of the outside glass pane of a double glazing, it limits to enter the infrared spectrum (or long wave spectrum) of the incident radiation [22] [47]. Low-e coatings are metals or metallic oxide spectrally selective coatings which allow visible light in the solar spectrum to be transmitted [48,49] and reflect the infrared (2000 nm–50,000 nm) [50,51]. Low-e coating for glazing should exhibit high transmission in the visible wavelength; emittance value should be low to restrict heat transmission from room and should have high durability under solar exposure. The operation of a low-e coated double-glazing is shown in Fig. 5. Soft low-e coatings to provide higher transparency and higher infrared reflection, though extra protective layers are required to provide durability [50,52–54]. Silver, gold, and aluminium low-e coating have low absorption coefficients of 5%, 8% and 30% respectively. As silver has poor stability to atmospheric moisture, silver coatings are protected using a dielectric layer of zinc, tin or titanium. Available low-e coatings have been reviewed extensively [34].

2.3. Prismatic glazing

Prismatic glazing reflects direct solar radiation whilst allows diffuse solar radiation enters into a building. Prismatic glazing consists two prismatic panes inclined within the window plane, positioned facing each other, with a small gap between the two

Fig. 5. Operation of low-emissivity coated double-glazing.

Fig. 6. Schematic and details of prismatic glazing. Reprinted from Ref. [57] with permission from Elsevier.

panes as shown in Fig. 6. The lower rib faces of the outer prismatic pane are coated with a specularly reflecting layer and the upper rib faces of the inner prismatic pane are coated with a diffusely reflecting layer. The prismatic glazing unit can be used for common window with significant solar gains in temperate climates to achieve relatively uniform daylight illumination of a room. The reflecting surfaces of the prismatic ribs do not create glare [55]. A fully functional dynamic prismatic optical element coating combined with conventional vertical daylight strategies, can reduce electric lighting demand by 85%. In another work, prismatic glazing decreased 10% incident direct solar radiation onto the front of a building whilst allowed 90% radiation in winter [56].

2.4. Water flow glazing

A water-flow glazing contains clean water to flow upward or downward between two glass panes as shown in Fig. 7. Water flow between two glass panes lowers the glass pane temperature and solar heat gain entering the room [58]. Thus, the cooling load due to air-conditioning is reduced. The water-flow between the glass

Fig. 7. Energy flow path at water flow glazing.

panes can be directed to a water heating system [59]. In China, 0.01 m/s optimum water flow speed was able enough to maintain room temperature [60]. The total energy performance for water flow glazing is better in winter than summer as heat from indoor space is also be absorbed by water and reclaim by using hot water [61]. Compared to conventional double and single pane window this water flow window reduces 32% and 52% annual room heat gain respectively. Water flow glazing is advantageous for combined performance such as reduction of air condition load and water heating [62]. Water flow inside a double-glazing can control more heat than airflow inside the double-glazing [63,64] as water has higher density and heat capacity than air. For tropical Malaysian climate, water flow glazing showed 70% short wave infra-red (1300 nm–2500 nm) absorption which offered thermal comfort for building interior [65]. Water is natural, colourless, odourless, non-toxic, and plentiful and does not have any impact on visibility from room to outside. Disadvantages of this type of systems are laborious construction process and design requirement for auxiliary water collector, which may not be feasible for retrofitting window application or even in new zero energy building. Pumping systems are required to generate the water flow from lower header to upper header. The cost of water flow glazing installation is similar to a solar panel installation [66]. Control over glare and allowable daylight are not possible using this glazing. This system is not commercially available.

2.5. Air flow glazing

In an airflow glazing, space between inner and outer glazing surface is an airflow path as shown in Fig. 8 [67,68]. This glazing can reduce effective U -value up to 30–40% compared to air-filled double glazing [69]. Air is supplied in from outside or from the building either buoyancy or mechanical extraction process. Air between two glasses panes gets heated due to incoming solar radiation. Warmer air flows in to the room from the top of the glazing outlet [69–71]. Warmer air enhances to reduce the heating load and improves indoor space quality in winter and for cold climatic area. For summer area, the warmer air can be thrown away from the glazing, which will act as a barrier for direct entering solar heat gain. Air supply in a room and air exhaust from a room both in a same window is also possible [72,73]. For airflow glazing, reduction of U -value is possible by adding a low- e coating facing into the ventilated layer to increase pre-heat air. Pre-heat inclusion

Fig. 8. Schematic diagram of the airflow glazing.

increases 1–5% of the window-shading coefficient. Addition of double pane instead of single glass for inner glazing unit of an airflow glazing can offer low U -value ($2.2 \text{ W/m}^2\text{K}$ to $1.8 \text{ W/m}^2\text{K}$) while speed of airflow increases ($20 \text{ m}^3/\text{h}$ to $80 \text{ m}^3/\text{h}$) [74]. U -value of a triple pane supply air window can vary from $0.5 \text{ W/m}^2\text{K}$ to $0.1 \text{ W/m}^2\text{K}$ while airflow speed changes from $10 \text{ m}^3/\text{h}$ to $30 \text{ m}^3/\text{h}$ [75]. This is 54% reduction of U -value than a classical triple glazing ($1.1 \text{ W/m}^2\text{K}$). Airflow glazings need a fan to collect and flow the air between the glazing panes and require internal cleaning as presence of dust in the air can create scatter and reduce the visibility through the glazing. Glare and daylight control are not achievable using airflow glazing. This is also not commercially available.

2.6. Vacuum glazing

Vacuum glazing is a highly thermally insulated glazing, which can offer high transmittance. Vacuum glazing consists vacuum between two glass panes. To maintain pane separation against outside atmospheric pressure, small support pillars are employed between two glass panes. This support pillars are negligible and do not create any viewing obstacle [76]. Vacuum glazing, shown in Fig. 9 has a hermetic (leak free) edge sealing around the periphery of two glass sheets and a stable pressure ($<0.1 \text{ Pa}$) between two glass sheets [77–79]. Vacuum glazing works on the principle of thermal insulation by eliminating any gaseous medium for convective heat transfer as in the Dewar flask (1893), was proposed by Zoller in 1913 with a patent granted in 1924 [78]. Transmission spectra of a vacuum glazing are shown in Fig. 10. It can be seen that long-wave transmission is restricted due to the presence of low- e coating [80,81].

Fig. 9. (a), (b), (c) details of vacuum glazing and (d) photographic view of a vacuum glazing. Reprinted from Ref. [80] with permission from Elsevier Ltd.

Fig. 10. Transmission spectra of a (i) SPACIA vacuum glazing sample coating of the two glass panes with one low-emittance coating, (ii) double glazing and (iii) AM 1.5 solar spectral irradiance. Reprinted from Ref. [80] with permission from Elsevier Ltd.

The first successful vacuum glazing fabrication process was achieved using solder glass edge sealing at above 450 °C [82–84] in 1989. Since then, many samples of vacuum glazing with U -value of 0.8 W/m² K using a solder glass edge sealing technique were fabricated. Addition of transparent low-e coating reduces radiative heat transfer between the panes [85]. High temperature vacuum glazing fabrication can cause performance degradation of soft low-e coatings. To enable lower emittance, soft coating is essential to lower overall heat loss. Low temperature edge seal fabrication (less than 200 °C) method using indium alloy was developed [86,87] for vacuum glazing with measured thermal transmittance less than 1 W/m²K for the centre-of-glass area [88,89]. Use of two low-e coatings does not reduce the overall heat transfer rate over a single low-e coating layer. One layer of low-e coating also reduces the overall system cost, as low-e coatings are costly [90]. Edge sealing, framing and glass pane thickness has direct effect on the thermal performance of vacuum glazing. In vacuum glazing, the edge seal allows heat flows from the glass sheet on the warm side through the edge seal to the sheet on the cold side, which decrease the overall thermal performance of the glazing. Thus, edge seal in vacuum glazing works as short circuit between two glass sheets [85]. However, scarcity and cost of indium can be challenging for advancing of indium edge sealed vacuum glazing. Thus, Cerasolzer type CS186 was investigated on vacuum glazing at University of Loughborough for replacement of indium edge sealing [91–93]. Metal-based array of opaque small pillars was also replaced by transparent pillars, which were prepared by using 76 wt% low melting glass powder and 24 wt% ethyl cellulose terpeneol solution. These small pillars showed higher transmittance, higher vickers hardness, uniform thickness compared to metal one [94]. Frame in vacuum glazing should provide high thermal insulation and maintain the structural strength. An insulating frame for vacuum glazing reduces the U -value of vacuum glazing. It also offers high

temperature of the glass at the edge to the entire glazing [88]. For vacuum glazing, one exoskeleton structure made from Aluminium was investigated. Exoskeleton structure can be made by wood, polypropylene or polyethylene polyvinylchloride, with a range of solid thermal insulations filling the internal cavities. Experiment and simulation work showed that increase of thickness of the frame decreased the rate of increases of U -value [88]. Though vacuum glazing is in research interest from last three decades, few works were undertaken at outdoor conditions. At University of Sydney, vacuum glazing was exposed from October 1995 to June 1996 for investigation of its long-term mechanical and thermal integrity performance [95]. At Dublin Institute of Technology, this glazing was performed from July to November 2014 to investigate its U -value and daylight performance. It was found that this glazing offered 53% reduction of heat losses compared to a similar area of double-glazing where daylight penetration through both glazing was nearly equal. SHGC for vacuum glazing was found to be 0.58 while incident angle was 42° [80]. Table 1 shows the detail of different type of investigated vacuum glazing. It is evident that U -value for vacuum glazing is the most available data. However, from Ghosh et al. [80] work, it can be concluded that vacuum glazing allows sufficient solar heat gain and control heat loss but enhances the possibility of glare.

To obtain much lower overall heat transfer coefficient triple vacuum glazing (shown in Fig. 11) was studied theoretically [96,97]. From simulation study, it was found that triple vacuum glazing can offer U -value of 0.2 W/m²K which lowered 60% heat loss compared to double pane vacuum glazing. However, manufacturing of triple vacuum glazing and indoor-outdoor experiment is required to prove the concept.

For vacuum glazing application, the best suitable locations are

Fig. 11. Schematic diagram of triple vacuum glazing and heat flow across the triple vacuum glazing (Redrawn from Ref. [98]).

Table 1
Literature data for Vacuum glazing.

Dimension	U -value (W/m ² K)	SHGC	Transmission	Remarks	Reference
1 m × 1 m	0.8 (solder glass edge sealing)	Not available	Not available	U -value was found using indoor experiment	[85]
0.4 m × 0.4 m	0.97 (indium alloy edge sealing)	Not available	Not available	U -value was found using indoor experiment	[89]
0.5 m × 0.5 m					
0.35 m × 0.21 m	1.4 (NSG SPACIA)	0.58	72% (visible)	U -value was found outdoor experiment 53% heating load saving	[80]

cold climatic area where heating load demand is high. Vacuum glazing will stop the heat transmission from room to external environment and reduce the heating cost. In warm climate, this glazing may work as heat insulator and increase the cooling load demand. Different optical and thermal parameters of investigated vacuum glazing has been summarised in Table 1.

2.7. Aerogel glazing

Aerogels are air permeable dried gels with a very high porosity, which make it to have lower thermal conductivity than air [99]. They are nontoxic, low flammable, lightweight, low refractive index [100], high specific surface area and low apparent density [101,102]. Aerogels can provide acoustic insulation and fire-extinguishing ability. Aerogels can be formed from silica, alumina, and carbon or from transition and lanthanide metal oxides, metal chalcogenides, and organic/inorganic polymers. Silica aerogel is the most common, being formed by aggregations of silica nanoparticles having 5–10 nm diameter and 50 nm diameters of mesoporous air voids [103]. Granules are irregular in shape and millimetres in size. Pore diameter of silica aerogel varies between 10 and 100 nm and this air void path is smaller than mean free path of nitrogen and oxygen and from other aerogel material. Small pore size in aerogel reduces heat flow due to conduction. Thus, aerogel has low thermal conductivity between 0.005 and 0.02 W/m K and act as barrier for thermal conduction [104]. Aerogel is infrared permeable and offer higher thermal conductivity at higher temperature [105,106]. Addition of carbon black, titanium di oxide (TiO_2) or zinc oxide (ZnO) helps aerogel to scatter the infrared, lowering radiation heat transfer and improving thermal conductivity [107].

Monolithic and granular are the two types of available silica aerogel. Manufacturing of large pieces of monolithic silica aerogels is troublesome due to aerogel's fragile nature. In comparison, monolithic silica aerogel (0.063 W/m²K, 60% transparent between two glass panes) has better thermal conductivity and optical transmittance than granular (1 W/m²K and 30%) [108–110]. Monolithic transparent aerogels are attractive for glazing application [111] though presently no commercial products are available because of the costly and time-consuming synthesis process. Translucent granular silica aerogels can be defined as nanogels, are suitable for highly energy-efficient windows and skylights. Nanogel filled double glazing can reduce 21% total energy consumption for heating (12%) cooling (5%) and lighting (4%) compared to air double-glazing in Oslo Norway [112]. Silica aerogel from Cabot Corporation had transmittance 0.45 which reduced 4–8% spaced cooling load compared to a 0.9 transmittance double-glazing [105]. Table 2 mentioned the list of aerogel glazing has been examined. Fig. 12 shows photographic view of aerogel material and aerogel glazing. Spectral transmission of aerogel is shown in Fig. 13.

Edge sealing of aerogel glazing is difficult due to fragility of aerogel. To achieve low thermal performance of aerogel glazing, edge sealing should have lower thermal conduction, airtight and

Fig. 12. (a) Viewing through an aerogel sample, (b) monolithic and granular aerogel, (c) an evacuated aerogel glazing in a well-insulated frame. Reprinted from Refs. [108,111] with permission from Elsevier.

Fig. 13. Spectral normal hemispherical and normal transmittance of aerogel with density 90 kg/m³ and thickness 12 mm. Reprinted from Ref. [116] with permission from Elsevier Ltd.

Table 2
Literature data for Aerogel glazings.

Type	Dimension	U- value	Transmission	Thickness	Reference
Monolithic silica aerogel	55 × 55 cm ²	0.72 W/m ² K	73–75%	15 ± 1 mm	[113]
Monolithic silica aerogel	0.58 × 0.58 m ²	0.66 W/m ² K	76–80%	15 mm	[111]
Monolithic Silica aerogel	55 × 55 cm ²	0.7 W/m ² K	76%	15 mm	[114]
Silica aerogel	7.5 × 25 cm ²		90%	10 mm	[115]
Monolithic Silica aerogel	a) 0.5 × 0.5 (m ²) b) 1.0 × 1.0 c) 1.5 × 1.5	0.40 W/m ² K			[116]
Granular silica aerogels	NA	0.4 W/(m ² K)	35%	20 mm	[117]

have enough strength to hold the two glass panes. Jensen et al. [113] mentioned polystyrene support based edge sealing for monolithic type aerogel granules sandwiched between glass panes. Reim et al. [117–119] used two glass panes filled with insulating granular silica aerogel. Huang and Niu [105,120] used an aluminium bracket to support glass cover and on the bracket-sealed surfaces, polystyrene was employed with sealant. As the fragility of silica aerogel limits their application, mechanical strength enhancement of silica aerogel has been achieved by incorporating a polymer. Silica aerogel scatters the transmitted light, which is a major barrier to production of transparent aerogel glazing. Light reflected off silica aerogels has a blue colour; hence, it is called “frozen smoke” [116,121]. Aerogels are available commercially (ASPEN aerogel) mainly for building wall insulation rather than specifically for glazing application. The scattering properties of silica aerogel can be overcome by using it as a spandrel component in a façade [122–124] to allow daylight through spandrels.

2.8. Photovoltaic glazing

In Photovoltaic (PV) glazing, organic or inorganic type PV cells are placed between the two glass panes. PV glazing reduces glazing transparency, reducing the solar heat gain coefficient (SHGC), which reduces the cooling load, and introduces daylighting control as shown in Fig. 14 [125–127]. Another advantage of this type of glazing is that the PV provides small-scale electricity generation [128]. The presence of low-e coating reduces the heat transfer through radiation process [48]. PV glazing can be a part of building-integrated photovoltaic (BIPV) [129] widely used as façades or roof [130]. Triple-point (maintaining day-lighting, reducing overall heat transfer value and generating clean electricity) effect is possible to be attributed by PV glazing.

Charron and Athienitis [132] reported a double glazing system with integrated PV and motorized blind in which the lower part of the facades was with PV and upper part was motorized blind. When PV was installed in the middle of the cavity, electrical generation reduced 21% though overall thermal and electrical efficiency increased 25%. Manually adjusted photovoltaic slat window (PV-SW) with $0.5 \times 0.6 \text{ m}^2$ surface areas, offered power generation of 15 W. Illuminance inside the test cell was 750 lux while window had 68° slat angle [133]. Area of PV cell has significant effect to reduce the solar gain. Theoretical and experimental work of new spaced type semi-transparent PV module offered 70% solar heat gain if 80% glazing area is covered by solar cell. PV cell efficiency and material thickness had no effect on solar heat gain control [134]. In a building, 40% transmittance PV glazing offered minimum electricity consumption of a building while window to wall ratio (WWR) was 50% [135]. Energy savings of 16.7–41.3% were achieved in Singapore for a WWR range of 70–100% [128]. Double-glazing

achieved superior performance compared to PV single glazing under Singapore climatic condition due to single glazing's less solar heat gain control [128]. In hot climatic area, a see through PV cell ventilated glazing was able to save 23% electricity saving in the space cooling for a year [136,137]. A new PV glazing consist of transparent a-Si PV, integrated with TiO_2 nano coating offered 7% higher power generation than conventional PV glazing. This type of glazing offers high insulation, power generation and self-cleaning due to nanocoating [138–140]. Dye-sensitized solar cells (DSSC) [141–146] and perovskite [147,148] based PV glazing are also currently under investigation. However stability under outdoor ambient conditions needs to be established before considering them for glazing application [149] [150]. Spectral transmission of DSSC glazing for different thickness of titanium dioxide layer is shown in Fig. 15. Table 3 shows thermal and optical parameters for different investigated PV glazing. Higher absorption of PV offers low visible transmission, which is suitable for glare control. However, this lower value also reduce the viewing and allowable daylight for building interior. Recently cadmium telluride (CdTe) thin film based PV glazing was investigated for building in Indian [151] and Brazilian [152] climate and satisfactory results were found. Difference of U -value between PV single glazing and PV double glazing is four times.

Table 4 summarised the glazing properties for constant or static transparent glazing systems. It is evident that these types of glazing systems are not able to offer control over heat transfer coefficient, solar heat gain, and daylight and glare in a single unit.

3. Non electrically actuated switchable material

This section introduces switchable glazings, which are activated by non-electrical impulses. Thermochromic, thermotropic, phase change material and gasochromic are the non-electrically actuated switchable glazing. Switchable glazing changes its transparency from transparent/bleaching state to opaque/coloured/translucent state or reverse depends on actuation. More than one transparency makes them attractive for glazing application as they can adapt with buildings demand. Switchable glazings are primarily responsible to control solar heat gain and introduce comfortable daylight.

Fig. 15. Spectral transmittance of DSSC glazing where L2, L3, L4, L5, L6, L7 indicates 3 μm , 0.5 μm , 6 μm , 8 μm , 10 μm , 12 μm , 14 μm thick TiO_2 layer [153].

Fig. 14. (a) Double glazing (b) Single glazing PV (semi-transparent amorphous silicon) window. Reprinted from Ref. [131] with permission from Elsevier.

Table 3
Literature data for PV glazings.

Dimension (m × m)	Type of PV	U-value (W/m ² K)	SHGC	Visible transmission (%)	Reference
0.98 × 0.95	a-Si single glazing	5.08	0.289	9.17	[128]
1.3 × 1.1	micromorph-Si single glazing	4.80	0.413	5.19	[128]
0.98 × 0.93	a-Si double glazing	1.67	0.154	6.91	[128]

Table 4
Glazing parameters control using static or constant transparent glazing.

Static or constant transparent glazing	Control of overall heat transfer coefficient (U-value) W/m ² K	Control of solar heat gain coefficient (SHGC)	Control of daylight/glare
Double glazing (made by clear glass)	✓	×	×
Low-e coated double glazing	✓	✓	×
Prismatic glazing	×	✓	✓
Water flow glazing	×	✓	×
Air flow glazing	✓	✓	×
Vacuum glazing	✓	✓	×
Aerogel glazing	✓	×	✓
PV glazing	×	✓	✓

3.1. Thermochromic

Thermochromic material changes its colour by changing its crystal structure above a particular environmental temperature [154–158]. Thermochromic materials can be inorganic and polymer based. Other thermochromic materials include iron oxide (Fe₃O₄), iron silicide (FeSi₂), niobium dioxide (NbO₂), nickel sulphide (NiS), and titanium oxide (Ti₂O₃; Ti₄O₇; Ti₅O₉). Inorganic vanadium dioxide (VO₂) thermochromic glazing has a 68 °C transition temperature (T_C). Below this T_C, it behaves like insulator and infrared transparent and above the T_C it behaves like metal and reflects infrared. This phase change from metal to insulator occurs within 10–12 s. VO₂ thin film made by two different precursor gels, V-H₂O₂ (V₂O₅·2.2H₂O) and V₂O₅-H₂O₂ (V₂O₅·1.8H₂O) and one step annealing at 750 °C in a vacuum can reduce the transition temperature from 68 °C to 62.5 °C [159]. Thermochromic dye BW 100 based thermochromic coatings were coated on glass substrate, which showed coloured phase at 20 °C and colour less phase at 30 °C. It was also found that addition of TiO₂ enhance the reflectance of this coating. Colourless phase showed higher visible and infra-red reflectance than coloured phase [160]. A thermochromic glazing is shown in Fig. 16. Spectral behaviour of thermochromic VO₂ film is shown in Fig. 17.

As its operation requires neither external power nor control devices, can lower VO₂ transition temperature by doping with valence metal dopant like tungsten (W6+), molybdenum (Mo6+), tantalum (Ta5+), niobium (Nb5+) and ruthenium (Ru5+). Magnesium (Mg2+) doping increases the visual spectral transmissivity whilst decreasing the transmission temperature. Tungsten doping

Fig. 17. Spectral transmittance of VO₂ film. Reprinted from Ref. [47] with permission from Elsevier.

reduces the metal–semiconductor transition of VO₂ to about 25 °C. VO₂ film having low transition temperature 30 °C was also reported [162]. Decrease of transition temperature and better transmission is possible using vanadium oxyfluoride (VO_xF_y). A polymer thermochromic was experimentally characterised in an outside environment, was found transition temperatures between 25 °C to 74 °C [161]. Adding an antireflection coating can increase the

Fig. 16. South-faced polymer thermochromic glazing (middle room with the dark windows) and infra-red image of glazing's surface temperature on June 16, 12:02 p.m., Berkeley, California (37.91° N). Reprinted from Ref. [161] with permission from Elsevier.

transmission at the visible wavelengths [163]. To obtain higher solar and luminous transmittance nanothermochromism is a possible way. VO₂ nano particles dispersed in a dielectric host have higher luminous and solar transmittance than VO₂ in continuous thin solid film [164]. Addition of gold nanoparticle changes the yellow-brown colour film to a variety of greens and blues and can be reflective for infra-red (IR). Colour changes and reflection percentage depends on the concentration of the gold nano particle [165].

First outdoor characterisation of thermochromic (VO₂) single glazing with a transition temperature (T_c) of 41.3 °C was performed [155]. Using outdoor data, simulation results showed that this glazing could save 15 ± 5% cooling energy for low mass room and nearly 9.4% cooling energy consumption for a residential room. These results enhance the possibility of the adoption of the VO₂ glazing for improving the thermal comfort and decrease the energy consumption in a passive building and an active building respectively [155]. First thermochromic double-glazed window was experimentally characterised using south facing outdoor low-mass test cell dimension of 2.9 m × 1.8 m × 1.8 m at the campus of the University of Science and Technology of China, Hefei, China. Results were compared with ordinary double glazing which showed that use of thermochromic double glazing saved 11.1% cooling energy demand. Using same meteorological data and BuildingEnergy simulation tool, performance of thermochromic single glazing was evaluated which showed that double glazing saves 23% higher cooling load demand due to its lower visible and solar transmittance than single glazing [166]. Using same test cell, 25 mm thick paraffin wax with graphite foam based PCM plates were employed over the floor. Indoor test cell temperature with PCM + VO₂ was 45 °C while without PCM + VO₂ the test cell room temperature was 68 °C. Interior thermal comfort using combined material was even better compared to a solo material application [167]. One hypothetical thermochromic glazing having solar transmittance range of 0.10–0.50, visible transmittance range of 0.30–0.60, 0.04 emissivity coated, solar heat gain coefficient range of 0.12–0.47, U -value of 1.45 W/m²K was investigated for Chicago (hot/cold climate) and Houston (hot climate) climate using EnergyPlus simulation. Result showed that critical switching temperature range between 14 and 20 °C, this thermochromic glazing offered 3.1–12.5% less annual energy used in large commercial office building compared to IR selective low-e windows having visible transmittance of 0.64, SHGC of 0.30 and U -value of 1.35 W/m²K [168].

Currently a dual intelligent thermochromic glazing has been investigated. This glazing can modulate both solar and long wave radiation. Ye et al. [47] indicated that modulation of long-wave and solar radiations are equally important for energy efficient glazings. For traditional VO₂ based thermochromic glazing has VO₂ films that are located on the external surface of the glazing and internal surface remain with traditional silica based constant emissivity glass. Thus, emissivity of the external side is changeable. During hot daytime, external surface low emissivity reduces radiative heat gain. However, higher glazing temperature due to higher incident, absorbed solar radiation and equal emissivity between internal surface and glass allow heat to dissipate into the indoor space. In a

dual intelligent thermochromic glazing VO₂ film located on the internal surface [169]. For sunny summer day, the surface temperature of VO₂ glazing becomes high which allows low solar transmittance. At this time long wave emissivity of internal surface of VO₂ glazing is also low which restricts radiative heat transfer from glazing to building interior. For cloudy day VO₂ glazed surface temperature is low and allow high solar and visible transmittance. At night absence of solar radiation heat dissipates from interior surface to cold sky by long wave thermal radiation [169]. Theoretically using reliable tool [154,155], dual intelligent glazing and traditional VO₂ glazing system energy saving potential were investigated for a south facing 5 m × 3 m × 3 m office room in Guangzhou, China. It was found that dual intelligent glazing save 15.5% energy compared to traditional glazing to maintain 26 °C indoor space temperature [169]. Daylight modulation using thermochromic glazing is not possible as visible transmission of thermochromic glazing varies between 38 and 40% that is low for glazing application. Solar energy modulation is only possible below 10% [170]. Table 5 shows thermal and optical parameters for different investigated thermochromic glazing.

3.2. Thermotropic

Thermotropic materials are hydrogels, polymer blends, lyotropic and phase change material [171]. Hydrogel type thermotropic is aqueous polymer gel, which has a long chain of second polymer. Hydrogel thermotropic glazing was reported for large area application where the matrix material was water with water-soluble polymer hydrophobic groups, sodium chloride, and an amphipathetic molecule [172]. A hydrogel type thermotropic glazing is shown in Fig. 18. Polymer blends thermotropic contains polystyrene-co-HEMA and polypropylene oxide. At low temperature, two layers of polymer blends material have different refractive indices mix to each other. These two polymers are separated until heated sufficiently to reach a switching temperature [173]. Thermotropic liquid crystals, change colour from “transparent” to “opaque/translucent” state. At low temperature thermotropic materials are “transparent” while above switching temperature it becomes opaque/translucent as both transmitted and reflected lights are scattered. Below switching temperature, the two main transparent components are homogeneously mixed as refractive indices of the particles and matrix are equal the layer appears transparent. Above the threshold switching temperature, the particles change to phase with unequal refractive indices; radiation is scattered by the particles and the material reflects a portion of the incident solar radiation and the layer becomes “opaque”. The switching temperature of the thermotropic material should be slightly less than the relative thermal index of the absorber material [174]. No visual contact with the external environment above the transition temperature makes its suitable for incorporation as high level glazing, as skylights or as roof lights [175]. Spectral behaviour of thermotropic glazing is shown in Fig. 19.

Thermotropic material prepared by hydroxypropyl methyl cellulose (HPMC), sodium chloride (NaCl) and pure water in ratio of 2:10:100 had transmission of 72% and 32% in transparent and opaque states respectively. A west facing installation of this

Table 5
Literature data for thermochromic glazings.

Dimension (m × m)	Type of glazing	state	U -value (W/m ² K)	SHGC	Visible transmission	Reference
1.65 m × 1.65 m	VO ₂ single glazing	insulator	5.8	0.58	43%	[166]
		Metallic	5.8	0.53	42%	
1.65 m × 1.65 m	VO ₂ double glazing	insulator	3	0.47	38%	
		Metallic	3	0.41	36%	

Fig. 18. From top to below thermotropic glazing in “transparent” and “opaque” state (redrawn from Ref. [171]), Hydrogel thermotropic glazing “Opaque” state, and “Transparent” state [172], Switching of a thermotropic glazing laminate Okalux GmbH, Germany Nitz 2005 Reprinted from Ref. [171], with permission from Elsevier.

Fig. 19. Spectral transmission of a thermochromic glazing filled with (a) 0.25 mm, (b) 0.5 mm, and (c) 1.0 mm substrates. Reprinted from Ref. [172] with permission from Elsevier.

thermotropic glazing allowed 14.5% comfort level compared to double glazing and 2.4% compared to tinted double glazing in summer and winter in Hangzhou, China [176]. Double-glazing filled with thermotropic material can reduce 19% cooling load and 3.6% whole building energy consumption compared to an air filled double glazing [176]. A thermotropic single laminated glass and a triple glazed unit had switching phase interval between 28 °C and

34 °C that reduced the solar and visual transmittance between the transparent and the opaque state by around 20% [177]. Switching behaviour of thermotropic material solely depends on temperature. High solar intensity low switching temperature will not heat up thermotropic material to change its phase [178]. Hybrid thermotropic hydrogels and electron-conducting indium-tin oxide using Joule heating can generate heat [179]. Table 6 shows thermal and optical parameters for investigated thermotropic glazing.

3.3. Phase change material

Phase change materials (PCM) are opaque when solid but become transparent while melted as shown in Fig. 20. As solar heat gain provides the latent heat for melting, the rate of solar heat gain through a PCM window is reduced at transition to become transparent [180]. It has potential to store considerable amounts of energy during their phase transition [180–184]. PCM slows the heat flow by absorbing some of the heat gain. PCM glazing is made by sandwiching the PCM material between two glass panes. At night, it releases store heat to become solid. PCM glazing is advantageous for winter evening as it can improve the thermal quality [185].

Working principle of PCM material is shown in Fig. 21. Fig. 21 (b) shows that PCM has ability to shift the peak energy demand from midday to afternoon period compared to sensible heat storage medium such as water, air or any other sensible storage medium which increase their temperature by absorbing heat and decrease

Table 6
Literature data for thermotropic glazings.

Dimension (m × m)	Type of glazing	States	U-value (W/m ² K)	SHGC	Visible transmission	Reference
NA	Thermotropic double glazing	Transparent Opaque	3.2	0.66 0.03		[176]

Fig. 20. Paraffin wax phase change material in double glazing unit (DGU-PCM) in “opaque” and “transparent” state, DGU_PCM glazing unit in a test cell and a dynamics of the melting and re-solidification process of the paraffin layer within DGU-PCM during a sunny summer day. Reprinted from Refs. [186–188] with permission from Elsevier.

Fig. 21. (a) Phase change of PCM and sensible heat storage (temperature of the sensible heat storage material rise when energy is absorbed and drops when energy is withdrawn). (b) Change of peak temperature using PCM.

the temperature by releasing the heat.

PCMs can be organic or inorganic or eutectic type. Optical properties of paraffin type of PCM for semi-transparent type application have been evaluated with a nominal melting temperature in the range 28–30 °C and a latent heat of fusion of about 230 J/g [189]. Intensive experiment and simulation work was also performed by Goia et al. [187,188,190] using paraffin type PCM material for glazing application as shown in Fig. 20. Spectral transmission of this PCM filled double glazing is shown in Fig. 22.

Large 1.00 m² PCM glazing was developed by using 13 kg paraffin wax PCM to fill the 15 mm cavity between two glass panes. Nominal melting temperature was 35 °C and the heat storage capacity (in the 26 °C–41 °C temperature range) was 170 J/g [186] of this PCM [188]. The large area of the glazing avoided edge effects of the aluminium frame. Specular and angular behaviour of paraffin based different thickness of PCM glazing showed that thickness of

PCM layer had weak effect on reflection of PCM however had high impact on the transmission and absorption coefficient. It was found that reflectivity of PCM in solid state was up to three times higher than PCM in liquid state. Absorption coefficient of solid PCM was also higher than its liquid state [191,192]. Commercially available salt hydrate PCM, CaCl₂·6H₂O with latent heat of fusion of approximately 190 kJ/kg, a nominal melting temperature of approximately 27 °C and small super cooling effects (1–3 °C) [193] was experimentally investigated using outdoor test cell. Transmission of this glazing was 1% and 80% when opaque and transparent respectively. Double glazing filled PCM showed 30% less heat losses compared to a double glazing without PCM, in south oriented facades. Solar heat gains are also reduced by about 50% [185]. Numerical investigation on PCM filled double glazing showed that this glazing had solar heat gain coefficient in the range of 0.65–0.8 under 600 W/m² incident solar radiation and 24 °C internal ambient temperature while outside was 35 °C. In this work, detail of thermo-optical parameters of PCM were not explained [184]. In hot summer and cold winter area of China, inorganic PCM glauher salt (Na₂SO₄·10H₂O) filled PCM double-glazing was able to restrict 39.5% entering heat compared to air filled double-glazing. PCM filled glazing had transmittance of 0.76 and absorptance of 0.19 [194]. No experiment work using PCM glazing for daylighting and glare control has been conducted. Thermal and chemical stability of paraffin based PCM glazing was investigated by Ref. [195]. It was found that latent heat of aged paraffin PCM reduced to 5% compared to pristine one. Melting temperature decreased about 2 °C for cooling mode and 1.5 °C for heating mode after one year of operation. As PCM become transparent mostly during midday period it is unsuitable for glare control. This mismatch behaviour limits application. PCM in solid phase increase the window weight

Fig. 22. Spectral transmission of a PCM double glazing filled with 15 mm thick paraffin type PCM layer in solid and liquid state. Reprinted from Ref. [191] with permission from Elsevier.

and the change of volume between the two states (~10%) are the major drawbacks of this type of glazing. Table 7 shows thermal and optical parameters for investigated PCM glazing.

3.4. Gasochromic

A gasochromic film is composed of tungsten trioxide (WO_3) layer with a very thin coating of a platinum (Pt) or palladium (Pd) type catalyst. This film becomes opaque or bluish colour when expose to a low concentration hydrogen. It becomes transparent on exposure to oxygen [196–198]. Gasochromic material sandwiched between double-glazing as shown in Fig. 23 has potential to offer up to 75% solar transmittance when transparent. In the opaque state, the gasochromic material absorbs solar radiation to produce heat is conveyed to the ambient by convection. Spectral transmission of gasochromic glazing is shown in Fig. 24.

Properties of a gasochromic glazing depend on the crystal configuration (i) water content inside it, (ii) chemical composition and (iii) microscopic structure. Controllable gasochromic properties are available in monocrystalline, polycrystalline, and amorphous films where amorphous type shows better gasochromic properties compared to others [200]. Gasochromic WO_3 film can be manufactured by electron beam evaporation [196,201], sputtering [202–204], sol-gel, electrodeposition [205,206]. For large scale WO_3 film manufacturing, low cost sol-gel methods are promising due to simple equipment requirement. Without heat treatment in sol-gel process develops easily stretchable and low stability WO_3 films [205,207,208]. Presence of WO_3 layer in gasochromic glazing makes it comparable with EC glazing though gasochromic glazing has structural difference with EC glazing. To obtain EC glazing 5 layers are required (ITO-ion storage-ion conducting-EC-ITO) where as gasochromic glazing is possible with only WO_3 layer with palladium (Pd)-catalyst. WO_3/Pd layer can be coated on any transparent substrate; however, for EC glazing usage of transparent conductor is limited [207,209–212]. Platinum (Pt) coated, porous, less than $1\ \mu\text{m}$ thick columnar film of WO_3 was prepared for a gasochromic glazing which offered a very fast less than 10 s

Fig. 23. Structure of a gasochromic glazing.

Fig. 24. Spectral transmission of gasochromic double-glazing. Reprinted from Ref. [199] with permission from Elsevier.

switching speed [213]. The switching process of this glazing takes less than 10 s. A homogeneous colouration process was achieved within a second [214]. A $1.1 \times 1.6\ \text{m}^2$ glazing offered 20,000 times switching for 2 years without any significant performance degradation. First few days of operation showed instantaneous transparent and bleaching transformation. After 2 years of operation, glazing transmission change from 60% to 24% took 1 min while remaining 10% changed in 10 min. To become transparent this glazing took 1 min to achieve 50% transparent while fully transparent became after 3 min [196]. A $0.8 \times 1.2\ \text{m}^2$ gasochromic switchable mirror, manufactured by magnetic sputtering machine [215] from Mg-Ni alloy and Pd films, switched from the mirror state to the transparent state by introducing 4% H_2 in Ar within 15s, while the reverse change took about 8 min by introducing 4% O_2 in Ar. The mirror state was able to reduce energy consumption by 34% compared to a transparent double-glazing window [215]. Annual consumption for use of GC DGU in an eight-storey commercial office building dimension of $45\text{m} \times 15.24\text{m} \times 3\text{m}$ in Shanghai city was evaluated using eQUEST 3.64 program. This glazing reduced the annual consumption of HVAC loads by 25–35% compared to single clear float glass [212].

Gasochromic window may present hydrogen explosion. Continuous monitoring is essential for hydrogen leakage at operation site or for storage [216]. The low concentration of hydrogen

Table 7
Literature data for PCM glazings.

Dimension (m × m)	Type of glazing	States	U-value (W/m ² K)	SHGC	Visible transmission	Reference
NA	PCM glazing (3 mm thick PCM)	Transparent	4.69	0.683		[183]
		Opaque				

used for switching process could limit the risk of the explosion. For large area application, gasochromic is more suitable as the coating structure is single layer, which is much simpler than double layer structure. Cost of this glazing can be reduced as here no need for transparent conducting oxide (TCO) layer and single chromic layer structure [199]. Table 8 shows thermal and optical parameters for investigated gasochromic glazing.

Table 9 summarised the comparative properties of non-electrically activated glazing systems.

4. Electrically actuated switchable material

This section outline the present research status of the electrically actuated switchable glazing in the laboratory level with industrial collaboration or commercial product. Currently three electrically activated glazings are well known, electrochromic (EC), suspended particle device (SPD) and liquid crystal (LC). Electrically activated switchable glazing offers user control, which is advantageous over non-electrically control.

4.1. Electrochromic

Electrically actuated electrochromic (EC) glazing is made by EC material sandwiched between two glass panes [218,219]. EC [220] includes (i) transition metal oxides like tungsten, iridium, rhodium,

ruthenium, manganese and cobalt possesses [220,221] (ii) organic material such as prussian blue, viologens, buckminsterfullerene, polypyrrole, polyaniline (PANI), Poly (3,4-ethylene-dioxythiophene) (PEDOT) [222–224].

Mechanical flexibility, multicolour adjustability, low cost easy fabrication process, short coloring and bleaching switching times, high optical contrast, and high colouration efficiency makes organic polymer EC material [225,226] a future potential for EC glazing application. However, low thermal stability of polymers is the hindrance for organic EC glazing applications [226]. Research activities are engaged to improve the stability of organic EC for glazing application. One polymer based EC glazing showed 50,000 times [227] and one viologen based EC glazing offered 2 years [228] durability. Further investigation is required for organic EC material to compete with inorganic, as they possess higher stability.

Inorganic materials have better lifetime and UV stability than organic materials. Among all the materials, tungsten tri oxide (WO_3) material is attractive for EC glazing [229,230]. WO_3 crystals structures are similar to perovskite-type, and birefringent by nature with 2.5 average refractive index [231,232]. The EC behaviour of WO_3 due to application of electric voltage was first observed by Deb in 1969, previously electrochromism was only associated with organic materials. EC material for glazing was proposed by Ref. [221]. In a typical EC glazing as shown in Fig. 25 an EC layer, ion storage layer, and ion conducting layer are sandwiched between

Table 8
Literature data for gasochromic glazings.

Dimension (m × m)	Type of glazing	States	U-value (W/m ² K)	SHGC	Visible transmission	Reference
		Transparent	2.612	0.65	0.54	[212]
		Opaque		0.28	0.15	

Table 9
Comparison of non-electrically activated switchable glazing systems.

Property	Thermochromic	Thermotropic	Phase change material	Gasochromic
Transparent state	Below the transition temperature	Below the transition temperature	Above the transition temperature	Addition of oxygen
Opaque state	Above transition temperature	Above transition temperature	Below the transition temperature	Addition of hydrogen
Memory	Transparent and opaque both state remain for hours depending on ambient /transition temperature and area of device.	Transparent and opaque both state remain for hours depending on ambient /transition temperature and area of device.	Transparent state remains for few hours depends on ambient temperature and heat release capacity of PCM	1 min
Durability	300 °C for dry air and 80 °C for 95% relative humidity, bare thermochromic VO_2 film degrades [217]	200 cycle operating between 20 ⁰ –80 °C [172]	Solar radiation has less impact Due to thermal cycle melting temperature decreased to 2 °C after one year. [195]	10,000–20000 cycles [196]
Near Infra-Red (NIR) control	Reflect NIR, Modulate NIR and IR	Reflect NIR	Absorb NIR for both states	Low NIR transmission in opaque state, Modulate NIR
Switching time	Vary with transition temperature and area of device	Vary with transition temperature and area of device	Vary with transition temperature and area of device	Less than 10 s
Intermediate states	Uncontrolled intermediate states	Uncontrolled intermediate states	Uncontrolled inhomogeneous intermediate states	Using different hydrogen and oxygen concentration, intermediate states are possible
U-value	Similar to single glazing	Close to double glazing.	Similar to single glazing (Double panes filled with PCM)	Close to double glazing.
SHGC	Modulation of SHGC is low due to low modulation of solar transmission. IR modulation is high	Modulation of SHGC is high	Controls	Modulation of SHGC is high
Daylight/glare	No daylight modulation as it offers similar visible transmission for both states.	Opaque and transparent both state can control daylight and glare. Opaque occurs during midday (high temperature) and transparent occurs during morning and afternoon (low temperature).	Inhomogeneous melting and solidification process may be unacceptable for users. Transition and opaque/translucent state can control daylight/glare.	High modulation of luminous/visible transmission thus control over daylight is high and potential for glare control.

Fig. 25. Schematic diagram of electrochromic glazing in its (a) “bleached” (b) “coloured” state (c) photograph of web coated EC glazing in its bleached and coloured state in an office building (Taken from Ref. [260] with permission of Elsevier).

two transparent conducting oxides [233–235].

Indium tin oxide is the most commonly used transparent electrical conductors. Used ion storage layer may or may not have EC properties. A transparent ion conductor (electrolyte) joins the EC and ion storage films. Electrolyte can be transparent liquid [236] or polymer type [237]. Presently, four different types of EC glazing systems have been manufactured by different research groups and commercial companies. Five layer monolithic device backed by single glass substrate was designed by SAGE glass electrochromic [238,239]. Flabeg/EControl Glass GmbH in Germany produced two parallel double-layer-coated glass substrates joined by a polymer electrolyte [240]. Cathodically coloring material WO_3 and anodically coloring Prussian Blue, Polyvinyl butyral (PVB) electrolyte based laminated EC device was successfully developed by Gesimat [241–243]. Polymer-foil-based laminated design [219,244] and low-cost technology developed by ChromoGenics AB spin off founded by Prof C.G. Granqvist and his team at Angstrom Laboratory of Uppsala University in Sweden. To achieve flexible EC, deposition was performed on a polyester [245,246].

The primary purpose of EC glazing is to control the solar heat gain [244] [247–250]. An EC material change from “transparent/bleach” to “coloured” by redox reaction when D.C. voltage between 0 and 5 V is applied [251] and is reversible by inversion of electrical supply [252,253]. Colouration and bleaching time of EC device depends on the active area of the device. EC also shows “iris” effect, which shows faster colour change at the edge while centre has slower compared to edge. This can be mitigated by using suitable powering [254]. EC glazing switching below and above design temperature is not permitted as higher operating power decrease the durability of EC glazing while lower operating voltage cannot

switch the glazing [255,256]. Switching below 0°C may cause device degradation due to ice in WO_3 pores [257]. EC material is potential glazing candidate as it can control transmission, absorption, reflection, and emission of a glazing [244]. EC device can be resembled as battery like in structure [258,259].

At “coloured” state crystalline type WO_3 blocks the near infrared (NIR) or reflects it [261]. Controlling NIR an EC glazing can provide heating and cooling energy savings range from 5 to $15\text{ kWh/m}^2\text{ yr}$ for commercial and residential building, in comparison with high performance static glazing [262]. Solar heat gain values were found to be 0.39 to 0.05 of an EC material having 63% transparent state and 1.2% transparent state respectively [263]. Energetic performances of an EC window was performed using PASSYS cell test with an array of 64 pieces of $12\text{ cm} \times 12\text{ cm}$ EC elements. This glazing had $3.8\text{ W/m}^2\text{K}$ overall heat transfer coefficient. For 4% transparent coloured state it had 0.16 SHGC and 60% transparent bleached state had 0.7 SHGC [264]. An EC system using tungsten oxide and vanadium pentoxide showed solar transmittance modulation between 58% and 9% and visible transmittance modulation between 65% and 13% in the “bleaching” and “coloured” states respectively [265]. Another work reported 72.6% transparency during “bleaching” state and 17.6% during “coloured” state of an EC glazing [235]. 45% energy saving was found using an EC glazing for an office building in hot climate area Arizona or very cold climate area Minnesota [238]. In USA, a simulation study showed that 18% retrofit of the total window stock of building (medium offices and midrise residential buildings in northern climates) using near infrared switching electrochromic (NEC) could save 50% energy and 39% retrofit could save 75% of buildings total energy (heating, cooling, ventilation and interior lighting) consumption [266].

EC glazing has also potential to introduce the daylighting control and reduce the lighting energy demand, reducing the use of shading device [267]. EC glazing can save 44–59% daylighting energy compared to an unshaded glazing [268]. EC glazing system with a transmittance range of 0.08–0.88 maintained stable daylight illumination levels of 500 lux in an office space under overcast and sunny conditions for sunny Arizona climate [269]. A small-scale EC glazing prototype using test cell has been investigated under real weather condition, which was able to reduce discomfort glare caused by EC glazing brightness from diffuse daylight. This result showed that switchable glazing is effective for glare comfort although it cannot be fully opaque when direct sunlight penetrates. It reduces the necessity of shading device, which does not obstruct any view to the outside [270–272].

Long-term durability and electrochemical cycling durability are the obvious criteria of EC device for glazing application. Recent development showed that rejuvenation of degraded EC films, both based on W oxide and Ti oxide are possible by galvanostatic treatment [273–275]. Large scale $1.2\text{ m} \times 0.8\text{ m}$ EC glazing was experimentally tested using one $2.7\text{ m} \times 2.7\text{ m} \times 5\text{ m}$ south facing PASSYS test cell and for a west facing office room. Both results suggested that this EC device has potential to offer user comfort and energy savings [241]. NIR controlling potential of EC glazing also makes it superior compared to other electrically activated switchable glazing [228] as shown in Fig. 26.

It was also found that EC glazing needs low voltage than its rated required voltage at high glazing temperature [276]. At high temperature due to higher ion mobility switching responses are faster which reduce the amount of required voltage [277–282]. EC material switching response decreases exponentially at higher device temperature. In addition, use of liquid electrolyte can reduce switching responses than solid electrolyte due to higher ionic mobility. EC glazing has memory effect, which make this glazing to be in coloured state for long hours even after the supply is disconnected. Low operating power requirement also make it

Fig. 26. Spectral transmittance for an Asahi EC window with 72% visible and 53% solar transmission at bleached state and 20% visible and 10% solar transmission while switching occurred at 2 V to -0.7 . (Taken from Ref. [224] with permission of Elsevier).

viable for building application [260]. Table 10 shows the literature data for thermal and optical performance of different investigated EC glazing.

4.2. Suspended particle device (SPD)

Suspended particle device (SPD) technology was first invented in 1930 and patented. SPD device works on same principle as of light valve where a cell is formed using two transparent sheets of insulating material spaced apart a small distance and containing a suspension of small particles in a liquid medium [284]. Particles can be dihydrocinchonidine bisulfite polyiodide or heraphathite. Shape of the particle can be needle-shaped, rod-shaped, or lath-shaped types. Presence of electrical field allows these liquid suspended particles to move randomly due to Brownian movement and absorbs light passing into the cell. Thus, light valve is dark in the opaque state or no power state. Percentage of light absorption depends on the cell structure, nature, and concentration of the particles and the energy content of the light. In the presence of an applied electrical field, particles become aligned and allow most of the light pass through the cell [285]. Thus, the light valve becomes transparent. This technology is known over seventy years for the application of modulation of light in the field of alphanumeric and television displays, and work as a filters for optical devices. For glazing applications, plastic films are preferred than a liquid suspension. Plastic film eliminates the possibility of bulging effect during high column of suspension due to hydrostatic pressure and leakage possibility from the device. In a plastic film, only small numbers of particles are available which do not noticeably agglomerate during repeatedly activation of the film using applied electric field. SPD light valve uses a film made of cross-linked polymer matrix having refractive index of 1.4 and suspended

Fig. 27. Suspended particle device (SPD) glazing switching for (a) “opaque” and (b) “transparent” states. Reprinted from Ref. [287] with permission from Elsevier.

liquid light valve distributed in the matrix [285]. In shatter-resistant laminated suspended particle device (SPD), SPD interlayer was laminated between two sheets of glass. Research Frontiers Inc (RFI) develops commercial SPD devices for goggles, eyeglasses, and windows.

Two groups Dublin energy lab, in Dublin and Grupo de Displays y Aplicaciones Fotonicas in Spain have investigated thermal, daylighting and optical properties of SPD glazing using outdoor and indoor characterisation. SPD glazing thermal [286], electrical [287] and daylighting [288] behaviour was investigated using outdoor test cell characterisation. This SPD glazing changed its state from 5% to 55% in the presence of 110 V, 0.07 W AC power [287,289] as shown in Figs. 27 and 28. It was also found that SPD glazing has intermediate transmittance state in the presence of variable applied power using indoor experiment. SPD glazing's high overall heat transfer $5.9 \text{ W/m}^2\text{K}$ makes it as a switchable single glazing [286]. However, it has potential to control the solar heat gain from 0.05 to 0.38 while it is opaque and transparent respectively [290]. Thus, SPD is a potential candidate for summer and in hot climates. However, SPD double-glazing can save 66% heat loss compared to an SPD single glazing, which is suitable for cold climatic area [286]. SPD vacuum glazing can be the best suitable option for cold climatic area as it can save up to 83% heat losses compared to SPD single glazing [76]. SPD glazing also offers comfortable daylight in the indoor environment for the occupant satisfaction [291]. Intermediate state 30% is recommended for SPD glazing which can offer comfortable daylight.

Indoor spectrometer measurement [292] and electro optical [293] simulation were performed by Barrios et al. The electro-optical behaviour SPD glazing was also analyzed. Impedance analysis showed that SPD glazing characteristics are similar to a Randles circuit. SPD glazing takes higher voltage to obtain fully

Table 10
Literature data for electrochromic (EC) glazings.

Dimension (m × m)	Type of glazing	States	U-value (W/m ² K)	SHGC	Visible transmission	Reference
0.105 m × 0.105 m	EC glazing	Transparent	3.9	0.7	65%	[264]
		Opaque	3.9	0.17	4%	
0.21 m × 0.28 m	EC glazing	Transparent	1.59	0.41	60%	[283]
		Opaque	1.59	0.09	1%	
NA	EC PPG, Solarban 72 Starphire,	NIR blocking	1.625	0.297	68%	[262]
	PPG, Sungate 400 Starphire	NIR transmitting	1.804	0.646	78%	

Fig. 28. Transmittance spectra of SPD glazing during on and off condition. Reprinted from Ref. [290] with permission from Elsevier.

transparent state, which can be reduced by decreasing the layer thickness of SPD layer. Thickness of SPD layer has ability to tune the luminous and solar transmittance. It was proposed that for adaptive glazing application SPD layer thickness between 200 and 300 μm is the most suitable as it offers the highest luminous and solar transmittance contrast. SPD glazing has higher infrared transmission and variation of this transmission is negligible for variation of power [294]. Durability of SPD glazing was investigated after four years of exposure (where one year laboratory environment and three years Dublin outdoor environment) which showed that contrast ratio (opaque to transparent) changed only from 1:11 to 1:10. To conclude any strong statement about SPD glazing's stability further investigation is essential [284]. It was also found that SPD glazing voltage requirement does not depend on its surface temperature [284]. Table 11 shows the investigated thermal and transmission parameters for different SPD glazing.

4.3. Liquid crystal

Liquid crystal (LC) is an AC powered electrically activated switchable glazing which is suitable for building glazing application. In this glazing LC are sandwiched between two glass panes. Twisted nematic, ferroelectric, guest host, and polymer dispersed are the major liquid crystal used for LC device [295].

Smectic A liquid crystal (SmA LC) and PDLC are the two form of LC which do not require polarisers to operate. PDLC needs 1–10 ms whereas SmA needs few ms to switch on. Scattering process of SmA LC devices start from the edges or conductive electrode of the devices and propagate towards the centre. Thus, scattering and clear both states depend on the size of the device, and to obtain uniform performance higher voltage is required. Non uniform particles alignment may cause localised hot spots where arcing of the LC device occurs [296]. A smectic LC glazing achieved “opaque” state

for 66 V and 100 Hz (rms) supply whereas 36 V 1 kHz supplies produce “transparent” state. In this system, response time strongly depends on voltage [297]. Transmittance of a 12.5 cm $\times$ 12.5 cm and 6 μm thick LC material based glazing varied from 30% to 55% [298]. Organic-based SmA LC panel of 1 $\times$ 1 m^2 changing from a clear state to a fully scattered state by more than three orders to a few tens of milliseconds [296].

PDLC types as shown in Fig. 29 are best suitable over other types for glazing as it does not require polarizer to operate, high brightness (because of its high transparency), wide view angle, fast response (in the order of milliseconds), absence of surface treatment and the possibility of intermediate electrically controllable transmission levels [299]. In general, PDLC films consist lower molecular weight micro sized droplets liquid crystal within a solid polymer matrix. These composite materials are sandwiched between two transparent conducting electrodes. Because of the refractive index mismatch between the droplets and the polymer matrix, lights are scattered in the absence of power. Presence of power LC molecules orient in order to pass the light and refractive index between polymer matrix and droplets also match. Scattering from PDLC depends on the size of droplets. Droplets radius smaller than incident wavelength allow light to pass through without scattering. For large size droplets scattering is mainly forward type [300].

Thermal conductivity of PDLC film increases due to increase of applied electric field as it enhances the thermal conductivity of the LC droplets. Increment rate depends on the concentration of LC in the composite and can be restricted [303]. This index method also depends on the temperature and the angle of incident light. PDLC

Fig. 29. The “transparent” and “translucent” states of a PDLC glazing (Taken from Ref. [301]) with permission from Elsevier.

Table 11

Thermal and visible transmission parameters for SPD glazing.

Dimension (m $\times$ m)	Type of glazing	States	U-value (W/m ² K)	SHGC	Visible transmission	Reference
0.21 m $\times$ 0.28 m	SPD single glazing	Transparent	5.9	0.35	55%	[286,290]
		Opaque	5.9	0.05	5%	
0.21 m $\times$ 0.28 m	SPD double glazing	Transparent	1.9	Not available	Not available	[286]
		Opaque	1.9	Not available	Not available	
0.22 m $\times$ 0.28 m	SPD single glazing	Transparent	NA	NA	40%	[292]
		Opaque	NA	NA	6%	

films can block 98% of UV; and modulate the NIR in the range between 12 and 38% [304]. PDLC films have stability between 0 °C and 60 °C temperature [305]. One PDLC film showed excellent durability up to 3 million times to electrical switching at 100 VAC, 60 Hz with switching interval of 1 s [306]. Less thick LC material requires less switching time. Electro–optical switching effect of a 50 μm thick PDLC film offered 190 μs rising time to be “transparent” and 2 ms day time when an external electric field was applied. Combined PDLC and electrochromic guest host molecules are able to offer fast switching from a scattering opaque state to a transmissive transparent state to control gain of incident daylight and glare [307,308]. Reverse mode PDLC glazing was also investigated which had transparent OFF state and opaque ON state. Switching of this devices was also possible using light source [309]. Daylight characterisation using PDLC glazing was investigated using outdoor test cell for Dublin weather condition. This glazing becomes 71% transparent in the presence of 20 V AC supply whereas becomes 27% transparent in the absence of power supply [301] as shown in Fig. 30. This particular type had 82.6% haze [310,311]. For clear sunny day, PDLC glazing was unable to control glare for both transparent and translucent states. For intermittent cloudy and overcast cloudy day PDLC glazing performance was acceptable to control glare [301].

Indium tin oxide (ITO) based transparent electrode is the most commonly used electrode for PDLC glazing. PDLC glazing is generally intended to apply for large scale glazing application (1 m^2) and for that big surface area ITO becomes costly [312]. Also for glazing, PDLC film substrates are plastic rather than glass. ITO deposition temperature is suitable for plastic substrate [312]. This issues can be solved using silver nano wire type electrode as they are cheaper than ITO, mechanically flexible, deposition is possible at room temperature using roll to roll fabrication [313]. It also offers high transparency at infra-red wavelengths [314], perfectly suitable for solar control glazing. From experiment it was also found that 58.5% specular transmittance was possible at 50 V for silver

nanowire based PDLC whereas while the ITO-based device needs 85 V to obtain 50.5% transmission.

LC glazing made of PDLC films possesses some disadvantages. PDLC films need a continuous power supply to remain “transparent” and provide haze due to scattering at wider viewing angles in transparent state. The scattering occurs in PDLCs due to the refractive index difference between the liquid crystal droplets and the polymer matrix where they are suspended. Reduction of droplet diameter maximizes the scattering, though it needs more driving voltage. PDLC films scatter blue and green light efficiently due to reduction of droplet size though transmit red light without significant scatter [297]. PDLC needs high driving voltage and presence of haze, which offer considerable amount of scattering and unwanted yellowing due to UV ageing. Thus, PDLC glazing systems can be less attractive choice for building engineer and architect for building application. Replacement of polymer to glass (glass disposed LC/GDLC) was investigated to reduce those aforementioned effects. One $5 \times 5 \text{ cm}^2$ GDLC device was fabricated which offered 10 times lower switching time and 85% low voltage (15 V) to achieve 80% transmission compared to similar PDLC device [315]. Table 12 shows the literature data of PDLC glazing.

Presently EC, SPD and LC are the three electrically activated switchable glazing systems. SPD and LC require high AC voltage that can vary between 10 V–110 V to become transparent. This requirement is higher than EC glazing's voltage requirement to operate. However, the root cause of this high voltage requirement is not well-documented work. Layer by layer investigation is required to enlighten the thickness dependent or material dependent voltage requirement. Table 13 summarised the comparison between three electrically activated switchable EC, SPD and LC types glazing.

5. Combined glazing

Described glazing systems in the above sections are applicable only for specific application. In general, buildings in most of the location around the world, experience high to medium cooling load demand in summer and medium to high heating load demand in winter due to variable weather. Thus, alone solar heat gain control or low heat loss glazing in a building is not capable to reduce building energy consumption. Work has been performed to achieve combined effect such as heat loss and heat gain reduction using vacuum–electrochromic (EC) or vacuum–suspended particle device (SPD) glazing. External power supply requirement for an electrically activated glazing can be reduced integration of PV. PV integrated electrically activated switchable enables fossil fuel generated electricity free glazing actuation, which trigger to modulate from opaque to transparent state or reverse depending upon indoor and outdoor ambient conditions. These combined technologies are promising approach for switchable/smart/dynamic/adaptable glazing. PV integrated all three electrically activated switchable glazing systems were investigated by various research groups. Description of this combined technologies are discussed in this section.

Fig. 30. Transmission spectra of a particular PDLC glazing in its “translucent” and “transparent” states. Taken from Ref. [302] with permission from Elsevier.

Table 12

Literature data for polymer dispersed liquid crystal glazings.

Dimension (m × m)	Type of glazing	States	U-value (W/m ² K)	SHGC	Visible transmission	Reference
0.2 × 0.15	PDLC	Transparent Translucent	NA	0.53 0.39	71% 27%	[302]

Table 13

Comparison of electrochromic, liquid crystal, and suspended particle device type glazing.

Properties	Electrochromic (EC)	Liquid crystal (LC)	Suspended particle device (SPD)
Power	DC powered, voltage varies between 0 and 10 V	AC powered, voltage varies between 10 and 110 V	AC powered, voltage varies between 10 and 110 V
Powered states	Opaque or coloured	Transparent	Transparent
Unpowered states	Transparent	Opaque or translucent	Opaque or coloured
Requirement of power	Power required to obtain opaque and transparent state	Power required to obtain transparent state	Power required to obtain transparent state
Contrast ratio	Transmission ratio between opaque and transparent state is high	Transmission ratio between opaque and transparent state is low as opaque/translucent state offers high diffuse transmission	High transmission ratio between opaque and transparent state
Memory	without supply “opaque” state still remain for few hours	No memory, Without supply it becomes “opaque”	No memory, Without supply it becomes “opaque”
Switching speed	Take several seconds or minutes depends on the area	Fast switching, Few seconds	Fast switching, Few seconds
Durability	~10 ⁵	~10 millions	~10 millions
NIR control	Possible to control NIR	Transmit NIR	Transmit NIR
Intermediate states	Controllable intermediate states between transparent and opaque states	Controllable intermediate states between transparent and opaque/translucent states	Controllable intermediate states between transparent and opaque states
U-value	Similar to single glazing	NA	Similar to single glazing
SHGC	Variation of SGHC for both states are high due to high contrast ratio	Variation of SGHC between both states are low due to low contrast ratio	Variation of SGHC between both states are high due to high contrast ratio
Daylight/glare	Possible to control glare using intermediate state and opaque state	Possible to control glare using opaque/translucent state	Possible to control glare using intermediate and opaque state

5.1. Low heat loss switchable glazing

5.1.1. Vacuum –electrochromic

Vacuum glazing and electrochromic glazing have been combined to achieve low heat loss, solar heat gain control and daylight all together as shown in Fig. 31 [316].

This device was fabricated using three glass panes where two glass panes were separated with a vacuum and the other glass panes having a small layer of EC are sealed with the vacuum glazing. This 0.4 m × 0.4 m vacuum–EC device [316] achieved variable transparency from 63% to 2% with a mid-pane U-value of 0.86 W/m²K. From theoretical investigation it was recommended that EC layer should always face the outside environment to avoid intolerable over heating [317] of an EC –vacuum glazing. During opaque state of EC layer, the absorbed solar radiations works as a

Fig. 31. Schematic diagram of EC-Vacuum glazing. Reprinted from Ref. [317] with permission from Elsevier.

heat source and transmit heat to the inside of the room. Addition of low emittance layer with the vacuum gap on the glass panes also works as heat source with EC and it was found that using two low-e coating is not effective compare to one low-e coating [318–320].

5.1.2. Vacuum - SPD

Combined effect of vacuum and SPD was investigated attached in a south facing test cell [76,321]. SPD glazing was kept in two different positions for this combined glazing. First one where SPD glazing faced the exterior environment and vacuum glazing faced the interior test cell environment and second one where SPD glazing faced the interior test cell environment and vacuum glazing faced the exterior ambient environment as shown in Fig. 32. Dynamic transmission range from 2% (opaque state) to 38% (transparent state) was achieved by this combined glazing system as shown in Fig. 33.

Vacuum glazing surface temperature was always lower than SPD glazing surface temperature. U-value for this combined glazing was significantly low and varied between 1.00 and 1.16 W/m²K. SHGC of this type of glazing varied from 0.045 to 0.26. Variation of U-value and SHGC was due to the SPD glazing opaque and transparent state [76]. From vacuum–EC glazing, it was recommended that EC layer should always be outside to overcome from over-heating. However, from vacuum –SPD glazing experiment, it was found that SPD glazing facing the outdoor ambient environment or facing the indoor test cell environment had negligible impact on test cell internal or glazing surface temperature.

Recommendation for vacuum EC was predicted from theoretical performance where ambient temperature was constant [319]. That could be the reason to achieve higher surface temperature when EC layer was placed inside.

5.2. Self-powered switchable glazing

A large area of EC glazing can be PV powered (i) to avoid the additional electricity load increasing the amount of grid supplied electricity consumed (ii) to give a readily installed autonomous device (iii) reliable long-term performance.

Fig. 32. Schematic and photograph of combined SPD-vacuum glazing Reprinted from Ref. [76] with permission from Elsevier Ltd.

Fig. 33. Hemispherical spectral response of SPD vacuum glazing for SPD opaque and transparent states. Reprinted from Ref. [76] with permission from Elsevier Ltd.

5.2.1. PV powered electrochromic

Combining of PV-EC device was first explored for an electro-photographic application [322]. Coupling of PV-EC are advantageous because (i) Photovoltaic (PV) device generates DC power, which matches the use of DC by EC, (ii) EC and PV temperature characteristics are matched; at high temperature PV device efficiency drops which enhance the reduction of maximum power output [323,324]. For crystalline PV above 25 °C its power drops with a coefficient between 0.4%/K to 0.65%/K [325]. At higher temperatures due to higher ion mobility, switching responses of EC devices are faster which reduce the amount of required voltage [280,281]. Fig. 34 illustrates the different combination of these types of PV-EC. Fig. 35 indicates the PV-EC device where the upper

Fig. 34. Different PV-EC combination.

Fig. 35. Schematic diagram of PV-EC device (Redrwan from Ref. [234]).

Fig. 36. Solution type PV-EC device.

half is the EC and the lower half is the PV. The middle contact permits battery and user control.

Classification based on types of PV

- Dye sensitized solar cell (DSSC) based PV–EC device [326–330] are potentially low-cost devices with a good match to typical diffuse solar spectra. However, they can have low stability due to photochemical degradation [331].
- The critical issue in silicon based PV-EC device [329,332–335] development lies in its low optical contrast in between opaque and transparent state. The transparency of the PV-EC device can be improved by the incorporation of wide band gap semi-transparent amorphous silicon carbon alloy. However, as the semi-transparent PV thin films become very thin, electrical short circuit occurs easily that renders the PV-EC stacks inoperable [234,326].
- Semi-transparent perovskite photovoltaic and solid-state electrochromic cells enables solid-state photovoltachromic devices with 26% average visible transmittance and 3.7% maximum light power conversion efficiency has been reported for a new PV-EC device. Activating self-tinting, the average visible transmittance drops to 8.4% [336].
- Using two-inverted transparent organic PV, a solution-processed polymer vertically integrated EC-PV window has been reported [337]. The achievement of low intensity illumination of 0.25 sun with a switching time of 3–6 s had demonstrated the feasibility of the EC-PV in window applications under oblique illumination of the Sun.

Classification based on EC

- All the aforementioned four types of PV can be integrated with solid type EC materials.
- Locating as electrochromic solution between the transparent non-conductive substrate and the silicon-thin film solar cell (Si-TFSC) substrate give electrodes in the PV-EC device planarly distributed in the semi-transparent Si-TFSC substrate as shown in Fig. 36. This can create a uniform electric field which makes large area PV-EC modules feasible. The thin film PV cell can be very thin due to low power requirement of PV-EC so overall system will have higher transparency [338,339].

Fig. 37. Full view of experimental set up of PV powered SPD glazing. Reprinted from Ref. [346] with permission from Elsevier Ltd.

Tandem structure- DSSC [326] (Nokki et al., 2007) and hydrogenated amorphous silicon-carbon (a-SiC:H) photovoltaic-powered monolithic tandem EC device was reported [334]. Monolithic and monolithic tandem both reduce the overall transmittance of the system as sunlight passes through the both PV and EC [327,333,334]. Fabrication process of this tandem structure is also challenging [234]. To obtain higher transparency semi-transparent PV is recommended which eventually reduces the overall cell efficiency [326]. However, no external wiring makes this type of device advantageous. For a side by-side PV–EC device, PV can be placed on the window frame [332] or PV can be building integrated photovoltaic (BIPV) types [340] [341]. Efficient opaque PV can be used as insulation is blocked by the PV device. Solution EC and PV type structures solve the short circuit problems encountered in the tandem PV-EC structures [234,334].

Presently this PV-EC technology is laboratory based and no commercial device has been manufactured [327,342]. However, work is still ongoing particularly photoelectrochromic where EC powered by DSSC [343–345].

5.2.2. PV powered SPD

First experimentally potential of PV powered SPD glazing was investigated in Dublin. One 0.0588 m² area of SPD glazing was powered by 0.3432 m² vertical PV as shown in Fig. 37. This SPD glazing only take 0.07 W continuous AC power to keep the glazing transparent. As SPD glazing works with AC power and PV generates DC, conversion of DC to AC was done by using one inverter. It was found that though SPD glazing needs 110 V to operate but the power requirement is less. For a 1 m² area of SPD glazing only takes 10.42 kWh power for 24 h and 365 days. Presence of inverter between PV and SPD glazing makes the process complicated. To obtain higher power from PV inverter combination the sizing in ratio between PV power and inverter rating should be nearly 1. To power SPD glazing few watts are sufficient but the low power rating inverter is not commercially available. Thus, high power rating PV needs to be installed. It can be concluded that for large-scale SPD glazing PV powering is advantageous. For few meter square area SPD application PV powering is not advantageous due to losses of power [346].

Battery storage is essential for PV powered SPD application as SPD becomes clear in the presence of power supply. In the night there can be need to make it transparent. To obtain power from PV in the nighttime battery storage is required.

5.2.3. PV powered LC

First PV powered LC device for glazing application was investigated where PV was DSSC type and LC was chiral nematic type [347]. Three different structures were manufactured as shown in Fig. 38. To generate higher electricity first structure is suitable as DSSC gets uninterrupted solar radiation. From experiment it was also found that structure (a) (b) and (c) offered current density of 16.43, 2.13, 5.67 mA/cm² respectively. This device had maximum

Fig. 38. Schematic of three structure of PV powered LC. Redrawn from Ref. [347].

transmission around 550 nm wavelength and took 60s to become transparent with power density of 100 mW/cm².

5.3. Low heat loss clean power generating glazing

This type of glazing is the combination of low heat loss vacuum glazing and photovoltaic glazing. Double panes vacuum glazing allows higher penetration of daylight which is similar to double glazing [80]. Addition of electrically activated switchable material can restrict the entering higher daylight; however, they need power to operate. Static transparent photovoltaic can control the allowable solar gain, daylight whereas they also provide clean power rather than consuming power. Thus, PV-vacuum combination is advantageous as they limit the high penetration of daylight, offer low heat loss and generate renewable power. For crystalline silicon type PV cells, to achieve semitransparency type PV glazing, spaced type structure can be utilized. Transparent gap between regularly

distributed PV will admit daylight [348]. Crystalline silicon based spaced type PV-vacuum glazing is shown in Fig. 39.

Amorphous silicon based 20% transparent laminated PV and one vacuum glazing with U -value of 0.8 W/m²K were attached together to form combined PV-vacuum glazing [349] as shown Fig. 40. Dimension of this PV–vacuum glazing was 1.3 m (width) × 1.100 m (height) × 2.087 m (thickness). Outdoor characterisation was performed using this device on the platform of Block Z in the Hong Kong Polytechnic University from June 2016. This combined system offered 0.08 transmittance. Maximum external glazing surface temperature was 75 °C whereas internal maximum glazing surface temperature was 45 °C.

Table 14 compared advantages and disadvantages or future scope for different combined glazing systems.

6. Conclusions

To quantify a glazing performance for building application, the required glazing parameters are overall heat transfer coefficient (U -value), solar heat gain coefficient and daylight. Low overall heat transfer coefficient is possible by introducing multiple panes glasses with single glass, presence of thermally insulating material or vacuum between two glass panes. Solar heat gain depends on the visible and NIR spectrum of incident solar radiation whereas daylight only associated with visible spectrum. Present available glazings are low heat loss control and solar heat gain control glazing. Solar heat gain control glazing also has potential to control daylight.

Potential static transparent glazings are vacuum and aerogel as they both offer U -value lower or close to 1 W/m²K. However, they have non-variable solar heat gain control. For glazing application vacuum is suitable, as they do not obstruct the viewing. Monolithic type aerogel is suitable for glazing; however, most of the present available aerogels are translucent granular type. Granular types block viewing but offer higher transmittance due to scattering. Further investigation is required to develop non-fragile transparent aerogel for glazing application.

For switchable glazing, control over switchable intermediate states, higher contrast ratio between opaque and transparent states, high durability, high luminous transmittance are the most essential criteria. Electrically activated switchable glazings meet most of the criteria over non-electrically activated switchable glazing. However, U -values are higher for double glazed switchable glazing compared to vacuum and aerogel. For diurnal variation of weather, glazings are required which can adapt with this variation. Thus, switchable transparent glazing is always preferable. To enable this glazing even for cold climate, integrating them with vacuum

Fig. 39. Schematic details of crystalline silicon based spaced type PV-vacuum glazing.

Fig. 40. Schematic structure of PV-vacuum glazing. Taken from Ref. [349].

Table 14
Comparison between different combined glazing systems.

Combined glazing type	Combination	Advantage	Disadvantage/future scope
Low heat loss switchable glazing	Vacuum -EC	Higher contrast ratio was found	EC glass panes must be kept facing ambient weather. However, that conclusion was made based on simulation work under constant ambient temperature.
	Vacuum -SPD	Nearly equal temperature rise of SPD glazing for facing indoor environment or outdoor environment	Low optical contrast between opaque and transparent state
Self-powered switchable glazing	PV-EC	Driving voltage of EC is low (typically 1–5 V). Direct coupling with PV is possible.	Tandem structure of PV-EC reduces the overall transparency of the glazing.
	PV -SPD	Low solar heat gain possible without switching. Generated power from PV can be stored and will be used for low insolation or cloudy day or night time	Inverter requirement for PV powered SPD can make the process complicated
	PV-LC		LC also need AC power and consequence will be similar to SPD
Low heat loss clean power generating glazing	PV-Vacuum	For cold climate heat loss reduction and power generation both possible from a single glazing unit	Presence of vacuum may rise the PV cell temperature compared to glass-PV-glass structure. However, to validate this comments experimental work is required

glazing is promising (low heat loss switchable glazing).

PV powered electrically activated glazing can be part of building energy management system (BEMS) [350]. For an intelligent building [351,352] glazing will be connected to the PV and its colour changes will be operated by BEMS based on specified criteria of buildings occupant's.

For future autonomous glazing technology, research should be focused on photovoltaic integrated electrically activated low heat loss switchable glazing. This type of combined technologies are still in research phase though they have ample potential for future fenestration application. PV powered electrically actuated switchable EC/SPD/PDLC–vacuum glazing can dominate the future building's glazing sector.

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