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Smart windows for energy efficiency of buildings

Marco Casini

Abstract – The increasing attention to issues of visual comfort and energy efficiency that characterize the architecture of the XXI century led to the development of innovative, high performance dynamic glazing systems, aimed not only at reducing heat loss, but also at controlling incoming solar radiation, in order to maximize solar gain in winter and minimize it in summer, as well as ensuring the best natural lighting conditions with no glare.

Such systems, called smart windows, enable varying the amount of heat (SHGC) and light (VLT) that penetrate through the glass surfaces as needed, while maintaining outwards vision. These new dynamic windows, the electrochromic ones in particular, are proving to be more effective than traditional static systems - low-e selective glazing and automatic shading devices - at reducing energy consumption for lighting and air conditioning and providing greater comfort to users.

The article offers an analysis of the different types of dynamic glazing on the market, with both passive and active control, illustrating their potential uses and the benefits achieved in terms of energy efficiency, environmental comfort, and architectural quality in both new constructions and in existing buildings requalification.

Keywords **– smart windows, dynamic glazing, emerging windows technologies, adaptive building shells, energy efficiency of buildings, smart buildings, sustainable buildings.**

I. Introduction

The objective of meeting the growing demand of thermo-hygrometric and environmental comfort, associated with an urgent need to improve the energy efficiency of buildings to achieve "carbon neutral" or "zero energy buildings" (ZEB), is determining a thorough review of the building envelope characteristics and requirements, directing toward technological solutions that can provide a continuous adjustment of the set of environmental flows in relation to climatic conditions and different exposures (dynamic anisotropy).

In fact, the building envelope plays a pivotal role in the energy performance of a building, significantly affecting the wellbeing levels of the indoor environment. It constitutes a complex system of barriers and environmental filters, not only potentially able to regulate the heat, solar radiation, air and steam flows, but also to convert radiations into energy (heat and electricity) essential for the building metabolism.

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In this context, the transparent part of the building envelope can play the important role of climate filter between the internal and external environments, able to balance visual comfort with hygrometric wellbeing control needs and reduction requirements for air conditioning and lighting energy consumption.

Transparent solutions, however, require a much more accurate design, focused on the characteristics of the environmental context, the integration with mechanical equipment and performance targets (distribution of radiant temperatures, air stratification, etc.); otherwise the transparent shell can turn into the major source of environmental discomfort and energy dissipation of the building. According to the Department of Energy of the United States, from 25% to 35% of energy in buildings is wasted due to inefficient windows. The California Energy Commission estimates that about 40% of the cooling demand of a typical building is due to the solar heat gain through windows.

Although the market is now offering high-performance glazing systems with regard to the characteristics of thermal insulation, with U thermal transmittance values less than 0,9 W/m^2K for double glazing and 0,4 W/m^2K for triple glazing, comparable to those of opaque components, the control of incident solar radiation, in order to optimize incoming thermal and lighting flows, is instead still particularly delicate.

The traditional static systems for solar radiation control are proving insufficient in meeting the objectives of energy efficiency and environmental wellbeing required by regulations while restraining freedom of expression in the use of transparent components. Dynamic shading systems, widely used in Europe especially in double-skin glass facades, as well as having higher installation, operation and maintenance costs, hinder external vision and are often not suitable for energy retrofits.

The solution for both new constructions and existing buildings renovation is now represented by dynamic or smart windows, able to continuously and automatically change energy and light transmission values in relation to external environmental conditions and users' needs. These systems, in conjunction with lighting and air conditioning control systems, may allow significant energy and environmental savings, as well as ensuring greater thermal and visual comfort for occupants. Several pilot projects in this specific field have shown savings up to 60% for lighting, a reduction of the cooling load up to 20%, and the reduction of peak power up to 26% [6] [15].

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II. Solar radiation control in buildings

The control of the incident solar radiation is a key element for the achievement of indoor wellbeing and more generally of greater energy efficiency in buildings.

In winter, solar heat harvesting through windows can help reduce energy consumption for space heating. During summer, especially in warmer countries and in countries with a Mediterranean climate, excessive solar radiation passing through the glass can instead cause overheating of the indoor environment resulting in high consumption for air conditioning. In these countries, in order to limit energy consumption for air conditioning during summer, national regulations require, in the case of new buildings, mandatory installation of sun shading systems or, alternatively, windows with solar heat gain coefficient (SGHC) less than or equal to 0.5, capable of substantially reducing the incoming energy flow.

Penetration of direct solar radiation within the indoor environment can also be a hindrance for visual activities, especially for facades exposed to the east and west, affected by low and deep reaching sunrays, with the consequent need for simultaneous use of screening systems and artificial lighting systems despite exterior light levels being very high. Direct solar radiation, especially in its UV component, is finally cause of deterioration of furniture and interior materials.

Incident solar radiation control can be implemented through the use of traditional static systems, consisting of solar protection glazing and/or fixed or mobile shading devices, or through dynamical systems, possibly integrated and coordinated with building automation systems, consisting of automated mobile shading devices or dynamic windows able to change their optical properties according to solar radiation.

A. *Static solar protection glazing*

Unlike simple high thermal insulation double glazing for heat loss reduction, solar protection glazing's task is to prevent the majority of the incident radiant flux on the window to penetrate inside the environment to protect.

Available on the market are "body tinted glazing", "pyrolytic" coated glazing and "selective" high-performance glazing with "magnetron" type coatings which, compared to the first, allow a better control of energy transmission without overly penalizing visible light transmittance. This property is measured using the Light to Solar Gain Ratio (LSG) index, also called spectral selectivity index, which defines the ratio between the light transmittance (VLT), and the solar heat gain coefficient (SHGC): glass with a high LSG (selective glass) transmits a high percentage of incident visible light radiation and a small fraction of the total radiation. Selective glasses on the market today have a visible transmittance between 34% and 69% and a solar heat gain coefficient between 24% and 56%, with a selectivity index LSG between 1.28 and 2.29.

Among solar protective glasses also falls thin film semitransparent photovoltaic glazing, organic or inorganic, available in several transparency ratios (10% - 20% - 30%) and colors and able to reduce incoming heat (SGHC between 0.29 and 0.41) and produce electricity at the same time.

The use of static solar protection glazing allows reducing heat load in summer while maintaining the vision through and limiting glare phenomena. However, such systems do not allow to follow daily solar path and weather conditions or seasons alternation, with the result of reducing energy harvesting during winter (especially in the south facing facades) and reducing natural light levels in the absence of direct solar radiation (in particular for the east or west facing facades, irradiated for only half of the day).

TABLE I. MAIN SELECTIVE GLAZING ON THE MARKET WITH HIGHER LSG

	GUARDIAN SUNGUARD SNX	SGG COOL-LITE EXTREME	AGC STOPRAY ULTRA	PILKINGTON SUNCOOL
VLT [%]	62	60	60	60
SHGC	0.27	0.28	0.28	0.32
LSG	2.29	2.14	2.14	1.87
Ug [W/m^{2}K]	1.36 (Argon fill)	1.00 (unspecified)	1.00 (unspecified)	1.00 (Argon fill)

TABLE II. TYPICAL THIN FILM SEMITRANSPARENT A-SI PHOTOVOLTAIC GLAZING CHARACTERISTICS

Properties	Transparency		
	10%	20%	30%
VLT [%]	10.80	17.30	28.40
SHGC	0.29	0.34	0.41
LSG	0.37	0.50	0.70
Power Yeld [Wp/m^2]	45	39	32
Ug [W/m^{2}K]	1,1 (Argon fill + Low-e coating)		

B. *Static and dynamic shading systems*

Among the various shading systems, external shading elements, such as horizontal or vertical projecting louvers (brise soleil), shutters, blinds or awnings, are preferable to internal ones because they block the solar radiation before it penetrates the building. Furthermore brise soleil, in particular, have architectural value and can therefore strongly

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characterize the external image of a building. It is however important to evaluate the behavior of such devices as their presence can significantly change the performance of the openings and therefore the ventilation coefficient of rooms.

Internal elements, however, such as curtains, blinds, or shutters, work primarily by reflecting and diffusing the radiation outward, often absorbing a significant share resulting in the release of heat inside the indoor environment. These elements have anyway good efficacy in preventing glare.

If carefully designed, outer shading systems are able to provide a differentiated behavior over the year, excluding solar radiation in the summer while allowing, instead, the access during winter. The effectiveness of such systems must be verified through the use of shading masks: the ideal screen blocks the sun path in the hours in which solar radiation is not desired. The presence of the screen, however, interferes with the visual enjoyment, natural lighting, natural ventilation, and the possibility of leaning out or passage offered by the window. In order to choose the most suitable type of screen is also necessary to know the behavior in relation of noise and vibration generation due to wind, façade encumbrance, ease of operation, and compatibility with the different types of opening of doors and windows.

With the development of building automation systems, ever more widespread especially in new constructions, dynamic screening systems are today able to change their geometric shape and optimize the amount of incoming solar radiation according to the climatic conditions (adaptive facades or kinetic facades). Especially in Europe these systems are normally made using adjustable louvers or blinds integrated into a double-skin curtain wall. There are examples of even more innovative solutions as in the case of Bahar Towers in Abu Dhabi (2013), designed by the engineering firm Aedas, where a special software allows the screening elements to open and close depending on the angle and power of solar rays, shaping a "thinking facade" completely self-sufficient thanks to photovoltaic panels placed on the roof and along the south façade.

However the use of screening systems, including dynamic ones, although effective in the maintenance of solar gains in winter, in the reduction of heat load in summer and in the elimination of glare in relation to external environmental conditions and users' needs, may cause an excessive reduction of inside natural lighting, while not allowing external vision and not being suitable for energy retrofits of existing buildings. Such systems have also higher costs of installation, management and maintenance.

C. *Dynamic Glazing*

The need to balance diverse needs from the energy and lighting points of view is leading to the use of next-generation products, such as chromogenic transparent materials that allow selective and dynamic control of thermal energy and incident light with the ability to change their optical properties in response to a light, electrical, thermal or chemical stimulus.

The chromogenic materials belong to the category of smart materials, a new class of highly innovative materials able to perceive stimuli from the external environment (such as mechanical stress or temperature variations, humidity, pH, electromagnetic fields, and solar radiation) and reacting immediately modifying independently and reversibly their mechanical, physical-chemical or electrical properties, or their geometrical characteristics, adapting to changing environmental conditions (self-cleaning materials, shape memory materials, phase change materials, piezoelectric, photovoltaic, electrochromic, photochromic, thermochromic materials, etc.).

The use of transparent chromogenic materials in architecture allows to realize transparent envelopes with variable performance, defined smart windows, dynamic glazing or switchable glazing, able to optimize the energy behavior of buildings and at the same time meet the comfort needs required by users. Intelligent glazing can be used in a wide range of daily use products such as windows, doors, skylights, partitions, and is easily integrated inside high performance IGUs. Expectations for demand growth for dynamic glass are very high. In 2013, the market for smart windows was worth over 1.5 billion dollars and is expected to reach more than 5.8 billion dollars by 2020 with an estimated CAGR of 20% (2014-2020) [13].

III. Smart windows

Based on their mode of operation, intelligent glass is distinguished in two main categories: with passive control, or self-regulating, and with active control, adjustable to user's needs.

A. *Passive dynamical systems*

Passive dynamic systems do not require an electrical stimulus for their operation. These systems respond independently to the presence of natural stimuli such as light (photochromic glass) or heat (thermochromic and termotropic glazing). Compared with active systems they are therefore easier to install and more reliable in the face of the impossibility of being controlled by the user on request.

1) Photochromic glazing

Photochromic glass is able to modify their transparency properties autonomously in relation to incident light intensity. This ability is due to the presence in the glass paste of organic or inorganic compounds which act as "optical sensitizers", such as metal halides (chloride and silver bromide) reactive to ultraviolet light, or plastics, which absorb the sun's energy according to the output color spectrum variation. When photochromic glass is directly exposed to solar radiation, the difference in spectral absorption between the energy layers of glass and additional substances leads to the formation of a reversible process of intense colouring. The speed of response to environmental changes is of the order of a few minutes and, generally, the passage from the tinted state to the clear one takes twice as long. These differences in response time can lead to problems in case of sudden and frequent changes in external brightness or in the case of cast shadows on the building that can cause uneven and unsightly areas of light and shadow. Furthermore, following the chromatic transition photochromic glasses become absorbent rather than reflective,

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with possible slab overheating phenomena, which may lead to rupture by thermal shock in the event of intense solar radiation.

Currently the main use of these products relates to the areas of glass for the optical and car industry. The diffusion of photochromic glasses in architecture is instead hampered by the still high cost, the complexity of the technological system, the inability for the user to directly control the performance, the difficulty in obtaining a uniform distribution of photochromic substances inside the slab and the gradual loss of the reversibility of the process over time. Still, the technological problems have significantly attenuated in recent years, allowing to extend slab sizes and to improve the stability over time.

2) Thermochromic Glazing

Thermochromic glazing (Pleotint, Ravenbrick, Solarsmart etc.) is capable of autonomously modifying its optical properties according to the external surface temperature, which determines a chemical reaction or a phase transition between two different states. The material therefore remains transparent when temperature is lower than the transition one, while becomes opaque for higher temperatures.

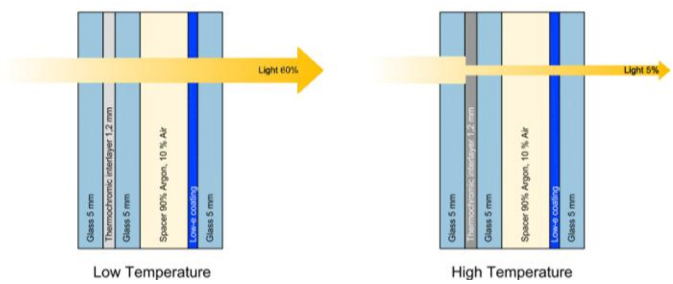

Figure 1. Thermochromic glazing

The interval of the transition temperature is generally between 10° C (maximum transparency) and 65° C (minimum transparency). The properties of thermochromism can be observed in a wide range of organic and inorganic compounds (such as cloud gel) and in films of metal oxides, such as vanadium oxide, that by switching from semiconductor to metallic state acquires a reflective behavior highly sensitive in the infrared zone.

At this time the most promising technological solution for the deployment of thermochromic glazing concerns the use of thermochromic materials directly into plastic film of polyvinyl butyral (PVB) with a thickness of 1,2 mm, introduced for the first time on the market in late 2010. Since PVB is one of the most used products for the production of laminated safety or acoustic glass, this solution in fact allows the best integration in the manufacturing processes and the possibility to provide at a reduced cost a higher quality product. The typical ranges of light transmission and solar heat gain in correspondence of transparent and opaque states when coupled with a clear glass are respectively VLT = 60-13% or 55-5% and SHGC 0,37 to 0.17 or 0,36 to 0.12 with switching times in the order of a few minutes. Among the disadvantages, in addition to the impossibility of user control, thermochromic glazing may not reach the temperature required for switching to the dark state even in the presence of solar radiation with the drawback of not eliminating glare for users. Duration is guaranteed for an operating time of at least 20 years and they are cheaper than active control dynamical systems (ROI < 4 years).

TABLE III. MAIN THERMOCHROMIC GLAZING ON THE MARKET

Temperature	VLT	SHGC	Ug	VLT	SHGC	Ug	VLT	SHGC	Ug
	PLEOTINT SUNTUITIVE CLEAR			INNOVATIVE GLASS SOLARSMART			RAVENBRICK RAVENWINDOW		
Low	60%	0.37	1.36	55%	0.36	1.36	33%	0.28	1.36
High	13%	0.17	Argon	5%	0.12	Argon	5%	0.18	Argon

B. *Active dynamical systems*

Active dynamic systems can be controlled directly or connected to a computerized building management system in order to respond to changes in external (temperature, solar radiation) or internal climatic conditions (temperature, artificial and natural lighting levels, heat intakes, presence of people) or the needs of users, allowing to adjust the intensity of penetrating visible and infrared radiation without the use of screening systems, significantly reducing energy consumption for air conditioning and lighting (savings are estimated at more than 20%). The most advanced systems on the market provide integration with photovoltaic systems for total electrical self-sufficiency, in addition to the possibility of remote control via smartphones, and allow independent adjustment of different panels of the same window (light-zoning), up to the possibility of becoming real imaging displays with touchscreen technology (Advanced Tech Windows).

Part of electrically controllable active systems are electrochromic glass (EC), suspended particle devices (SPD), liquid crystal devices (LC / PDLC) and the most recent, still experimental glazing devices, based on micro-blinds (MEMS) or with a special, nanotechnological coating. Each of these technologies has different characteristics, performances and costs, making it more suitable for determined applications or requirements (privacy, switching speed, solar gain reduction etc.).

1) Electrochromic devices (EC)

Electrochromic glazing (Sage, View, Infraselect etc.) exploits the properties of some materials to vary the parameters of transmission, reflection, and absorption of solar radiation according to an electrical stimulus adjustable by an external user. Change of the properties of these elements is attributable to the addition or extraction of mobile ions from the electrochromic layer: when the electric field is activated,

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the introduced ions react generating compounds which alter the coloring of the material.

The central part of an electrochromic device is constituted by an ion conductor (or electrolyte) sandwiched between two layers, respectively constituted by an electrochromic film (also called electrode) and an accumulation layer (counter-electrode). The two outer layers are made of transparent conductive materials, but the electrons accumulation layer and the transparent conductor may be incorporated in a single layer. When electric potential difference is applied between the two transparent conductors, ions extracted from the accumulation layer pass through the conductor layer and are lead into the electrochromic layer, thereby changing its optical properties. Conversely, when the electrical stimulus is turned off, the ions are extracted from the electrochromic layer and, through the conductive layer, are deposited into the accumulation layer making the device transparent again.

Obtainable glazing has typically green or blue colors in relation to the electrochromic materials most widely used (for example, the tungsten oxide which varies its color from transparent to blue) and the degree of transparency can be modulated in intermediate states from clear (off device) to completely tinted. Light transmission varies from 60% in the transparent state to 1% when opaque. SHGC is instead comprised between 0.46 and 0.06.

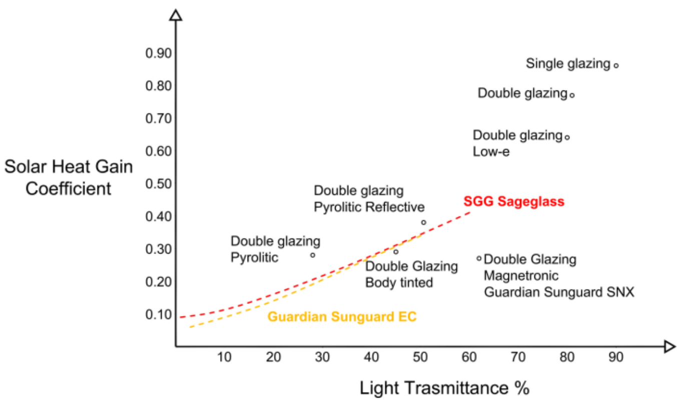

Figure 2. Electrochromic glazing dynamic range

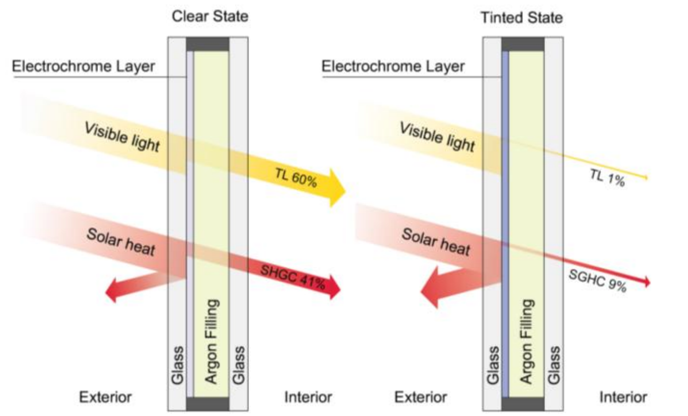

Figure 3. Electrochromic glazing

The amount of energy required by the system to switch between the different coloration states is minimal (1-2.5 Wp/m^2) and, thanks to the property of electrochromic materials to possess a bistable configuration, even less is the amount of energy required to maintain the desired tinted state (less than 0.4 W/m^2).

If the device is working properly, the change of properties of the glass is almost perfectly uniform over the entire surface. Darkening occurs from the edges, moving inward, and is a slow process, ranging from several seconds to some minutes depending on panel size. Switching speed is also linked to the glass temperature. The coloring process typically takes little longer than the clearing process. In conditions of moderate or warm climate, a 90 x 150 cm window usually takes between 5 to 10 minutes to accomplish at least 90% of its colouring cycle. The time increases in conditions of low temperature when, any how, the need to control the coloring of the glass is less likely. The gradual change of light transmission, however, is advantageous because it allows the occupants to adapt naturally to changes in light levels without ailment or distraction. The electrochromic glass provides visibility even in the darkened state and thus preserves visible contact with the outside environment.

Technological room for improvement for electrochromic glass concerns the possibility to increase the number of control states (currently four) and the switching speed, to raise opacity in tinted state to improve privacy and to further reduce the already limited energy consumption.

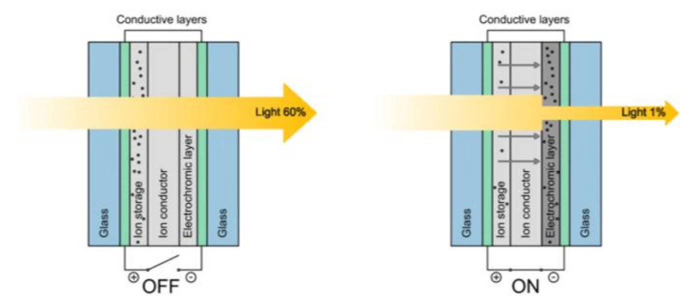

Figure 4. Electrochromic glazing operation

TABLE IV. MAIN ELECTROCHROMIC GLAZING ON THE MARKET

Tinted state	VLT	SHGC	Ug	VLT	SHGC	Ug	VLT	SHGC	Ug	VLT	SHGC	Ug
	GUARDIAN SUNGUARD EC (Low-e)			VIEW DYNAMIC GLASS			INFRASELECT (Low-e)			SGG SAGEGLASS		
0	50%	0.34	1.10 Argon fill	58%	0.46	1.64 Argon fill	55%	0.40	1.10 Argon fill	60%	0.41	1.64 Argon fill
1/3	35%	0.24		40%	0.29		-	-		18%	0.15	
2/3	18%	0.13		20%	0.16		-	-		6%	0.10	

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3/3	3%	0.06		3%	0.09		15%	0.12		1%	0.09	

2) Suspended particles devices (SPD)

Suspended particles devices (Isoclima, Vision Systems, Innovative Glass, Hitachi Chemicals, etc.) consist in a double sheet of glass within which is located a layer of thin laminate of suspended particles similar to rods immersed in a fluid, placed between two electrical conductors of transparent thin plastic film. When the power is turned on, the suspended rod particles align, light passes through and the SPD smart glass panel clears. When the power is switched off the suspended rod particles are randomly oriented blocking the light and the glass appears dark (or opaque), blue or, in the more recent developments, gray or black. In this way, SPD glass can lighten or darken, allowing instantaneous control of the amount of light and heat passing through. SPD smart glass, when dark, can block up to 99.4% of the visible radiation. SPD glass finally protects from harmful UV rays both when switched on or off.

The typical ranges of light transmission and solar heat gain in correspondence of transparent and opaque states are respectively VLT 65-0.5% and SHGC 0.57-0.06 with switching times of some seconds. The very high switching speed, along with the total controllability by the user and the fact that the obscured state coincides with the device powered off, make SPD glass particularly suitable for the automotive (side and rear windows, transparent sunroofs), marine (windows, skylights, portholes, partitions and doors) and aviation sectors (more than 30 different models of aircraft have SPD windows installed).

The device requires about 100 volts AC to operate from the off (tinted) state to the transparent one and can be modulated to any intermediate state. The power requirements are 5 W/m^2 for switching and 0,55 W/m^2 to maintain a state of constant transmission. With further research, operating voltages may drop to about 35 volts AC. New suspensions are also being developed to obtain different colors than blue (green, red and purple) and to obtain a greater variation in the solar factor. At the moment slab sizes can be up to 1524 x 3048 mm (length any size) and are available in several shapes, both planar and curved. Durability and optical-solar properties have not been verified in the long term as the products are now entering the market, but the high cost remains a problem (to date they are the most expensive dynamic glass on the market).

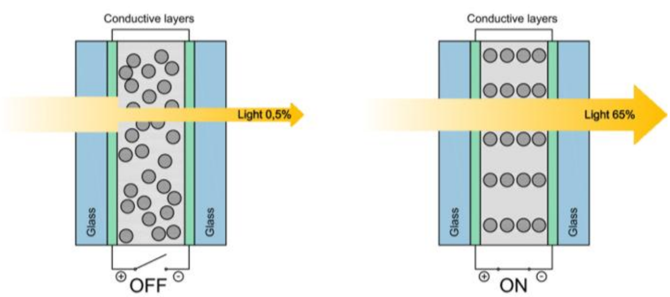

Figure 5. Suspended particle devices operation

3) PDLC devices

Liquid crystal devices (Scienstry, Polytronix, Essex Safety Glass, Switchglass, Smartglass International, Magic Glass, Dream Glass, etc.) consist in a double sheet of glass within which is located a package (called Polymer Dispersed Liquid Crystal Device, PDLC) comprising of a polymer matrix film sandwiched between two electrical conductors of transparent thin plastic film. Within the film are dispersed tiny liquid crystal spheres with a diameter of the same order of magnitude as the wavelength of visible radiation.

In the absence of electrical stimulus the liquid crystals have a disordered arrangement and the light rays undergo random diffractions so glazed elements appear white and translucent; on the other hand, when an electric field is applied, the liquid crystals align in the same direction ensuring the transparency of the panels. The degree of transparency can be controlled by the voltage applied. The light transmittance of liquid crystal glazing in the active state does not normally exceed 70%, while in the off state is about 50%, although appropriate dyes may be added to darken the device in the off state. The liquid crystal systems, while able to optimally spread direct incident solar radiation, do not to block enough to obtain a significant reduction of the solar factor, usually between 0.69 and 0.55. Furthermore, compared to electrochromic systems, liquid crystals systems are not bistable and require a constantly applied electric field for correct operation, resulting in a continuous consumption of electrical energy (about 5-10 W/m^2 of surface operating between 65 and 110 volts AC). PDLC systems are mainly used for the construction of interior or exterior partitions in applications that usually require privacy such as shop windows, meeting rooms, intensive care areas, bathrooms and showers doors or transparent walls to use temporary as projection screens. PDLC devices are also available in rolls as an adhesive, bespoke intelligent film to apply to existing glazing.

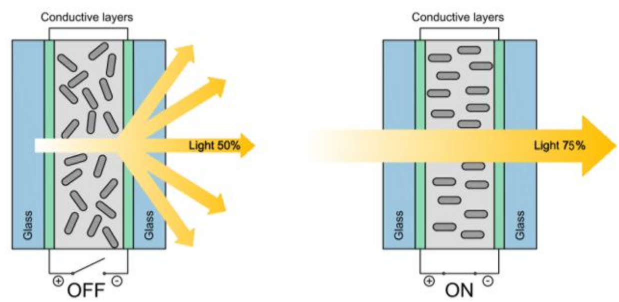

Figure 6. Polymer dispersed liquid crystals devices operation

4) Emerging Technologies

Among the emerging dynamic technologies, intelligent glass with integrated micro-blinds and nanocrystals based electrochromic materials are of particular interest for possible future applications in architecture.

Micro-Blinds shielding glass is composed of inorganic pre-stressed curling electrodes, invisible to the naked eye (size of 100 micrometers) and able to unwind following a weak

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electrostatic stimulus. These MEMS (Micro Electrical Mechanical Systems) are manufactured by depositing on the glass slab a magnetron layer not dissimilar to a low-emissivity coating and subsequently patterning it by laser. At the current experimental stage their performance is comparable to conventional dynamic electric control glass; however, they do not require expensive indium-tin oxide conductive layers, and have activation and deactivation times in the order of milliseconds. MEMS can be realized with materials of different properties, allowing for example to favor UV rays resistance, or, on the contrary, permeability for healthier indoor environments, or by using highly reflective materials in order to further improve performance in the shielding (unwound) configuration. Development is now focusing on laser etching modes and the possibility to create market sized products.

As regards instead nanotechnological electrochromic materials, researchers at the University of Berkeley have recently developed a novel material consisting of indium tin-oxide nanocrystals embedded in a glassy matrix of niobium oxide. With an electrical pulse, the resulting compound allows to independently control visible light radiation and infrared radiation (NIR, Near Infrared Radiations), allowing to block unwanted energy intakes while maintaining, at the same time, the possibility of best exploiting natural light.

TABLE V. COMPARISON BETWEEN MAIN ACTIVE AND PASSIVE CHROMOGENIC GLAZING ON THE MARKET

Properties	**Dynamic glazing**			
	Passive systems	**Active systems**		
	TC	**EC**	**SPD**	**PDLC**
Optical and Thermal performances				
Clear state	Low temperature	Off	On	On
Dark state	High temperature	On	Off	Off
Visible Light Trasmission (Clear)	60%	60%	65%	Up to 75%
Visible Light Trasmission (Dark)	5%	1%	0.5%	50%
SGHC (Clear)	0.37	0.46	0.57	0,69
SGHC (Dark)	0.12	0.06	0.06	0,55
UV Trasmission (Clear)	0%	0.4%	0.1%	0.5%
UV Trasmission (Dark)	0%	0%	0.1%	0.5%
Privacy in dark state	No	No	Limited	Yes
Number of light control levels from clear to dark	No	Typically 4 states	Unlimited	2 (Transparent and frosted)
Continuos states between dark and clear	Yes	Yes	Yes	No
Light Zoning	n/a	Yes	Yes	Yes
Operating temperature	from -20 to 160 °C	from -20 to 70 °C	from -40 to 120 °C	from -20 to 70 °C
Configuration options				
Maximum size	1651 mm x any lenght	1524 x 3048 mm	1524 mm x any lenght	1828 x 3567 mm
Shapes	Any shape, including curved	Rectangle, square, trapezoid, trangle	Any shape, including holes anywhere and curved	Any shape, including holes anywhere and curved
Colours	Blue, Green, Bronze, Gray	Blue, Green	Tipically Blue	Clear, Bronze, Gray, Green tint
Electrical Properties				
Operating voltage	n/a	12 V DC	65-110 V AC	65-110 V AC
Power requirement for state transition	n/a	2,5 W/m^2	5 W/m^2	5-10 W/m^2
Power requirement for state maintenance	n/a	0,4 W/m^2	0,55 W/m^2	5-10 W/m^2
Switching speed	Several minutes	Tipically 3 to 5 minutes to reach 90% of its range	Tipically 1 to 3 seconds	Instantaneus (0.1 sec)
Control	No	Wall switch, Remote control, Movement sensor, Light and temperature sensor, Timer	Wall switch, Remote control, Movement sensor, Light and temperature sensor, Timer	Wall switch, Remote control, Movement sensor, Light and temperature sensor, Timer
Integration with BMS	n/a	Yes	Yes	Yes
Costs and durability				
Cost	Lowest	Medium	Highest	High
Durability	>20 years	>30 years	>20 years	>10 years

IV. Energy and environment benefits in the use of electrochromic glass

Among the different dynamical active control systems, electrochromic devices (EC) are particularly interesting, and are currently considered the most suitable and promising chromogenic technology for the control of radiant energy through the transparent components of the building envelope (to switch from clear to completely tinted, a 200 m^2 EC glass façade needs about the same energy used to power a single 60 W light bulb). Compared to SPD and PDLC glass, electrochromic glazing has lower power consumption for both the switching and the maintenance of the desired tint state. It

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also allows excellent protection from solar radiation, with SGHC values variable from 0.46 to 0.06, and ultraviolet radiation while always allowing vision through (unlike PDLC) and, to date, has a higher and proven durability, guaranteed up to over 30 years (one of the first installations of electrochromic glass in the Desert Regional Medical Center in Palm Springs, California, dates from the year 2003 and the glass is still operative today) along with inferior costs compared to SPD and PDLC devices.

Compared with the first installations, registered in the early 2000s, new electrochromic products allow for greater slab sizes (up to 1524x3048 mm); are available in different shapes (circular, triangular, trapezoidal, etc.) and colors; offer the possibility of adjustment between four different tinted stages; allow independent modulation of individual panels (light zoning); can be self-powered by window-integrated photovoltaic systems; are controllable via Wi-Fi by smartphones; have considerably higher durability, guaranteed for more than 30 years.

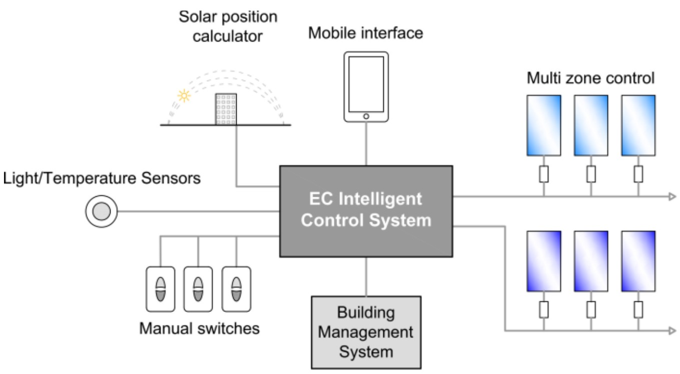

Figure 7. Dynamic active glazing intelligent control

There are now several hundred examples of buildings that have electrochromic glazing installed around the world and in different climatic zones, from education buildings, commercial offices and public buildings up to hotels, hospitals and worship facilities. According to the US Department of Energy (DOE), the goal of achieving zero energy or positive energy buildings is not feasible without the use of dynamic glazing.

The main advantages of using electrochromic glass (EC) concern, in particular:

- reduction to up to 60% of the needs of artificial lighting by increasing the light transmission through the windows resulting in increased visual comfort for the occupants and reduced energy costs;
- the ability to adjust the lighting levels in indoor environments while maintaining transparency and the exterior vision resulting in greater satisfaction for the occupants, who have the opportunity to enjoy the outdoor views both during the day and at night (even in its most dark state, with less than 2% of visible light transmission (VLT), the glass is still transparent);
- the reduction of summer and winter air-conditioning (HVAC) requirements thanks to the ability to control heat gains from solar radiation with consequent reduction of energy costs for management and installation, the latter thanks to the possibility of resorting to plants of smaller size (up to 25% less power needed);
- the elimination of both internal and external solar control screens, with consequent reduction of installation, maintenance and, in the case of powered mobile systems, management costs;
- the protection of materials and furnishings from direct solar radiation reducing discoloration and degradation due in particular to solar ultraviolet radiation UV entirely blocked by the electrochromic glazing;
- greater freedom in architectural design, allowing to increase the glazed surface to opaque surface ratio of the envelope (window-to-wall ratio or WWR) without affecting the building's energy performance, or to use glass components in situations where it would not normally be indicated in order to not compromise the environmental comfort;
- the possibility of use in all cases of upgrading the energy efficiency of existing buildings;
- the ability to achieve high scores on environmental certification systems such as LEED buildings and BREAAM (see table VI).

TABLE VI. DYNAMIC GLASS AND LEED

LEED Certification Criteria	Points (up to 28 pts)
Energy and atmosphere	18
Indoor environment quality	8
Thermal comfort	1
Daylight	3
Quality views	1
Interior lighting	2
Sustainable sights	1
Material and Resources	2

In view of these indisputable advantages, the costs for installing electrochromic glass, and dynamics glazing in general, still remain high for their mass application both in the residential that for the commercial one.

The extra cost of dynamic windows compared to traditional insulating glass units is around 215 €/m^2 with a payback period of between 26 and 33 years for residential buildings and between 57 and 61 years for commercial buildings.

V. Conclusions

This study shows how the use of dynamic windows can bring numerous benefits in terms of energy efficiency, environmental comfort and architectural quality of buildings. Static solutions with selective glass and fixed or mobile screens do not allow to optimize solar gains and light conditions during the year thus limiting, in the design phase, the size of glazed components. Solutions with automated dynamic sun screens coupled with building automation systems offer excellent energy performance, but have high

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installation, maintenance and management costs, and hinder the view from the inside to the outside.

Dynamic glazing, and electrochromic in particular, instead enable to adjust the amount of incoming light and heat according to the effective need, allowing to realize a building envelope able to fully adapt to the weather conditions (climate adaptive building shells), improving building overall performance for every kind of climate, and in hot climates and Mediterranean countries in particular.

Electrochromic systems also prove more convenient both with respect to static systems, thanks to the significant reduction in energy consumption for artificial lighting and air conditioning during summer and winter, and with respect to automated screens systems due to lower installation costs (absence of internal and external screening systems and the relative motion devices, possibility to use lower power air conditioning systems) and management.

The critical aspects still reside in the high cost of the products, anyhow destined to drop following increasing market penetration and improvement of production processes, and the still limited information between professionals and consumers, also due to a lack of standardization in the technology.

Rather than improving the already good performance, it therefore appears more important to drastically reduce the cost of dynamic glass, focusing on materials, production processes improvement and easier installation.

To ensure wide market penetration of the dynamic glass, the 2025 target should be to achieve less than 65 €/m^2 extra cost, allowing a payback time of 10-12 years for residential buildings and 21-22 years for commercial ones [17].

Regarding existing buildings, in addition to high costs, spread is still hindered by the necessity of having to replace the entire window and the need for extensive wiring. It is therefore essential to promote research in the field of dynamic high-performance films to be used to retrofit existing windows and in the development of internal self-powering systems and built-in remote control via Wi-Fi for windows (Internet of Things).

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