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Approaches of Energy-Saving Facades – Review Article

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ABSTRACT

Energy-saving facades is getting excessive attention nowadays as it is considered a step towards achieving zero-energy environment. Using good management of energy flowing into buildings, the energy consumption could be saved in term of heating, cooling and lighting load. With integration to Photovoltaics, extra electricity could be obtained to support building energy consumption. Overall energy performance of different designs and innovations of building's façades have been introduced and evaluated in many researches. The ability to control energy flow and/or to produce some sort of extra energy is currently known as "Smart Windows". In this article, the basic concepts of performance of the different façade designs, as well as energy-saving and energy-producing emerging technologies to this field were reviewed.

1. Introduction

Fossil fuels in the form of coal, oil and natural gas are the major sources of conventional energy for many countries to meet their requirement for power. The reserves of such fossil fuels are exhausted largely due to its continued use. Besides, it has a very high impact on the globe. Many of the environmental problems we face (climatic change, atmospheric pollution, oil leaks, etc.) result from consumption of such fossil fuels.

Solar energy is one of the most competitive free sources of renewable energy that could be exploited without any limits. It can produce electricity or heat, or both, depending on how they capture solar energy [1–3].

As the world's demand for renewable energy is increasing, great attention is given to the zero, or minimum -emission building [1]. For aiming as such, building need to stop or minimize its energy loss through the building's facades and produce energy from its surroundings. Energy from the sun is the most candidate for such job.

Reaching these goals could achieved by a choosing an appropriate design of the Building's façade, depending on the climatic zone, besides introducing Building integrated photovoltaic (BIPV) systems.

Old-style façade designs regarded the external building's skin as a blocking barrier between the outdoor climate and the highly controlled interior environment. Efficiency of such façade was measured by its ability to isolate the building's interior from the outdoor environment so that the cooling system could operate as efficiently as possible [4]. However, recent concepts of facade designs consider the building facade as a filter between the external and internal environment [5].

The building's façade serves as the interface between the interior and the exterior space and plays an important role in thermal load control, ventilation, noise control, design quality and visual comfort. Fresh air, heat and sunlight can be achieved through building's façade, and they can be dissipated.

For providing the occupier with a comfortable thermal and visual environment, a façade should satisfy many functions, without which additional components must be added to or in the vicinity of such façade [6].

Energy saving smart windows are those windows and façades that can prevent energy from escaping to or from the building. Energy producing smart windows and building integrated photovoltaic (BIPV) systems are those windows that can use such prevented energy to produce electricity by means of solar cells. Such smart windows can utilize solar radiation to produce electrical energy. They may signify a powerful and useful tool for achieving such increasing demand for zero energy and zero emission buildings of the near future

In this review, different façade technologies will be briefly overviewed. Smart windows and their advanced approaches, the latest technology regarding energy-saving and energy-producing windows technologies will be overviewed. Building integrated Photovoltaics will be under focus.

2. Modern Building Design and Façades

At the present time, there is an increasing concern on the development of sustainable building over the world. Energy conservation in buildings is one of the major concerns. Building experts can add to this area by the supervision of the energy consumption of buildings, especially the fully air-conditioned buildings (as in the case of the Middle East, and similar climatic zone over the world), through a refined building design.

Globally, buildings are responsible for approximately 40% of the total world annual energy consumption with the resulting carbon emissions substantially more than those in the transportation sector. Most of this energy is for the provision of lighting, heating, cooling, and air conditioning [7]. In a typical commercial building, air-conditioning system is the largest source of power consumption. It may account for up to 45% of the total power consumption of such buildings. Surplus heat energy is extracted to the outdoor space by air-conditioning system. One of the major thermal loads in the building envelope heat gain is the heat transfer through window glazing of the building façade [8, 9].

Not that the Middle East is alone in its love of the shiny stuff. Across the US, Europe and China, architects have been designing and building glass towers since long time ago. Nevertheless, in most of these markets, temperatures do not reach 40°C for weeks as in the case of Middle East, turning those modern towers into greenhouses [10].

User comfort is an essential demand that characterizes the design of the buildings construction. Different demands on the comfort level are posed for different types of buildings such as residential or office buildings Essential criteria are [11]

- Thermal comfort
- Hygienic comfort
- Acoustic comfort
- Visual comfort

Façades are very eminent architectural and design elements for architects as it gives their designs a unique appearance. Besides

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affecting the building's indoor thermal and visual comfort that is responsible for satisfaction of the residents or employees [11,12], it also determines the overall consumed energy (including lighting, heating and cooling loads) and the operating costs of a building [13].

Choosing to block sunrays by traditional curtains – for preventing direct sunlight and glare – results in complete or partial darkening of the room and raising the need of using artificial light sources inside the building. On the other hand, choosing not to use curtains will result in allowing direct sunlight with glare to harm the human eyes besides allowing thermal energy to flow to the room resulting in heating up the area, hence, using air conditioners with higher electric load. Blinds are frequently used with such glazing façades or room external windows to control transmitting direct (beam) solar radiation component, but without the use of such valuable blocked energy.

In order to monitor building's energy consumption especially in cooling and air conditioning, different ways have been developed and discussed [14–16].

Because of the increasing demand of new domestic and business constructions using building facade technologies, such demand for high energy-efficiency buildings requires more application of building thermal and visual simulation to examine the energy consumption for the building by selecting the effective façade system considering the availability of material in the region under discussion [17,18].

In this context, BIPVs offer an aesthetic, economic and practical solution for integrating photovoltaics in order to harvesting solar radiation to produce electricity and minimize energy consumption as well. Building integration of photovoltaic cells are installed on sloped or flat roofs. It could also be installed as facades and solar shading systems, BIPV systems can easily replace the outer building envelope, serving as a climate screen and a power source for electricity generation simultaneously [19].

Solar façades could be classified in many different ways according to different scopes or different specific points of interest. They might be classified according to their transparency, type of energy produced, energy consumption, etc. The following is a general classification of the existing façade technologies.

2.1. Type of Energy Generated

Solar façades may utilize solar energy for thermal energy gain like space heating, cooling or ventilation. Electrical energy generation could also be utilized by means of PV. There exist systems that can generate both thermal and electrical energy simultaneously [20].

2.2. Opaque and Transparent

Opaque facades absorb and/or reflect the incident solar radiation but cannot transfer directly solar heat gain into the building, while transparent and translucent facades can absorb, reflect, or transfer the incident solar radiation gain into the building's interior [2].

2.3. Concentrated and Non-Concentrated Solar Energy

Solar concentrators may be used in building façades in order to increase total system collection efficiency. They could be used for both solar thermal as well as PV technology, or a combination of both.

However, regarding their energy generation or consumption, building facades are classified mainly into three categories, passive façades, energy-consuming façades, and energy-producing facades.

3. Passive Building-Integrated Façades

In general, facades are considered passive if they interact with the incident solar radiation but cannot transfer such energy into a useful electrical or thermal energy. They are considered as energy-consuming facades if they consume energy during their operation. Finally, they are considered energy-producing façades if they use such incident energy to generate electricity. Double skin solar façade systems are the simplest amongst all facades. Those systems directly use solar energy to achieve energy gains. They neither use external energy for operation (although internal fans may be used for air circulation and spread)., nor generate energy during operation.

3.1. Heating, Cooling or ventilation due to differential air densities

Using the fact that hot air is less in density than that of cold air hence goes up; facades could be used for purposes of space heating, cooling or just air ventilation depending on the design.

Ventilation of facade elements decrease thermal transfer through the building envelope and reduces the need of the conventional insulation materials usually used in the buildings. Being a two stages protection against wind and rain reduces the occurrence of building defects of the outer layer [21]. Fig. 1 shows different designs for double-skin passive façade. Fig. 1(a) is a monolithic porous façade design for air ventilation that could also be considered to serve for worming process. Transparent or semi-transparent glazing could be used as an envelope of the building exterior in order to transmit thermal energy and choose a proper design to use such energy. Fig. 1(b) is a transparent or semi-transparent glazing façade for space heating by swapping cold air accumulated in the bottom of the room (as it has a higher density) to outside and is then heated up as it elevates to enter the room as a hot air. This design could be considered as a thermal storage wall. Transparent or semi-transparent glazing façade may be used for either space heating and ventilation by rejecting cooler air accumulating in the bottom of the room as shown in Fig. 1(c); or for space cooling and ventilation by rejecting hot air accumulated in the top of the room as in Fig. 1(d). Fig. 1(e) is the traditional double façade that isolates building's interior from interaction with external weather, while Fig. 1(f) is used for thermal energy rejection for reducing thermal energy flowing into the building.

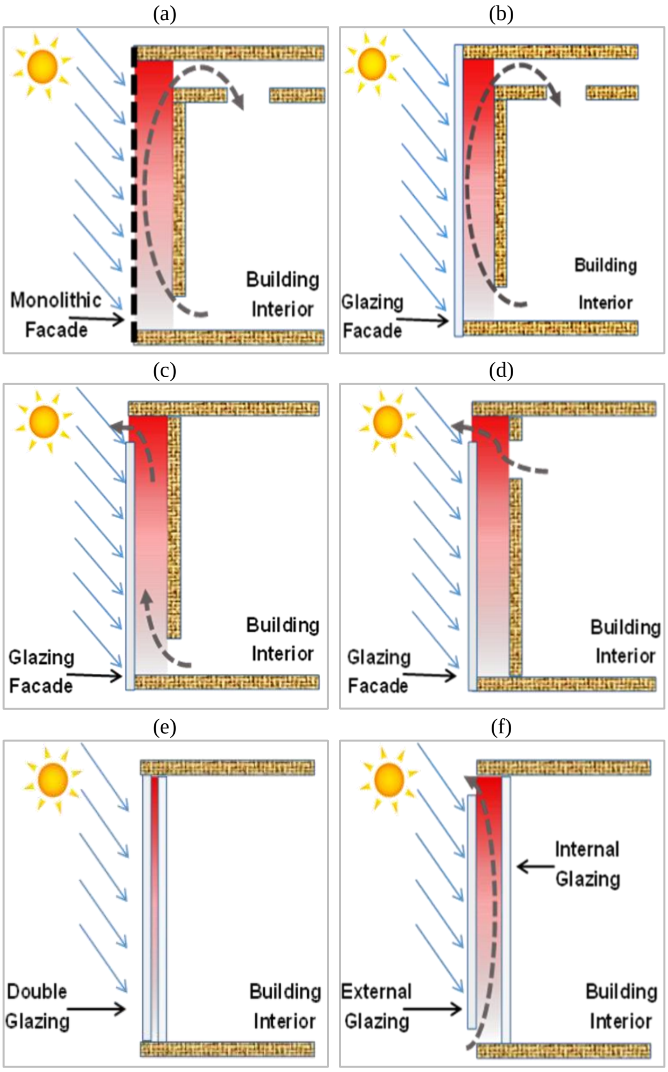

Figure 1: Passive building-integrated façade designs for (a) air ventilation and worming; (b) space heating; (c) space heating and ventilation; (d) space cooling and ventilation (e) thermal insulation, and (f) cooling.

3.2. Low Emissivity Glazing

Low emissivity (Low-E) coatings are spectrally selective films aiming to allow the visible light to pass through it, and block the infrared radiation which generally create heat. Schematic of Low emissivity glazing window is shown in Fig. 2. Because of its high IR-reflectance, this type of glazing has been developed greatly, and many have studied their different properties. Currently there are two existing technologies of low-e coatings, namely, tin oxide based hard coating, and silver based soft coating that has higher IR reflectance and lower transmittance than the former. However, the visible transmittance of hard coatings can be increased using antireflection property of silicon dioxide [22].

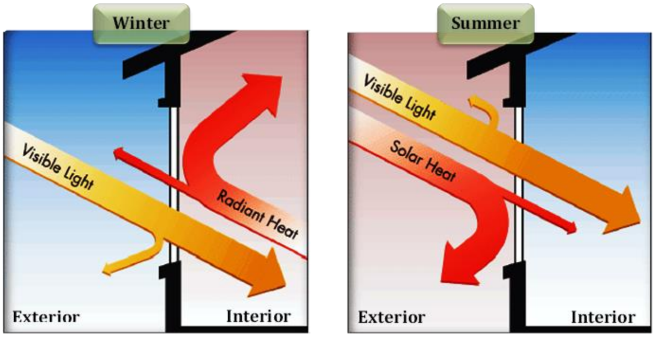

Figure 2: Schematic of Low emissivity glazing window [22].

3.3. Dielectric/metal/dielectric Glazing

Dielectric/metal/dielectric films coated on top of glass substrates show great energy saving effects by reflecting the IR radiation by the metal film and transmitting visible and near IR radiation through the two antireflective dielectric coatings. Design, fabrication and optical properties of dielectric/metal/dielectric films have been studied by many researchers aiming the optimization of such layer. Beside the optimized performance, cost of these films in terms of their material and the fabrication technique is also important [22,23]. Glazing coated with $TiO_2/Cu/TiO_2$ as an example is shown schematically in Fig. 3 along with its optical properties [24].

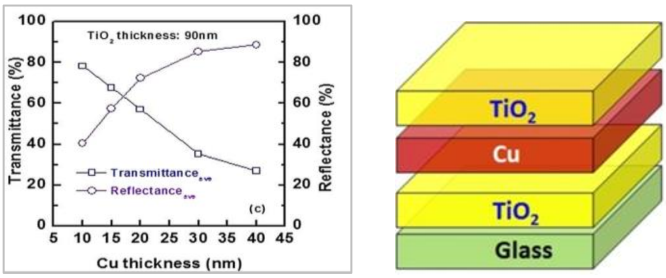

Figure 3: TiO_2 / Cu / TiO_2 deposited on a glass substrate (left), and effect of varying Cu thickness on the transmittance and reflectance (right) [25].

3.4. Thermochromic Glazing

Broadly speaking, thermochromism is the temperature-dependent changes in the optical properties of a material [26]. Thermochromic material shown schematically in Fig. 4 [24] has the ability to control the quantity of solar energy entering the building or escaping from it [27,28], by changing its optical properties hence color upon reaching a characteristic "transition temperature". Thus, reducing cooling or heating loads as appropriate.

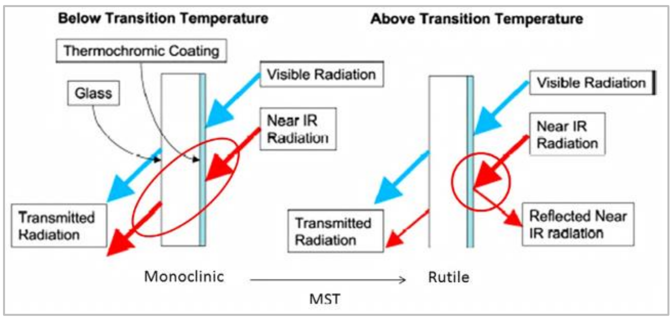

Figure 4: Schematic representation of thermochromic materials applied as an intelligent windows coating [24].

3.5. Thermotropic Glazing

Thermotropics are types chromogenic materials that can show an adjustable change in their optical properties depending on its temperature. These materials are either a combination of two components that show a phase separation at and above a specific temperature or are formed by particles uniformly embedded in a polymer [29] which change its orientation at and above a specific temperature. In other words, a material is considered thermotropic if it can be re-oriented or rotated by changing its operating temperature. At high temperature, such material induces a phase transition: and changes to an isotropic liquid., In contrary, if temperature is too low to support a thermotropic phase, the material will change to glass phase [30], as shown schematically in Fig. 5.

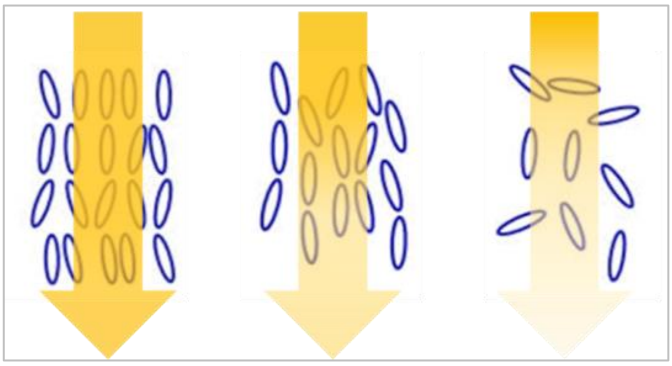

Figure 5: Thermotropic material changes its phase with increasing temperature.

3.6. Photochromic Glazing

Photochromic windows are made from transparent materials that can change their color upon exposing to sunlight, with similar materials used in sunglasses. Such materials response to light intensity, regardless any temperature changes. Cost-effectiveness and durability of such glazing for mass production are not yet commercially available.

4. Energy-Consuming Façades

Flow of energy through façades and windows may be controlled using energy-consuming technologies, by applying external electric power to adjust their optical properties and their transparency as will be reviewed in the next paragraphs.

4.1. Polymer Dispersed Liquid Crystals (PDLCs)

In these glazing or windows, the liquid crystals respond to an electrical charge by aligning parallel and letting light through. When the electrical charge is absent, the liquid crystals in the window are randomly oriented resulting in complete blocking of incident sun light. In PDLCs, the window is either clear or translucent, without any ability to control its transparency. Fig. 6 shows a schematic of PDLC operation method.

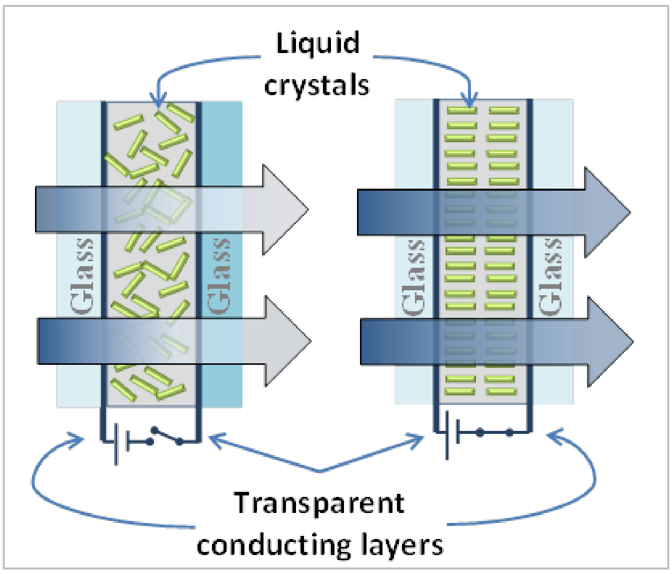

Figure 6: Schematic of PDLC Glazing

4.2. Suspended Particle Display Devices (SPDs)

Whose operation principle is similar to the PDLCs except that the polymer crystals are replaced with smaller particles or to switch from clear to dark. In such window, SPDs are sited between two glass panes coated with a transparent conductive material. When the triggering electric circuit is closed, an electric field is generated between the two glass panes which makes the SPDs to line up in a straight line allowing light to flow through the window. Once the circuit is disconnected, SPDs disperse back randomly and block light from transmitting through. By controlling the applied voltage, the window's transparency is reduced until it's completely opaque. Fig. 7 shows a schematic of SPD smart windows operation method.

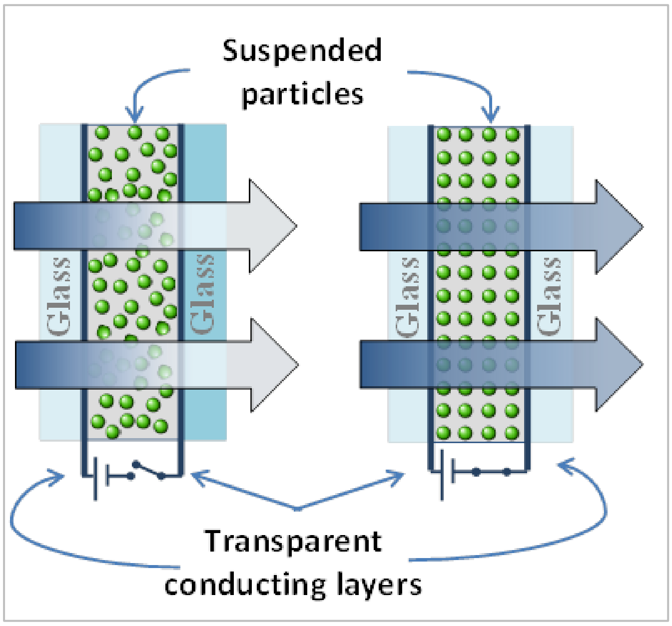

Figure 7: Schematic of SPD Glazing

4.3. *Electrochromic Windows*

Electrochromic materials have the property of changing their color as affected either by an electron-transfer process or by a sufficient electrochemical potential. Essentially, electricity triggers a chemical reaction in this sort of material. This reaction changes the properties of the material. In this case, the reaction changes the way the material reflects and absorbs light. In some electrochromic materials, the change is between different colors [31]. In electrochromic windows, the material can change its color and transparency as illustrated in Fig. 8.

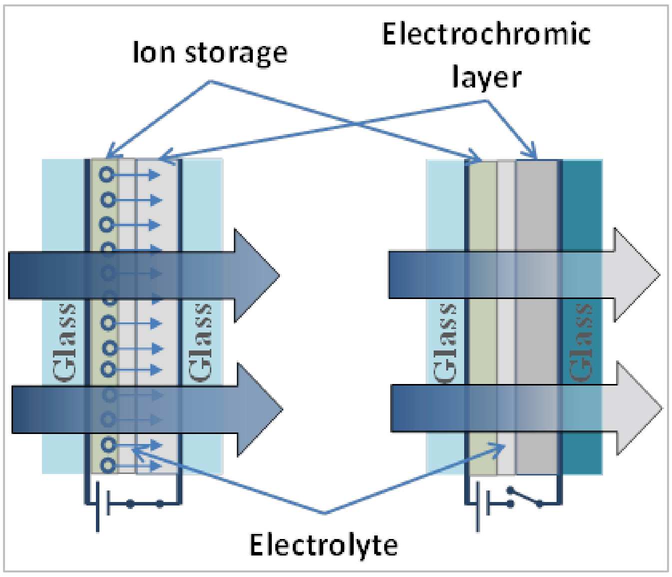

Figure 8: Electrochromic Glazing

5. Energy Producing Façades

Energy could be produced by integrating PV to the building's façades or by fixing to the roof. Building integrated photovoltaic (BIPV) system is defined as photovoltaic cells which can be integrated into the building envelope as part of the building structure, and therefore can replace conventional building materials, rather than being installed afterwards [32]. The PV modules serve a dual function of building skin by replacing conventional building materials and generating power [33]. In the next paragraphs, an overview of the possible technologies of BIPV are presented.

5.1. *Façades and Roof-top mounted PV*

Many papers have either proposed new ideas or tested existing technologies as will be mentioned below. The most straight forward solutions to build a BIPV is to integrate directly into the building's roof to use the whole building's roof area as shown in Fig. 9. This is most suitable for one story buildings like Airports, Train stations, etc. Such roof-top PVs could be semi-transparent (amorphous PV, or opaque PVs that are arranged in panels with large spacing between the PV units) for daylight utilization.

façades intended for cooling besides generating clean electricity are shown schematically in Fig. 10, in which PV acts as a building façade with an ample spacing with the building's body. Since the operating PV temperature plays a crucial role in its performance [34], this configuration is very effective, as making a channel for air to circulate and remove heat accumulated on the PV back side, hence cooling both building's interior and the PV itself for better performance. In contrast, such heat accumulated could be allowed to emerge into the building's interior acting as a heating source as in Fig. 11.

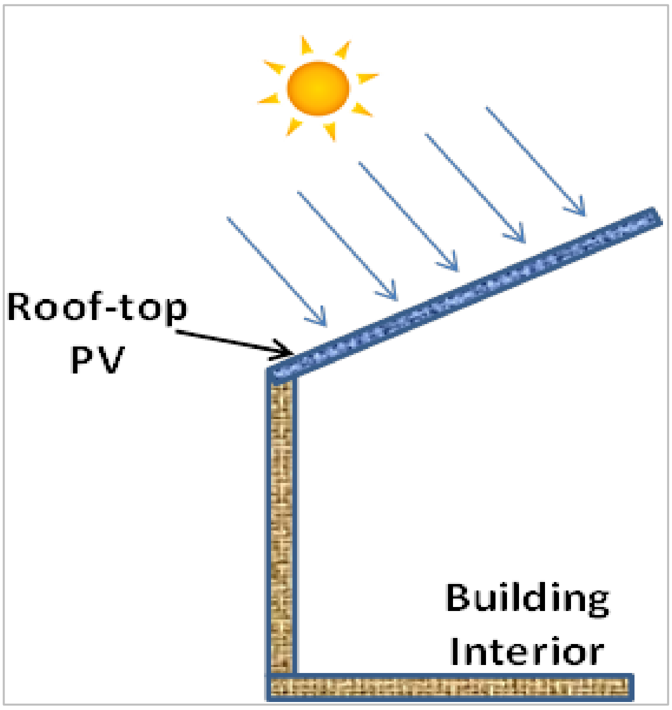

Figure 9: Roof-top integrated PV

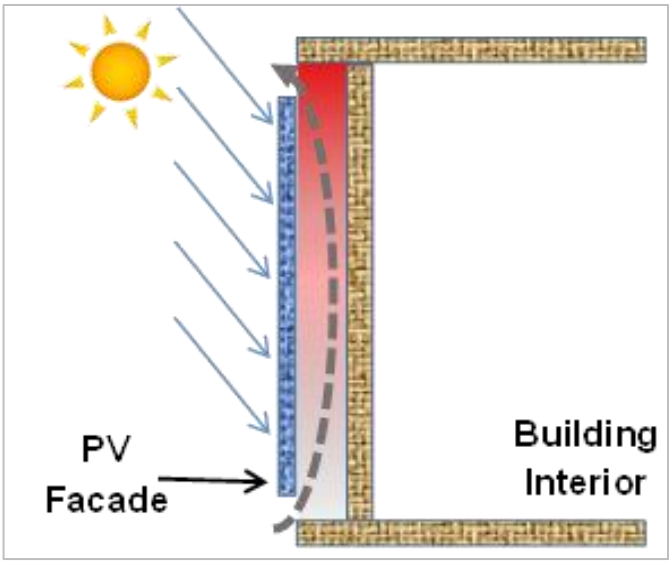

Figure 10: PV integrated façade for electricity production while rejecting accumulated thermal energy behind PV (space cooling)

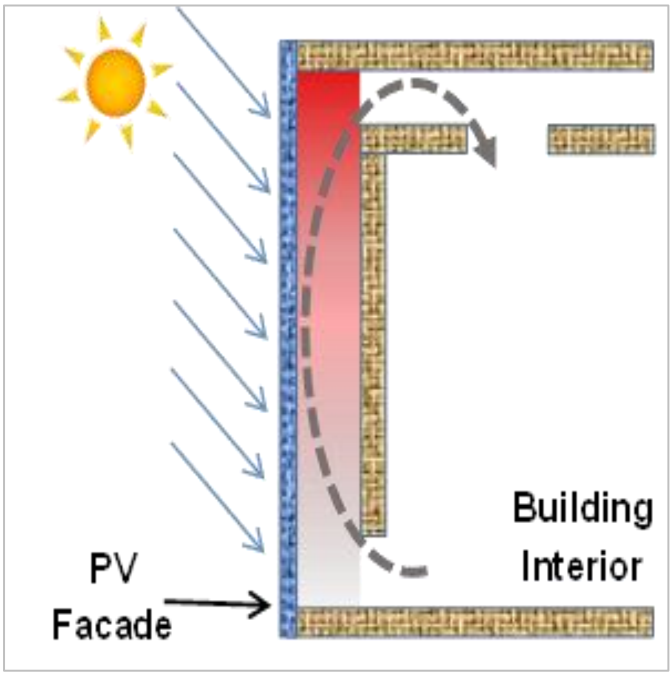

Figure 11: PV-integrated façade for electricity production, while utilizing accumulated thermal energy in space heating,

5.2. Radiation Capturing by Total Internal Reflection Glazing

Concentrated PV can play a role in BIPV in different ways to maximize the use of PV and minimize its cost. Solar radiation could be concentrated with the use of a phenomena called total internal reflection of a light ray that occurs when it strikes a medium boundary at an angle larger than the critical angle with respect to a normal to the surface. This phenomenon could be of use by redirecting solar radiation incident on windows to be collected by means of small area solar cells embedded in such window. This will happen at a specific orientation of such Window based on the design, latitude of the building, and principle of operation.

Transparent acrylic CPC Smart Windows having the absorber (solar cell) inclined with the latitude of the location (i.e. facing sun) has been investigated [35]. Schematic of the investigated system is represented in Fig. 12.

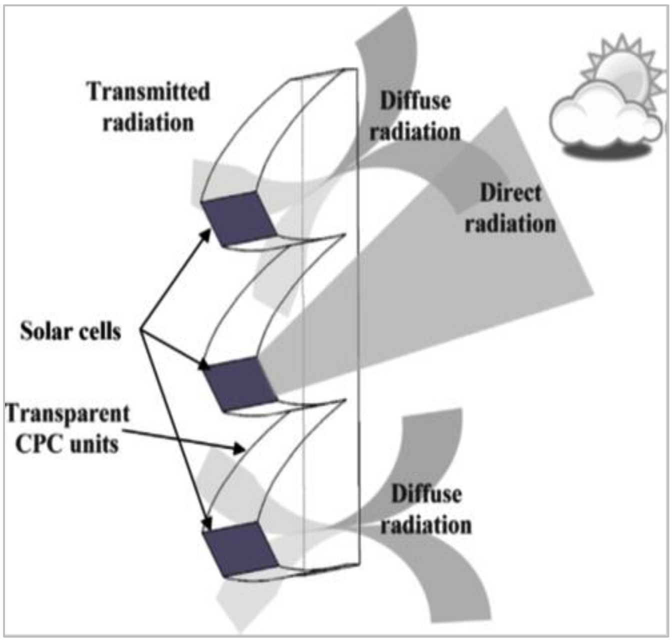

Figure 12: PV-integrated CPC for transparent façades [35].

Another Smart Window consisting of Low-concentration Photovoltaic system in the form of prismatic segmented façade. Prism head angle determines the zenith angle after which direct solar radiation is reflected internally to be collected by solar cell integrated in the window as shown in Fig. 13 [36].

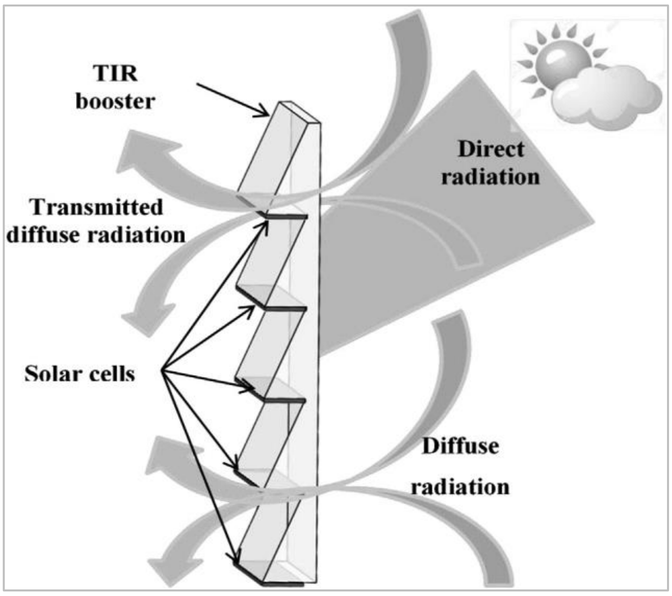

Figure 13: Prismatic low-concentration PV integrated façades [36].

5.3. Thermotropic with built-in PV Glazing

Another approach of energy-producing glazing consists of a thermotropic layer with integrated PVs. This system responds to climatic conditions by varying the percentages of solar energy reflected to the PV for electricity generation and the transmitted the building for light and heat provision [37, 38] as shown in Fig. 14.

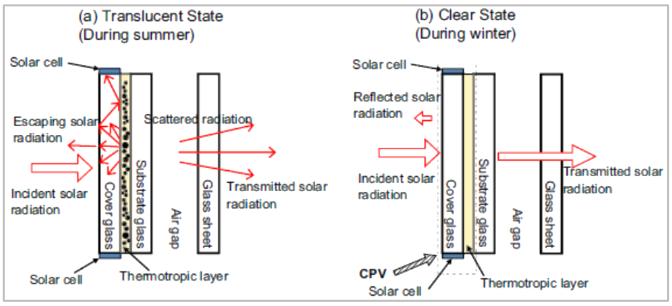

Figure 14: Design and development of a reflective membrane for a Building Integrated Concentrating Photovoltaic [37].

5.4. PV/T Integrated Glazing

Thermal as well as electrical energy could be extracted from a window whose solar cells operate under high concentration ratio. Such system can generate both electricity and hot water or air directly for domestic use inside the building in addition to allowing diffused radiation to penetrate to the building's interior [20] as shown schematically in Fig. 15

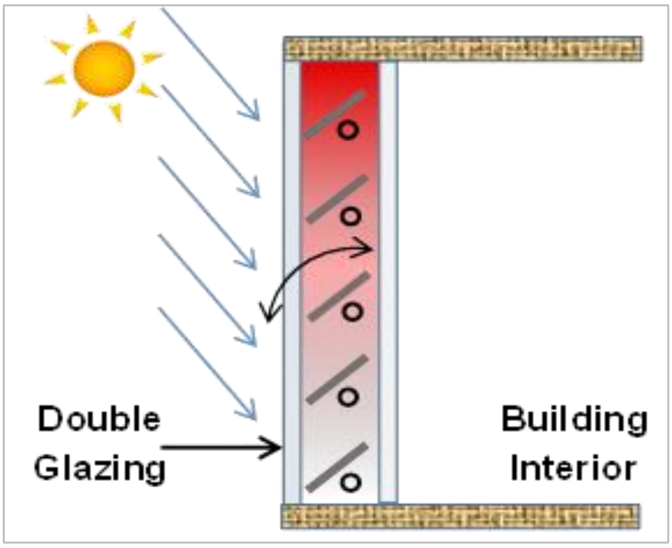

Figure 15: PV/T integrated façade.

6. Conclusions

The ability to control energy flow and/or to produce some sort of extra energy is currently known as "Smart Windows". In this article, the basic concepts of performance of the different façade designs, as well as energy-saving and energy-producing emerging technologies to this field were reviewed. Different types and strategies of Energy-saving facades was adopted in this review, which is considered a step towards achieving zero-energy environment. Accepting a specific type of such reviewed types was based on the appropriateness of accompanying factors, like sky clearness, height of the surrounding buildings, area of the roofs of façades of the building under test, etc. Using good management of energy flowing into buildings, the energy consumption inside the considered building could be saved in term of heating, cooling and lighting loads. This could even produce energy if integrated with Photovoltaics. Extra electricity could be obtained to support building energy consumption.

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