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Review Article

Solar Glass Panels: A Review

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Abstract

The need for energy sources in the world is gradually increasing day by day. Photovoltaics (PVs) usage has worldwidely spread thanks to the efficiency and reliability increase and price decrease of solar panels. The photovoltaic (PV) glazing technique is a preferred method in modern architecture because of its aesthetic properties besides electricity generation. Traditional PV glazing systems are mostly produced from crystalline silicon solar cells (c–SiPVs). The development of low–cost PV cells for the production of cost–effective and energy–saving glass systems has been of great interest. Solar control glass which is one of the crucial components of PV panels is largely employed for architectural and automotive windows to lower the sunlight and heat inlet for the comfort. Hereby a general overview of solar glass panels is presented.

Keywords: Solar glass panels, History, Production, Properties, Applications, Development.

Cam Güneş Panelleri: Bir Derleme

Öz

Dünyada enerjiye olan ihtiyaç günden güne artmaktadır. Verimlilik ve güvenilirliklerindeki artış ve fiyatlarındaki düşüş sayesinde güneş panellerinin (fotovoltaiklerin) kullanımı da dünya genelinde yaygınlaşmaktadır. Modern mimaride güneş paneli estetik özellikleri ve elektrik üretimi açısından tercih edilmektedir. Geleneksel güneş paneli sistemleri ağırlıklı olarak kristalin silisyum güneş hücrelerinden (c–SiPVs) üretilmektedir. Düşük fiyatlı güneş paneli hücreleri fiyat etkin ve enerji tasarruflu cam sistemlerinin üretimi bağlamında büyük ilgi çekmektedir. Güneş panellerinin önemli bileşenlerinden birisi olan güneş control camı iç mekana giren gün ışığını ve ısısını azaltması böylece yaşam konforu sağlaması ile mimaride ve otomotiv pencerelerinde yaygın olarak kullanımaktadır. Bu makalede cam güneş panelleri hakkında genel bir derleme çalışması sunulmaktadır.

Anahtar Kelimeler: Cam güneş panelleri, Tarihçe, Üretim, Özellikler, Uygulamalar, Gelişim.

1. Introduction

Glass is an inevitable material of daily life, in a large color ranges and shape varieties, with numerous different applications from the screens, windows, bottles, jar, or tableware to fiberglass or sealant/solder glass. For all these usages and applications, different types of glasses with compositions tailored to meet specific requirements are required. Every single sector is mentioned with subsectors. For example, one can classify the fiberglasses as insulation, reinforcement, mineral wool, and optical fibers. Similarly, the flat glass can be divided into windows, automotive glazing, internal and solar glasses (Fig. 1). Container and flat glasses are the two large sectors, and approx. 45–50 % and 30 % of the world production belongs to them respectively [1].

From the years 1990 to 2007, the world energy consumption increased by 40 %. Until 2035, it is expected that another 8–10 % increase will occur because of the rapid growth of urbanization. The major energy–consuming sectors are transport, industry, and

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buildings being specifically responsible for 40 % of global energy alone. For fulfilling such a high energy request, zero energy, or low energy buildings attract considerable attention [2]. There are many studies conducted on solar glass for photovoltaic (PV) modules [3].

The conventional construction materials like glazing or cladding are replaced by solar glass. In multi–floor buildings with limited roof space, for generating electricity, façades and windows are the most potential units. Therefore, the development of solar glazing becomes a great issue in the growth of 'urban micro–generation'. Besides possessing aesthetical pleasure and visual innovation, the solar panel glass may result in the return on investment from the building [4].

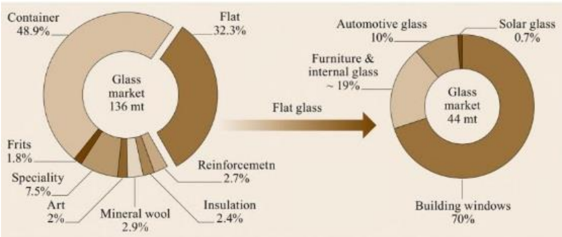


Figure 1. The distribution of the glass market in 2007, focusing on the flat glass market [1]

Curtain walls are becoming a popular application for PV glass in buildings, allowing owners to generate power from areas of the building that have never been considered. Thus, buildings became a real power plant, preserving their desired features such as design, aesthetics, efficiency, and functionality. For these applications, amorphous Si (a–Si) and crystalline Si (c–Si) glasses can be employed, and selecting one or another will rely on the design choices, energy requirements, and daylight situations. PV glass for curtain walls comes frameless and can be integrated into any commercial system. A typical curtain wall system can come together semi–transparent PV glass for the vision areas, with completely dark glass for the spandrel [5].

2. History

Although the beginning of the artificial production of glass is uncertain, it is assumed that it dates back 4000 years ago to the Phoenicians in Eastern Mesopotamia. The glass industry has benefited from the inspiration and experience of the Hellenistic glass manufacturers and has made progress in the Roman period. The Romans used glass not only in the production of everyday items but also for decorative purposes such as mosaic, paneling, and exterior cladding. For example; it was again the Romans who covered the rear surface of the glass with metal foil (Au or Ag coating) and used it as a reflective material. Modern glassmaking began to develop in Venice in the 11th century as a result of the collapse of the Byzantine Empire under the influence of the Crusades. Venice has been the center of the glass industry in Europe for 400 years. Subsequently, significant progress has been made in the glass industry and many glass factories have been established in Europe in a short time. The introduction of coal instead of wood in 1615, the construction of crystal glass in the late 17th century, and the discovery of optical glass in the 19th century accelerated the development of the glass industry and made firm conclusions about the principles of glass technology. Although glass production and diversity have shown significant improvements since ancient times, it is not possible to say the same about surface coating technologies. In 1817 Fraunhofer in Germany found that a non–reflective layer could be obtained on the glass surface using sulphuric or nitric acid, but technically it was not applied in those years. In 1935, Strong in the USA and Smakula in Germany tried the evaporation and vacuum methods for coating these non–reflective glasses. In 1938, multi–layer surface coatings began to show up largely in the United States and in Europe on a small scale, but the first successful two–layer systems were achieved in 1949. Becquerel in 1839 watched over that PV cells transform the sunlight energy into electricity by the PV effect. In 1883, the first working solar cells were built by Fritts employing Se with a very thin Au layer. Ohl's research on semiconductor resulted in a patent presenting the first modern solar cells, and in the 1950s Chapin, Fuller and Pearson developed the Si–based Bell solar battery. About 50 years after, solar panels became capable of generating a billion watts of electricity for powering technology on Earth, satellites, and space probes. The collaborations between scientists and mathematicians carry on for the improvement of solar panel technology [6].

Figure 2. John Bayliss, President of the Solaron Corporation, the first publicly owned solar energy company in the nation by Boyd Norton, 1975 [7]

The major historical events in the development of solar energy can be outlined as follows:

Solar panels in outer space–In the year 1958, the Vanguard I satellite employed a very small one–watt panel for powering its radios. Afterward, with PV technology onboard the Vanguard II, Explorer III, and Sputnik–3 had been launched. In the year 1964, NASA launched the first Nimbus spacecraft that was a satellite with the ability for running completely on 470–watt solar array and the world's first orbiting astronomical observatory powered by one–kilowatt array was erected in 1966.

Figure 3. Nimbus 1, the 1st in a series of 2nd generation meteorological research and development satellites launched in 1964 [8]

First solar residence–In 1973, the Delaware University constructed Solar One which was the first solar building, system of which worked on a hybrid supply of solar thermal and solar PV power. This was the first example of a building–integrated photovoltaics (BIPVs)–Instead of using solar panels the array had solar integrated into the rooftop.

Obtainments in solar conversion efficiency–Between the years 1957 and 1960, several breakthroughs with PV efficiency were made by Hoffman Electronics, enhancing the efficiency record from 8 to 14 %. In 1985, for Si cells, South Wales University obtained 20 % efficiency. In the year 1999, the National Renewable Energy Lab. worked on with SpectroLab Inc. for making a solar cell that was capable of 33.3 % efficiency. In 2016 South Wales University broke the record again when the gain of an efficiency level, 34.5 %, was reached by researchers.

Solar–powered airplanes–In 1981, the first aircraft running on solar power, named Solar Challenger, was built by Paul MacCready. In the year 1998, the remote–controlled solar airplane, named Pathfinder, broke a record of altitude with 80,000 feet. In 2001 this record was broken by NASA when they had a success of reaching 96.000 feet with their non–rocket aircraft. In the year 2016, the first zero–emissions flight around the world was completed by Bertrand Piccard with Solar Impulse 2, which is classified as the world's largest and most powerful solar–powered airplane today.

Solar–powered presidencies–In the year 1979, President Jimmy Carter had solar panels installed on the White House. However, in 1981, President Ronald Reagan ordered their removal. In 2010, during his first term, President Barack Obama required solar panels and a solar water heater to be installed on the White House [9].

Figure 4. President Jimmy Carter when inspecting the new White House solar hot water heating system in 1979 [10]

3. Solar Glass

Glass is employed in PV modules as a protection layer for the elements. In thin–film technology, it also serves as the substrate, on which the PV material and other chemicals are deposited. Glass is also the basis for mirrors employed to concentrate sunlight. Most commercial glasses are oxide–based ones with a similar chemical composition (Fig. 5) [11].

Iron (Fe) in the glass comes from the raw and refractory materials or the metallic manufacturing equipment etc., and it is not completely removed. Its amount in the glass can only be minimized through controlling the manufacturing. The Fe content of solar cell glass is at the level changing between 0.008 and 0.02 %, while that of ordinary float glass is above 0.7 %. For the most widely employed 3.2 and 4 mm thick glass, the visible light transmittance of sunlight is generally 90–92 %. Since solar PV glass needs that the glass plate has to be highly transparent, Fe_2O_3 level coming from the raw materials employed in the production of solar glass is very strict, generally 140 to 150 ppm [12].

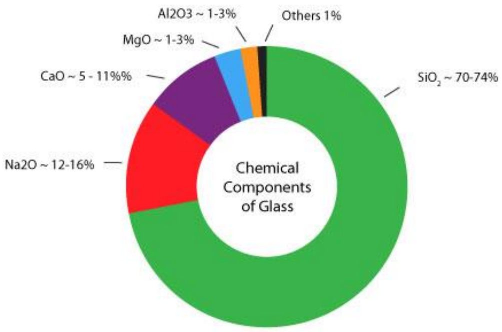


Figure 5. Chemical components of glass [11]

The main expected features from a glass to be used in solar applications are transmission, mechanical strength, and specific weight. Typical crystalline modules employ 3 mm front glass, whereas thin–film modules consist of two laminated glass layers of 3 mm each for front and back. Glass has great inherent strength and shows fast brittle fracture as localized stresses can not be reduced. So–called Pattern Glass is mostly employed as front glass in crystalline modules, whilst float glass is employed for substrate and back glass in thin–film modules. There are certain objectives of glass: Ultra–bright glass is required with high solar transmission to make sure high efficiencies in the overall PV module. Satisfactory mechanical strength is needed to resist snow and wind. Depending upon the application, the glass may require to be laminated and coated. Self–cleaning features would help to decrease maintenance costs [11].

3.1. Classification of PV Glass

PV solar glass substrates are usually ultra–thin, surface–coated, and low–Fe (ultra–white) glasses. PV glass could be classified as the cover plate of a flat–type solar cell, a conductive substrate for thin–film solar cells and lens, or mirror type glass employed in the collector PV system. Today's most largely preferred solar PV glass is the one with high transmittance, having low–Fe content and known as ultra–white glass. The presence of Fe impurities colores the glass and also raises the heat absorption rate of the glass, thereby lowers the light transmittance of the glass.

3.2. The Application of PV Solar Glass

Germany is the world's first country using transparent flat glass as a substrate for solar cells. For directly supplying the ingested electric energy to the households this kind of plate–shaped solar cell as a window glass on a building was installed by German technicians. This initial solar cell glass was developed and utilized. It was soon followed by the U.S. and Japan, where the acceleration on the development and application of low–Fe and ultra–thin glass for solar energy was observed [12].

One can utilize solar glazing in various 'BIPV' applications such as translucent or semi–transparent solar windows; privacy protection panels; rear–ventilated façades, atriums, skylights; barns with transparent solar roofs; greenhouses; balustrades and fencing; rain screens, curtain walling, bus shelters [4].

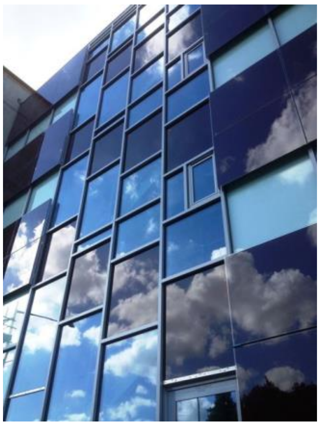
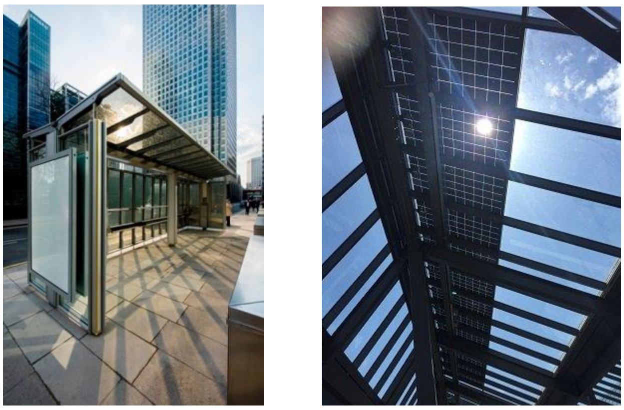


Figure 6. Polysolar (PS)–A opaque series panels, Future Business Center, Cambridge shelters [4]



(a)
(b)

Figure 7. Polysolar (PS) (a) *PS–CT–64/48 units,* (b) *PS–MC–SE monocrystalline glass panels shelters [4]*

Any building–integrated solar system's design requires the optimization of the solar energy generation while respecting to building regulations, fulfilling the requests of desirable aesthetic and economic restrictions, and also permitting future maintenance. BIPV glass can obtain the functionalities of solar electricity generation, targeted light transmission levels (between 0–50 %), shading and glare control, weatherproofing, structural strength, sound protection, thermal control: thermal insulation, decrement in thermal gain and aesthetic.

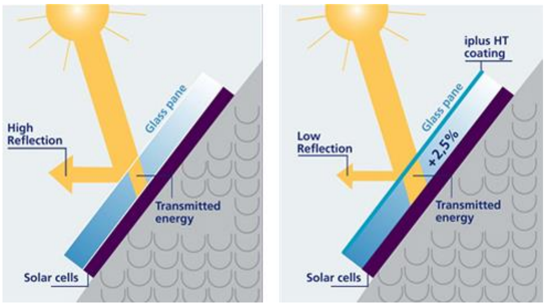
3.3. Types of Solar Glass

Crystalline cells (both mono–or polycrystalline) and thin–film [e.g. a–Si, Cd–telluride] are available for a standard roof–mounted solar panels. The highest 'STC' (standard test conditions) efficiencies of 12–17 % for multi–crystalline modules and up to 20 % for monocrystalline ones are usually supplied by crystalline technologies. With thin–film technologies the STC efficiency can typically range from 6 –8 % for a–Si and up to 13 % for contact image sensor (CIS) modules. Thin–film technologies are liable to work optimally at 700 to 800 W/m^2 radiance and carry on operating to highly low levels of radiance: about 10 % sunlight. The thin–film operates in ambient and reflected light on the dullest days while crystalline modules require direct sunlight. At high temperatures, it shows less degradation than crystalline cells. The performance depends on the geographic location, the local climate, the panels' orientation on the building, and the application. Lower levels of light than those optimally angled on a roof will be received by PV panels on a vertical façade. Equally less direct light than those facing South will be received by those facing North (Fig. 7). In PV modules, the transparency effect is generally obtained as a result of the combination of a pattern of opaque solar cells and transparent unoccupied areas. With crystalline cells, modifying the gap between the cells adjusts light transmission. In the case of thin–film usage, the active layer can be partially removed to permit the light to pass through, or an ultra thin–film deposition can be combined with two transparent conductive coating layers. When crystalline Si is mentioned, traditional solar cells are usually in black or blue color, and in brown or black with the thin–film. For obtaining coloring influences differing from the color of a cell, colored coatings, laminates, or films could be employed shelters [4].

4. PV Solar Cell

The PV solar cell's Si wafer facing the sun has the electrical contacts and is covered with an anti–reflective (AR) layer helping to absorb the sunlight efficiently (Fig. 8). The connection between the semiconductor and the external electrical load, like a light bulb or battery, is supplied by the electrical contacts. Certain chemicals, as dopant, are incorporated into the composition of the semiconductor for helping to establish a path of the freed electrons, which is making an electron flow generating an electrical current that begins to flow over the PV solar cell surface. Metallic strips are placed across the surface of the PV cell to collect these electrons forming a positive connection. The back of the PV cell contains a layer of Al or Mo metal generating a negative connection to the cell [13].

As stated above, one can describe solar panel glass as a crucial barrier, protecting solar PV cells from water, vapor, and dirt, which are known as damaging external factors. It also provides low reflection, high transmissivity, and high strength. Solar panel glass being highly transmittive possesses a direct positive influence on the solar PV panels' performance. An AR layer can be applied onto solar panel glass through plating before the tempering process is applied to the glass. With this plating, the reflected light level will decline and % of sunlight absorbed from solar PV cells will be inclined by 2.5 %. Such a plating action will also supply the solar PV panel high efficiency and mechanical stability. Solar panels are made of tempered glass. The reasons for preferring this type of glass becoming suitable in the production of solar PV panels are: being up to 4 times stronger when compared to standard plate glass and its safeness [14]. When broken, the tempered glass will break up small pieces lowering the serious injury risks (Fig. 9).



(a)
(b)

Figure 8. The comparison between uncoated (a) and ultra–durable AR coated glass (b) [15]

Figure 9. Breaking behavior of annealed, tempered, and laminated glasses [16]

Large glass planes, like glass façades and large glazing, are employed in modern architecture. The interior of buildings absorbs the heat penetrating through windows, causing the interior to be heated to an unacceptable level. As to a passenger car, it can easily be said that windows are the largest heat penetration sources and approx. 1/2 of this comes from the windshield. Therefore, certain enhancements in the glass features for decreasing heat penetration are inevitable, either for improving passenger comfort or because of ecological necessity.

Soda–lime–silica (SLS) glass with no coating is considerably transparent at complete solar radiation wavelength with only slight absorption and small reflection taking place (Fig. 10). One can lower heat gain by inclining the solar energy reflection and/or absorption thanks to the usage of a solar control coating, and at the same time, a satisfactory visible light level is allowed to transmit through the glass [17].

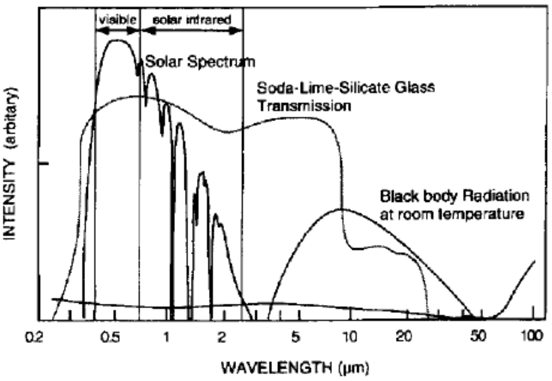


Figure 10. Transparency of glass [17]

Semiconductors can be classified as intrinsic and extrinsic. Former ones are pure in their form. There is no impurity incorporated to enhance their conductivity. Latter ones are not pure and doped. When a semiconductor is doped, three types can be achieved;

P–type semiconductors are formed when a–Si, Se, or Ge is doped with a trivalent element like B.

N–type semiconductors are capable of carrying negative charges and formed when Si or any other semiconductor is doped with a pentavalent element.

PN–type semiconductors: When P and N type semiconductors are joined by subjecting the surfaces in contact to a high temperature, a boundary or a junction is formed between them and called PN junction.

Si and Se are the most largely employed semiconductors in the Si–solar cells manufacturing. Ga, arsenide, In–arsenide, and Cd–sulfide, etc. are in use as well [18].

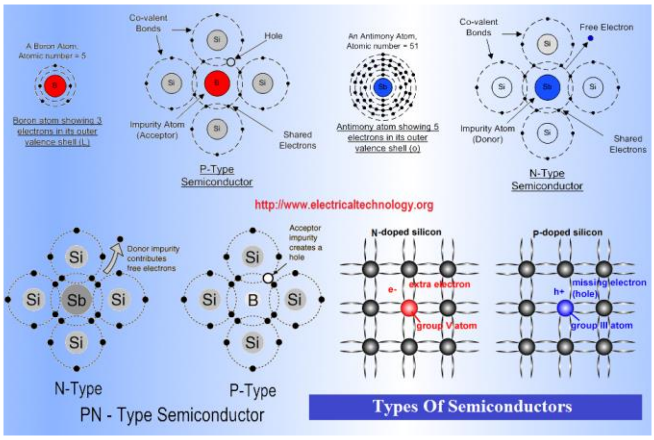


Figure 11. Types of semiconductors [19]

The principle operation of a solar cell is similar to conduction in a semiconductor like Si. As indicated in Fig. 12, the dark surface is the part exposed to sunlight. When electromagnetic radiation hits the cell surface, it excites the electrons, leading them to jump from one energy level (orbit) to the other leaving holes behind [19].

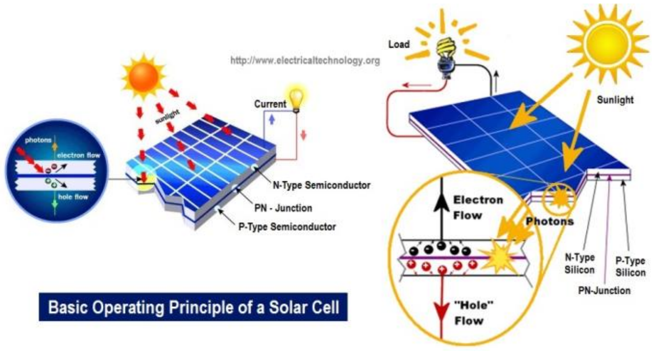


Figure 12. Basic operation principle of a solar cell [19]

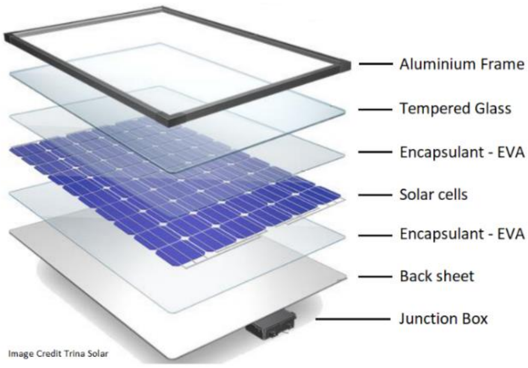


Figure 13. An example of the latest technological PV module (2019) [20]

It has been reported that the worldwide solar PV glass market is projected to reach over US$ 21.8 billion by 2025. The U.S. will maintain a growth momentum of 29.4 %. Within Europe, Germany will contribute over US$ 1.4 billion. The rest of Europe's markets will demand over US$ 1.2 billion. In Japan, the utility is expected to have US$ 930.4 million market size. As the world's 2nd–largest economy, China will possibly inhibit the growth potential of 39 % and contributes approx. US$ 8.6 billion [21].

5. Production of Solar Glass Panel

Windows are the main units of the building envelope for the ventilation of buildings, solar energy gain, and easy visibility from outside [22]–[24]. On the other hand, what kind of role they play in the total energy consumption in buildings is uncertain. When the window area in buildings gets large, their contribution to total energy losses from the building envelope becomes much tougher. The thermal isolation performance of traditional glazing products is insufficient. So, there has been an agreement among researchers that extra actions, like developing highly thermal resistant, and cost–effective glazing technologies, are immediately required for fulfilling the needs of the latest building fabric standards [25].

Great importance has been recently given to new glass technologies for enhancing the existing thermal isolation properties of windows, thus reducing energy losses associated with windows in buildings. Unfortunately, in most studies, an exact solution may not be obtained because of certain issues such as cost, performance, and aesthetics. For example, high–temperature resistant windows can be obtained by different methods, but this leads to very thick and heavier structures not being entirely desired. As a result of this, a lot of different techniques have been done from past to present time. Vacuum glazing, for example, can supply desirable thermal isolation performance with thin designs [22]–[24], but commercialization is still a challenge for vacuum glazing due to a considerably higher production cost than traditional glazing products. Air gel glazing [26], phase change material (PCM) glazing [27] and adaptive glazing [28] are thermally efficient in the building envelope, but possess a considerable negative effect on the visual quality and thermal comfort. Intelligent vacuum tube windows are also promising from the viewpoint of thermal isolation performance. The desired values reported by Cüce and Cüce require larger tube diameters, causing all larger thicknesses [24]. Adaptive glazing technologies are logical, however, the total cost is not still at the desired level [29].

PV glazing technique is a chosen method as far as modern architecture is concerned thanks to its aesthetical properties besides generating electricity. However, the thermal isolation performance of ordinary single glass is better than that of traditional PV glazing products according to Pengetal's recent extensive experimental research. However, the PV glazing concept has been developed and numerous researches are underway to increase existing power generation and thermal power in isolation performance [30]. This method can be implemented in three different ways as shown in Fig. 14.

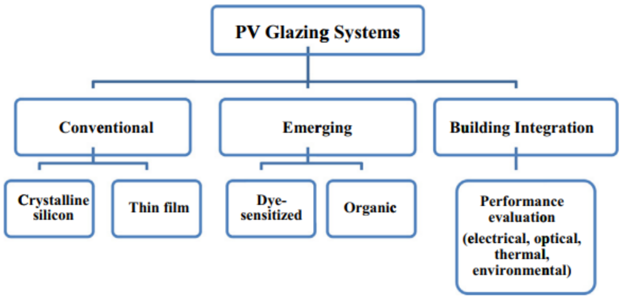
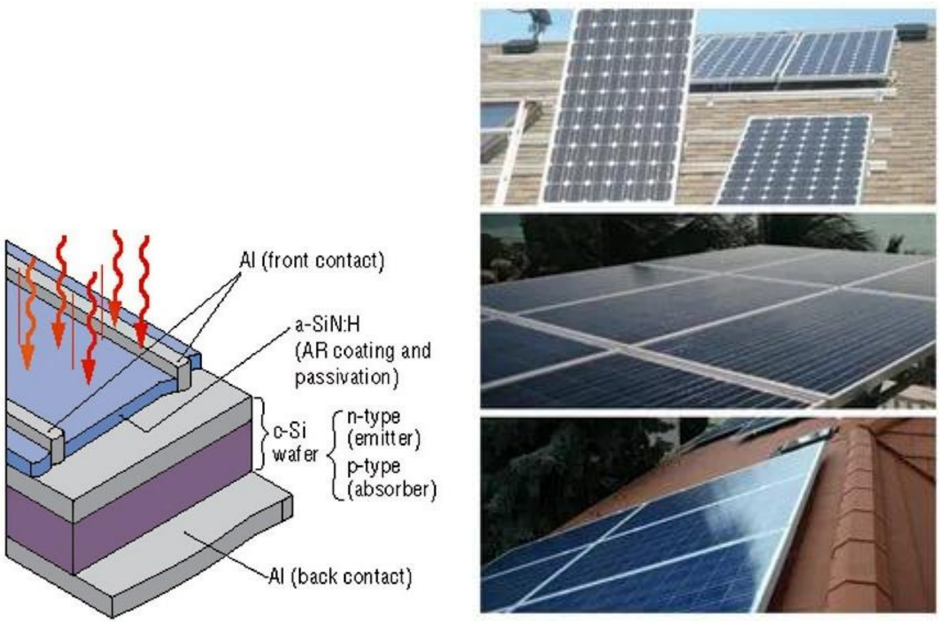


Figure 14. PV glazing systems and their performance [30]

Crystalline Si, thin–film, dye–sensitized, organic, and building–integrated PVs modules are presented in Figs. 15–19 respectively.



(a) (b)

Figure 15. (a) Crystalline Si (c–Si) PV cell construction and (b) its application [31]

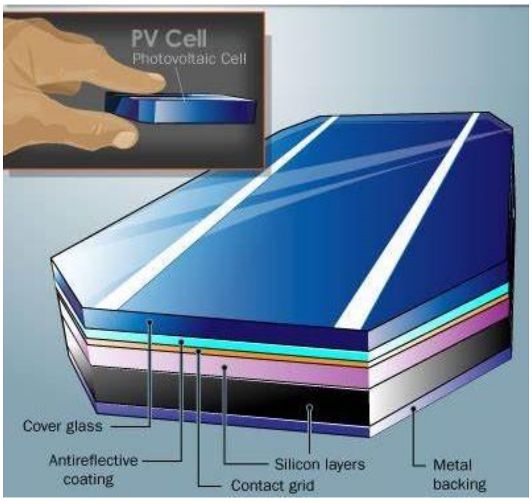
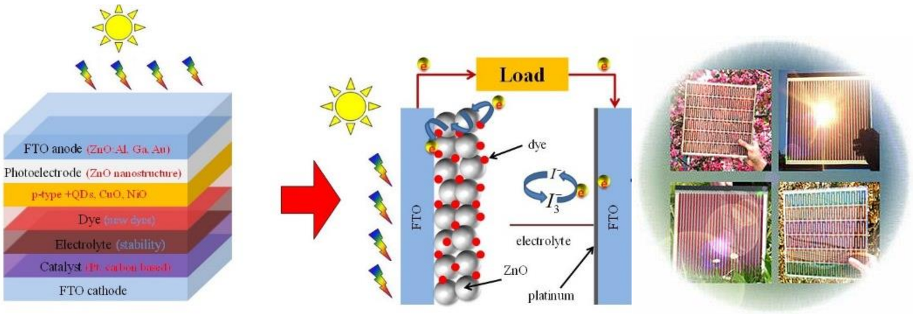


Figure 16. A thin film module [20]



(a) (b)

Figure 17. Structure (a) and applications (b) of dye–sensitized solar cell (DSSC) [20]

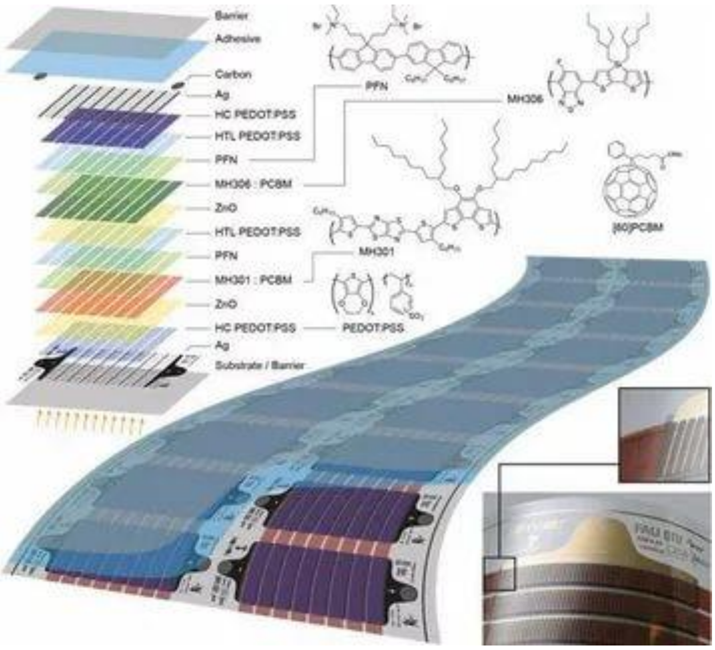
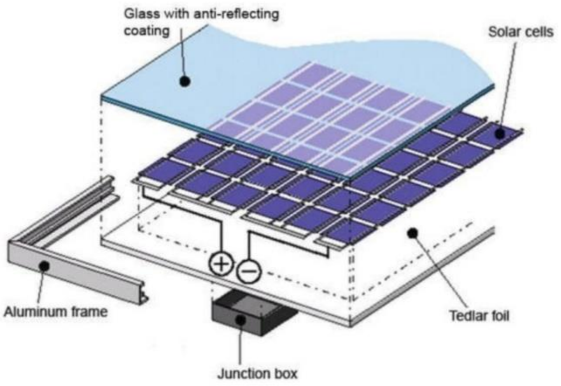


Figure 18. An organic solar cell [32]



(a) (b)

Figure 19. (a) Solar panel BIPV façades glass curtain wall with solar modules cell cladding and (b) an example of its application [33]

Traditional PV glazing systems are predominantly produced from c–SiPVs. In the literature, there are various studies using semi–transparent c–SiPVs instead of traditional glasses in residential and commercial buildings [30]. Fig. 20 exhibits an exemplary c–SiPV glazing method, the technology of which is expensive. Another disadvantage of these products is that the views are typically opaque. Translucent–SiPVs supply better illumination performance, and enlarging the cells area in a translucent PV glass results in more electricity generation. However, this leads to an excessive solar heat gain in the summertime, causing a noteworthy increase in the cooling demand of buildings [34].

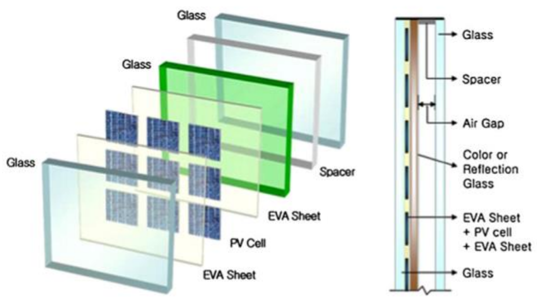


Figure 20. Diagram of a c–SiPV window [35]

The low–cost PV cell development for the production of cost–effective and energy–saving glass systems has recently taken great attention. In this context, because of its numerous special properties, and low costs, it has expanded the world on dye–sensitive and organic PV cells [36]. Easy capability, simple production process [37], [38] low material consumption, low light level sensitivity, and great ease of use [39]–[43] can lead them to be ideal for the energy windows use [44], [45]. Fig. 17 depicts the representation of dye–sensitized PV cells for window applications. Paint–sensitive PV glazing products are appealing thanks to their low cost, but their energy conversion efficiency is significantly poorer than that of traditional PV glazing systems [46]–[51].

Glass–PV–glass orientation is advantageous when compared to conventional PV devices since they permit daylight to pass into indoor if placed as a BIPV. Consequently, a semi–transparent BIPV glazing, which is controlling the entering solar heat gain and discomforting glare, provides convenient daylight as well as electricity generation. PV device for BIPV glazing covers 1st–generation Si, 2nd–generation a–Si, Cd–telluride (CdTe), Co–In–Ga–selenide solar cell (CIGS), and 3rd–generation dye–sensitized solar cell (DSSC) and perovskite. 2nd and 3rd–generation PV devices possess advantages when compared to Si since they make the thickness modulation of transparency possible. On the other hand, DSSC and perovskite show stability problems, preventing them to be used as practical glazing under the circumstances of outdoor environment. Crystalline Si is yet preferential over all these mentioned PV, supplying high efficiencies and stabilities under the outdoor environmental conditions [2]. BIPVs are PV materials replacing traditional building materials in building envelopes. In the case of BIPV application to buildings, the power generated directly by these buildings could partly help to solve the inefficient energy consumption problems. Although BIPVs are among the best methods in terms of power generation by solar energy, they have several problems, like the requirement to constantly adjust the angle for tracking, the contradiction between daylighting and electricity generation, being unable to respond to the demand for light control etc. For promoting and responding to the BIPV's concept, Young et al. developed a multi–functional heat isolation solar glass (HISG) differing from conventional transparent PV modules and supplying heat isolation and self–cleaning besides power generation (Fig. 21). HISG possesses multiple layers with differing structural and thermophysical features. HISG could easily be evaluated in any transparent PV module. Depending upon the needs of the climatic situations a suitable inert gas can replace the air [52].

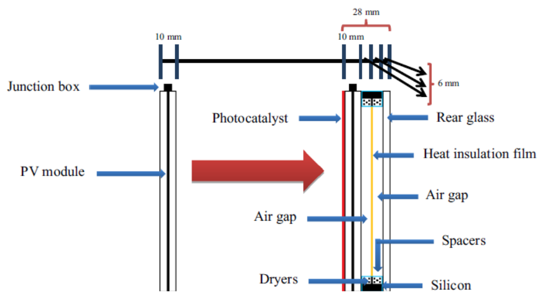


Figure 21. The view of HISG cross–section [52]

In the manufacture of solar control glasses, the sputter coating of solar control layers and then tempering and/or bending of glass substrates have been used. The former one cannot be cut and the rate of deposition on the latter one is less than that on flat glass due to the wider distance between sputter targets and the bent glass substrates. A heat–resistant solar control glass possessing a basic $SnO_2/SiN_x/CrN_x/SiN_x/SnO_2$ layer has been developed [53].

The optical bandpass filter is an idealized solar control model, reflecting the solar IR radiation as much as possible. A multilayer interference coating consisting of stacking a high index dielectric (e.g. TiO_2) with a low index dielectric (e.g. SiO_2, MgF_2) is close to this model. Oxide films with high refractive indices, like SnO_2, TiO_2, and the spinel family of oxides are produced by wet coating processes; like chemical vapor deposition, spray coating, printing, and dip coating. Thanks to their high refractive index the gain of heat is declined. They also improve the color of tinted glass for decoration purposes. On the other hand, such a solar control lowers visible transmission along with IR. Another reason for why the solar control coatings manufactured by wet processes having limited applications is the restrained selection of coating appearance. Solar control by the sputtering phenomenon was discovered in the 19th century but sputtering did not begin to be used as a coating technique until the invention of the planar magnetron cathode in the 1970s. A large scale sputtering coater was developed and started to be placed by major glass industries in the 1980s and since then the sputter–coated glass market has rapidly grown. One can also form oxide and nitride films by sputtering metal targets in a reactive gas atmosphere. For such an achievement some metals, metal nitrides, high and low index dielectric metal oxides can be employed. The market of coated glass began with absorbing film systems but the trend is now toward solar control employing a low–E coating with high visible transmission [17].

For a glass curtain wall, a new type of transmissive concentrating system is proposed, enhancing the solar PV glass curtain wall's performance (Fig. 22) [54].

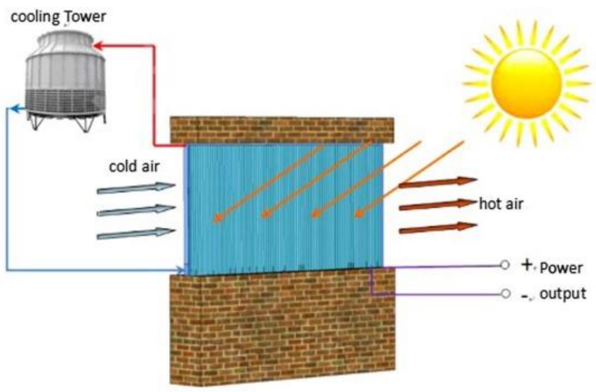


Figure 22. Schematic diagram of the solar concentrating PV/photothermal glass curtain wall system [54]

In Hong et al.'s work, the new type of transmissive concentrating system was composed of a plurality of hollow micro–concentrating units, it was made by polymethyl methacrylate (PMMA), its outer surface was compound parabolic concentrator (CPC) structure, PV cells were attached at the bottom, the hollow portion was axially fed with cooling water also an air sandwich between the double glazings, and the function was to absorb heat generated by the PV cell. The structure is given in Fig. 23, and its working principle is presented as follows:

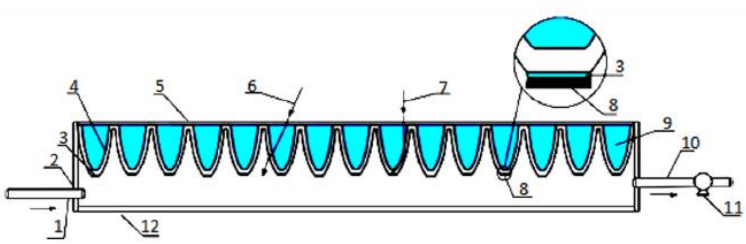


Figure 23. The working principle of the transmittive concentrating systems. 1 Air inlet, 2 Side plate, 3 AR coating, 4 Sidewall surface of concentrating unit, 5 Outer glass, 6 Oblique incident light, 7 Direct incident light, 8 PV battery, 9 Cooling water, 10 Air outlet, 11 Fan and 12 Internal gas [54]

The vertically incident ray 7 passes through the upper surface 5 and is refracted in the micro–concentrating unit, after that, concentrated in the bottom of the PV cell 8 by AR coating 3, then it can generate electricity and heat. As the light passes through into the bottom of the micro–concentrating unit, it will be partially reflected, not conducive to PV cell 8 reception, therefore, an AR coating 3 is placed between the PV cell 8 and the glass curtain wall, that can increase the amount of ray to make it be received by PV cell 8, thereby the generation efficiency of PV cell 8 can be improved. The obliquely incident ray 6 passes through the upper surface 5, shot on the curved inner wall 4 of the CPC, then refracted in the micro–concentrating unit and finally shot out from its lower part and enters the interior of building through the bottom plate 12 for daylighting. The side plate 2 is provided with a venting hole, and the fan 11 is installed on the external air outlet 10. It makes the airflow through the opposite side inlet 1 into the concentrating system. The PV cell 8 is heated when it is generating airflow, and water flow while cooling the PV cell 8, and the efficiency and service life of the PV cell 8 can be increased [54].

6. The Latest Studies on Solar Glass Panels

In the literature, there have been numerous studies on solar glass panels. Hereby only recently published some works will be mentioned.

Ballif et al. presented the first overall work on sets of commercial multi–crystalline Si solar cells with patterned low–Fe containing glasses with or without AR coating [55]. The algorithms' efficacy for obtaining real–time control of the acoustic transmission was reported highways [56]. They stated that the noise–blocking glass windows could presumably be of great importance for houses built in areas near airports and noisy.

Hongsheng et al. prepared a Ce–Fe oxide solar control coating on glass by using citric acid sol–gel method, dip–coating techniques and decent heat treatment process, and indicated that such a coating possesses remarkable UV–sheering and heat–isolation feature, and could be employed as an efficient solar control glass in the automobile industry and architecture [57].

Weinhardt et al. investigated the interfaces of Cu (In, Ga) Se_2/Mo and the Mo/glass in highly effective thin–film solar cells [58].

Gall et al. studied poly–Si thin–film solar cells on glass for reaching the single–junction efficiency of 15 % or more at low costs [59].

Tachan et al. presented a DSSC manufactured inside a glass tube for forming a dye–sensitized solar tube (DSST) [60]. Rosa–Clot et al. examined the behavior of a PV panel which was submerged in water [61].

Nagamedianova et al. prepared a new 3–layer near–IR reflective glasses by coating clear float soda–lime glass with nanostructured TiO_2 and SiO_2 films. They advised that the monolithic windows application in the automotive industry and architecture is promising [62]. Dominguez et al. evaluated the indirect gains of rooftop PV systems for building isolation by measurements and modeling (Fig. 24) [63].

Figure 24 (a) Photograph of Powell Structural Systems Laboratory (PoSL) at the University of California, facing South, (b) photograph of PoSL from inside facing North, ***(c)*** *Google Earth image of PoSL (north is up) [63]*

In the research of Sumitomo et al. nano grinding was applied on the cross–sections of a–Si thin–film solar panels having nanoscale multi–layer structures that consist of hard and brittle materials [64]. Verma et al. showed that non–lithographic nanostructuring of the packaging glass surface reduces the reflection at the air/glass interface and possesses a self–cleaning ability. The processing steps are given in Fig. 25 [65].

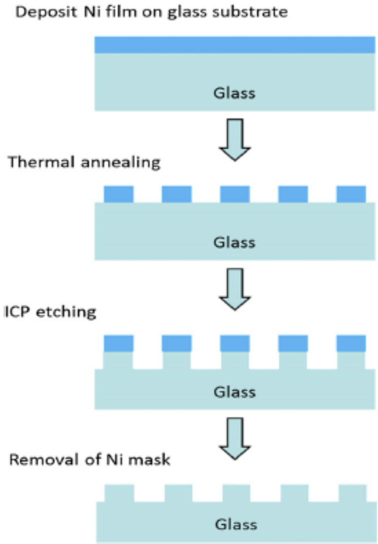


Figure 25. Process steps employed in forming nanostructures in the solar packaging glass [65]

Some details of the Zondag analysis were developed and the thermal behavior of a thermal electric solar panel integration (TESPI) system was searched. The simulation of TESPI thermal behavior was based upon the scheme shown in Fig. 26 [66].

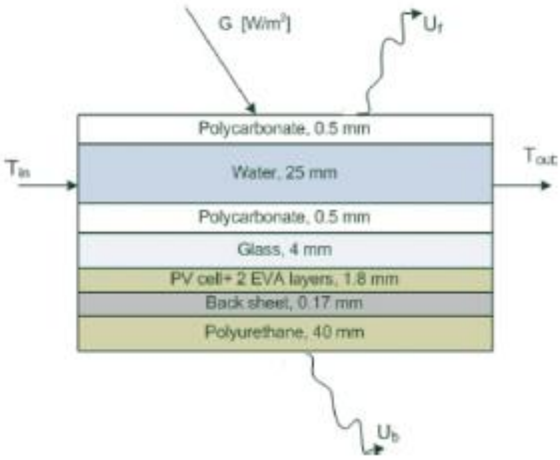


Figure 26. TESPI layers and main energy fluxes [66]

For having simplicity under the scheme given in Fig. 27, PV panel has the layers of polycarbonate, glass, PV cells + EVA, back sheet, polyurethane.

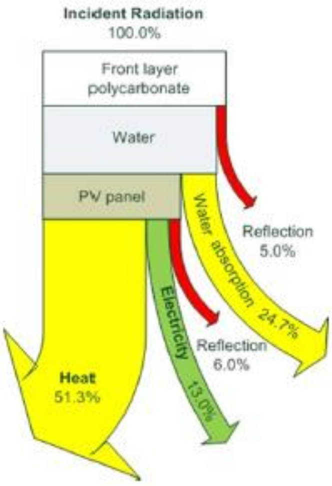


Figure 27. Solar energy transformation in TESPI [67]

In the work of Tina et al., submerged PV systems were searched concerning the efficacy increment of PVs under high irradiance and ambient temperature. Fig. 28 depicts the structure of a system composed of the interface air–water–glass–PV [67].

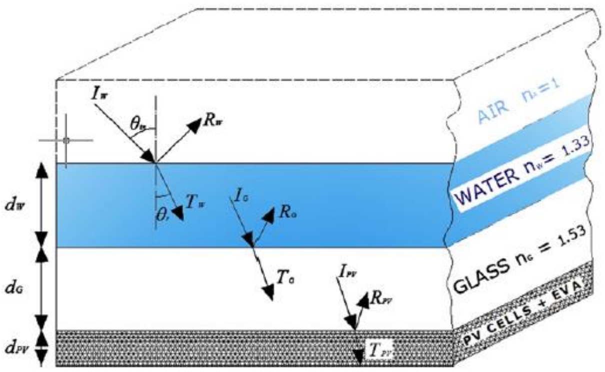


Figure 28. % of radiation striking the PV module submerged in water [67]

Lee et al. investigated the performance of anodic, self–organized TiO_2 mesoporous structures in DSSCs under front–side illumination conditions [68]. Hee et al. worked on the conditions influencing dust–fall in Singapore and its efficacy on the optical transmission through glass modules [69].

Xin et al. modifed the base–catalyzed sol by acid–catalyzed polysiloxane and nano–TiO_2 sol. The results showed that modified sol derived films possess great weather resistance [70]. Lua et al. numerically investigated the role of AR coatings composed of SiO_2 and/or ZnO in the presence of the transparent conducting oxide [Al–doped ZnO (AZO)] (Fig. 29) [71].

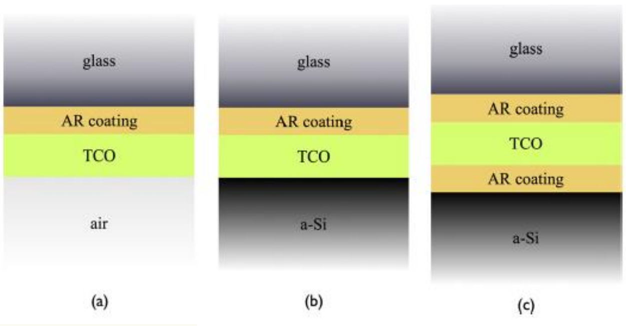
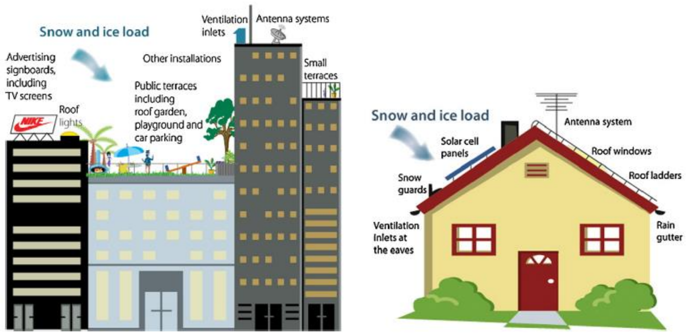


Figure 29 (a) Traditional AR coatings for flat panel displays and OLEDs, (b) AR coatings for Si thin–film solar cells, and (c) Enhanced AR coatings for Si thin–film solar cells with the glass encapsulation [71]

For maximizing the solar energy efficiency Jelle searched for removing snow downfall on PV solar cell roofs, solar thermal panels, and walls (Fig. 30). Within that work, a special impact was made on the various material surfaces (hydrophilic, superhydrophobic, or ultra hydrophobic and coarse microstructured or nanostructured surfaces) [72].



(a) (b)

Figure 30. Various active roof installations for flat (a) and pitched (b) roofs [72]

Naumenko and Eremeyev developed a layer–wise theory for analyzing the glass and PV laminates structurally. They exhibited how important the additional boundary conditions were for examples of free and framed plate edges [73]. Young et al. increased the maximum usage efficiency of skylights, windows, and glass curtain walls by using HISG rather than common architectural glass [74]. Cattaruzza et al. examined how glass slides employed to cover and protect solar cells can achieve downshifting features through luminescent metal ions and ion exchange additive [75]. Yiannis presented the designs and applications of the advised new solar energy systems [76].

Pop et al. demonstrated the decrease and possible hindrance of potential induced degradation (PID) by using functionalized films on the inner and outer surfaces of the PV module front glass [77]. Womack et al. deposited ZrO_2/SiO_2 multilayer coatings onto soda–lime glass substrates. According to their experimental results they assessed at which point damage takes place and also established the damaging nature [78]. Gerthoffer et. al. exhibited CIGS solar cells with the efficiency of 11.2 % grown on the flexible glass as thin as 100 µm [79]. Spasiano et al. summarized the current status of solar photocatalysis and identified future opportunities for the relevant researches and industries, covering recent relevant bibliography [80]. Kawamoto and Shibata developed an enhanced cleaning system for the uses of electrostatic force for removing sand from the solar panels' surface [81]. Mahadik et al. deposited a silica sol on cleaned glass substrates by dip–coating method and subjected them to a heat treatment at 400 °C and reported that their process supplies a simple and cost–effective method for preparing AR coatings with huge potential to improve the efficiencies of receiver tubes, solar cells, and other solar devices [82]. Medium–temperature solar collectors have been realized with all–glass solar evacuated tubes. The solar transmittance of envelop tubes was raised to 0.94 with porous SiO_2 AR coating deposited by the sol–gel method [83].

In the study by Humood et al., an analytical elastoplastic model coupled with a transient impact model was developed to investigate the single normal impact of small sand particles on the surfaces of solar panels glass [84]. In the work of Garcia et al., the efficiency of Si solar cells covered with GeO_2–Bi_2O_3 glass doped with Eu^{3+} and Au nanoparticles exhibited ~ 4.4 % enhancement compared to the same glass sample without Au nanoparticles [85]. One obvious property of the luminescent solar concentrators (LSC) (Fig. 31) is its bright, fluorescent coloration. As the devices can be transparent, this opens the possibility of using the LSC as a power–generating window. Vossen et al. studied the effect of a red LSC on the visual convenience and impression of volunteer participants (Fig. 32) [86].

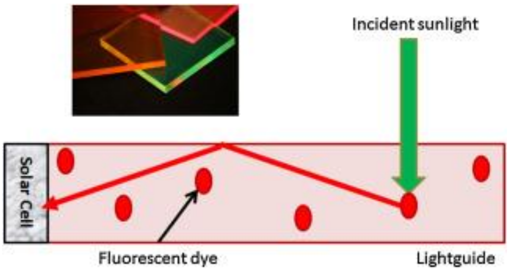


Figure 31. Schematic visualization of the LSC [86]

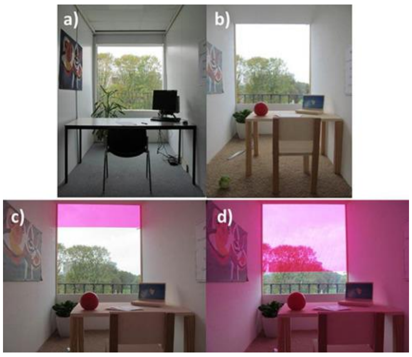


Figure 32. Photographs of (a) full–scale and (b) model space employed for evaluating the LSC window, (c) model space employing 25 %, (d) 75 % LSC window covering [86]

Gupta and Chauhan designed MATLAB/Simulink surroundings based upon their mathematical modeling, using a single diode and double/bypass diode–based PV systems, and validated them with a commercially available solar panel [87]. For smart textiles Plentz et. al. prepared a–Si thin–film solar cells on textile glass fiber fabrics (Figs. 33–34) and characterized the PV performance. They realized the efficiencies and pseudo efficiencies up to 1.4 and 2.1 % respectively on textile fabrics, and also mentioned that a transparent conductive oxide can enhance the efficiency to above 5 % [88].

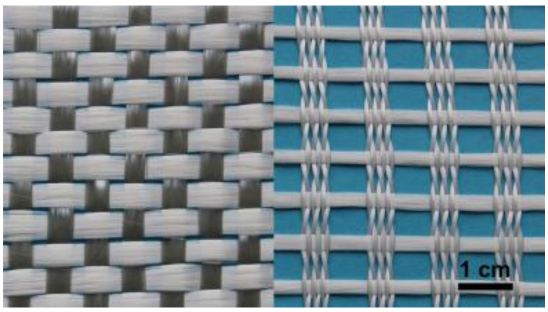


Figure 33. Textile glass fiber fabrics employed as substrates [88]

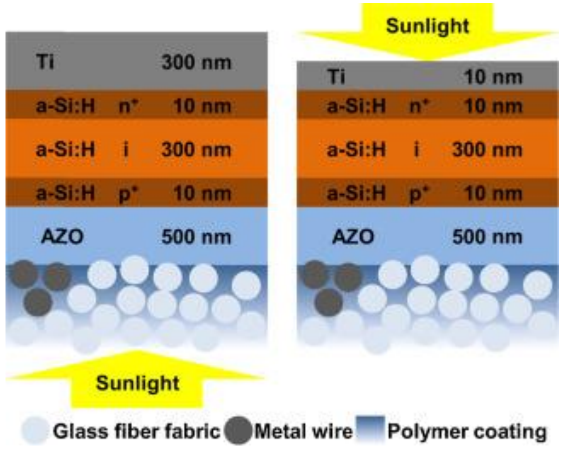


Figure 34. a–Si: H thin–film solar cells prepared on glass fiber fabrics in superstrate (left) and substrate (right) configuration [88]

Barroso et al.'s modeling work had a basic task for a better comprehension of the behavior and capabilities of a PV panel when subjected to changes in meteorological situations [89]. Kumar et al. have shown a simple and non–lithographic method to manufacture the broadband quasi–omnidirectional AR nanoporous surface on glass substrates via HF acid–based vapor phase etching method [90]. Zarcone et. al. presented a solar canopy specifically designed for the Liv–lib' project at Solar Decathlon Europe 2014 [91]. In the works of Mainini et al. an alternative dynamic solar gains mitigation strategy was presented and applied to a double layer, non–cushions, ethylene tetrafluoroethylene (ETFE) panel for façades [92].

Nayshevsky et al. examined the features of KleanBoost™ a thin AR and anti–soiling fluoropolymer coating for glass [93]. Soiling can be decreased by employing hydrophobic coatings. Isbilir et al. studied the test methods for simulating the stresses that coatings go through in their lifetime. They suggested that these methods help to guess the endurance and useful lifetime of the coatings when applied to solar cover glass [94]. Jiang et. al. synthesized Pb–free Ag pastes based upon SnO–B_2O_3 glass frits and employed them for the front–contact electrodes of c–Si solar cells [95]. Humood et al. investigated two different (annealed and tempered) solar surface glasses' mechanical behavior [96]. In the study of Maurer et al., it was written that for glazed collectors, the texture of the cover glass pane can aesthetically supply successful BIST integration. An overview of some possible glass textures is shown in Fig. 35 [97].

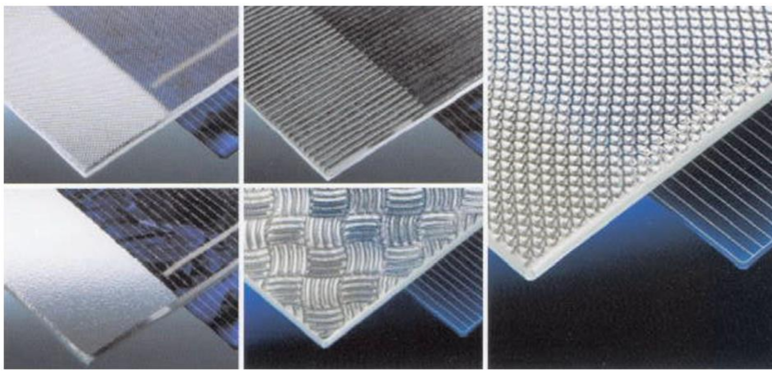


Figure 35. Glass with different textures over a solar cell [97]

In the case of preferring transparent glass covers, the texture of the absorber affects the aesthetic integration (Fig. 36).

Figure 36. The solar thermal collectors with strongly textured absorbers [97]

Maurer et al. summarized noteworthy recent contributions to BIST research as a basis for future progress in BIST systems [97]. In arid areas, the dust accumulation on transparent surfaces, leading to an intensive drop in the transmission coefficient, is one of the prime problems of solar systems. Transmission coefficient loss up to 22 % (in a 70–day test period) caused by the dust accumulation on the surface was reported in the work of Gholami et al. To overcome such a problem, they deposited nanocoatings on glass samples to achieve self–cleaning features, and indicated that the surface modifications possess a considerable effect on the decrease of dust accumulation and the transmission coefficient loss [98]. Brew et al. reported successful laboratory–scale manufacturing of CZTSSe solar cells on flexible glass substrates from nanoparticle inks of Cu_2ZnSnS_4 (CZTS), and identified necessary process changes to bridge device performance to standard devices manufactured with soda–lime glass [99]. Thin film solar cells (Fig. 37) are appropriate thanks to their minimum material usage and increasing efficiencies. The three major thin–film solar cell technologies cover a–Si, Co–In–Ga–selenide (CIGS), and Cd–telluride (CdTe) are presented in Figs 38–39, respectively. Lee and Ebong discussed the evolution of each technology in lab. and market share, commercial settings, and reliability [100].

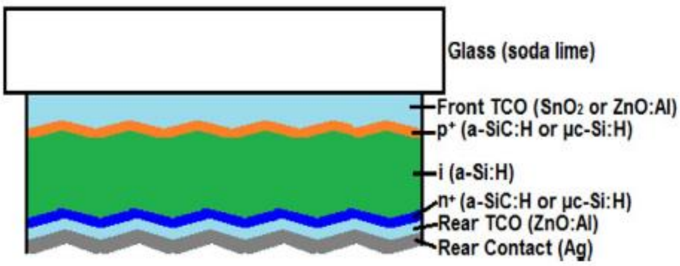


Figure 37. The structure of p–i–n a–Si: H solar cell on a glass superstrate [100]

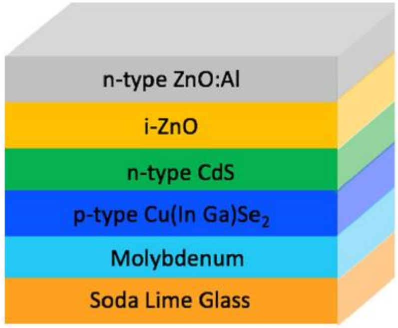


Figure 38. The structure of CIGS solar cell [100]

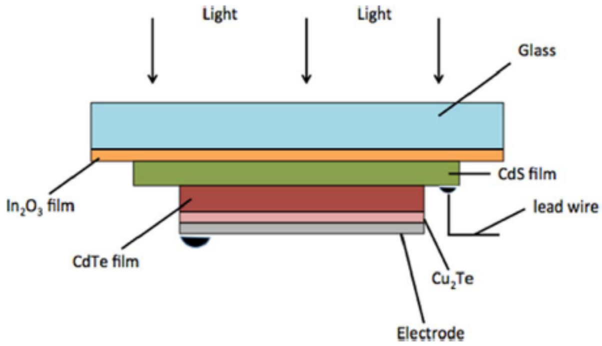


Figure 39. Cross–section of a ceramic thin film CdTe solar cell [100]

Baumgärtner et al. presented the evaluation of a new glass façade system, named as Fluidglass (Fig. 40) [101].

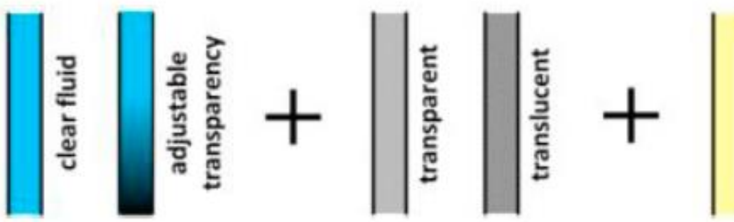


Figure 40. Modular layer approach: fluid + glass + barrier [101]

For minimizing solar gains and keeping the heat outside the building, the outer layer was colored (yet visual transmittance was still possible) during summer day (Fig. 41a). As to the winter days, when needed, the inner fluid could be tinted for the protection against glare, but still, gets the benefit from solar gains and lets the heat inside the building (Fig. 41b) [101].

Figure 41. Basic operation modes of two fluid layers: (a) summertime; (b) wintertime [101]

Selecting different materials like CdTe, GaN, SiGaAs, Ge, InP, a–SiH, c–Si offer variation in the bandgap, change in the PV cell efficiency. Praveen and VijayaRamaraju presented how different materials would incorporate to incline the efficiency of solar cells [102]. They have discussed CIGS and CdTe heterojunction solar cells along with the bandgap and laboratory–scale solar cell diagrams. The number of layers in CIGS cell is depicted in Fig. 42. Laboratory–scale CIGS cell is given in Fig. 43.

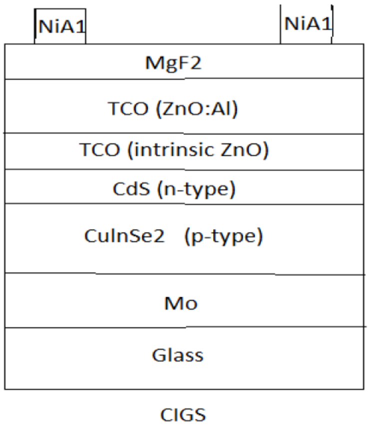


Figure 42. CIGS layers [102]

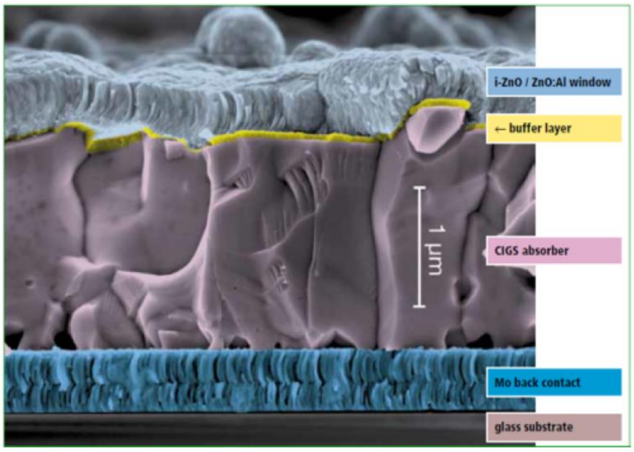


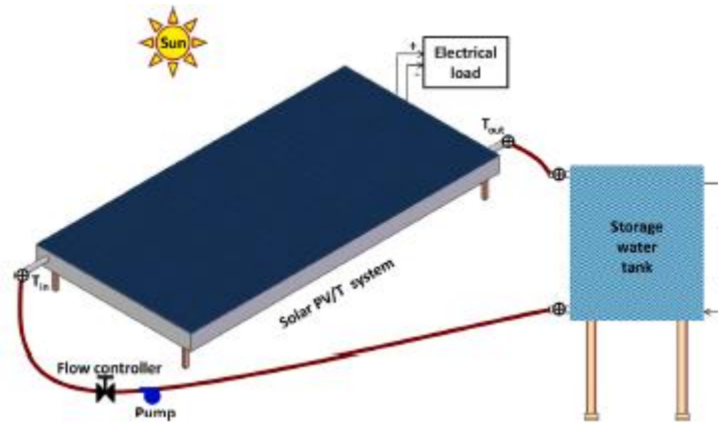
Figure 43. Laboratory–scale CIGS solar cell [102]

Sutha et al. pointed out that the glass substrate with no coating and the superhydrophobic one with aluminum oxide recovered the efficiency of solar panel degraded by sawdust as 67 % and 91 %, respectively. Consequently, they reported that the manufactured superhydrophobic glass substrate could be efficiently suitable for self–cleaning cover glass applications [103]. Moutinho et al. studied the adhesion mechanisms between dust particles at various relative humidity values and solar glass with different surface roughness [104]. Several methods of glass cover cooling employed to improve the performance of the solar still were reviewed [105].

The use of PVs spread worldwide thanks to the efficiency increment, reliability, and price reductions of solar panels. Therefore, soiling became critical, specifically in areas of limited rain for naturally cleaning the installed solar panels, or in areas of special soiling types that strongly stick to the PV module's surface. Moutinho et al. investigated the effects of solar–glass coatings on the adhesion forces related to soiling [106]. Andenæs et al. worked on several surface coatings to prevent snow and ice formation on the surfaces [107]. Chen et al. developed a method for measuring the sweeping force that reflects the cleaning efficiency of dust particles by a brush–on–disk apparatus, which would be beneficial for the solar panel's maintenance [108]. Grosjean et al.'s work focused on the theoretical study of glass windows in applications where solar radiation must be transmitted onwards, for solar heating or lighting (PV, CSP, building) [109]. To enhance the performance of the solar thermal cooling system, Ge et al. proposed some novel concepts and provided a good alternative for future development [110]. Settino et al. supplied an overview of the main solar energy technologies and analyzed various process chains to produce electrical and thermal energy [111].

Taniguchi et al. presented a detailed spectroscopic study of photoluminescence in Te–W glasses doped and co–doped with Pr^{3+}–Yb^{3+} and Ag nanoparticles [112). The life–cycle assessment (LCA) of the window–integrated PV systems employing DSSC module in Malaysia was evaluated and qualified [113]. Li et al. advised a very promising application of the luminescent solar concentrators (LSCs) in indoor light energy recycling which has not been proposed before [114]. Penga et al. introduced a novel c–Si–based BIPV laminate formed by cutting standard crystalline Si solar cells into narrow strips and then automatically welding and connecting the strips into continuous strings for laminating between two glass layers [115]. Neugebohrn et. al. demonstrated how the optical model of the oxide–metal–oxide (OMO) stack being necessary for accurate tuning of the color was developed for OMO/glass samples [116]. The damage resistance of a single–layer closed–surface hard coat ARC deposited by sol–gel methods and applying various accelerated weathering, scratch, and abrasion test methods was investigated by Womack et al., reporting the lowered reflectance loss at the glass surface by 74 % [117]. PV panels of different technologies (polycrystalline Si, a–Si, and CdTe) mechanically treated in pilot–scale by single shaft shredder were examined [118]. Liu et al. fabricated a novel type of dual–responsive microencapsulated phase change material (PCM) [119]. Dhavalkumar et al. optimized film–thickness and morphology by changing the synthesis parameters, coating thickness, and curing temperatures; to obtain dual characteristics for the coating [120].

PV panels working at high temperatures are exposed to thermal stresses besides raised electrical stresses leading to a panel life's reduction. With and without cooling the effect of panel temperature on the electrical performance of a PV system was worked by Song et al. As a conclusion, it has been given that lowering the panel temperature leads to better electrical efficiency and so, a lower payback period [121]. A steady, 3–dimensional model considering all the layers of the water–cooled PV–thermal collector with a sheet and tube heat exchanger (Fig. 44) was developed [122].



F,

Figure 44. The solar PV–T collector system [122]

Chi et al. proposed 1–, 2–, and 3–direction–automatic–rotation (1–DAR, 2–DAR, and 3–DAR) vertical sun–tracking shading panel arrays placed on the southern wall of the office building and concluded that the shading panel array integrated with the automatic rotation control method simultaneously prevented sun glare [123]. For the first time, Anctila et al. demonstrated the net energy benefit of transparent PVs in building applications, using a life cycle approach that is thought of as a change in electricity generation and building performance [124]. Gürtürk et al. analyzed two different solar glass types. Firstly, they cooled the solar glass types and later, applied the heating process to them. Finally, the changes in the features of solar glass were examined [125]. Özden et al. compared the estimation of three software (PV*Sol, PVsyst, HelioScope) using a whole year field data obtained in Ankara, for five–module types [126]. Karasu et al. published a general review paper on borosilicate glasses which are used in vacuum tube solar energy systems [127].

7. Conclusions and Recommendations

Glass is employed in PV modules protecting them from water, vapor, and dirt, which are known as damaging external factors. It also provides low reflection, high transmissivity, and high strength. as a protection layer for the elements. PV solar glass substrates are usually ultra–thin, surface–coated, and low–Fe (ultra–white) glasses. Today's most largely preferred solar PV glass is the one with high transmittance, having low–Fe content and known as ultra–white glass. Crystalline cells (both mono–or polycrystalline) and thin–film [e.g. a–Si, Cd–telluride] are solar glasses available for a standard roof–mounted solar panels.

Large glass planes, like glass façades and large glazing, are employed in modern architecture. In automobiles, it can easily be said that windows are the largest heat penetration sources and approx. 1/2 of this comes from the windshield. Therefore, certain enhancements in the glass features for decreasing heat penetration become inevitable, either for improving passenger comfort or because of ecological necessity.

PVs are a truly elegant means of generating electricity on–site, directly from the sun, without concern for energy supply or environmental harm. The use of PV worldwidely spread thanks to the efficiency and reliability increases and price decrease of solar panels. Easy capability, simple production process, low material consumption, low light levels sensitivity, and great ease of use can make them ideal for the use of energy windows.

When PV maters there are several important issues to be taken into an account some of which are: AR coatings have great importance thanks to their ability to improve the efficiency of the solar cells and solar selective coatings by minimizing the reflections of the incident light from the front surface. Performance losses take place due to the soiling of the cover glass on modules. Soiling can be lowered by employing hydrophobic coatings.

It is expected that the worldwide solar PV glass market is projected to reach over US$ 21.8 billion by 2025.

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