Fenestration integrated BIPV (FIPV): A Review

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Abstract:

Building fenestrations are the key components maintaining the connection between building exterior and interior. However, they are also the weakest allowing heat loss, gain and light. To tackle the enhanced building energy demand, active and passive both ways must be included. Benign energy-generating components and passive energy-saving are both concomitantly possible using photovoltaic (PV) window fenestration. In this work, three different generations PV based fenestration integrated photovoltaics (FIPV) have been reviewed to understand how effective FIPVs are for low energy building. Later advanced technologies suitable for FIPV applications are also discussed.

Keywords: FIPV, BIPV, windows, CCT, CRI, *U*-value, SHGC, CdTe, a-Si, CIGS, DSSC, Perovskite, Organic, Switchable BIPV

1. Introduction

The building is one of the places where humans spend 90% of their time. Hence building interior health hugely influence the mood, wellbeing, and cognitive work producibility of buildings occupant. Depending on the local climate building needs heating, cooling, and lighting energy to create a soothing comfortable indoor environment (Nundy et al., 2021b). This excessive energy is required because of the diurnal variation of the external ambient. Low thermally insulated building envelope such as window, wall, and roof allows external heat to penetrate inside the building or internal heat to outside. In a hot climate dominated modern cities, buildings are fully air-conditioned which consume a considerable amount of fossil fuel-generated energy (Feng et al., 2021). In a cold climate, buildings require a heating load. Glazed units are an essential part of buildings' envelopes which provides views from interior to exterior, allow natural light and solar heat into a building's interior space. Compared to other building envelopes, the thermal performance of glazed windows is poorer. About 50% of the total energy consumption within buildings occurs through heat loss or gain via their windows, which increased significantly over the last decades (Nundy and Ghosh, 2020). From a sustainable point of view, a building should have protection from unwanted light, heat, air flow and low or zero consumption of energy. A window has a considerable amount of impact on the buildings lighting, heating and ventilation, hence overall building energy performance is influenced by the window. Building windows are also responsible for the building interior health and wellbeing. In the USA, window accounts for 25% of the utility bill of a household (Feng et al., 2020). Also, now there is a high demand for glazed facades based building architecture specially commercial building.

1.1. Overview of FIPV (BIPV window)

Hence, traditional building windows or fenestrations need to be replaced with an advanced system that has the potential to work with better capacity. Photovoltaic (PV) window is currently a major investigating area. PV system which generates benign energy in the presence of solar radiation can be employed in a building in the form of a window (Skandalos and Karamanis, 2015). As PV window is a part of a building, they can also be termed building integrated photovoltaic (BIPV) window. In general, the integration of PV systems in the building by replacing traditional building envelopes such as a wall, roof, and window is termed BIPV (Kabilan et al., 2021; Kaliappan et al., 2021; Karthick et al., 2018b; Kumar et al., 2021; Singh et al., 2021). According to IEA Task 15, PV modules are only considered to be building integrated if it provides “(i) mechanical rigidity or structural integrity (ii) primary weather impact protection: rain, snow, wind, hail, (iii) energy economy such as shading, daylighting or thermal insulation, (iv) fire protection, (v) noise protection” (Iea-pvps, 2018). Integration of PV devices into a building is now growing rapidly (Ghosh, 2020a). Due to the inadequate space in urban regions, a cogent choice for PV technology applications is to integrate them into buildings (Chandrika et al., 2021; Karthick et al., 2020). These building integrated photovoltaic (BIPV) trim down the construction and material cost and electricity cost of a building. Transparent or semi-transparency is the precondition for the BIPV window (Ghosh, 2020a). For BIPV applications, electricity generation from PV is not only the main focus. Overall building energy performance in terms of heating, cooling and daylighting are also considered. However, currently opaque PV based BIPV is also considered such as BIPV tiles (Ballif et al., 2018; Kuhn et al., 2021). Also coloured PV cells are often employed to hide the PV functionalities and asthetic application(Ghosh, 2020a).

Fenestration integrated PV (FIPV) or BIPV window is gaining prime importance as traditional single or double panes fenestration technologies are not energy efficient. To obtain maximum potential from FIPV, transparency, orientation (azimuth, tilt angle, and building self-shading), PV devices temperature, window-to-wall ratio, coverage, fresh air infiltration, the mass of the floor and ceiling, solar heat gain coefficient, conversion efficiency, should be considered according to the surrounding climatic conditions. The primary purpose of a window is to allow visual and thermal comfort into an interior of a building. Thus, to understand the potential to attain thermal and visual comfort from the BIPV window, understanding these parameters are essential. **Figure 1** represents heat and light transfer mechanisms of a BIPV window (excluding power generation). BIPV window’s visual comfort includes comfortable daylight (Knoop et al., 2020; Quek et al., 2021), glare (Wienold et al., 2019; Wienold and Christoffersen, 2006), correlated color temperature (CCT) and color rendering index (CIR) (Ghosh and Norton, 2017a). External daylight penetrated through the BIPV window and reach to building interior should be between 100-2000 lux (Nabil and Mardaljevic, 2006). Above this range is identified as discomfort due to glare. Glare analysis can be done by using DGP or DGI methods. Transmitted daylight through the BIPV window experiences spectrum changes which may create issues for occupants. Understanding these CCT and CRI studies is worthwhile. The most desirable criteria are CRI which should be over 80 (out of 100) and CCT between 3000-7500 K. To realize the thermal comfort the key factors are overall heat transfer coefficient or thermal energy transmission (*U*-value) and solar heat gain coefficient or solar energy transmission or solar factor (SHGC/SF). *U*-value (in W/m^2K) is a heat-insulating property of glazing which includes heat loss from an outer surface of FIPV to ambient, heat loss from an interior surface to an internal ambient and heat loss from the thermal conduction through the glass panes. For a typical single- and double-glazing air-filled window, *U*-values are 3-5 W/m^2K and 2-2.99 W/m^2K respectively. Some providers are able to offer double glazing having *U*-value of 1.9 (Pilkington glass). *U*-value can further be reduced by increasing the glass thickness or number of glasses (Cerne et al., 2019), filled the air gap with inert gas, aerogel (Buratti et al., 2021) or make it vacuum (Ghosh et al., 2017, 2016a). SHGC indicates the fraction of transmitted solar radiation through the glazing and this unit less number varies between 0.1 to 1. A glazing having 0.5 SHGC indicates that 50% solar radiation admitted through the glazing (Tait, 2006). *U*-value and SHGC also deal with building interior room comfortable temperature (~ 18-20^{0}C) which eventually predicts the thermal comfort. High SHGC of glazing is beneficial for cold climatic areas and hot climate it increases the cooling load demand of building. High *U*-value of glazing is beneficial for the hot climate while in winter it increases the heating load of a building. Estimation of buildings windows overall performance is essential as they have may have an impact from humidity, UV from the sun. This is more prominent in the case of BIPV type windows where PV material may be sensitive to external weather.

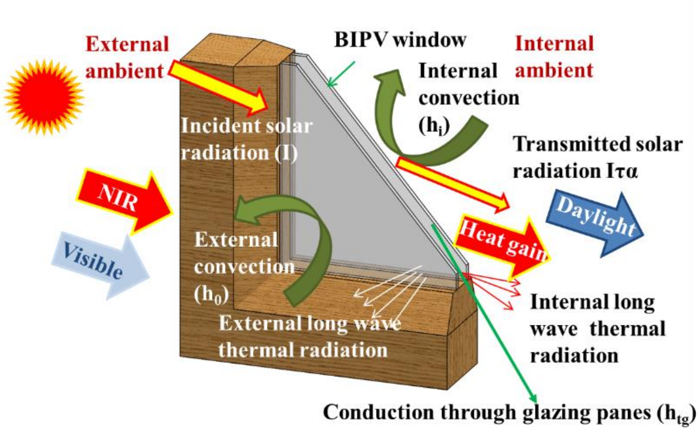


Figure 1: Schematic of BIPV window (FIPV) showing different heat transfer mechanisms.

In this work, a detailed review based on fenestration integrated PV (FIPV) or BIPV window has been reviewed. BIPV window-based review is very rare. This work critically reviewed three-generation PV cells for FIPV application and other advanced technologies. The structure of this work is as follows: section 2 discussed the methodology applied to perform this review work, section 3 illustrated the first generation, second generation and third generation PV based FIPV, section 4 introduced advanced BIPV window, Section 5 discussion and perspective while section 6 concluded the overall work.

2. Methodology

Currently, advanced fenestration technologies are gaining importance because of their building energy-saving property (Gorgolis and Karamanis, 2016; Rezaei et al., 2017). Fenestration or window technologies generally possess static transparency. Single and double glazing windows which dominated the building window industry for years after years now should be replaced. Currently, the windows industry possess static and dynamic transparent window (Ghosh and Norton, 2018). Most often static transparent advanced windows are capable to control the heat loss from the building interior to the Exterior e.g. evacuated, aerogel glazing, low-e coated and inert gas-filled. On the other hand, dynamic windows control SHGC and daylight e.g. phase change material, thermochromic (Tällberg et al., 2019), thermotropic (Aburas et al., 2019), gasochromic (Feng et al., 2016), electrochromic, suspended particle (Ghosh and Norton, 2019) and polymer dispersed liquid crystal (PDLC)(Ghosh et al., 2018a) types. Among them, BIPV windows are different as they not only control the SHGC and daylight but also generates benign electricity. Advanced windows are considered energy-saving elements which employ a passive way. However, advanced BIPV windows work in both active and passive ways and they can be built in such a way that can be influential for both hot and cold climates both. This review is limited to the only BIPV window and its derivatives. There are many different directions are available in the research area with BIPV system such as BIPVT, investigation of new material for BIPV window or FIPV, PV shading element. In this work, we strictly concentrated on the BIPV window. Other elements were not considered as from aesthetic point of view those are still not mature. Also, we focused on those elements which at least reached high technological readiness level.

For this review, we searched relevant databases, including, Google Scholar, Science Direct, Web of Science, to investigate published literature in the past few decades. As indicated by the title, this paper focuses on the research and development of the BIPV window. The search keywords were BIPV window, crystalline silicon (c-Si), amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), thin-film, Perovskite, dye-sensitized solar cell (DSSC), third-generation PV, switchable PV, highly insulated BIPV. However, because of the diverse terminology, we also employed other terms to obtain more work to review which included adaptive, advanced, dynamic, responsive, and smart window. Windows energetic parameters such as thermal and daylighting properties were investigated for this work.

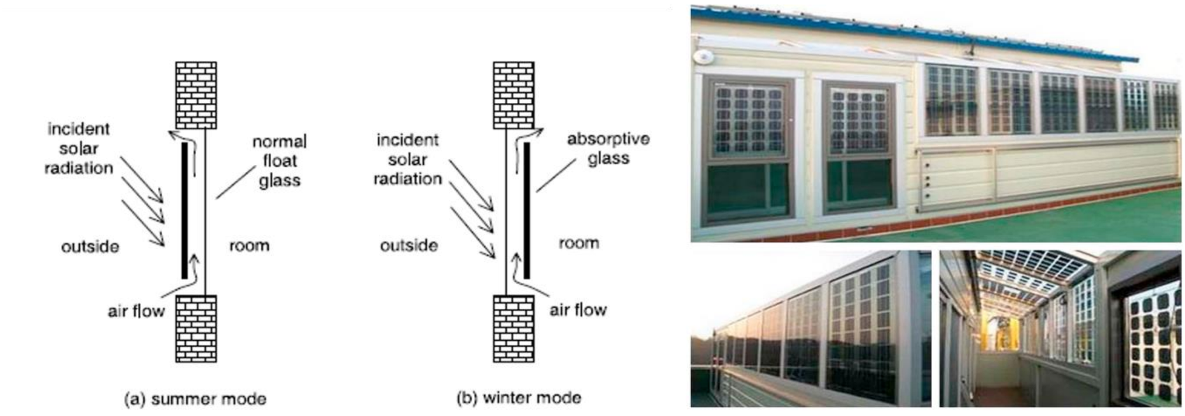
3. Different generation PV based FIPV (BIPV window)

Available PV technology for FIPV or BIPV integration includes first-generation crystalline mono and multi, second-generation thin-film CdTe, CIGS and a-Si and third-generation DSSC, Perovskite and Organic type. In this section all three generations BIPV windows are evaluated.

3.1. First Generation PV FIPV/BIPV window

Crystalline silicon (c-Si) is the most mature, and highly efficient (27%) technology (Green et al., 2019). Silicon possesses an energy band gap of 1.12 eV while absorbing solar light up to 1160 nm. Semi-infinitely thick silicon solar cell has a theoretical conversion efficiency of 33.5% at 25°C (Green, 2005)(Dupré et al., 2015). The mid-infrared emissivity (MIR) of commercial silicon solar cells for an unencapsulated case is around 80% which is dominated by surface texture and highly doped regions. The MIR emissivity is 90% for an encapsulated cell due to cover glass high emissivity (Riverola et al., 2018). Long term durability under extreme outdoor conditions and mature technology make c-Si a suitable candidate for BIPV application. The price of silicon also reduced from $475/kg in 2000 to $25/kg in 2008 (Fu et al., 2015). From the 2016 level, it is expected that the c-Si PV market will grow 11.3% by 2022 with a market amount of $163 billion (Luo et al., 2018; Ogbomo et al., 2017). Presently, Canadian Solar JA Solar, JinkoSolar, Hanwha Q-CELL, LONGI, Tongwei, Trina Solar are the leading vendor for c-Si PV cells.

c-Si based FIPV needs a special arrangement of cells because c-Si PV has 90.5% absorption which makes it behaves like an opaque system (Santbergen and van Zolingen, 2008). To enable the transmission through a c-Si PV based FIPV, spaced are given between two cells. For a given area of glazing depending on the number of PV cells transparency can be varied. Using space between crystalline PV cells, semi-transparent PV glazing was fabricated using glass, encapsulation material (Ethylene Vinyl Acetate (EVA), Polyvinyl butyral (PVB), Thermoplastic polyolefin (TPO)), PV cells, encapsulation material, glass, air gap with spacer and glass. A total of 500 cells, where each cell had 0.127×0.127 m dimensions was connected to form this device. Minimum and maximum power from these 500 cells were achieved 2.3 W and 2.5 W, respectively. For indoor condition, power decreased about 0.48% /°C while 0.52% changed for outdoor condition at 500W/m^2 intensity. Solar gain factor, heat loss and daylighting analysis using this spaced type semi-transparent PV glazing were not included in this work (Park et al., 2010). c-Si PV based FIPV with a 180-degree reversible mechanism was proposed by (Chow et al., 2006) as shown in **Figure 2 .** In summer, PV will block the unnecessary solar gain and natural or mechanically driven air flow will go out. Thus, it will reduce cooling energy. In winter, the opposite phenomenon will occur. Numerical analysis based on Hong Kong climate, potential of energy saving in summer was high but in winter due to limited period of mild winter, an 180° rotation was not justified. It was also noted that for summer dominating countries where cold weather never exists reversible mechanisms may not be necessary. In another work, spaced type, semi-transparent c-Si BIPV window was employed for skylight application. At Kovilpatti (9°10”0N, 77°52”0E), Tamil Nadu, an experiment was performed for rooftop window application. Three PV cell coverage were maintained for three modules and they were 0.62, 0.72, and 0.85. A maximum daylight factor of 4% and indoor illuminance of 850 lux is obtained in 0.62 (Karthick et al., 2018a). Later temperature enhancement was reduced using Glauber salt inorganic PCM (Karthick et al., 2018c).



(a) **(b)**

Figure 2: (a) Working principle of ventilated solar screen window ((Chow et al., 2006) (b) spaced type PV glazing in a sunroom at the republic of Korea ((Park et al., 2010))

The primary issue with spaced type semi-transparent type FIPV is the presence of tabbing wire which can create an obstacle to view. Also viewing through this window is not aesthetic. Temperature is an immense factor for c-Si PV cells. For an unencapsulated c-Si absorption are 90% between 400 nm to 1000 nm and 80% between 1000 nm to 10 µm (Nikolskaia et al., 2019). For an encapsulated c-Si emissivity in the mid-infrared region is 90% (Santbergen and van Zolingen, 2008). Omission of the highly doped regions and no surface texture Si wafer possess less than 20% emissivity above 1100 nm (Zhu et al., 2014). The absorption factor of c-Si PV cells depends on the front texture and the metal grid coverage and is less dependent on the wafer. For c-Si solar cells, every temperature rise of 1 K leads to a relative efficiency decline of about 0.45% (Skoplaki and Palyvos, 2009a, 2009b).

3.2. Second-generation PV based FIPV

3.2.1. Amorphous silicon (a-Si)

Amorphous silicon (a-Si) PV works with a much higher efficiency under low illumination compared to c-Si because of its very high ratio of photo to dark conductivity (Stuckelberger et al., 2017). 25 years of operation life and 2-3 years of the energy payback time is possible for a-Si (Peng et al., 2013; Zhang et al., 2018; Zhou and Carbajales-Dale, 2018). According to PV reports developed by Fraunhofer Institute for Solar Energy Systems, a-Si had a market share of 0.2% in the year 2020. The annual energy consumption of an office building in Japan having a-Si based FIPV showed that 40% transparent PV and 50% window-wall ratio achieved the minimum electricity consumption. This FIPV was able to reduce 55% electricity consumption compared to the single-glazed window without lighting control. No experiments were performed to support this Energy Plus simulation results (Miyazaki et al., 2005). In another work, for the cooling load dominated climate, in the Huazhong University of Science and Technology campus (as shown in **Figure 3**), 20% and 32% transparent single glass a-Si FIPV performed better than 87% and 71% transparent single and double glazing. However, 62% low-e coated double glazing performed well compared to FIPV because of the control over NIR transmission (Liao and Xu, 2015). Thermal performance of double-glazed PV showed reduction of 53.5% and 43% solar heat gain (infrared radiative heat transfer and convective heat transfer) and power generation respectively than single glazed FIPV in Hefei (31.87° N, 117.27° E), east region of China. Higher thermal comfort was achieved using double glazing due to lower surface temperature than single glazing (He et al., 2011).

In terms of experimental field research, Olivieri et.al. investigated four see-through a-Si BIPV windows of different transmittances in Madrid and found that the solar protection and insulating properties of a-

Si BIPV windows are lower than those achieved by a reference glazing (traditional glazing) (Olivieri et al., 2014). Energy performance of a medium-sized office building having 10000 m^2 floor area, 30% window to wall ratio (total window area 652 m^2) was investigated for six different climatic conditions in the USA using three different transparent a-Si based retrofit double-pane glazing. 30% visible transparent a-Si had 120 nm thick a-Si:H absorber while14% had 180 nm thick (flat PV cell), 6% had 180 nm thick (textured PV cell) a-Si:H absorber. For semi-arid Los Angeles, CA (34^{0}03N, 118-150W) thick textured PV cell-based glazing saved annually 34% and 66% cooling and heating energy compared to 88% transparent (visible) double-pane glazing for this office building (Chae et al., 2014). Net energy performance of a-Si FIPV (5.497 W/m^2K, 0.471 SHGC, 15% visible transmittance, 26% solar transmittance) integrated to an office building in Hong Kong dimension of 2.3 m × 3.0 m and 2.5 m where WWR was 0.41 was investigated using Energy plus software. Results were compared with single (5.8 W/m^2K, 0.81 SHGC, 88% luminous transmittance), double (2.68 W/m^2K, 0.704 SHGC, 78% luminous transmittance) and low-e coated glazing (1.618 W/m^2K, 0.275 SHGC, 63% luminous transmittance). This a-Si FIPV saved up to 18%, 16% and 1% electricity energy compared to clear single glazing, double-pane glazing and Low-E glazing respectively. For south-facing FIPV, total electricity saving was up to 7% higher than the east-oriented ones (Zhang et al., 2016). Energy analysis of see-through PV windows in Singapore revealed that optimisation of the window-to-wall ratio with different design strategies is essential to achieve the maximum energy benefit (Ng et al., 2013). Potential energy savings by using a-Si based semi-transparent BIPV window for office buildings located at Fortaleza and Florianopolis which are the two Brazilian cities were evaluated and found this type of technology is more suited in Brazil than Germany (Leite Didoné and Wagner, 2013).

Double glazed ventilated FIPV consists of a semi-transparent a-Si PV at the external surface (a-Si STPV), an inner layer of glass sheet as well as an intermediate air ventilation cavity. The air outlet and inlet louvers are installed above and below the PV modules, respectively. This particular type is lucrative as cold air from the exterior environment exchanges heat from PV and remove waste heat from a cavity. Thus, PV cells operating temperature reduces, lessens building cooling load, improves conversion efficiency of PV. Using meteorological weather data of Hong Kong, daylight simulation of the Energy Plus program showed that PV cell transmittance in the range of 0.45–0.55 best suited for electricity generation (Chow et al., 2007). In another study, ventilated FIPV having 0.45-0.55 transmittance saved up to 55% energy (Chow et al., 2007).

Theoretical models developed via the ESP-r simulation validated results experimentally which showed that a 23% and 28% reduction in the annual electricity consumption for cooling is possible when single-glazed and ventilated double-glazed PV windows are used, respectively(Chow et al., 2009). Optimized air gap for ventilated semi-transparent a-Si DSF was evaluated. It was found that for Berkeley climate the air gap depth between 400 and 600 mm is beneficial as they save 15% net electricity compared to the 200 nm thick air gap. In Berkeley, the naturally-ventilated PV-DSF saves about 35% of electricity use per year than non-ventilated PV-DSF (Peng et al., 2016).

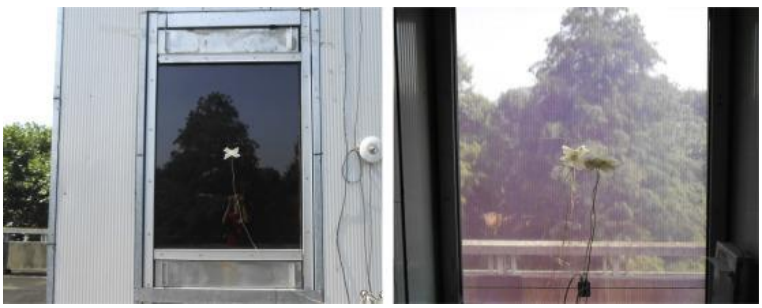


Figure 3: See-through a-Si PV glazing (20% visible transmission) in an experimental room at Huazhong University of Science and Technology, Wuhan, Hubei, China (Liao and Xu, 2015).

3.2.2. Cadmium telluride (CdTe)

Cadmium telluride (CdTe) PV based FIPV is another option that is currently under major investigation. According to PV reports developed by Fraunhofer Institute for Solar Energy Systems, CdTe had a market share of 6.1% in the year 2020. Currently, CdTe has an energy payback time between 0.75 to 2 years and 20 years of operational lifetime (Peng et al., 2013; Zhang et al., 2018; Zhou and Carbajales-Dale, 2018; Zidane et al., 2019). Cadmium itself is toxic, but not toxic when bound to telluride. CdTe solar module manufacturer First Solarpanel recently developed a module having 0.2% degradation per year and -0.28%/°C temperature coefficient. This degradation rate is 60% lower than c-Si and is expected to work efficiently for 30-years (Bellini, 2021).

CdTe for FIPV application was performed using EnergyPlus software for a building located at the Indian city of Jaipur, (26.82°N, 75.8°E) as shown in **Figure 4a**. Five different luminous transmittance CdTe (7.0%, 12.3%, 17.7%, 25.2% and 32.7%) were employed for investigation. All these glazings had a uniform *U*-value of 1.812 W/m^{2}K. SHGC changes for all devices based on the transmittance. It was found that low increase of cooling load and higher decreased rate of heating load while transparency increased. In this location with that SPTV system SHGC had a lower impact on building heating and cooling load. For south-facing, 20% WWR using this CdTe PV was capable to meet the artificial lighting energy demand however for the east and west larger areas are required (Barman et al., 2018).

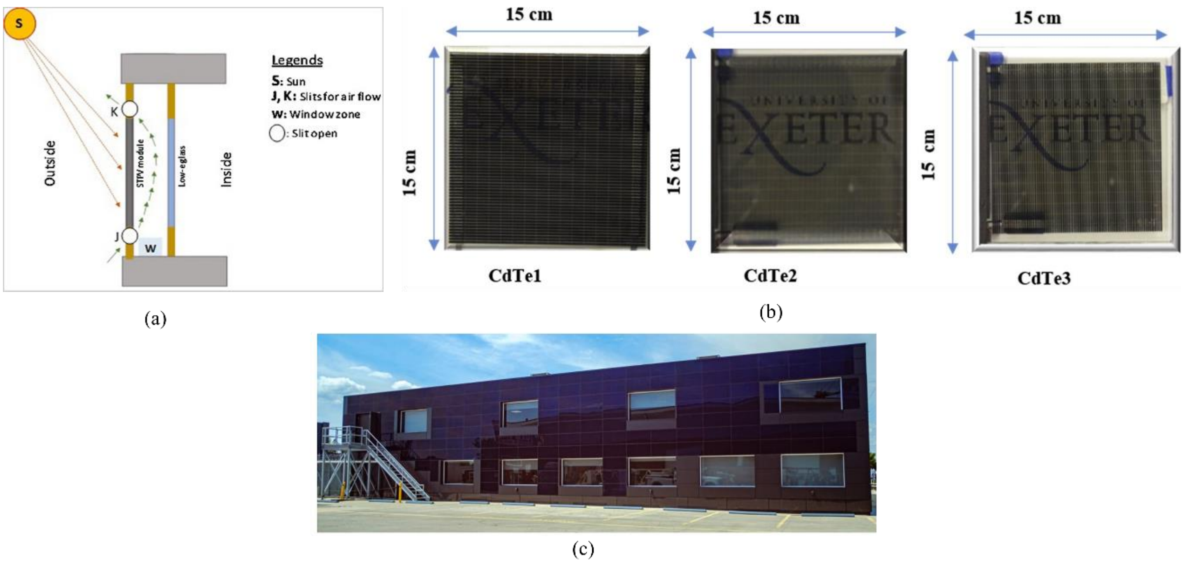


Figure 4: (a) Schematic of CdTe based air flow FIPV glazing (Barman et al., 2018) (b) Photographs of three different transparent CdTe PV for BIPV window. (c) Solar Facade System integrated of the EllisDon offices in London (Image source: Solstex)

CdTe FIPV for roof integration was evaluated using EnergyPlus software for five different cities (Florianópolis, Curitiba, São Paulo, Rio de Janeiro, Brasília Belém) in Brazil. This glass on glass CdTe PV module had 122.5 Wp power, a *U*-value of 5.7 W/m^2 K, a solar heat gain coefficient of 0.35 and a visible light transmittance of 50%. For Sao Paulo city and a particular building, rooftop and façade application produced 62% higher energy than the buildings energy demand and excess was recommended to employ to recharge electric vehicle (Sorgato et al., 2018). Using EnergyPlus, CdTe FIPV was evaluated for Hong Kong climate. This 10 storied building was designed using the standard

Building code for Hongkong while the window to wall ratio was 0.6. Net energy saving potential using CdTe BIPV window as 15.5% higher than a-Si based BIPV window and 19.6% than a traditional window. Transmission of a-Si (6%) was lower than CdTe (10%) which increased the lighting energy demand for a-Si BIPV. For traditional windows the solar heat was higher which was reduced due to the CdTe integration hence cooling load demand was possible to reduce (Meng et al., 2018). Solar and luminous light transmission control potential of three 15 cm × 15 cm CdTe based BIPV windows was evaluated using Indoor spectral characterisation as shown in **Figure 4b**. Three different CdTe glazing systems were 5.77% (CdTe1), 9.54% (CdTe2) and 12.34% (CdTe3). Spectral behaviour of reflections in the range of solar and visible wavelengths was similar for these three different transparent CdTe glazing. Near infrared (NIR) reflection was higher compared to luminous reflection after 1500 nm for all three glazing systems. Solar factor (SF) for CdTe1, CdTe2 and CdTe3 glazing were 0.23, 0.28, and 0.26. CdTe3 is the best candidate for glazing application as it has 113% higher luminous transmission while SF only increases by 21% compared to CdTe1 (Alrashidi et al., 2019). *U*-value and g-value of semi-transparent CdTe FIPV were experimentally characterised at temperate climate which confirmed that 25% visible transmission and 12% solar transmission. Thermal transmission and solar heat gain coefficient were calculated from measured thermal data. *U*-value of 2.7 W/m^2 K was found for outdoor and indoor characterization of CdTe BIPV windows (Alrashidi et al., 2020a). Façade buildings are generally highly glazed and energy-intensive especially in countries with hot weather. Power consumption in these buildings is even more significant when the air conditioning (AC) is added to the figures. Building with semi-transparent photovoltaic (STPV) materials is bringing advantageous energy-saving features to these façade structures. Energy is saved by more heat being reflected resulting in less AC power consumption with the STPV thermal properties. In addition, the optical and electrical properties provide indoor sunlight with power generation. This paper investigates the net potential energy-saving via applying cadmium telluride (CdTe) in Façade buildings. The analysis has been carried out using indoor and outdoor experiments considering different orientations and transparencies. Compared to a single glazing case as a reference, the applied CdTe achieved a net energy saving of 20%. Furthermore, a trade-off between saving energy and environmental comfort has been discussed as less transparency windows lead to more artificial light consumption. The findings indicate that STPV is a promising solution for sustainable buildings (Alrashidi et al., 2020b). Daylighting performance using CdTe FIPV (10% to 50% transparent) was evaluated by employing UDI, DGPs, Uniformity ratio (Sun et al., 2020). It was found that even a 10% transparent CdTe BIPV window can produce UDI levels 500 to 2000 lux. **Figure 4c** shows a solar facade system integrated into the EllisDon offices in London.

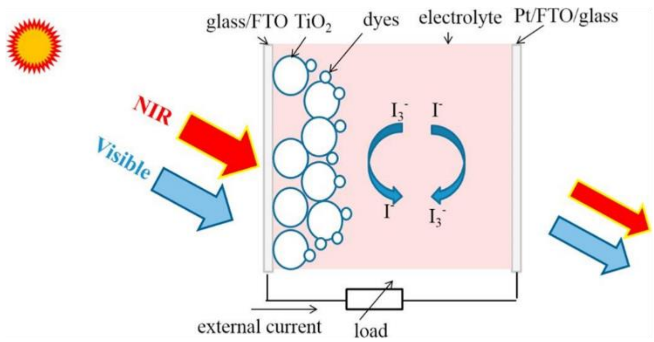
3.3.3. Copper, indium, gallium and selenium (CIGS)

Copper, indium, gallium and selenium (CIGS) thin-film solar cells are another promising thin-film technology that can be employed as FIPV. In this type of structure, on glass or flexible substrate, thin-film, the buffer layer and transparent upper electrode are coated. Due to low-cost fabrication methods compared to c-Si solar cell CIGS gaining importance (Mufti et al., 2020). Compared to CdTe this is not toxic. Because of the lack of highly efficient cells, this technology is still yet not very commercially popular. For large-scale deployment of CIGS, Indium is not a limiting factor (source: PV magazine). Recently, 23.35% record efficiency was achieved by Japanese manufacturer Solar Frontier for a CIGS solar cell and 19.64% efficiency was recorded for a CIGS module by German thin-film module maker Avancis. Potential of CIGS-BIPV for energy saving and environmental protection, economic, innovation and safety shows it can score high enough (86/100) which make it competitive compared to other commercial product (Kong et al., 2020). However to capture the global market, low price, better quality and low user costs are also essential in addition to high efficiency. According to PV reports developed by Fraunhofer Institute for Solar Energy Systems, CIGS had a market share of 1.5% in the year 2020.

3.3. Third-generation PV based FIPV

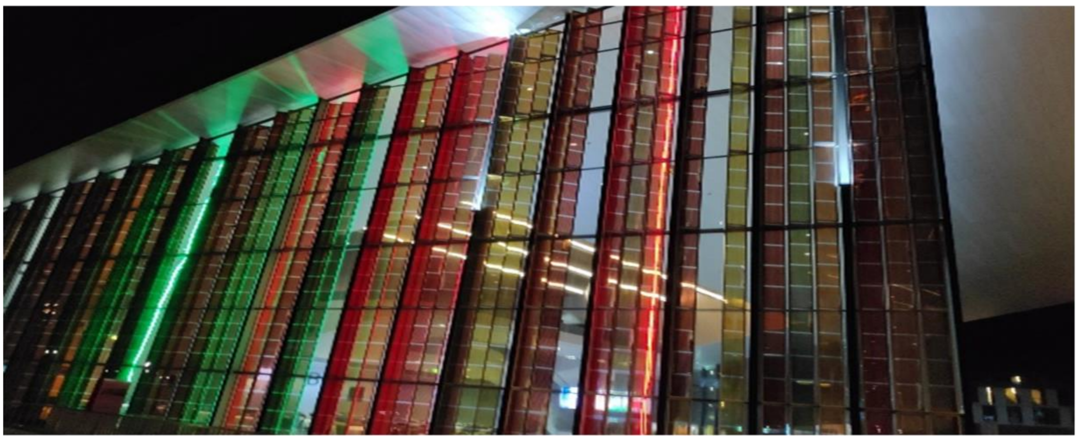
3.3.1. Dye-sensitized solar cell (DSSC)

Dye-sensitized solar cells (DSSC) is potential for FIPV application due to their, transparency, low-cost fabrication process, eco-friendly property (Gong et al., 2012). The energy payback period of DSSC varies from 1.99 years to 2.63 for varying cell efficiency (Greijer et al., 2001; Mustafa et al., 2019; Parisi et al., 2014, 2011). The market value of DSSC is expected to be USD 49.6 million in 2014 and is estimated to grow at a CAGR of over 12% from 2015 to 2022. In the presence of sunlight radiation dyes of DSSC degrades. The use of liquid electrolytes leads to leakage problems it may expand at high temperature and freeze at low temperature (Richhariya et al., 2017). Solid electrolyte based DSSC is in research nowadays. Figure 5a shows the schematic of DSSC while Figure 5b shows the LSC window at Hanbat National University, Daejeon, in the Republic of Korea and Figure 5c shows the LCS window at EPFL.



(a)

(b)



(c)

Figure 5: (a) Schematic of DSSC, (b) 4 vertically placed DSSC module 81.36 Wp (each module has 20.34 Wp) at Hanbat National University, Daejeon, in Republic of Korea (Lee and Yoon, 2018), (c) LSC window at EPFL.

One DSSC for FIPV application was designed by a nine-unit solar cell connected in series. One unit cell had 80 × 80 mm^2 active areas, 8 mm thick TiO_2 layer, open-circuit voltage of 0.64V, short circuit current of 250 mA. This FIPV generated Voc of 5.7 V and Jsc of 220 mA at one sun light intensity. This DSSC glazing had an average of 60% transmission in the visible and a maximum of 67% transmission at 670 nm. However, no thermal or energy performance was performed using this glazing (Kang et al., 2003). In another work, 7 µm, 9 µm and 11µm thick TiO_2 and red and green coloured dye-based total six DSSCs were fabricated to investigate their optical and thermal performance using Window 6 software. Unit cell dimension was 10 mm × 10 mm × 4.5 mm. The average transmission of these cells was greatly influenced by the thickness of the material and varied from 6% to 30% in the visible range. Average 27% visible transmission DSSC glazing offered 0.29 SHGC whereas 0.78 transmitted double glazing offered 0.71 (Kang et al., 2013). Varying TiO_2 thickness, four different transparent DSSCs were fabricated. This 39%, 31%, 24% and 20% luminous transparent DSSC glazing had conversion efficiencies of 10.26%, 11.50%, 12.60%, 13.00% respectively. The higher thickness of TiO_2 offered low transmission and high power conversion due to higher short circuit current from a thicker electrode. Using these DSSC glazing, the energy performance of a building in Korea was evaluated by using energy simulation techniques. Without DSSC glazing showed that lower transmission enhanced energy consumption due to heating load requirement where as DSSC showed reverse as it generated electricity (Yoon et al., 2011). The *U*-value of these four-glazing varied from 1.49 to 1.53 W/m^2K. To achieve a lower *U*-value a combined system was considered where this DSSC glazing was external surface and one low-e coated glass was placed between this DSSC glazed pane and clear pane. New overall *U* –value varied from 0.79-0.84 W/m^2K while SHGC of 0.2, 0.19, 0.17 and 0.15, respectively. Using ESP-r program building energy performance for integration of this glazing was simulated for seven different cities (Miami, Sao Paulo, Sydney, New York, Seoul, Berlin, and Moscow). This glazing was performed best in New York City due to its variable heating and cooling load demand. For cooling dominant Berlin and Moscow climate, the glazing performance was less effective (Lee et al., 2014). DSSC integrated between glass block ((*U*-value of 3.0 W/m^2K, solar factor 79.7% and 79.5% light transmission) were investigated at the University of Palermo. COMSOL Multiphysics, WINDOW, Zemax were employed to explore the thermal, optical and electrical performance (Morini and Corrao, 2017). On other work, 5 different DSSC glazing including opaque green, transparent green, opaque red, transparent red, double glazing red having a dimension of 60 cm × 100 cm was selected. Because of the low visible transmittance, it was advised to employ half of the façade (Bouvard et al., 2015). Varying TiO_2 electrode thickness six small-scale DSSC based FIPV were fabricated which offered luminous transmittance between 0.19 and 0.53. Evaluation of the colour rendering index (CRI) and correlated colour temperature (CCT) of below 0.5 transmittances showed a CRI lower than 80. Interestingly, the CRI of 53% transparent DSSC glazing had only 2.7% lower CRI than 77% transparent double glazing and 72% transparent vacuum glazing (Ghosh et al., 2018b). It is found that the 37% transparent DSSC FIPV reduced 21% disturbing glare than a traditional double glazed window for a clear sunny day in a temperate climate (Selvaraj et al., 2019). After two years the same device showed that though average visible transmission reduced, colour properties were enhanced for them which is essential properties for FIPV (Roy et al., 2019). First outdoor characterisation of DSSC FIPV to understand long term performance was carried out employing 20.34 Wp, 0.975 m (W) × 0.965 m (H) system at Hanbat National University, Daejeon, Republic of Korea. The structure had DSSC module (9 mm)" + "air space (12 mm)" + "clear glass (5 mm)". Results were compared with 40° sloped DSSC FIPV. Power yield of sloped DSSC was higher because DSSC is reactive with diffuse solar radiation than direct solar radiation (Lee and Yoon, 2018).

3.3.2. Perovskite

Perovskite solar cells (PSC) possess tuneable transparency and simpler fabrication methods and gained efficiency from 3% to 22% within a decade which most trending technology for FIPV application. Currently, the highest efficiency of single-junction PSC has reached 25.5% (Green et al., 2020). Perovskite's energy payback analysis is not a much-explored area, however, few works suggested that it can be between 0.2 to 5 years depending on the employed material. Depending on the module efficiency the LCOE also varies. It was evaluated that the LCOE of a perovskite-based PV module can have a cost of 0.25 US$/W for 15 years of a lifetime. For varying module efficiency such as 12%,15%,20%, the LCOEs were 4.9 US cents/kWh, 4.2 US cents/kWh, and 3.5 US cents/kWh respectively (Cai et al., 2017). It is expected that by 2022 the global Perovskite PV market will be $5.2 billion by 2022 (Research, 2018). Oxford photovoltaics, OIST's Technology, Solliance, Toshiba and NEDO are currently the major Perovskite PV cell developer (Roy et al., 2020).

Long term device stability is one of the most imperative challenges for the emerging PSC technology. Moisture, oxygen, temperature, and illumination are the four key elements that degrade the PSC. Although encouraging ageing results have been reported at milder or controlled environmental conditions, still, there is a long way to go to meet stability standards similar to thin-film PV technology (IEC 61646) and crystalline silicon PV technology (IEC 61215). Especially, no promising results have been reported yet for heat damp test (85 °C, 85 RH) and light soaking tests at 85 °C. Passing the IEC 61215 is necessary for Perovskite to clear the minimum requirement for commercialisation (Holzhey and Saliba, 2018). Both the materials and their preparation methods have been found to influence the device stability (Asghar et al., 2017). Large scale fabrication of PSC is challenging because it's hard to produce a large uniform layer of perovskite as defects become more pronounced which can only be solved by increasing the film thickness. However, higher thickness reduces the transmission property. Recently, Perovskites modules having dimensions of 5 cm × 5 cm and 10 cm × 10 cm, with efficiencies of 14.55% and 10.25% were developed as shown in **Figure 6a,** which performed well for 1,600 hours maintaining 80% of its standard efficiency while the larger module maintained its 10.25% efficiency for over 1,100 hours (Tong et al., 2021). Spiro-OMeTAD-free ST-PeSCs in normal type devices were achieved at AVT values between 10 and 30% as shown in Figure 6b (Choul et al., 2020). Figure 6c shows the semi-transparent perovskite made by Saule technologies.

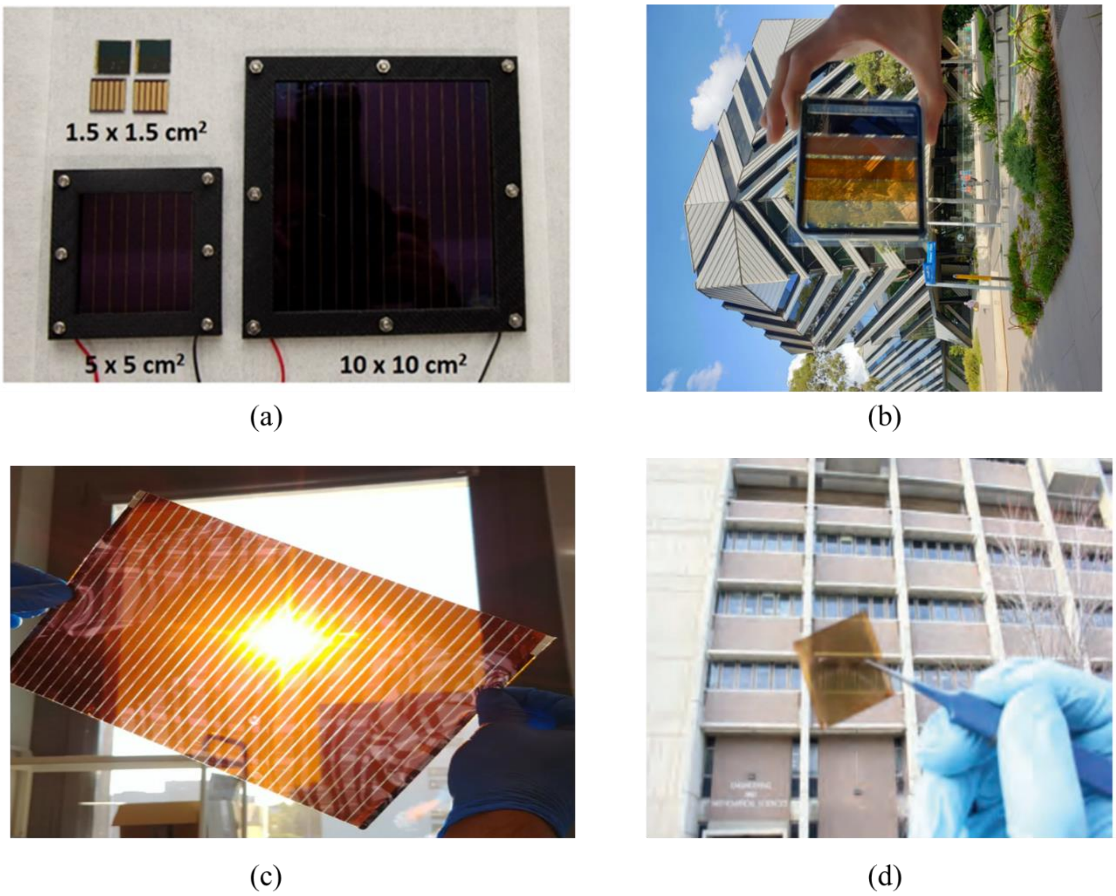
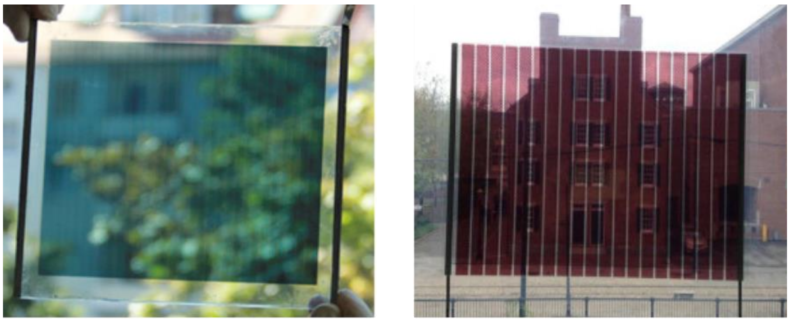


Figure 6: The two mini solar modules developed by Korean researchers. Image: Okinawa Institute of Science and Technology Graduate University (OIST). (b) A semi-transparent perovskite solar cell with contrasting levels of light transparency. Source: Dr Jae Choul Yu (Choul et al., 2020), (c) A4 size semi-transparent Perovskite by Saule technologies (d) Photograph of semi-transparent Perovskite solar cell (Wang et al., 2020)

Perovskite PV use toxic lead (Pb) which can create a negative impact on users and can be an obstacle for its market acceptance. Two types of corrective measures (a) replacing lead with other similar properties metal, (b) use of less toxic material could improve the situation. However, it is believed that the amount of lead used in PSCs is not significant compared to lead used in lead-cadmium batteries, integrated circuits, infrared detectors. PSC uses only 0.4 g/m^2 of Pb, which is comparatively much lesser than the lead used in soldering of commercial Si PV panels (M. Chen et al., 2019). On the other hand, completely getting rid of Lead is not a possibility as the performance of lead-free PSCs are still lagging behind the lead-based PSCs. The FIPV based on perovskite was reported by (Cannavale et al., 2017). In this work, perovskite was prepared by FTO/glass substrate, coating of TiO_2 n-type layer, deposition of dewetted perovskite islands. This particular type of perovskite had an array of perovskite microstructure islands and each island absorbed visible light while the transparent region was colour neutral (Eperon et al., 2014a, 2014b). This cell had an active area of 0.0929 cm^2, FF, conversion efficiency was 0.65 and 6.64% respectively (Eperon et al., 2014b). The color perception of transmitted light through this 42.4% transparent cell was neutral. Using Matlab and Daysim software, these data were applied as input to investigate the glare control potential and energy analysis of perovskite FIPV based building. Maximum power conversion reduction was only 3% in hot climates whereas no reduction was noticed in colder climates which implied that transparent perovskite absorbs less radiative heat. Thus efficiency reduction is less due to temperature (Cannavale et al., 2017). Carbon counter electrode-based Perovskite was developed and experimentally and analytically investigated to understand its behaviour as FIPV or BIPV window application. At 1000 W/m^2 solar radiation condition, this Perovskite had 8.13% efficiency while visible and solar average transmittance was 20% and 30% respectively. Angular incident angel dependent solar heat gain coefficient (SHGC) or solar factor (SF) varied from 0.14 to 0.33 for the University of Exeter, Penryn (50.16° N, 5.10° W) UK location. *U*-value was 5.6 W/m^{2}K while colour properties analysis found that 20% visible transmittance is the threshold limit, to obtain colour or visual comfort using this glazing (Ghosh et al., 2020). EnergyPlus simulation with an advanced FIPV having semi-transparent Perovskite and nanophotonic multilayer coating showed that 13560 kWh energy saving potential of a single story building (residential 2000 ft^2 area) which was located at Pheonix, Arizona (shown in **Figure 6d**) (Wang et al., 2020). Recently semi-transparent Perovskite visual impact for different Kopean climate based location was explored which indicates the positive future potential of this technology for FIPV application (Bhandari et al., 2022).

3.3.3. Organic

Made with no toxic material, lightweight semi-transparent organic solar cells (OSCs) are another alternative to FIPV application. Long term durability at outdoor conditions is a critical issue with organic PV based FIPV. Outdoor stability of organic PV (OPV) system having 35.5 cm^2 active area was performed at 3 different locations in Germany, one in Israel, one in Denmark and one in Australia. Stability was retained for 17th months (Gevorgyan et al., 2013). It was suggested that efficient terminal sealing is essential to limit the stability issue. Eight different OPV systems degradation was evaluated at the outdoor condition for 8 months (Owens et al., 2016). OPV has a lower thermal coefficient compared to c-Si and thin film as it absorbs a lower amount of infrared than the other two (Bristow and Kettle, 2018). Outdoor characterisation of OPV system at Japan climate showed three types of degradation which included initial rapid degradation, secondary gradual degradation, and seasonal variation (Sato et al., 2019). Lucera et.al. 2017 developed 197.40 cm^2 active area based semi-transparent Organic PV based FIPV which achieved 4.8% efficiencies on rigid substrates (FTO) and 4.3% on a flexible substrate (ITO-Metal-ITO (IMI) sputtered polyethylene terephthalate (PET)). Details of transmission and other window parameters were not evaluated. **Figure 7** shows two different types of organic solar cell based FIPV.



(a) (b)

Figure 7: (a) Green like with active area of 197.40 cm^2 (Lucera et al., 2017) (b) Red like (Yan et al., 2013) semi-transparent Organic FIPV

In another work, semi-transparent organic PV based FIPV was developed which had 3% efficiency and after accelerated durability test following IEC 61646:2008 only 8% degradation occurred (Yan et al., 2013). Organic FIPV for greenhouse shading in Israel for agriculture purposes was investigated which had 20% transmission, 15% reflection and absorption was 65% absorption. This system also had a *U*-value of 6.0 W/m^{2}K (Friman et al., 2019). The cost of organic FIPV is lower than the first generation as roll to roll technology can be employed here. Also, the temperature coefficients are positive for OPV

BIPV. Table 1 lists here the difference between three different generations of PVs for the BIPV window or FIPV application.

Table 1: Comparative analysis of three different generations of PV for BIPV window application.

Type	Solar cell type	Transparency	Current highest efficiency	Stability	Temperature impact/temp. coefficient (K^{-1})	BIPV window application
1st Generation						
	Silicon (Si)	Opaque	26.7%	Mature technology 20-25 years working capacity	High-temperature power reduces/ -0.2 to -0.45 (Skoplaki and Palyvos, 2009a, 2009b)	Spaced type structure is possible
2nd Generation	a-Si	Opaque, Semi-transparent	10.2%	Mature technology 20-25 years working capacity,	Wekaer effect than Si/ −0.10 to −0.30	possible
	CdTe	Opaque, Semi-transparent	21%	Mature technology Expected to work over 20-25 years, however no such work is reported yet	Wekaer effect than Si/ -0.25 (Lee and Ebong, 2017)	possible
	CIGS	Opaque, Semi-transparent	23.35%	Partially mature technology, Expected to work over 10 years however no such real work is reported yet	Wekaer effect than Si/ −0.33 to −0.50 (Virtuani et al., 2010)(Deceglie et al., 2014)	possible
3rd Generation	DSSC	Opaque, Semi-transparent, transparent	11.9%	Stability with high efficiency is still challenging issues	+0.1 (30^0C-50^0C) (Tian et al., 2012)	possible
	Perovskite	Opaque, Semi-	22.6%	Not stable at outdoor environment	a) 0.035 between	possible

		transparent, transparent			5°C and 25°C b) -0.021 between 25°C and 75°C (Bhandari et al., 2020)	
	Organic	Opaque, Semi-transparent, transparent	15.2%	Life span maximum 4-5 years	+0.7	possible

4. Advanced FIPV/BIPV window

4.1. Concentrating PV based FIPV

The use of environmentally benign materials based concentrators replace the costly PV material with low cost concentrating material, generates higher electrical power, abate the use of toxic material during PV cells production. Concentrator includes a high, low, and medium type. Concentrator below 10 is considered as low while between 10 to 100 is medium and above 100 is high. For high and medium, cooling agent is required while for low natural air flow can reduce the thermal enhancement. For building applications, a low concentrator is popular.

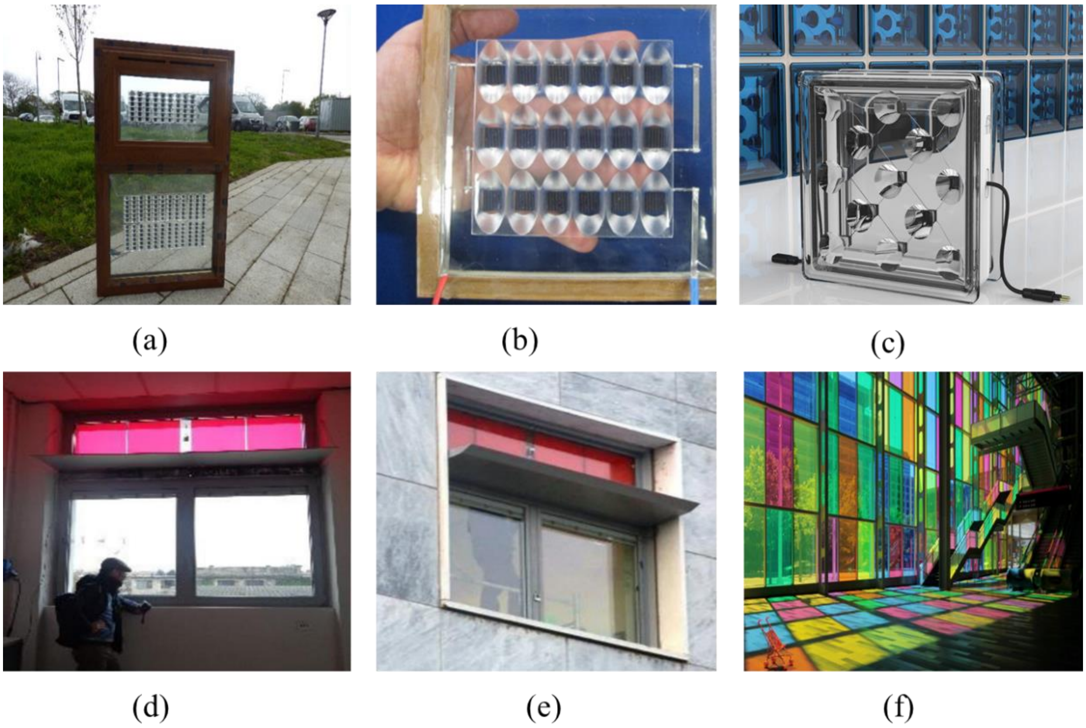


Figure 8: (a) BICPV window at the University of Exeter, Penryn Campus (b) Semi transparency effect of the square elliptical hyperboloid concentrator for BIPV window application (taken from(Sellami et al., 2012) (c) Solar squared (Image courtesy Build Solar (taken with permission)), (d) red LSC window installed in building internal view (Aste et al., 2017) and (e) external view (Aste et al., 2017), (f) LCS window (Interior view of the Palais des Congrès, Montreal, Canada (photo courtesy M.Nguyen)).

Low concentrator for FIPV application includes compound parabolic concentrator (CPC) (Liu and Wu, 2021), luminescent solar concentrator (LSC) and holographic solar concentrator. Mirror-based or dielectric-filled compound symmetric asymmetric parabolic concentrator's non-imaging nature, this type of concentrator can collect both direct and diffuse solar radiation. For CPC, mostly c-Si solar cells are employed and CPC is placed on the top of the PV (shown in Figure 8 a and b). To allow sufficient light and view this structure is very much similar to c-Si based FIPV (Li et al., 2020). The only advantage is the power generation is high and the overall system cost is low as less solar cells are used. However, other types of solar cells such as DSSC (Selvaraj et al., 2018 and Perovskite (Baig et al., 2020) were recently used to understand the impact of high light intensity on the cell material. BuildSolar is now the only commercial player for CPC based FIPV as shown in **Figure 8c.**

Luminescent solar concentrator (LSC) as shown in **Figure 8 d,e,f** is another alternative for FIPV application that harvests both diffuse and direct sunlight. An LSC consists of a transparent polymer sheet or film, doped with either organic dyes, quantum dot or rare-earth material which absorb a portion of the incident solar light and emit photons with a near-unity quantum yield. If the refractive index of the carrier material is higher than that of the surrounding medium (in this context, air), a large proportion of the emitted photons will reach the edges following total internal reflection. LSCs are less sensitive to their orientation angle compared to silicon PV modules (Aste et al., 2017). Because of the presence of solar cells at the edge of the LSC, no special arrangements are required compared to CPC based FIPV. LCS types FIPV can be different coloured depending on the presence of dyes hence transmission modulation is possible and thus the daylight control and limiting are also possible.

4.2. Bi-facial solar cell-based FIPV

Bifacial solar PV collects solar light from both front and back faces which enhances the energy generation than that of the same footprint as monofacial modules as shown in **Figure 9**. Though it was developed first in 1960 but had to wait before making its further accelerated innovation (Guerrero-lemus et al., 2016). In 1984, the first industrial production of bifacial PV (bPV) module was developed by ISO-FOTON which is a Spanish company (Lorenzo, 2021). As bPV collects higher solar light, it can be considered that the temperature of the cell can be higher than monofacial one. However, because of the structure of the bPV module, most of the infrared light transmitted through the system makes its temperature rise low (Lamers et al., 2018). Thus, glass-glass structure-based bPV can have higher LCOE than a traditional glass-back sheet and the rear glass is better to withstand the exposed UV rays and water vapour intrusion (Gu et al., 2020). Because of the low-temperature coefficient of bPV, energy yield is 20-40% higher than monofacial (Al-BSF) structure (Patel et al., 2020).

In general, building integration of the PV module is interesting because of its low degradation due to the bird droppings, dust, snow, tree leaves. Although it can have a large collection area but suffer from non-optimal orientation. bPV can be a solution as the gap between the inner wall and module allows rear side albedo and forced or natural air circulation to reduce the cell temperature. It can be advantageous seasonally as can allow penetration of heat during winter and vertical shading in summer (Soria et al., 2016). Power generation from the rear side of the PV from a bPV depends highly on the building exterior materials which can be various different materials (Russell et al., 2017; Soria et al., 2016). Also, the distance between this exterior wall which can act as a reflector is not often constant because of the protruded and/or sunken exterior features of buildings (Deline et al., 2020). This inhomogeneous rear surface has an adverse impact on the reliability and power generation from bPV (Kim et al., 2021).

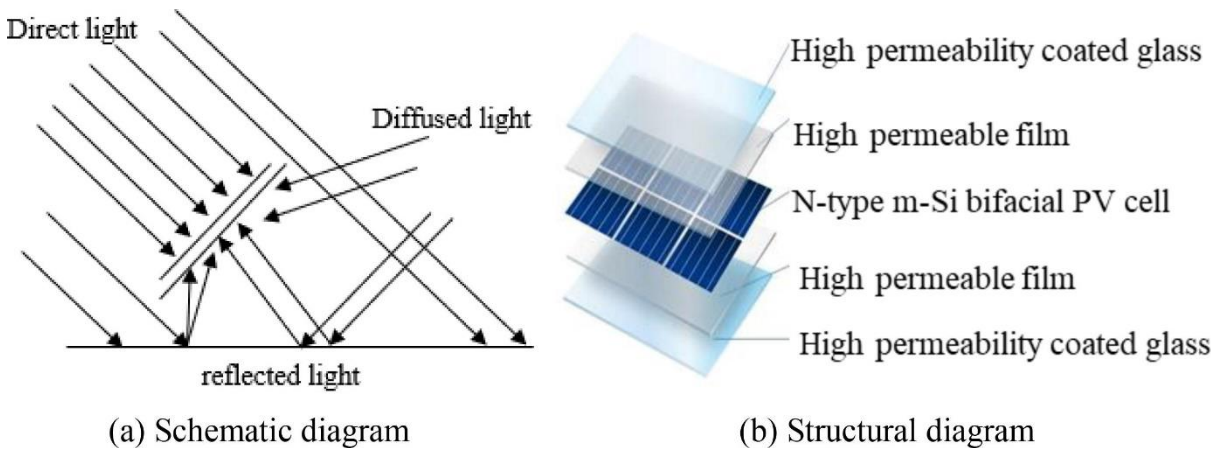


Figure 9: (a) Schematic (b) structural diagram of bifacial PV cells.(Chen et al., 2021)

4.3. Thermally insulated FIPV

In general, a BIPV window or FIPV is two glass panes where PV material is sandwiched between two glass panes. While because of PV material different transparency, solar factor varies however, the *U*-value remain similar to double glazing. If there is no space between two glass panes, then overall the system works as single glazing. Single glazing possesses a higher *U*-value which enhances the building heat energy demand. Hence, double, and single glazing are not suitable for cold climatic building integration. To enable a glazing system in cold climate building, evacuated (vacuum) glazing is now in research interest. Evacuated glazing consists of two glass panes and a vacuum is maintained between these two glasses. To withstand outside atmospheric pressure small support pillars are there which might be stainless steel or aerogel made. Vacuum glazing has a *U*-value close to or lower than 1 W/m^2K (Fang et al., 2014) and 53% lower heat loss potential compared to double glazing (Ghosh et al., 2016a). The presence of vacuum, conduction and convection losses are reduced while the presence of low emission coating abates the radiative heat transfer (Memon et al., 2019). Support pillars are most often stainless steel (Wilson et al., 1998) (Collins et al., 1995; Griffiths et al., 1998) made while recently transparent support pillar made from Bismuth boron glass powder (Zhao et al., 2013), translucent aerogel (Büttner et al., 2019) were also investigated. Edge sealing is a critical task for vacuum glazing to maintain the low pressure between glasses for the high durability of the system. Solder glass (Collins and Robinson, 1991), indium alloy (Zhao et al., 2007), Cerasolzer type CS186 (Memon et al., 2015) based edge sealing was investigated for vacuum glazing. Hence, the BIPV-vacuum glazing window is the most advantageous for cold climates. C-Si PV based Vacuum integrated FIPV glazing **(shown in Figure 10 a, b and c)** was reported where indoor test cell characterisation found an overall heat transfer coefficient (*U*-value) of 0.8 W/m^2K and solar factor of 0.42. Results were compared with a similar area of double glass pane based FIPV. Vacuum based system had a 66% lower *U*- value and 42% lower solar factor than a double glazing-based system. Also, for the cold climate, this vacuum-based system is a suitable candidate as lower ambient temperature can abate the enhancement of PV cell temperature (Ghosh et al., 2018c). Thermal comfort analysis reported that for a clear sunny day soothing or comfortable indoor temperature is possible during mid-day. For a combined BIPV-vacuum glazing, vacuum glass facing external ambient is suitable for cold climate and warm climate vacuum glass facing internal room ambient is applicable (Ghosh et al., 2019a). Another work reported that 35% and 42% transparent vacuum-based PV windows possess comfortable CCT and CRI for building interior (Ghosh et al., 2019b).

a-Si based vacuum-based 20% transparent FIPV having a dimension of 1300 mm (width) ×1100 mm (height) × 20.87 mm (thickness) was characterised at The Hong Kong Polytechnic University from June 2016. The U-value of this system was 1.5 W/m^{2}K (Qiu et al., 2019). Power output from this system was linearly correlated with incident solar radiation (Zhang et al., 2017). Employing Energy Plus simulation for two different locations in Hong Kong and Herbin showed a reduction of 81.63% and 75.03% of the heat gain while 31.94% and 32.03% respectively. This work also confirmed that vacuum-based FIPV is suitable for cold climate areas (Huang et al., 2018). Highly insulated solar glass made by a-Si PV was experimentally characterised in the Institute of Sustainable Energy Technologies at the University of Nottingham as shown in **Figure 10 d**. This glazing had 79% absorption, 7% visible transmittance, 100% UV blockage, 95% restriction of undesired thermal radiation, 24.9% better daylighting performance compared to ordinary glazing while *U*-value was 1.10 W/m^{2}K (Cuce et al., 2015a, 2015b). The presence of photocatalyst TiO_2 on the glazing surface allows self-cleaning as pollutants on the glazing surface are decomposed by photocatalysts and will be washed away during rain. These layers also offer high transmittance and low reflection. Semi-transparent thin-film PV insulated with vacuum layer-based FIPV was investigated theoretically where support pillar was aerogel made and edge sealing was epoxy resin type to reduce the overall weight and conductive heat transfer of the window. COMSOL Multiphysics was employed to evaluate the *U*-value of the system which was 0.3255 W/m^{2}K (B. Chen et al., 2019). Aerogel support pillars have the ability to reduce 20% of *U*- value compared to stainless steel as the support pillars (Jarimi et al., 2020). To lower the *U*-value further for BIPV-vacuum glazing an intermediate air cavity between PV and vacuum glazing was theoretically investigated. The three-dimensional heat transfer model showed that this PV-vacuum-double glazing window can achieve a 0.23 W/m^{2}K *U* -value while PV side faced cold outdoor environment and vacuum glazing facing indoor environment, an air cavity is 12 mm and pillar spacing is 60 mm (Huang et al., 2021).

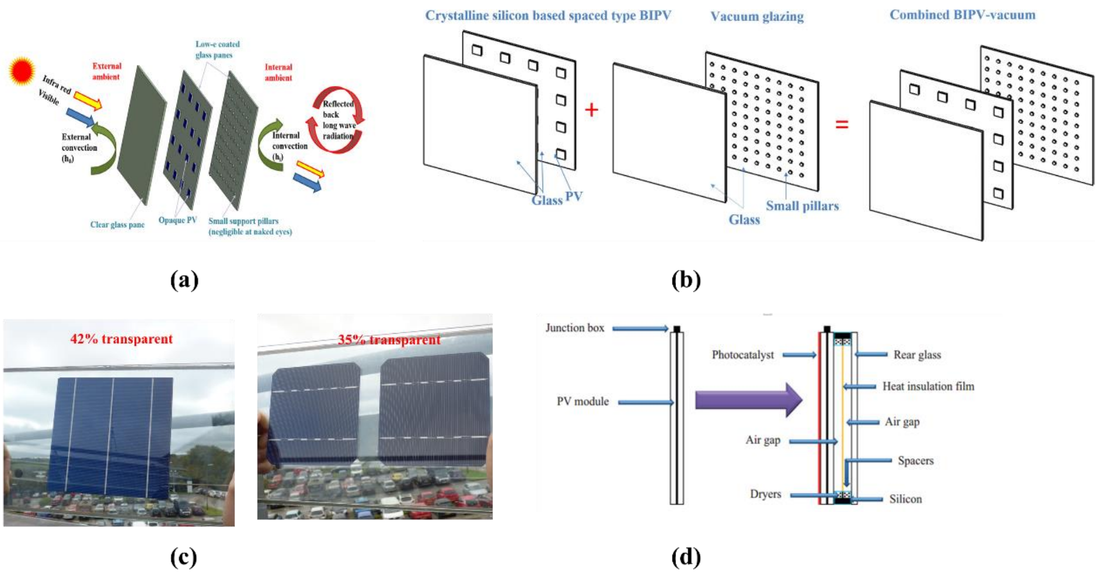


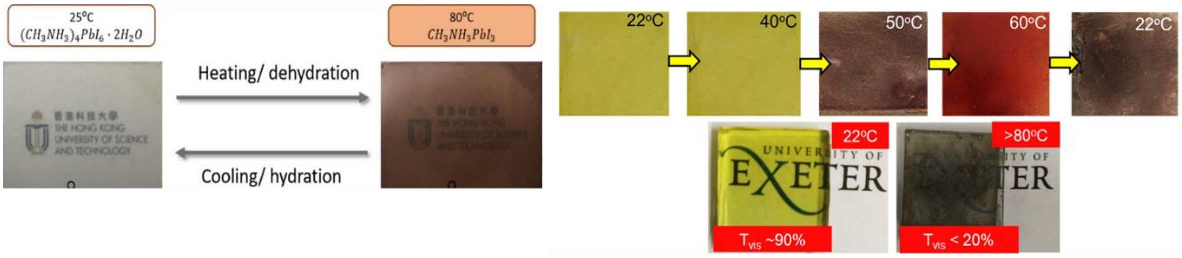
Figure 10: (a) and (b) schematic of spaced type semi-transparent vacuum FIPV glazing (Ghosh et al., 2018c), (c) photographs of BIPV- vacuum glazing (Ghosh et al., 2019b), (d) Schematic of highly insulated FIPV glazing (Cuce et al., 2015) and

4.4. Switchable BIPV

Currently, static or constant semi-transparent PV dominates the BIPV window sector, which concomitantly provides power and shading. However, they are incapable to change the transmission similar to a smart window, which can alter their transmission by employing some external stimuli. It is highly desirable to develop the material, which can have the potential to generate electricity in an opaque state and allow light transmission in the transparent state while both states are switchable and stable under external ambient. Perovskite material has the ability to change the transparency in the presence of daylight. Perovskite solar cell has thermochromic properties which also make it an efficient switchable FIPV technology. This change occurs because of the influence of temperature and humidity. In the presence of moisture, and exposure time, Perovskite gets hydrated (either mono or di) but is capable to regain its original structure upon releasing the water molecules (Halder et al., 2015).

Inorganic CsPbI3-xBrx perovskite window changed its visible transparency between 81.7% transparent cold state to a 35.4% coloured hot state and also maintained 7% device efficiency in the coloured hot state. However, this material offered stability even after switching cycles However, their transition temperature (100–350 °C) and switching time (up to 25 h) are significantly high for consideration as a window application. In general, CsPbI3 has a transition temperature close to 200°C which was reduced to 100°C by the inclusion of Br (Lin et al., 2018). In another work (as shown in **Figure 11a**), at room temperature, 91% transparent Perovskite in the visible range had the transition temperature at 43 °C while the relative humidity was less than 60%. Perovskite transition time was less than 5 min. This window was able to reduce the 2.5°C indoor temperature compared to traditional windows while characterised by external ambient direct sunlight in Hong Kong (Zhang et al., 2019). In another work, thermochromic perovskite (methylammonium lead iodide-methylamine complex (CH3NH3PbI3•xCH3NH2) changed its transmission between 68% visible in the bleached state to 3% visible transmittance in coloured state and conversion efficiencies was 11.3% in the colored state. Over 20 switching cycle was achieved from this device (Wheeler et al., 2017). Liquid biconstituent $MAPbBr_{3-x}I_x$ perovskite solution became yellow, orange, red and dark red due to the heat treatment at 25°C, 60°C, 90°C and 120°C respectively. The required time to reach from 25°C to 120°C was inversely proportional to the temperature (De Bastiani et al., 2017). This colour change process was stable and reversible. Recently, nanorods based $CH_3NH_3PbIBr_2$ showed high transparency of ~92% at 22 °C and 30% at 60 °C. This semi-switchable FIPV one changed its colour yellow at 22 °C to reddish-brown at 40 °C and at (60 °C) became maroon (**shown in Figure 11 b**) (Roy et al., 2021).

Another way to change the transmission for FIPV is possible by including switchable material with FIPV. The electrically activated smart switchable window is popular for adaptive less energy-hungry building integration. Currently, electrochromic (EC)(Bui et al., 2021), suspended particle device (SPD)(Ghosh and Norton, 2017b) and polymer dispersed liquid crystal (PDLC)(Ghosh and Mallick, 2018a, 2018b) are the popular three electrically activated smart windows. Combining EC and PV is called photoelectrochromic or photovoltachromic (Cannavale et al., 2016). Silicon solar cell-based PV was reported which suffers from low optical contrast between transparent and opaque states (Deb et al., 2001). Later DSSC(Costa et al., 2019) and solution type EC (Huang et al., 2012) based switchable system was also developed. Further Perovskite solar cell-based EC window was also investigated for switchable PV application (Cannavale et al., 2015). Ghosh et.al. investigated an outdoor experiment at Dublin climatic condition where SPD was switched by powering silicon-based PV module and observed tremendous potential in this sector (Ghosh et al., 2016b). Polymer dispersed liquid crystal has the potential to improve the building interior by providing complete privacy when no power is applied and transmission when power is applied(Ghosh et al., 2018a). This PDLC film can be integrated with first and second-generation PV. If the PDLC film is placed on the top of the solar cell it can also control the light intensity on the cell. On the other hand, if the PDLC film is placed in the backside of the PV then PV can get uninterrupted light while depending on the occupant's criteria transmission and opaque state from the combined system is achievable (Khalid et al., 2021).



(a) (b)

Figure 11: (a) Schematics of the cold to hot state transition by heating (dehydration) and the hot to cold state by cooling (hydration)(Zhang et al., 2019) (b) Photographs of Semi-switching properties of $MAPbIBr_2$ based perovskite FIPV(Roy et al., 2021).

5. Discussion and perspective

5.1. Cost of FIPV

Installed photovoltaic (PV) capacity exceeded 500 GW at the end of 2018, and by 2023 an additional 500 GW of PV capacity is projected to be installed which will bring us into the era of TW-scale PV (Haegel et al., 2019). Thus, a 600-fold enhancement of global photovoltaic capacity has been experienced in the past two decades. **Figure 12** depicts the current cumulative PV installation globally. The key driver to boost this market growth is the 99% cost reduction of crystalline Si (c-Si) PV cells since 1980. It is estimated that the efficiency improvement has 23% contribution to this global expansion while private and public R&D contributed an estimated 22% and 59% respectively for the PV cost reduction between 1980 and 2012 (Kavlak et al., 2018). Solar energy system's cost includes soft cost because of the supply chain, installation for labour, relevant permits, overhead costs such as marketing and hardware cost or equipment costs which is due to a module, inverter and electric wiring cost, cost of a tracking system. Reduction of soft cost is currently under consideration as this sometimes accounts for 80% of the PV system installation cost. Price can be further decreased because of knowledge of spillover ("Knowledge spillovers occur when firms do not capture all the benefits from investments in innovation because a portion of the knowledge created "spills over" to other firms") (Nemet et al., 2020). Over the past decade, levelized cost of electricity (LCOE) for solar PVs are forecasted as shown in **Figure 13**. It is evident that all optimistic outlooks are actually wrong and within a few years, all initial projections are now outdated. The price for FIPV is still not available very straightforward like other single or double glazing windows. If BIPV is considered as whole building skin, for all European regions, the northern façade is suitable considering all societal and environmental benefits. BIPV building skin can always reimburse the investment cost and building can work as a source of income (Gholami and Røstvik, 2020).

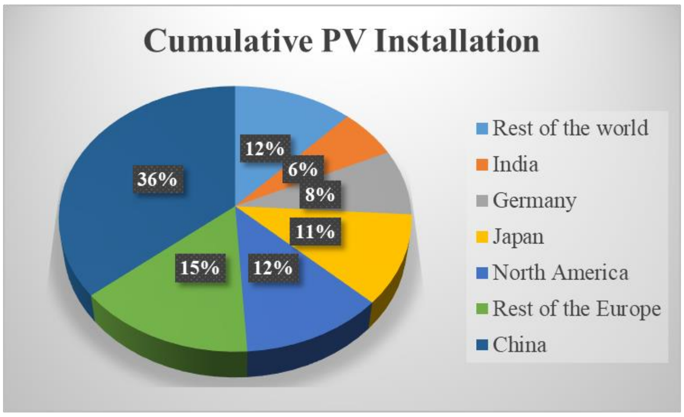


Figure 12: The total cumulative installations amounted to 584 GWp at the end of the year 2019 (Systems, 2021)

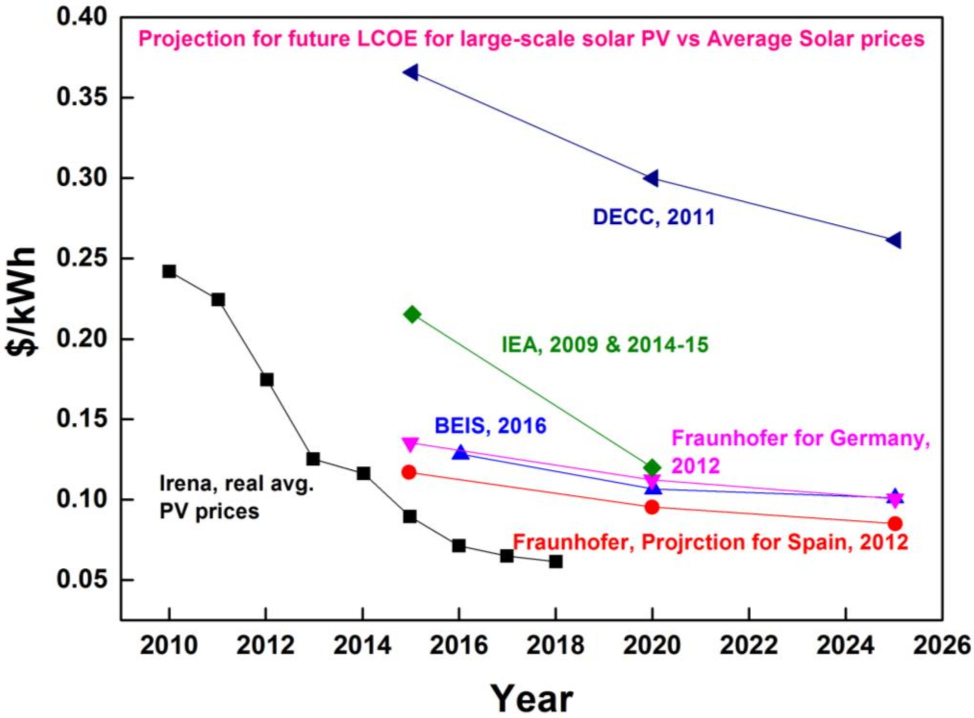


Figure 13: Forecasts for the levelized cost of electricity (LCOE) of solar PV (Tasgas, 2021)

5.2. Technical reliability

As PV solar power plant needs a considerable amount of land, integration of PV into the roof was adopted. However, the limited rooftop area in most of the high rise buildings in urban locations cannot offset the energy demands supplied by PV. Thus, BIPV and particularly BIPV window (FIPV) can be a potential option as it not only generates power but also offers privacy and solar heat gain reduction and heat loss reduction. Currently, European Nearly Zero Energy Building requires on-site renewable energy production which is possible by employing more BIPV windows or FIPV integration. However, in an urban location, an urban heat island is now a major issue that increases the urban ambient and also the surface temperature of the building. This enhanced air temperature can also increase the PV cell temperature can degrade the performance. However, the employment of thin-film or 3rd generation based FIPV can eliminate the challenges because of their weak relation between temperature and efficiency compared to first-generation silicon. Also, due to the dense and compact placing of building in an urban location, shading is predominant which also reduce the power generation (Boccalatte et al., 2020). As FIPV is not the best-oriented surface, and also solar radiation impinges on the vertical surface is lower than horizontal surface thus further lower power generation is expected from any generation PV based FIPV compared to their rated values. However, if we consider the recent trend of glassy commercial buildings where façades possess larger areas compared to the roof then FIPV has great potential. In addition, vertical FIPV facades receive more solar radiation in winter and early and late hours of any day (when sun position is lower in the sky) which can produce relatively higher power than summer and mid-day period. It is well established that the solar radiation reaching a surface is the inclusion of direct, diffuse and reflected components. Bi-facial solar cell technology should come more on the front as it can work with diffuse and reflection components from both ends. Commercialization of an integrated FIPV is challenging because of the lack of available information which is available for traditional PV systems which are either rack-mounted or ground-mounted.

5.3. Perspective

Hence, a smooth entry of the BIPV window or FIPV, collaborative links between different stakeholders are essential. Initiatives from government and then BIPV industry and building construction and architectural people conjunction with academia can enhance the installation for new and retrofit buildings. Building users understanding and motivations are also key for any new technological integration. While other advanced windows can work as retrofitted, BIPV needs special arrangements because of the presence of electrical connections. A clear standard must be introduced which can be country-specific or based on Kopean climate-specific. However, currently, most of the BIPV reports on power generation, heat loss and gain properties, semitransparency level. Noise protection and fire protection (Cancelliere et al., 2021) ability by BIPV is not a very popular research interest; nevertheless, they are also the most prominent sector where more exploration must be prepared. If BIPV windows are treated with replacement of traditional windows then snow (Borrebæk et al., 2020) and dust (Ghosh, 2020b) accumulation must not be ignored. While for traditional windows, dust or snow-covered can just create issues with visual impact and daylight, for BIPV it can stop the power generation or will generate power at much lower rates. Depending on the local climate, the cleaning mechanism should be prearranged. Self-cleaning methods can predominate the BIPV window industry in future (Nundy et al., 2021a, 2020). **Table 2** documented the difference between traditional (single and double glazed) window and BIPV window

Table 2: Comparative analysis between a traditional window and BIPV window (FIPV)

Property	Traditional window	BIPV window
Purpose	Visual impact and connection between interior to exterior	Visual impact and power generation
Transparency	Single glazing~90% Double glazing~80%	Depends on the type of PV cell
Cost	Well advanced technology and depends on the supplier cost is decided. Recently ISSOL , Belgium based solar glass manufacturer estimated the cost for air-filled double glazing 200 euro/m^2	Cost depends on the global market PV price and due to immature technology no standard rate is available. ISSOL estimated the price for silicon based BIPV window 350 euro/m^2

Protection (noise and fire) ability	Traditional single and double glazing are not efficient. There are specific types are available to perform this.	Few investigations have been done to know the capability to tackle these challenges.
Hot Climate application	Single glazing is better as they have a high *U*-value, however high transmission allows excess heat and light	Very potential as it stops the solar energy penetration (including daylight)
Cold Climate application	Double glazing performs better than single glazing due to its low *U*-value. Triple or multiple pane windows performs well. No control over daylight and heat.	Modification is required. Vacuum integrated BIPV can be a suitable option as they possess significant low *U*-values

6. Conclusions

In this work, three different generations of solar PV system for building integrated photovoltaic (BIPV) window or fenestration integration PV (FIPV) was employed. For windows applications, PV must be transparent or semi-transparent type. Thus, first-generation PV which is opaque in nature must be spaced types whereas second generation and third generation are suitable. One of the main challenges for the wide adoption of BIPV windows is the optimisation of both daylighting and electricity generation. In this work, the key conclusions are

- c-Si-based spaced type BIPV is still under consideration and ready to install stage because of the maturity, however, 2nd and third-generation PV based FIPV should be commanding in future
- advanced FIPV technologies can control the four essential factors (*U*-value, SHGC, CCT, CRI) required for window application
- switchable FIPV can be a great alternative compared to static FIPV as it will behave with occupants demand and generate benign power
- bi facial PV based FIPV has more ability to generate power than any other technology and can be a great alternative for future FIPV
- Currently, most of the FIPV only consider transmission and power generation however inclusion for the window frame and how they behave as a combined system will be an interesting approach.

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