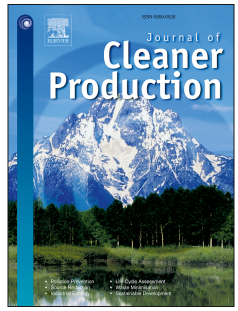


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# Potential of building integrated and attached/applied photovoltaic (BIPV/BAPV) for adaptive less energy-hungry building's skin: A comprehensive Review

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**Abstract:**
The inclusion of photovoltaic (PV) technologies add extra functionalities in a building by replacing the conventional structural material and harnessing benign electricity aesthetically from PV. Building integration (BI) and building attached / applied (BA) are the two techniques to include PV in a building. Currently, first, and second-generation PV technologies are already included for BIPV and BAPV application in the form of wall, roof, and window whereas third generation PVs are under rigours exploration to find their potential suitability. To alleviate enhanced temperature from both BIPV and BAPV, active and passive cooling can be introduced, however passive techniques are influential in trimming down the temperature for retrofit building. Shading from snow, dust cover and nearby building can be an obstacle for BIPV/BAPV application. The hydrophobic (icephobic) self-cleaning coating is suited for snow covering PV while hydrophobic and hydrophilic are both applicable for anti-soiling. Electric vehicles, autonomous switchable glazing, low heat loss glazing and lightweight BIPV are the different future application for PV in BI and BA integration.

**Highlights:**

- A review about building integrated/ attached photovoltaic is presented
- Different possible PV application in building has been discussed
- Issues associated with BIPV/BAPV system has been critically reviewed
- Potential future BIPV application has been introduced.

**Keywords**: BIPV, glazing, energy, temperature, zero energy, dust, snow, shading, PCM, active, passive

## 1. Introduction

### 1.1. Necessity of BIPV/BAPV

It is expected that in 2035 the world energy consumption can be increased up to 50% compared to 1990 due to urbanization and rapid population growth, which will have an impact on the consumption of building energy. Presently buildings consume 40% energy globally due to heating, cooling and artificial lighting loads by the exploitation of fossil fuel (Belussi et al., 2019; Cao et al., 2016; Lu and

Lai, 2019; Y. Zhou et al., 2019)(Ng and Mithraratne, 2014a). Thus, the environment is greatly affected by the emitted pollutant gas during the energy generation process. Energy consumptions and greenhouse gasses (GHG) emission from building sector in megacities such as New York, San Francisco, Tokyo, Hongkong are much higher than even their transport sectors (IPCC, 2014)(Yoo, 2019). International roadmaps target to convert all high energy consumed buildings to zero-energy or net-zero energy building by replacing the energy generation from green sources over fossil fuel sources (Bauer and Menrad, 2019; Jacobson et al., 2017; Taveres-Cachat et al., 2019). In Europe, to fulfil these targets, the new building will be built as near-zero energy consumption by the end of 2020. By 2050, the UK government has set the ambition of reducing national emissions by 80% (García Kerdan et al., 2016) which was later modified and aimed for a more ambitious zero-emission target (The Lancet, 2019). In Asia, Japan has set that all new public buildings by 2020 and all new residential buildings by 2030 should be zero energy. In the USA, new residential construction should be zero energy by 2020, and by 2030 all-new commercial construction should be zero energy (Hu and Qiu, 2019). To achieve this, primary energy use in buildings should be reduced by using an energy-efficient building envelope (Lufkin, 2019).

Photovoltaic (PV) technologies are one of the potential candidate which generates benign energy by harnessing abundant, inexhaustible, clean solar power (van Sark et al., 2010)(Jäger-Waldau et al., 2020). At the end of 2018, global installed PV capacity exceeded over 500 GW (Haegel et al., 2019)(Kurtz et al., 2020). The worldwide PV technology market is expected to grow at a 1.7% compound annual growth rate which shows an increment of 46700 million US$ in 2024 from 42100 million US$ in 2019 (Research, 2020). In Europe, 40% electricity demand by 2020 can be achieved by 1400 TWh electricity production from 1500 GWp installed PV plant which requires 22000 $km^2$ ground floor area, 40% of existing building’s roof and 15 % of façade buildings (Hachana et al., 2016). Use of PV device in a building replaces the actual dead load of the building, i.e., walls, rooftops made with concrete, generates building energy from fossil-fuel free sources which in turn offers a pollution-free environment (Norton et al., 2011). In addition, this can introduce daylighting by replacing opaque building façade which can save 50-80% artificial lighting (Bodart and De Herde, 2002), 11% cooling load and 13% electricity consumption for an office building (Lam and Li, 1999). Addition of PV over a glass, steel and other common cladding material, increase the marginal extra cost only between 2-5% (Paul et al., 2010). Primarily, the inclusion of PV in a building is possible by building integration (BI) or building attached or applied (BA) techniques (Cronemberger et al., 2014).

### 1.2. Overview of BIPV/BAPV

Building integrated photovoltaic (BIPV) is an integral part of a building which substitute or replace the traditional building materials or envelopes such as roof, window, atria and shading elements, components by PV and concomitantly generates benevolent electricity at the point of use (Peng et al., 2011). Glass on glass type semi-transparent type BIPV structure is attractive due to its ability to allow daylighting into indoor space and control over solar gain and offers to view from interior to the exterior (Reddy et al., 2020). Semi-transparent BIPV is also promising for large glazed façade architecture. However, damaged BIPVs have direct access to the internal function of the building (Wang et al., 2006).

The building attached/applied photovoltaic (BAPV) does not replace the construction component, can be rack-mounted or standoff arrays type, opaque in nature and are only employed for power generation and do not contribute to any heat gain into building interior, rather it alleviates heat gain by generating shading the roof or wall from direct solar heat (Peng et al., 2011). Thermal regulation of BAPV systems is straightforward compared to BIPV due to available space between PV systems and building skin. Comparison between BIPV and BAPV is documented in Table 1.

Table 1: Comparison of BIPV and BAPV system (Shukla et al., 2018)

| **Property** | **Building integrated photovoltaics** | **Building applied photovoltaics** |
|---|---|---|
| Integration | Integrated directly within the building structures like roof or façade | Indirect integration by using mounting hardware and roof perforations |
| Weight | Lightweight and heavyweight | Heavyweight |
| Stability | Durable | Breakable |
| Wind effect | Highly resistance to winds | Lift or drag is possible |
| Visual impact | Aesthetically pleasing | Clunky looking |

BIPV and BAPV both generate onsite clean energy which reduces the transmission and distribution losses. Absence of moving part makes it silent, and no hazardous comes out during operation (Scognamiglio, 2017; Scognamiglio and Rostvik, 2013). BIPV has triple-point effect as it maintains day-lighting, controls thermal transmittance and generates electricity. Performance of BIPV and BAPV both depends on the different selection criteria as shown in Figure 1; however, the most indispensable parameters are local meteorological conditions, the tilt angle and the type of material. To obtain electricity from BIPV and BAPV systems, a converter is required to alter direct current (DC) to alternating current (AC) for building and grid both application (Norton et al., 2011). The main component of a BIPV/BAPV system is PV devices which are made from PV cells. Other necessary components of BIPV/BAPV systems are referred as a balance of systems (BOS) which includes an inverter, storage device (battery), switches for control, electrical wiring, and support structure (Shukla et al., 2016a) (Benemann et al., 2001)(Spiliotis et al., 2019) (Saretta et al., 2020). Application possibilities of BIPV and BAPV systems are shown in Figure 2.

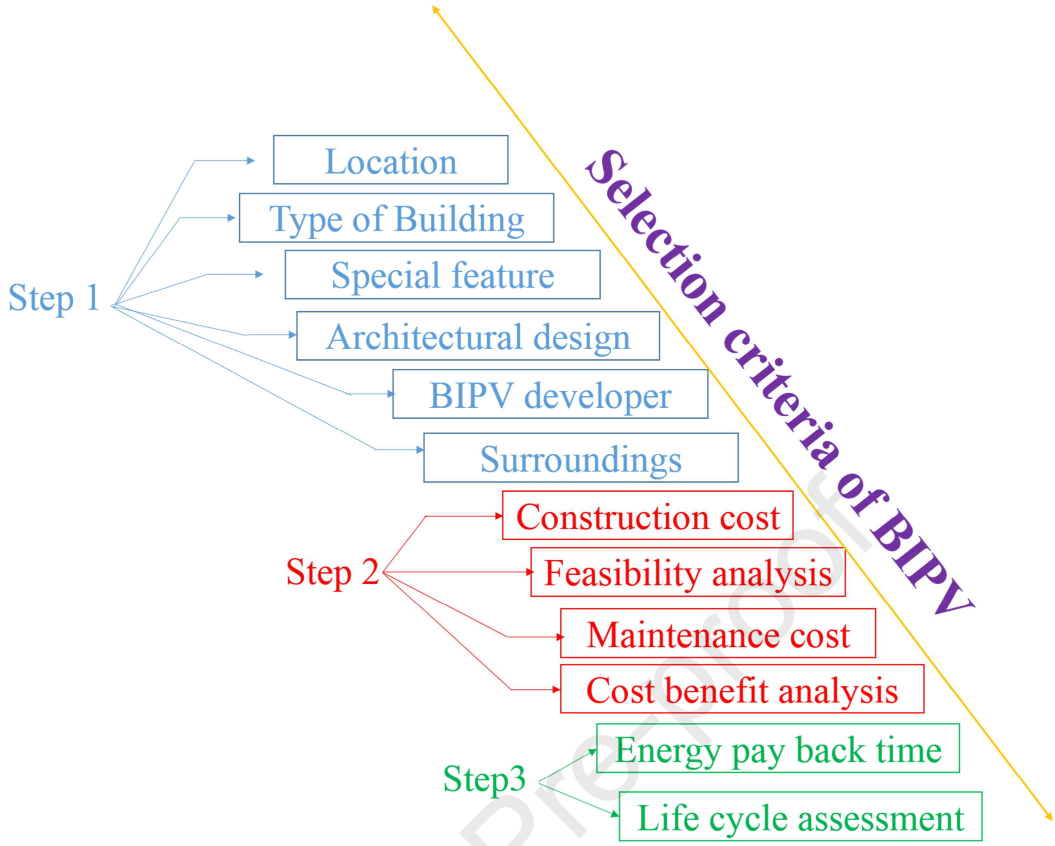



Figure 1: Best selection methods for BIPV. Redrwan from (Alim et al., 2019).

(a) BIPV daylighting application

(b) BIPV wall application

(c) BIPV window application

(d) BAPV roof application

(e) BIPV roof application

(f) BIPV roof application

Figure 2: Application of different BIPV and BAPV systems in building (Photo taken from (Cronemberger et al., 2014)). (Image source: SDEurope)

Due to the present interest of BIPV/BAPV systems, several researchers made high-quality review work. Tripathy et.al. reviewed and mentioned the state-of-the-art of the building envelope products and their properties along with international standards and test conditions, which suggested that the roof-integrated BIPV is lucrative for experiencing uninterrupted incident solar radiation. Monocrystalline PV is responsible for generating much higher greenhouse gasses compared to other PV technologies while life cycle was considered. This work lacks abysmally from providing information on emerging new BIPV application and also shading from snow and dust accumulation (Tripathy et al., 2016). BIPV and its thermal regulation using BIPVT applications have been reviewed in terms of energy generation amount, nominal power, efficiency, type and performance assessment approaches (Biyik et al., 2017). Advancement of dye-sensitized PV based BIPV application has been reported in this work. However, emerging new BIPV technologies are missing from this work (Biyik et al., 2017). Another BIPV and BIPVT review documented that BIPVT system is the future for less energy-hungry building application (Debbarma et al., 2016). Seretta et.al. summarised literature review for building energy demand in urban area and retrofit rate of BIPV and predicted that these two disciplines could merge together where multifunctional BIPV element improve building's energy performance and produce electricity from solar radiation in urban contexts (Saretta et al., 2019). Shukla et.al. reviewed the properties of BIPV products such as foil, title, module, glazing and BAPV system were investigated based on PV performance parameters (efficiency, open-circuit voltage, short circuit current, maximum power, fill factor ), and their life cycle was assessed by considering energy payback time and GHG emission (A. K. Shukla et al., 2017a).

In this review, a detailed application of BIPV and BAPV system, their advantages and challenges associated with this application and solution for these obstacles are presented. Potential future application has been documented in this work which transforms this review to a unique study.

## 2. PV technology for BIPV and BAPV

PV technologies for three different generations have been included in this section where first and second generations are already exploited for BIPV, and BAPV application and third generations are under exploration for their potential integration (Nayak et al., 2019; Sinke, 2019).

### 2.1. First-generation crystalline silicon PV cell

Crystalline silicon (c-Si) (as shown in Figure 3) PV cells are produced from silicon wafers and can be subcategorized into single /monocrystalline (m-Si) and multi/polycrystalline (p-Si). c-Si PV technology is mature, non-toxic, abundant and possess long term performance (Battaglia et al., 2016; Glunz et al., 2012; Zarmai et al., 2015). Monocrystalline cells are produced by the Czochralski process from single silicon crystals which are expensive manufacturing methods due to precise processing requirement form large single crystals. The efficiency of the monocrystalline type lies between 17%-18% (Saga, 2010; Sharma et al., 2015). Polycrystalline type of cells is produced by molten silicon solidification. The efficiency of this type of cells is between 12%-13%. c-Si PV shows 20-30 years of durability under outdoor exposure (Aste et al., 2016; Rand et al., 2007). High durability and mature technology make c-Si suitable for BIPV and BAPV systems application. Silicon prices which rose steeply between 2000 to 2008 with a peak of \$475/kg, also declined rapidly in the last decade having steady prices of approximately \$25/kg (Fu et al., 2015). It is estimated that globally c-Si PV market would reach \$163 billion by 2022, which is 11.3% enhancement from the 2016 level. Energy payback period lies between 3-4 years for this type of technology (Luo et al., 2018; Ogbomo et al., 2017). Canadian Solar, JA Solar, JinkoSolar, Hanwha Q-CELL, LONGI, Tongwei, Trina Solar are the present leading vendor for first-generation crystalline silicon PV cells.

(a) (b)

Figure 3: Crystalline silicon (a) mono and (b) poly type. (Image courtesy: SHINESOLAR and DH-SOLAR)

### 2.2. Second generation thin film technology

Cadmium telluride (CdTe), copper indium gallium selenide sulphide (Cu (In, Ga)Se2, CIGS) and amorphous silicon (a-Si) are the second generations thin film technology which has low manufacturing cost and low-temperature coefficient compared to crystalline silicon solar cell (Tossa et al., 2016). However, low solar to electrical conversion efficiency compared to crystalline silicon PV cell and performance degradation after long-term outdoor exposure (Jordan and Kurtz, 2013; Muñoz-García et al., 2012) is the significant barrier of using this technology. Irradiance, spectrum, angle of incidence, ambient temperature and wind speed also affect the performance of thin-film technologies in a similar way to c-Si technology; however, the temperature dependence is weaker in comparison to c-Si technologies. These technologies absorb the solar spectrum much more efficiently than single crystalline or multi-crystalline and use only 1–10 µm of active material (Shukla et al., 2016b, 2016a)

#### 2.2.1. Amorphous silicon (a-Si)

a-Si PV absorbs a higher amount of solar radiation than c-Si because of the absence of the crystalline structure (Muñoz-García et al., 2012). Low-temperature coefficients of a-Si cells make it a potential candidate than c-Si cells in summer and warm climate (Ruther and Livingstone, 1995)(Virtuani and Strepparava, 2017). Due to the Staebler–Wronski effect, a-Si shows light-induced metastability which requires time to produce a sufficient amount of power from a-Si PV (Matsui et al., 2018; Staebler and Wronski, 1977). Spectral changes of terrestrial insolation in summer and winter remarkably influences the changes of efficiencies for a-Si (Eke et al., 2017; Polo et al., 2017; Ruther and Livingstone, 1995). Investigation in India showed that a-Si module offered 14% higher energy than p-Si in summer while 6% less in winter (Sharma et al., 2013). Experiment results from Spain also supported that argument (Cañete et al., 2014). Spectral variation of external incident solar radiation has an adverse impact on fill factor (FF) (FF depends on both quality and quantity of solar radiation) of an a-Si PV cell. Blue spectra have a positive impact, while red spectra reduce the FF (Rüther et al., 2002). Device flexibility, low-temperature processing, low negative temperature coefficient of a-Si has created commercial interest significantly for BIPV applications (Stuckelberger et al., 2017). To rectify a-Si's light-induced degradation, tandem amorphous/microcrystalline silicon thin-film PVs have also been investigated (Tsai and Tsai, 2019). **Figure 4** shows the a-Si PV module integrated into a building. The energy payback time and operational lifetime of a-Si PV are 2-3 years and 25 years, respectively (Peng et al., 2013a; Zhang et al., 2018; Zhou and Carbajales-Dale, 2018). Presently they have a market share of 5% (Ogbomo et al., 2017).

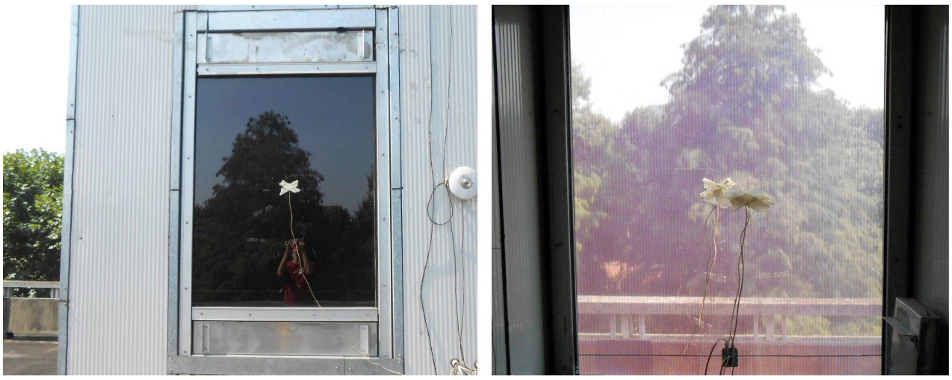


Figure 4: Photograph of an a-Si integrated to a building and viewing through a-Si PV from building interior to exeterio. (Liao and Xu, 2015).

### 2.2.2. Cadmimum teluride (CdTe)

In cadmium telluride (CdTe) PV cells, consist cadmium which is a by-product of zinc and telluride. Cadmium (Cd) is a heavy metal and has a potential toxic property for human, animals and plants. CdTe contains ≤7 g of elemental Cd in per square metre of PV cell compared to average single-cell nickel-cadmium battery (Kuhn et al., 2016; Kuribayashi et al., 1983; Ogbomo et al., 2017; Rodriguez et al., 1995; Shukla et al., 2016b, 2016a). The second material, telluride (Te), is scarce and as rare as platinum in nature which increases the price of the CdTe PV cell. The limited supply of Cd and its potential environmental hazards are the main issues with this technology (Fthenakis, 2004; Raugei et al., 2012). Thus recycling and disposal of CdTe cells are expensive (Sethi et al., 2011). Although the Cd element is hazardous, however, the compound CdTe used in PV cells is much more environmentally benign. CdTe thin-film PV was commercialized in 2001 which had power density between 62.5 W/m$^2$ to 76.38 W/m$^2$ and the efficiency for this 55 Wp module had 8% (Enríquez and Mathew, 2003; Lee and Ebong, 2017). CdTe type PV cell has a theoretical efficiency limit of 29% (Dobson et al., 2000). Synthesization of CdTe became popular after the development of screen printing, vacuum evaporation and electron deposition techniques (Virtuani et al., 2011). It is recommended that the CdTe PV module should be kept under direct sunlight for four hours before taking the measurements (Muñoz-García et al., 2012). Long term (23 months) outdoor analysis in tropical climate (Delhi 28.70° N, 77.10° E, India, as shown in Figure 5) showed 2.91% open circuit voltage deviation, and no deviation was found for short circuit current (Rawat et al., 2018). The energy payback time of CdTe varies between 0.75 to 2 years while operational lifetime is 20 years (Peng et al., 2013a; Zhang et al., 2018; Zhou and Carbajales-Dale, 2018; Zidane et al., 2019). Presently they have a market share of 5% (Ogbomo et al., 2017).

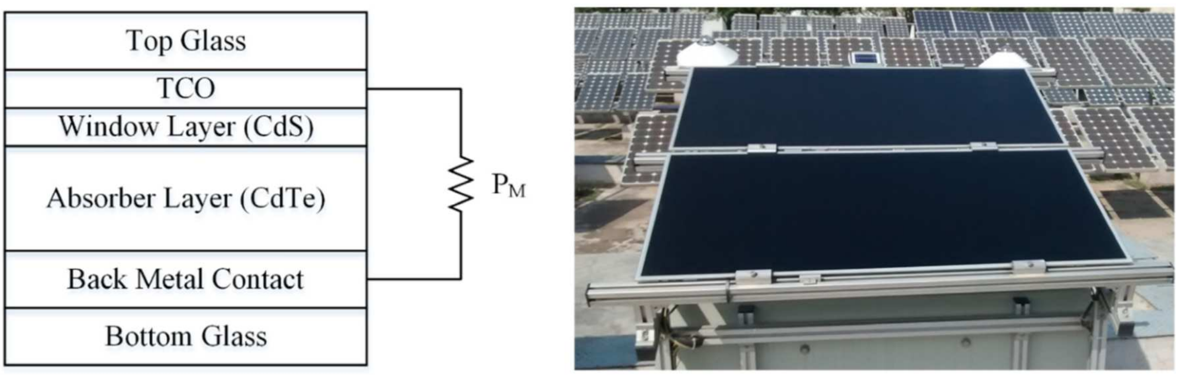


Figure 5: Layer diagram and experimental test setup of CdTe module (Rawat et al., 2018)

#### 2.2.3. Copper indium gallium diselenide (CIGS)

Copper indium gallium diselenide (CIGS) PV cells as shown in Figure 6 comprises of the four elements, namely: Copper, Indium, Gallium and Selenium (Dhere, 2011; Kazmerski et al., 1976). Gallium-free variants of the semiconductor material are abbreviated as CIS. The manufacturing cost is lower than the crystalline silicon PV cells but more expensive than other single-junction thin-film cell like cadmium telluride.

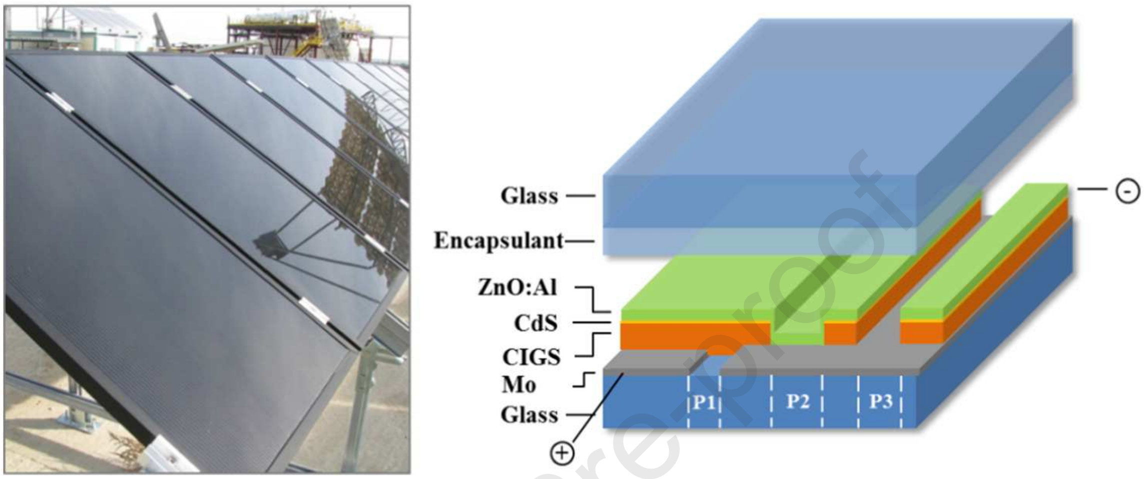



Figure 6: Large scale CIGS PV module [taken from (Delgado-Sanchez et al., 2017)]

CIGS PV technology has average production efficiencies between 12% to 15% for commercial modules and achieved a record efficiency of 22.3% in the laboratory. Degradation rates of CIGS are the most significant challenge (Theelen et al., 2015). Through the simulation process, it is predicted that CIGS modules will still yield 80% of their initial power after 20 years of field exposure. However, a real-time experiment is required to prove this (Yalçin and Öztürk, 2013) hypothesis. Results from different outdoor experiment offered a significant variation from 0.02% to 4.1% degradation (Theelen et al., 2015). The energy payback time of CIGS varies between 1.2 to 2.4 years while operational lifetime is 20 years (Peng et al., 2013a; Zhang et al., 2018; Zhou and Carbajales-Dale, 2018). Presently they have a market share of 4% (Ogbomo et al., 2017).

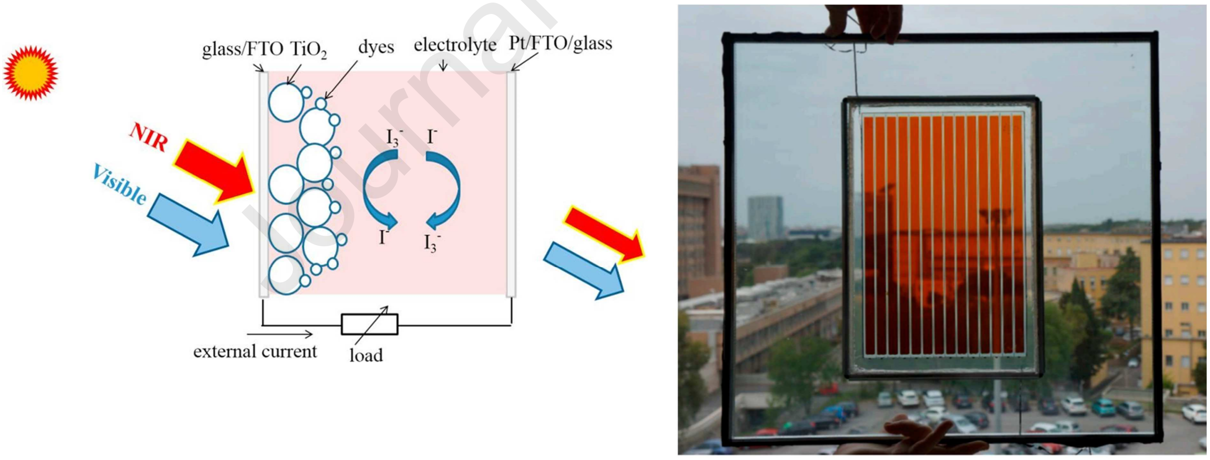
The Global thin-film PV cell market is expected to be USD 13,256.13 Million by the end of 2025 with a compound annual growth rate of 12.87% from USD 5,678.13 Million in 2018. Leading vendors for global thin-film PV cell are Ascent Solar Technologies., Asia Ltd., First Solar, Global Solar, Miasole Hi-Tech Corp., US, Hankey Kaneka Corporation, Trony Solar, Mitsubishi Electric and Xunlight Kunshan Co. Ltd (Report, 2020).

### 2.3. Third or new generation PV

Sunlight can generate electricity with close to Carnot limit or 95%. However, first and second-generation solar cells can only exploit 31% due to Schockley-Queisser limit. Rest of the energy for single-junction cells are lost as heat. Third-generation solar cells are free from this Schockley-Queisser limit. The aim of using third generations is to generate low-cost electricity using high-efficiency conversion (Dupré et al., 2015).

### 2.3.1. Dye-sensitized solar cell (DSSC)

A dye-sensitized solar cell (DSSC) consists four main components: mesoporous oxide layer ($TiO_2$), dye sensitizer, an electrolyte containing redox couple, counter electrode made of platinum-coated glass as shown in Figure 7 (O'Regan and Gratzel, 1991). DSSC fabrications are simpler and low cost, environmentally benign than other PV cells as it is processable under ambient temperature. Flexible, lightweight, convenient design such as multicolour option and transparency and short energy payback time, working in cloudy weather or low-light conditions make it more viable for building integration (Gong et al., 2017, 2012) (Mathew et al., 2014). DSSC efficiency currently reached to 11.9% (Green et al., 2019). Photochemical degradation of sealants, solvents, dyes and solvent leakage is the hurdle for its promulgation. Thermal stress due to day/night cycle can also influence of intrinsic chemical degradation. Instability issue of DSSC due to leakage from a liquid electrolyte can be rectified by using solid-state hole transport material. Highly conductive and stable polymer electrolytes are better candidate for large scale DSSC manufacturing (Xia et al., 2006). Replacement of platinum catalyst with graphene can offer higher electrochemical stability which solves the degradation of the platinum catalyst (Kavan et al., 2011) and 20 years lifetime of DSSC is possible by solving these issues (Grätzel, 2003) (Upadhyaya et al., 2013). Recently the use of uncleaned FTO glasses showed the highest efficiency for DSSC than that of cleaned FTO glasses by using water, acetone, isopropanol or ethanol. Uncleaned FTO glasses contained stains and residual dirt (Gossen and Ehrmann, 2019). 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). In 2022, the market value of DSSC is expected to be USD 59.52 million, while the significant application of DSSC will be in BIPV and BAPV. Globally major DSSC companies include 3GSolar Photovoltaics, Dyesol, Exeger Sweden AB, Fujikura Ltd., G24 Power., GCell, Merck KGaA(View, 2016).

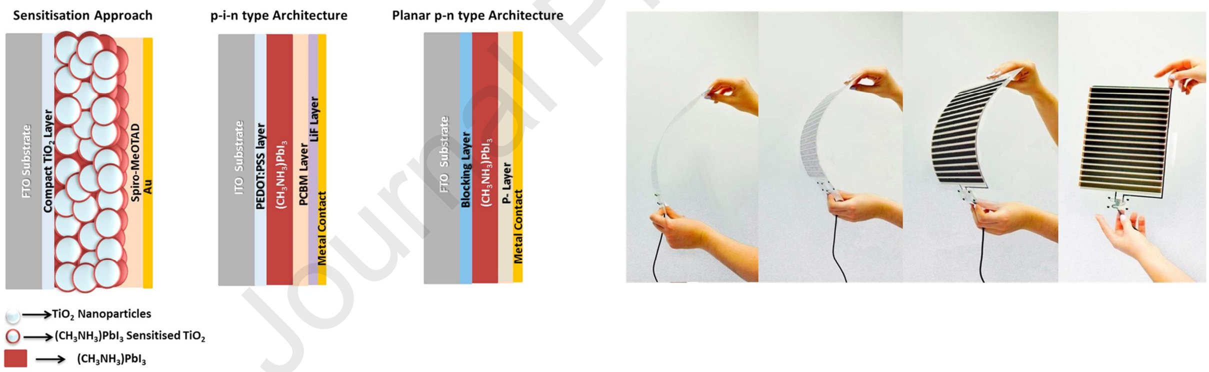



**(a)** **(b)**

Figure 7: (a) Schematic diagram of the dye-sensitized solar cell (DSSC), (b) Semi-transparent DSSC (Cornaro et al., 2018).

### 2.3.2. Perovskite solar cells

In a perovskite solar cell (PSC) perovskite structure absorbs light similar way as dye work in a DSSC. PSC offered efficiency from 3% to 22% within a very short span of less than 10 years which attracts researcher to work on it (Bi et al., 2016; Son et al., 2016). The general formula for perovskite is ABX3, where A indicates cation and B indicates anion. **Figure 8** shows different perovskite architecture. Most popular PSC consists of Methyl-ammonium-lead-iodide (MAPbI3/ CH3NH3PbI3) (Asghar et al., 2017; Ku et al., 2013; Seo et al., 2014; L. Zhou et al., 2019). This type of PV cells can offer semitransparency which is suitable for BIPV glazing and glazed façade application (Cannavale et al., 2017a, 2017b). Stability of perovskite under outdoor environment is a critical issue as exposure to moisture and oxygen; perovskite performance degrades significantly which limits its large scale production (Asghar et al., 2017). Due to the presence of moisture, the formation of $CH_3NH_3PbX_3$'s mono- and di-hydrates, convert to PbX. Thus airtight conditions are recommended during perovskite processing. Efficient PSCs contain toxic lead which can hamper the acceptance of this technology and could conflict with legislative barriers (Bush et al., 2016; Howard et al., 2019; Z. Wang et al., 2017). Ambient processed perovskite have also been under investigation(Bhandari et al., 2019) (Niu et al., 2018; Tai et al., 2016; Wei et al., 2019; Yang et al., 2018). Two-dimensional Ruddlesden–Popper (RP) PSCs exhibited a power-conversion efficiency as high as 20.62% and with 2880 hours without encapsulation stability (Niu et al., 2018). Recently perovskite stability till 1,800 hrs at 70 to 75°C, and 8% drop from peak performance after 5,200 hrs was achieved (Bai et al., 2019). Considering its lower stability, PSC still in consideration as its transparency can be tuned.  Making thinner PSC  (Della Gaspera et al., 2015) or controlling the morphology of PSC, semitransparency is achievable.  In 2017 alone, over 3000 academic journal regarding perovskite indicates its popularity among the researcher (Snaith, 2018).  Work on energy payback for perovskite is less explored are however few works suggested that it can vary between 0.2 to 5 years depends on the type of material employed (Espinosa et al., 2011; Gong et al., 2015; Ludin et al., 2018). In 2017, the global perovskite market was $3.7 billion and it is growing with compound annual growth rate (CAGR) of 7.0%  hence, in 2022 market value should reach $5.2 billion (B. Research, 2018). Oxford photovoltaics, OIST's Technology, Solliance, Toshiba and NEDO are currently the major perovskite PV cell developer (Roy et al., 2020).



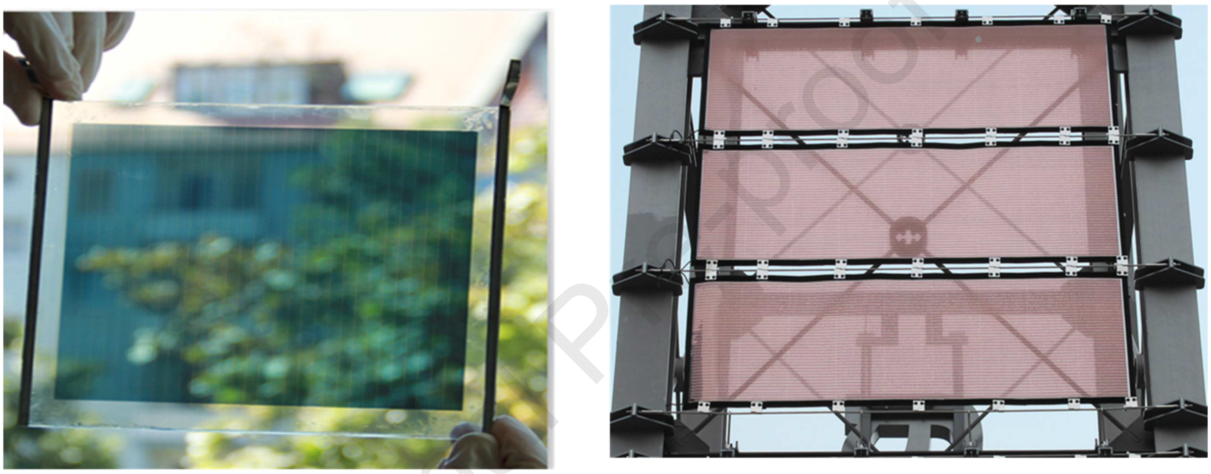

**(a)** **(b)**

Figure 8: (a) Schematic of different perovskite PV cells architectures (Taken from (Senthilarasu et al., 2015)) (b) Printed, flexible, perovskite photovoltaics by injket printing tehcnique developed by Saule Technologies, (image courtesy: Saule Tehcnologies)

### 2.3.3. Organic PV

Organic materials have the ability to absorb the entire solar spectrum due to the presence of π-bonded electrons being able to move along the delocalized π-orbitals arising from sp2-hybridization states of carbon atoms (Kippelen and Brédas, 2009). Most organic semiconductors are p-type with a relatively large optical bandgap (1.5–3 eV), reducing the production costs and the cell mass, because of the very thin layers involved. The excitons diffusion length is relatively small for organic PV cells which are a drawback compared to inorganic cells. Organic PV (OPV) is not suitable for low light condition as it affects with photon having energy level, between 1.7 to 2.1 eV; however, its open-circuit voltage rarely crosses 1.0V (Elumalai and Uddin, 2016). Open circuit voltage of OPV may have a logarithmic relation with irradiation (Bristow and Kettle, 2016) (Mulligan et al., 2014). Though it has low efficiency still possess shorter energy payback time (~2.02–0.79 years) is shorter compared to c-Si

(~4.12–2.38 years) CIGS (~2.26–2.2 years) (Darling and You, 2013)(Anctil et al., 2019). Figure 9 shows a photographic view of OPV module. OPV shows lower thermal coefficient due to lower infrared absorption than silicon (Bristow and Kettle, 2018). After three years of outdoor exposure, OPV module initially degraded rapidly while secondary degradation rate was gradually, and following seasonal variation due to metastability of the solar cells (Sato et al., 2019). In 2012, the world's first grid-connected 0.2kW OPV system where nine flexible and transparent OPV modules formed of a sun sai was commissioned at Mainova AG in Frankfurt. The global market value of OPV is expected to be US$97.4 million by the end of 2020 which expanded with the phenomenal compound annual growth rate of 21.20% between 2014 and 2020. Epishine, Heliatek GmbH, Merck Group, OPVIUS GmbH, infinity PV are the major companies which manufacture organic PV cells (Report, 2018). Table 2 listed comparison of different PV cells.



**(a)** **(b)**

Figure 9: Rigid organic PV (OPV) module.(Lucera et al., 2017)

Table 2 : Comparative analysis of different PV cells.

| Type of PV cell | Generaion | Efficiency | Advantages | Disadvantages |
|---|---|---|---|---|
| Mono-crystalline silicon (m-Si) | 1st | 26.7% (Green et al., 2019) | Highly standardized, highly efficient, commercially abundant | Expensive manufactruing process and silicon waste is maximum in the production process |
| Polycrystalline silicon (p-Si) | 1st | 22.3(Green et al., 2019) | Lesser energy and time needed for production, lower costs, Easily available on the market, Highly standardized | Relatively low efficiency than mono-crystalline silicon |
| Copper indium diselenide (CIGS) | 2nd | 22.9(Green et al., 2019) | High temperatures and shading have lower impact on performance, | Higher amount of space is reuiqred for the eqaul amount of output |

| | | | | |
|---|---|---|---|---|
| | | | Highest cost-cutting potential | power is needed |
| Cadmium telluride (CdTe) | 2nd | 21%(Green et al., 2019) | Higher temperatures and shading have lower impact on performance, Less silicon needed for production | Similar to CIGS degradation, limited supply of Cd and potential environmental hazards. |
| Amorphous silicon (a-Si) | 2nd | 10.2%(Green et al., 2019) | Higher temperatures and shading have lower impact on performance, Less silicon needed for production | Similar to CIGS and CdTe |
| Perovskite | 3rd | 20.9%(Green et al., 2019) | High efficiency achivable, transparency is possible | Instability issue at outdoor ambient, Large scale deveice |
| DSSC | 3rd | 11.9% (Green et al., 2019) | Low cost and low favrication process, semitransparency is possible by tuning thickness | Instability issue at outdoor ambient, and large scale fabrication |
| Organic | 3rd | 11.2%(Green et al., 2019) | Presence of π-bonded electrons absorb huge range of soalr spectrum, Tempereature has lower impact on the efficiency degradation | Degradation varies from weeks to about 2 years, Positive and negative both type temperature coefficients are possible depdns on the employed material |

## 3. PV for BI/BA application

### 3.1. roof integration

Inclusion of PV on the roof of a building utilizes the not productively used roof area and PV system act as a power generating roof. Roof integration includes both BIPV and BAPV(Alnaser, 2018) types. Commercially available mature silicon and thin-film technologies are the presently employed for roof-integrated BIPV and BAPV (Aaditya et al., 2013; Aste et al., 2016; Sorgato et al., 2018; Zomer et al., 2013). For BAPV system naturally ventilated are preferred for simpler installation while for BIPV technology, semitransparency is a precondition. BAPV generates higher power while BIPV enhances the overall performance of the building as semi-transparent BIPV roof renders daylight into an interior and also controls the heat gain and loss (Jelle et al., 2012; Zomer et al., 2013). For roof integration, the area available on the roof is essential parameters which can be evaluated from the ground floor (Yadav and Panda, 2020). In general, it was found that the ratio between potential PV-suitable rooftop area vs. ground floor area is 0.4 (Peng and Lu, 2013). For pitched roof commercially available standard BIPV, BAPV or solar tiles are applicable (A. K. Shukla et al., 2017a). BIPV and BAPV Roof integration with traditional PV systems are shown in Figure 10. Figure 10 (a) 3. 6 kWp BAPV roof in Australia, (b) BAPV roof integration, University of Exeter, Penryn Campus, (c, d)Typical house construction with BAPV in Southwest of England (Truro and Falmouth), (e) Typical house BAPV in South Korea (f) Rooftop BAPV application at a school in Suriname (Raghoebarsing and Reinders, 2018) (g) Typical roof-integrated semi-transparent BIPV installed in Taipei Public Library Solar LEO House BIPV, (h) shows India's first zero energy building using BAPV, constructed in 2014 where PV panels occupy 4,600 m$^2$ area and annual energy generation: 14 lakh ($19k) Unit kWh while the cost of installation was Rs 18 crore ($2533k), (i) Semi-transparent spaced type crystalline silicon-based glass-glass BIPV for roof application having installed capacity of 168kWp (Image courtesy: HHV Solar Bangalore, India. Roof integration of PV is beneficial if they are not shaded by nearby trees, tall buildings.

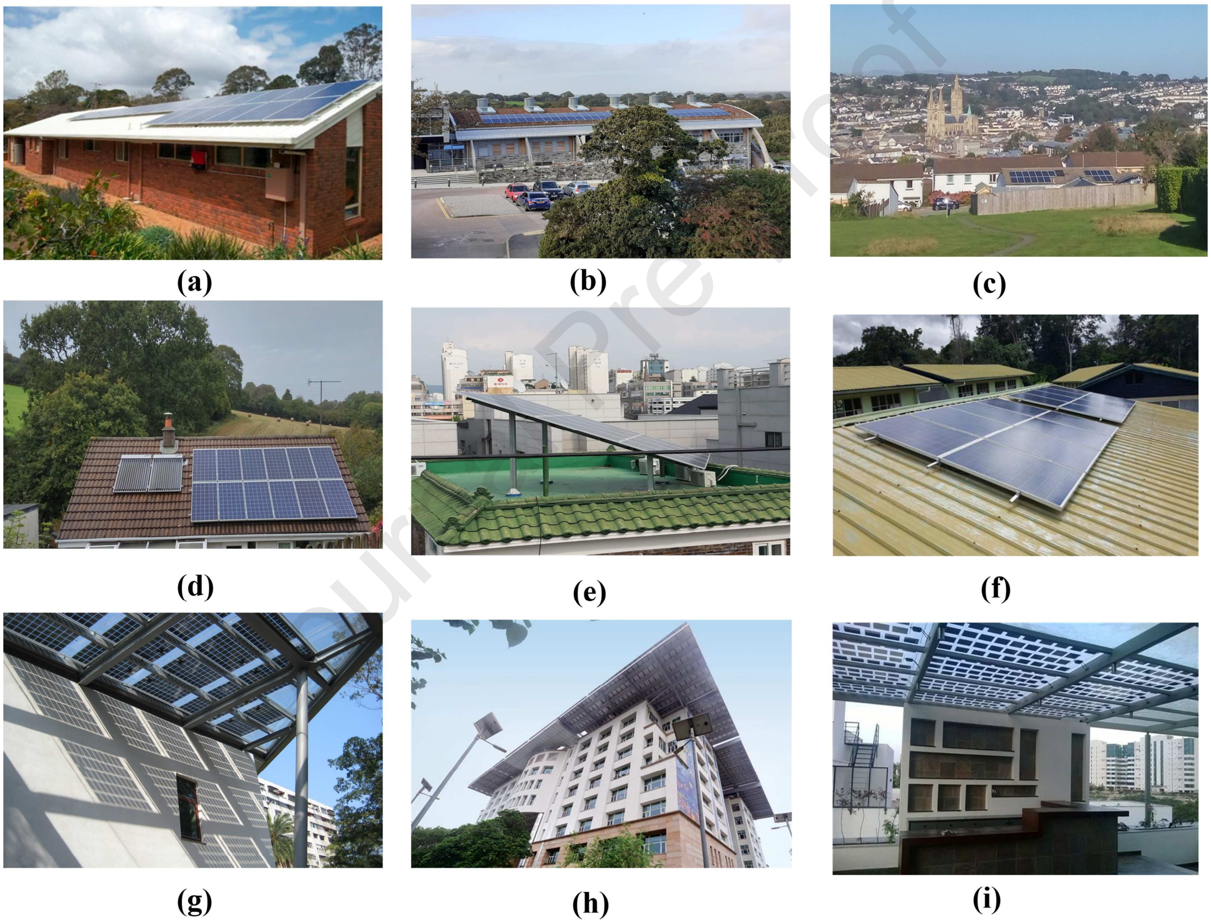



Figure 10: (a) 3. 6 kWp BAPV on equatorial facing roof in Australia (taken from (Miller et al., 2018)), (b) BAPV roof integration, University of Exeter, Penryn Campus, Figure (c, d)Typical house construction with BAPV in Southwest of England (Truro and Falmouth), (e) Typical house BAPV in South Korea, (f) Rooftop BAPV application at a school in Suriname (Raghoebarsing and Reinders, 2018), (g) Taipei Public Library Solar LEO House BIPV (no copyright was required), (h) Indira Paryavaran Bhawan India (Jaymin, 2018), (i) semi-transparent spaced type crystalline-silicon based glass-glass BIPV for roof application (Image courtesy : HHV Solar Bangalore , India

Solar tiles replace the  conventional 'roof tiles' with solar PV tiles which are elegance in looking, aesthetics for roof and also eliminate existing utility costs, easy for installation and highly durable

(Huang et al., 2014). Presently Dow Chemical, CertainTeed (Apollo line), SunTegra, Atlantis Energy (SunSlates), and Tesla are the provider of solar shingles. CertainTeed product contains14 high-efficiency monocrystalline silicon solar cells in a single solar shingle which produce 60W. For Luma Solar product, airflows are allowed underneath the shingle, which shows 21% solar-to-electricity conversion efficiency, even higher than rack-mounted panels. SunTegra's solar shingles are lightweight and use 50% less wiring than rack-mounted solar panels. Powerhouse 60-Watt shingles will have an energy conversion efficiency factor of 17.1. Figure 11 shows the presently available different solar shingles. In 2016, the global BIPV roofing market value was US$ 2.4 billion, which is expected to grow with a compound annual growth rate of 14.65 % over the between 2019 - 2027. In 2027, BIPV roof market values are expected to be US$ 37.26 billion (Analysis, 2020).


Figure 11 : Different Solar Shingles (image courtesy : CertainTeed, Suntegra, LumaSolar, Powerhouse, Sunflare)(Guess, 2018)

### 3.2. Wall integration

PV systems for wall application includes (Peng et al., 2013b) (1) mounting of PV module on the existing wall as BAPV systems and (2) direct integration of PV module on the building wall to replace the external wall or glass as BIPV system and. PV cladding is the common BAPV wall application where between building envelope and PV, gaps are maintained to enhance the PV performance (Yang et al., 2000) (Peng et al., 2013b). The external wall of a black-painted Trombe wall can be replaced by a bluish PV system to transform it aesthetically in nature (Sun et al., 2011). Performance of the PV Trombe wall depends on the PV coverage as opaque PV cells restrict the incident solar radiation to reach the Trombe wall and the wall thickness can vary between 0.3-0.4 m to minimize the thermal swing inside the room and zero thermal heating (Taffesse et al., 2016) (Sun et al., 2011).

Investigation on retrofit building in Italy using c-Si, a-Si and CIGS based BIPV exhibited 45% and 20% less power generation from a-Si and CIGS respectively than c-Si. This was due to a higher operating temperature of a-Si and CIGS as they had lower NOCT than c-Si. Semi-transparent a-Si thin-film based BIPV wall is shown in **Figure 12a**. The performance showed that PV power generation was almost half of that in the rated values. The possible reason was predicted that the building was tilted to 50° to the southwest and also was affected due to the self-shading created from its own building mass (Yoon et al., 2011). (Evola and Margani, 2016). Ventilated a-Si based BIPV wall at Zhuhai, China ( Latitude 22.37 N, 113.54 E) showed 0.5~1.5°C lower operating temperature and 0.2%~0.4% higher power generation compared to non-ventilated counterpart. Annual energy output difference between both the system was 0.41% (**shown in Figure 12b**) (Zhang et al., 2014).


Figure 12: (a) Photograph of wall integrated completed building of R&D Institute, Kolon Engineering and Construction, Yongin city, Gyeonggi, the central region of Korea (latitude 37°17′ N, longitude of 127°12′ E)(Yoon et al., 2011), (b) The two amorphous silicon PV walls under experiment Zhuhai, China ( Latitude 22.37 N, longitude113.54 E) (Zhang et al., 2014), (c) BIPV wall made of dye-sensitized cell (DSSC) technology; System provider: Konarka Technology* (Heinstein et al., 2013).* Konarka Technology was spin out company from University of Massachusetts, Lowell, USA, presently out of operation (d) Ekoviikki Sustainable City Projects, Finland (image courtesy: SOLPROS), (e) External elevator glass was integrated with OPV. (Image courtesy: OPVIUS GmbH), (f) energy-efficient ETFE façade installed using printed

Organic Photovoltaic implemented it as part of the rebuilding work on the premises of Merck KGaA in Darmstadt (Image courtesy: OPVIUS GmbH).

First and second-generation PVs are predominant for wall application whilst third-generation PV cell-based BIPV/BAPV wall is rare. Figure 12c shows DSSC based wall, which was developed by Konarka Technology (Heinstein et al., 2013). OPV based BIPV for cladding application was investigated using indoor experimental data which was scaled for simulation of commercial size OPV BIPV cladding. The system simulations compare typical energy demand profiles of small commercial buildings and illustrate that OPV arrays show strong potential to be used with excess energy generation for 8 months of the year based upon a 4.22 kWp OPV system and can adequately meet the energy demand in spring, summer and autumn for a small commercial building in Northern Europe (Stoichkov et al., 2019). Installing PV in balcony also another approach where obstacle for viewing is negligible. Total 240 $m^2$ of photovoltaic modules were installed for balcony glazing on the south and west sides of the house in a residential building in Finland, as shown in Figure 12d. Figure 12 e and Figure 12f show external elevator glass were integrated with OPV and first energy-efficient ETFE façade installed using printed OPVwhich was implemented as part of the rebuilding work on the premises of Merck KGaA in Darmstadt.

### 3.3. Grid integration

Grid-connected BI/BAPV reduces the necessity of storage device and generated electricity to supply both building and grid or grid only (Benemann et al., 2001; Eltawil and Zhao, 2010; Gorgolis and Karamanis, 2016; Hagemann, 1996; Leon and Vinnikov, 2015). Figure 13 shows the schematic of the grid-connected BIPV and BAPV system.

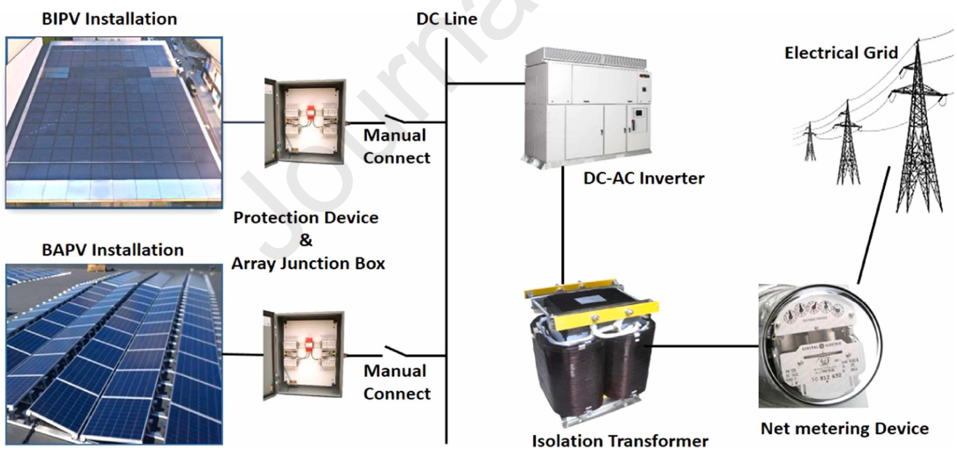



Figure 13: Schematic view of grid-connected BIPV and BAPV system (Taken from(N. M. Kumar et al., 2019))

Energy from grid-connected BAPV and BIPV both depends on rated characteristics of a PV system, the geographical location of the systems while the reliability of control systems also play an essential role. For grid connection, employed different types of inverters are central, string, multi-string, AC-module and microinverter (Kjaer et al., 2005) (Allouhi et al., 2016; Aristizábal and Gordillo, 2008; Kazem and Khatib, 2013; Liu et al., 2012; Yang et al., 2004)(Elavarasan et al., 2019). To use string inverter, BA/BIPV modules are connected in series, and the string is connected to one inverter which can lead to a lower PV energy yield during partial shading conditions, thereby degrading the overall system performance. Especially when different sizes and types of PV are used, stringing becomes extremely challenging (Ravyts et al., 2019). Microinverters are attached to the back of each PV module and beneficial for partial shading condition and different types and sizes of PV systems (R. Hasan et al., 2017). To obtain maximum power from PV-inverter combination, the power rating of inverter should match the power rating of the PV system (Mondol et al., 2006). Except inverter to convert the generated DC power output from PV to AC, filters are required between PV and grid to reduce the inverter's harmonics and minimize or neutralize the spikes from the grid (Liserre et al., 2004; Milan Pradanovic and Timothy Green, 2003). Voltage level fluctuation, voltage flicker and unintentional islanding is the major issue occur for PV and grid connection (Shivashankar et al., 2016). Intermittent nature of PV changes the voltage level, which creates trouble for grid connection. The magnitude of cloud cover is independent of the voltage fluctuation (Woyte et al., 2006). Voltage harmonics in grid mainly the effect of generated current harmonics due to PV inverters. Harmonics are the biggest reason for losses in the distribution system. PV power output changes also create frequency fluctuations which can not be nullified by the PV system due to its lack of inertia. Voltage flicker and fluctuation of the PV system can be reduced if the size of the PV arrays is big enough. Larger the size of the PV array lowers the fluctuations (Marcos et al., 2011). Inverter selection and design of new inverter are required for grid-tie PV as inverter converts DC power to AC, controls power factor, regulates reactive power (Tsengenes and Adamidis, 2011)(Yan et al., 2019).

### 3.4. Window application

BIPV window plays a vital role in the overall building energy performance of retrofitted or new buildings. A window of a building is responsible for viewing while it allows daylight and higher heat to flow from interior to exterior and admits solar heat gain (Ghosh and Norton, 2018). BIPV window controls the entering daylight and solar energy transmission while can also reduce the heat flow from building interior to the exterior (Ng and Mithraratne, 2014a; Yoon et al., 2013). BIPV for window application should be transparent or semi-transparent in nature (Alrashidi et al., 2020a, 2020b). For BIPV glazed window the most indispensable fact is to maintain a balance between the visible light transmission and power conversion efficiency, in addition, considering colour comfort and thermal comfort (Wheeler and Wheeler, 2019). To achieve BIPV window, spaced type structure by maintaining gaps between PV cells (Sánchez-palencia et al., 2019) (Park et al., 2010) or by tuning the PV material thickness, transparency is achievable. Spaced type structure is popular for first-generation opaque crystalline silicon which has higher absorption and low transmittance (Riverola et al., 2018; Santbergen and van Zolingen, 2008). The percentage of PV area coverage offers the semi-transparency of this type window as depicted in **Figure 14a**. Thus, solar heat gain, indoor illuminance, daylight factor for spaced BIPV window depends on the glazing area covered by PV whereas efficiency and thickness of PV have less impact on those parameters (Chau et al., 2010; Fung and Yang, 2008; Karthick et al., 2018; Park et al., 2010; Peng et al., 2019). This spaced type semi-transparent BIPV window offers similar quality of daylight as the light passes through only the glass materials (Ghosh et al., 2019b).

Tuning the material thickness, semi-transparency is achievable from second-generation thin film and third-generation emerging PV technologies. For this type of BIPV window, transmittance or material thickness is directly related to PV power generation where thinner material posses higher transmittance and generates low power (Chow et al., 2007; Miyazaki et al., 2005; Takeoka et al., 1993). The solar factor is directly related to transmittance, while *U*-value has no impact on the window transmittance (Alrashidi et al., 2019; Barman et al., 2018). a-Si type has temperature enhancement issue which can be reduced by creating airflow in a double pane window while tilted always showed higher operating temperature than horizontal or vertical orientation (Han et al., 2009) (Yoon et al., 2013)(Chatzipanagi et al., 2016). Recently, highly insulated a- si based BIPV window was fabricated which showed 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 energetic performance of CdTe and Perovskite-based window was evaluated which recommended that for higher transmission window to wall ratio needs to be high to generate higher power than low transmission material (Sun et al., 2018) (Cannavale et al., 2017b, 2017a). Organic PV (OPV) based BIPV window (OBIPV) also currently under investigation (shown in Figure 17 b). The efficiency of this OPV system varies between 4%-10% (Chemisana et al., 2019; Chen et al., 2012; Duan et al., 2019; Yan et al., 2012). In another work one 20% transmittance, 15% reflectance and 65% absorptance OPV glazing overall heat transfer coefficient was about 6.0 Wm$^{-2}$ K$^{-1}$(Friman Peretz et al., 2019).

Visual comfort gets higher priority for BIPV window. DSSC based BIPV window (Figure 14 d) where dye colour can be anything, colour property analysis is essential before installing them (Kang et al., 2003)(Aritra Ghosh et al., 2018c). Material degradation often enhances the transmissivity which may enhance the visual perception and colour render (Roy et al., 2019; Selvaraj et al., 2019). Carbon counter electrode based mesoscopic Perovskite was investigated for BIPV window where this PV device had 20% visible transmission, 0.33 solar heat gain coefficient and 5.6 W/m$^2$K overall heat transfer coefficient (Ghosh et al., 2020). 25% visible transmittance and CRI close to 100 (Chen et al., 2012) while in another work CRI close to 90.7 was possible for and visual transmittance 16.3%, suitable for semi-transparent BIPV window integration (Duan and Yi, 2019).

Currently, BIPV glass providers are Asahi Glass Co., Ltd., Ascent Solar, Canadian Solar, Centrosolar Group AG, DuPont, EMMVEE Solar Systems Private Limited, First Solar, Hanergy, Hanwha Solar One, Onyx Solar, Power Film, Inc Sun Power, GE, Pythagoras Solar, Suntech Power Co., Ltd , Solar Frontier Pilkington (Z. M. Research, 2018).

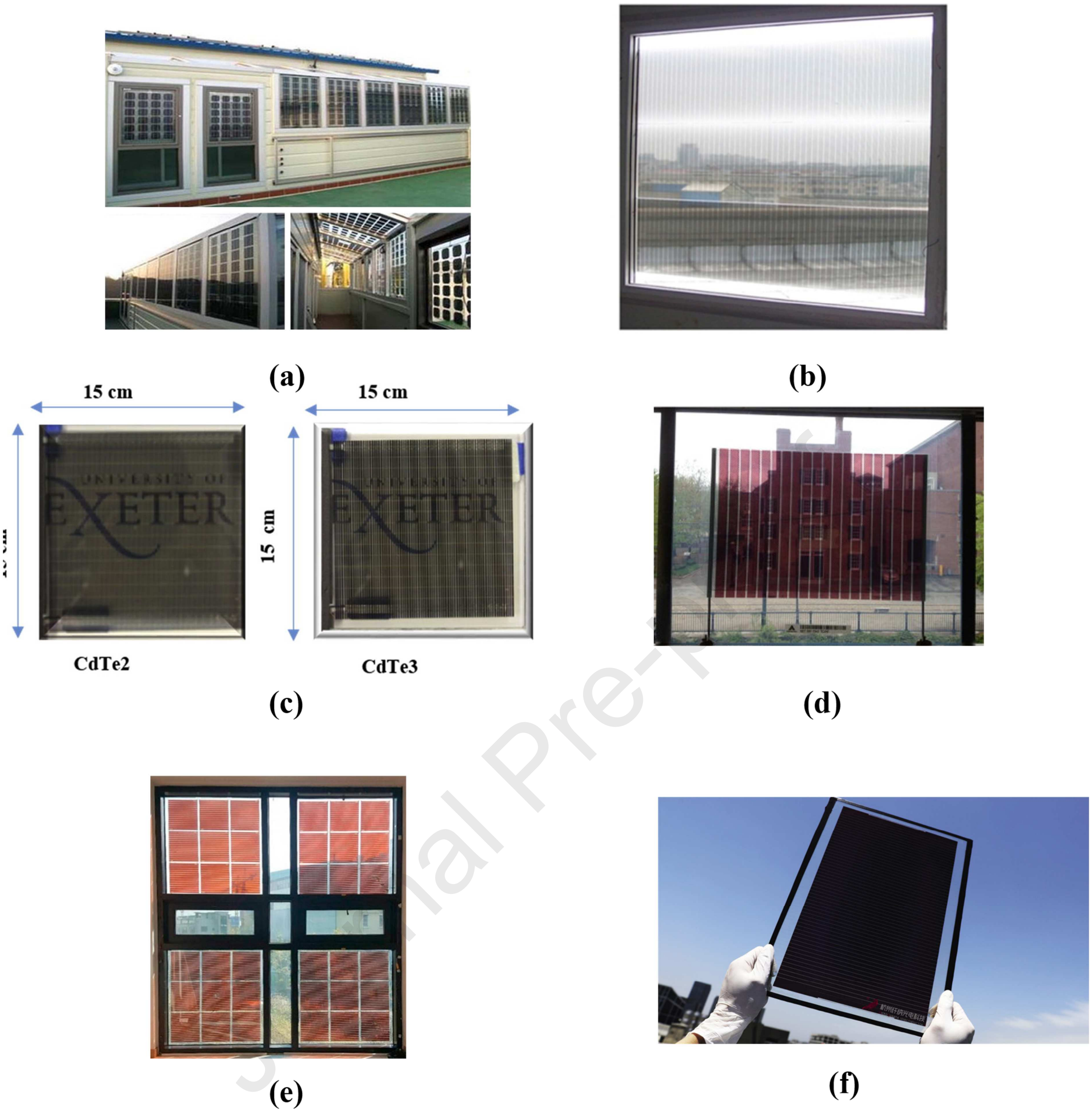



Figure 14: (a) Overview of crystalline silicon based semi-trasnparent BIPV installation in a sunroom, Republic of Korea (Park et al., 2010) (b) amorphous-silicon BIPV single window (He et al., 2011) (c) Photographs of three different CdTe glazing (Alrashidi et al., 2019) (d) Viewing through Organic BIPV window (Yan et al., 2012), (e) DSSC glazing for outdoor experiment (Lee and Yoon, 2018) (f) 14.24% conversion efficiency record for a large-area (200×800 $cm^2$) perovskite solar module (image source: microquanta)

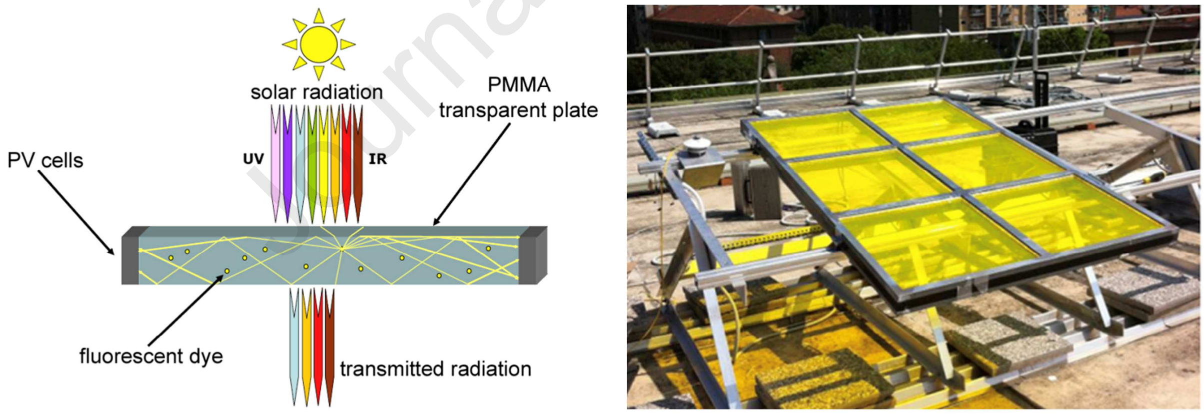
### 3.5. Low concentrating façade

Use of concentrator in the PV system reduces the expensive PV material cost by reducing the use of expensive and toxic product involved in the production of PV material, better use of space, ease of recycling of constituent materials (Baig et al., 2015, 2014, 2013, 2012). The concentrator includes low (<10), medium and high (>100) type based on the concentration ratio (Chemisana, 2011)(G. Li et al., 2020)(Chong et al., 2013). Low concentration is suitable for BIPV application, as no coolant is required to cool down an enhanced PV system temperature (Amanlou et al., 2016). Low concentrator for BIPV application includes compound parabolic concentrator (CPC) (Tian et al., 2018)(Jaaz et al., 2017), luminescent solar concentrator (LSC) (Meinardi et al., 2017; Rafiee et al., 2019) and holographic solar concentrator (HSC) (Collados et al., 2016).

Mirror-based or dielectric-filled compound symmetric (Muhammad-Sukki et al., 2014) and asymmetric (Sarmah et al., 2014) parabolic concentrators have a prospect for BIPV application. Due to non-imaging nature, this type of concentrator can collect both direct and diffuse solar radiation. Asymmetric two dimensional (2d) compound parabolic concentrator (CPC) can improve the maximum power point by 62% compared to its non-concentrating counterpart (Mallick et al., 2004). In another work, asymmetrical dielectric-filled 2dCPC based PV generated 2.27 times higher electrical power than a system without concentrator which could bring the solar panel cost down by 20% per kWp (Sarmah et al., 2014). The circular entry and exit apertures in 2d CPC create hindrance for placing with the most available square and rectangular PV cells in the market. Thus, three dimensional (3d) CPCs were proposed which is formed by the rotation of 2d CPC. 3d CPC geometry can be improved by intersecting two symmetrical 2d CPCs orthogonally and this new shape is called crossed compound parabolic concentrator (CCPC) (Sellami and Mallick, 2013a). Reflective type 3dCCPC achieved three times higher power output than similar non-concentrating PV panel. Dielectric material filled CPC (dCPC) is an alternative to the mirror CPC. Refraction on air–dielectric interface allows it to collect solar radiation from a wider angle. Using 2d dCPC 40% cost reduction possibilities have been reported earlier (Mallick and Eames, 2007). Square elliptical hyperboloid shape dielectric-filled 3d CPC was investigated for static window application. The geometrical concentration ratio of this system was 6× while optical efficiency was 55% (Sellami and Mallick, 2013b). It was found that the CCPC with a concentration ratio of 3.6× represents an improved geometry compared to a 3-D CPC for the use as a static solar concentrator. In another work, mimicking of V-shaped posture of basking white butterflies as V-trough concentrator to a solar cell increased its output power by 42.3% (Shanks et al., 2015). However, the experimental work is still requiring to validate this hypothesis. Recently CPC-perovskite combination offered 10.73 times higher short circuit current than non-concentrating counterpart (Baig et al., 2020). In northern latitude due to cloud cover, solar irradiance is mostly the diffuse type whose spectral characteristics are different and lower in intensity than direct irradiance. Thus, the inclusion of low concentrating CPC window, as shown in **Figure 15** is potential which collects both direct and diffuse solar radiation.

Figure 15: Semi transparency effect of the square elliptical hyperboloid concentrator for BIPV window application (taken from Sellami and Mallick 2013).

Luminescent solar concentrator (LSC) is another suitable low concentrator and promising for transparent solar BIPV window application, as shown in Figure 16. LSC harvest both diffuse and direct sunlight was proposed in late 1970 for PV applications (Hermann, 1982; van Sark, 2013). An LSC consists of a transparent polymer sheet, doped with a low concentration luminescent particles (Luminophore) which can be organic dyes (Reisfeld et al., 1994), quantum dot (Chandra et al., 2015, 2012) (AbouElhamd et al., 2019) or rare-earth material (Day et al., 2019). These particles absorb a fraction of the incident sunlight 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; however, LSCs are unaffected by efficiency losses and electrical stresses due to shadow effects, often occur in bulk and thin-film PVs. The prime advantages of LSC-BIPV window are they can be the shaped to any size and its, transparency, colour and flexibility is fully controlled depends on occupant needs (Meinardi et al., 2017). Using double-glazed LSC may offer lower electrical performance than an LSC plate without glass due to higher reflection losses (Aste et al., 2015a). They can also behave as a spectrally selective window where UV spectrum can be shifted to the visible spectrum and directed to the edge of the window where PV cells are mounted. Thus building interior can be protected from the adverse effect of UV and will generate benign electricity from them concomitantly (Fathi et al., 2017). High power generation from an LSC window depends on the higher percentage of coloration of the film or glass, however, for visual performance a lower percentage of colored glass is required (Vossen et al., 2016). At the Netherlands location, 25% window covered by an LSC was found soothing than that of a traditional clear glass window (Vossen et al., 2016). It is expected that concentrating PV market will reach USD 2,710.6 Million by 2023 (Future, 2018). However, this includes low, medium and high all three types of the concentrator.




**(a)** **(b)**

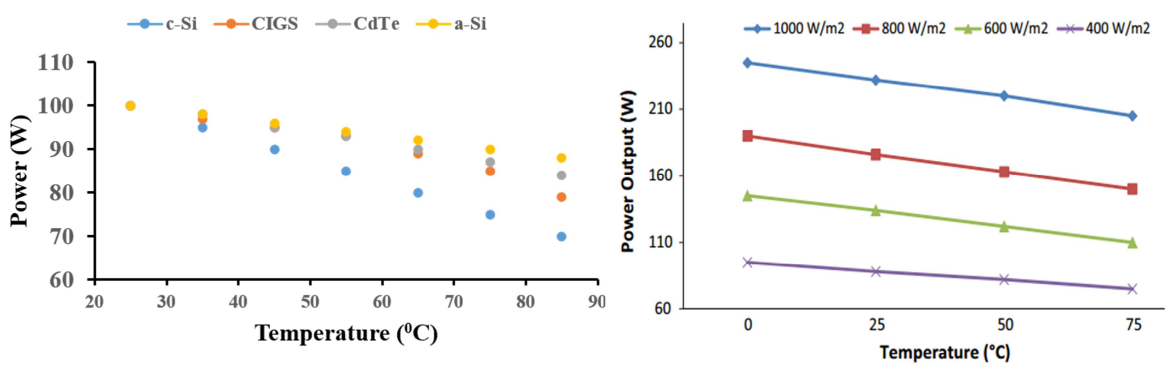
Figure 16: (a) Diagram of the incident photons and of the photons emitted by a dye molecules inside the LSC (b) LSC window (Aste et al., 2015b)

Holographic solar concentrator technology employs holographic optical elements (HOE) to enable the solar spectrum incident on the PV cell (Collados et al., 2016). Dichromated gelatin, photoresists, photopolymers, photochromic, silver halide photographic emulsions are the different types of HOE recording material(Abhijit Ghosh et al., 2018, 2015; Naydenova et al., 2013). Due to the spectral selectivity, HOE allows only those solar spectra similar to PV cell to incident on it and rejects above and lower spectrum band of solar radiation. Hence overheating of PV cells can be avoided (Brooks et al., 2012; Hull et al., 1987; Müller, 1994; Zhang, 2011). Holographic solar concentrator (HSC) are diffractive structures that are constructed holographically by the interference of two beams of light. HOE diffracts light due to the ability of angular selectivity which makes it a see-through building envelop suitable for window and transparent facade application. HOEs are classified based on recording geometry, thickness, and method of modulation of optical properties. Based on recording geometry hologram can be transmission or reflection types. The thickness of hologram can be thick and thin. Modulation during recoding of hologram can be amplitude and phase type. Because of the low efficiency thin amplitude and phase, both holograms are not, are not suitable for solar applications. Ludman in 1982 for the first time proposed the use of holographic solar concentrator for PV power generation. HOE with a concentration ratio of 1.23 (holographic cylindrical lens and c-Si PV) (Chemisana et al., 2013), 1.27 (holographic spherical lens and a p-Si PV) (Aswathy et al., 2018),1.80 ( holographic spherical lens, an array of two holographic cylindrical lenses and an array of two holographic spherical lenses with c-Si PV ) (Akbari et al., 2017), 1.90 (two holographic gratings and a dye-sensitized PV cell) (Sreebha et al., 2018), 3.48 (cylindrical holographic lenses and c-Si PV)(Marín-Sáez et al., 2019) were investigated and found to be an excellent result.

# 4. Technical challenges associate with BI/BAPV

## 4.1. PV performance degradation at elevated temperature

PV cells convert a certain wavelength of the incoming irradiation that contributes to the direct conversion of light into electricity, while the rest is dissipated as heat. Only 15–20% of incident solar energy is converted into electricity. The remaining part of the solar energy is converted into heat, which causes heating of the solar cells in PV panels (Agathokleous and Kalogirou, 2016). **Figure 17** shows the linear power drops of c-Si, a-Si, CdTe, CIGS PV for enhanced temperature. Maximum power drop occurred for c-Si and minimum was for a-Si. Minimum drop for a-Si was found because of annealing of a-Si cells, which promotes regenerative effect (Stabler-Wronsky effect) and an intrinsic drop of the cell's conversion efficiency at a higher temperature. With elevated temperature, reverse saturation current and open-circuit voltage of c-Si, a-Si, CdTe and CIGS PV increase and decrease respectively which in turn decrease the fill factor and thus the overall PV cell efficiency becomes lower than its standard test condition (STC) value (Singh and Ravindra, 2012). c-Si PV cell has temperature coefficients around 0.4%/K, whereas for a-Si, this value is approximately −0.1% K (Bücher, 1997). PV temperature for first and second-generation can reach as high as 80 °C, particularly in hot arid regions (Reddy et al., 2015). Long term thermal stress on PV cells also can damage the PV module (Chow, 2010) (B. J. Huang et al., 2011).




(a) (b)

Figure 17: (a) Effect of temperature on different PV materials,(Özkul et al., 2018) (b) The maximum power output of the mono-crystalline Si-PV modules (Jiang et al., 2012)

Temperature impact on third-generation PV cells is not similar to the first- or second-generation type. DSSC PVs show temperature coefficient of 0.1% between the temperatures from 30° to 50°. After that temperature, the generated vapour pressure from the liquid electrolyte may crack the cells (Tian et al., 2012). Increased FF was also found for DSSC PV at a higher temperature (Selvaraj et al., 2018). Also DSSC temperature coefficient shows positive and negative such as oscillatory behaviour which can be from the different velocities of the redox processes occurring at the electrolyte/counter electrode TiO2/dye, dye/electrolyte interfaces of a DSSC stack (Sebastián et al., 2004; Selvaraj et al., 2018). Ruthenium based DSSC showed that efficiency decreased at a rate of 0.05%°C (Parisi et al., 2017). Another work reported that DSSC efficiency first increased from -7°C to 40°C and after 40°C it's started decreasing due to accelerated recombination (Raga and Fabregat-Santiago, 2013).

Under the real operating condition, perovskite solar cells temperature can easily reach up to 45 °C. Effect of temperature on the performance of Perovskite was explored by exposing the PV cells in a range of temperatures between −5 °C and 80 °C. The performance perovskite cells at -5$^{0}$C displayed approximately 5 % less power conversion efficiency than at 22 °C. At 80 °C, a significant decrease occurred for open-circuit voltage and short circuit current which leads to a decrease of 36.0±5.5 % (Mesquita et al., 2019). Table 3 listed the temperature coefficients of different PV devices.

Table 3: Details of temperature coefficient of different PV technologies.

| PV types | Temperature coefficient ($K^{-1}$) |
|---|---|
| c-Si | -(0.2-0.3) |
| CdTe | -0.25 (Lee and Ebong, 2017) |
| CIGS | −0.33 to −0.50 |
| a-Si | −0.10 to −0.30 |
| Perovskite | Not available |
| DSSC | |
| Organic | +0.7 |

## 4.2. Thermal regulation of BI/BAPV using active and passive approach

Dissipation of heat from BIPV/BAPV systems is possible by active or passive heat removal methods to improve PV performance similar or better than STC. The passive systems depend on convection, conduction and radiation while active methods utilize pumps or fans to maintain a flow of air or water over the front or at the back of the PV panel for cooling purposes (Baljit et al., 2016) as shown in Figure 18a. Thus, the inclusion of thermally regulated PV system produces electricity and thermal energy simultaneously which enhances 15–30% higher annual exergy output than that of the similar non-thermally regulated PV system (Agrawal and Tiwari, 2010a, 2010b; Chow, 2010; Hasanuzzaman et al., 2016; Lamnatou and Chemisana, 2017; Prakash, 1994). Temperature regulation of crystalline PV is the most economical compared to organic or thin film due to the detrimental effect on the efficiency of the silicon PV (Browne et al., 2015).

The gap between PV and building façade element should be between 10 to 15 cm to allow the ventilation (natural air flow) that can reduce the PV device temperature and enhance the electrical power output producibility.  No gap between PV and building skin creates a thermal bridge and conductive heat flow allow unwanted solar heat gain into the building space and degrades the PV efficiency(Agathokleous and Kalogirou, 2016; Fossa et al., 2008; Wang et al., 2006). No maintenance, low initial cost, no noise, no electricity consumption, simpler integration are the advantages of natural air flow for reduction of elevated temperature of PV panels (A. Shukla et al., 2017). However, natural airflow offers limited gain on PV performance due to low thermal conductivity, low density, low volumetric heat capacity and low mass flow rate of air. As wind speed is influential for this system, higher wind speed can reduce PV temperature significantly whereas lower wind speed restricts to lose heat (A. Shukla et al., 2017).

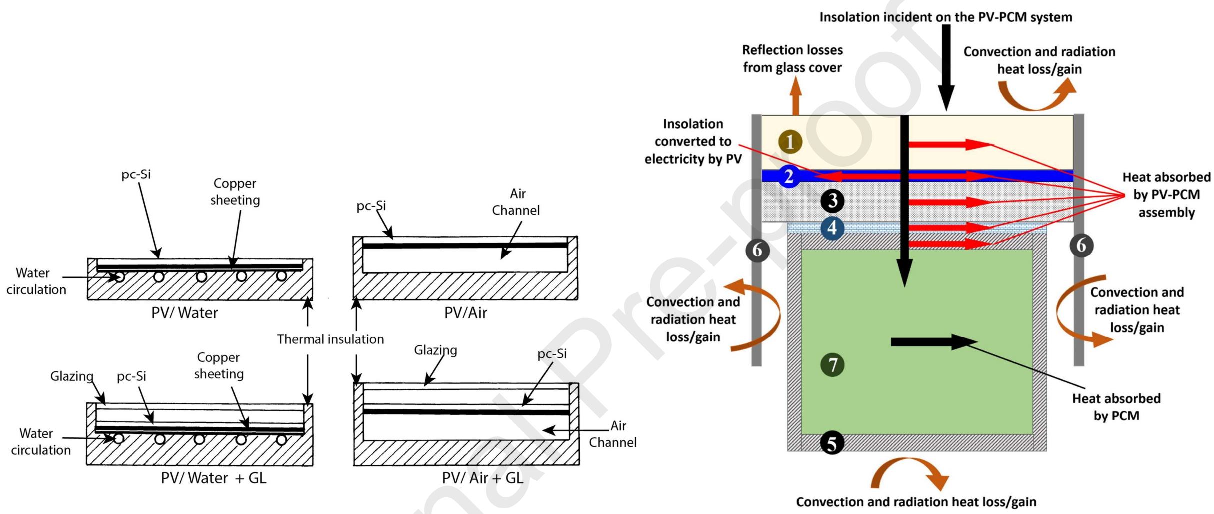
To regulate the PV temperature using active forced airflow circulation requires an auxiliary pump and the warm air can be used for end-users to supply space heating demand, agriculture/herb drying, increased ventilation, as well as the electricity generation (Kamthania et al., 2011). Using duct/collector behind the PV panel dissipates heat due to airflow buoyancy created from warm air at the rear of the panel (Brinkworth et al., 1997)(Phiraphat et al., 2017). Increase the rate of uniform airflow, collector diameter and collector length enhance the thermal and electrical efficiency for a PV system (Garg and Adhikari, 1999; Ghani et al., 2012; Hegazy, 2000; Solanki et al., 2009; Vats and Tiwari, 2012; Yang and Athienitis, 2014). For BIPV system air cooling are most investigated than water cooling (Joshi and Dhoble, 2018) while they offer energy payback period around 1 to 14 years (Lamnatou and Chemisana, 2017).

Using water flow on the top or rear of the PV device can maintain a PV device's STC temperature and water has higher heat capacity than air (Gil-Lopez and Gimenez-Molina, 2013a, 2013b). This water can be employed for the building hot water application (Krauter et al., 1999; Shyam et al., 2015; Tomar et al., 2017; Tripanagnostopoulos et al., 2002; Wilson, 2009). Depends on location water flow rate varies to offer best results such as 0.003 kg/s water flow was suitable to obtain the optimum based result for polycrystalline silicon solar cell based BIPV in Hong Kong (Chow et al., 2009) whereas 0.2 kg/s  in Älvkarleö, in the central part of Sweden (Davidsson et al., 2012). Natural circulation water type PVT systems are more economical as compared to forced circulation systems (Joshi and Dhoble, 2018). Investigation of BAPVT using water is higher than BIPVT system (Lamnatou and Chemisana, 2017). Depends on the technology this BPAVT water system energy payback time varies between 1 to 4 years (Lamnatou and Chemisana, 2017). Addition of water and air both can serve the seasonal energy demand of the building where air mode will provide hot air in winter to reduce space heating load and water will work for the rest of the year (Xu et al., 2020).

To enhance further PV performance by dissipating elevated heat, fluids with less than 100 nm size metallic nanoparticles of copper (Agarwal et al., 2016), aluminium  (Rejeb et al., 2016), zinc (K.S. et al., 2016), silicon (Singh et al., 2009), iron (Ghadiri et al., 2015), titanium (Sardarabadi and Passandideh-Fard, 2016), gold (Wang et al., 2019), silver (Stephen et al., 2019) and non-metallic nanoparticles of aluminium oxide ($Al_2O_3$), copper oxide (CuO), silicon carbide (SiC), carbon nanotubes (SWCNT, DWCNT and MWCNT)(Mizuno et al., 2009; Said et al., 2014; Shende and Ramaprabhu, 2016) can be used while ethylene glycols, engine oil, distilled water, glycerol can be the base fluid (Farhana et al., 2019). The mass fraction of nanoparticles influence the thermal performance of the combined PV thermal system significantly and slightly on electrical performance.

The phase change material (PCM) has the ability to reduce the elevated PV temperature by absorbing a large amount of heat at a constant temperature (Alagar Karthick et al., 2020) (Kant et al., 2019; A. Karthick et al., 2020) Thus, it behaves isothermally during charging and discharging process (Browne et al., 2016, 2015; Huang et al., 2006, 2004; M. J. Huang et al., 2011). The energy flow of a typical

BIPV-PCM system is shown in **Figure 18b**. The paraffin waxes, salt hydrates, fatty acids and eutectic organic/non-organic compounds are different types of PCM used for thermal regulation from PV (Baetens et al., 2010; Kalnæs and Jelle, 2015; Pielichowska and Pielichowski, 2014). BAPV-PCM is able to improve 2-6% electrical efficiency compared to without PCM-PV(A. Hasan et al., 2017; Park et al., 2014; Smith et al., 2014). PCM can reduce the c-Si PV cell temperature up to 10 °C in temperate climate while can reduce up to16-21°C at a hot and humid climate (Hasan et al., 2015, 2014) and 10°C for CIGS PV in a temperate climate (Curpek et al., 2019; Čurpek and Čekon, 2020). BIPV cooling using PCM for high ambient temperatures are effective, however, for low ambient temperature PCM may reduce heating effect if the stored heat is not dissipated by introducing another facility (metal matrix, conductive particle) (Chandrasekar et al., 2015). PCM based BI/BAPV system shows a payback time of 14.5 years (Panayiotou et al., 2016). Table 4 summarises the comparison of different thermal regulation techniques.




**(a)** **(b)**

Figure 18: (a) Cross section of PV/Water, PV/Water+Glazing, PV/Air, and PV/Air+Glazing experimental models (Tripanagnostopoulos et al., 2002) (b) Schematics of the energy flow in the BIPV–PCM system (taken from (A. Hasan et al., 2017) )

Table 4: Comparison of different thermal regulation techniques.(Chandrasekar et al., 2015)(Hasan et al., 2010)

| Thermal regulation | Types | Advantages | Disadvantages |
|---|---|---|---|
| Natural Air | Passive | • low initial cost,<br>• no maintenance,<br>• no noise,<br>• no electricity consumption,<br>• longer life | Low -thermal conductivity<br>-heat capacity,<br>-heat transfer rates,<br>-mass flow rates<br>Depends on – wind direction and speed, dusty air reduces heat transfer,<br><br>Not useful for low latitude location where ambient temperature is higher than 20 $^0$C |
| Forced air | Active | • higher heat transfer rates compared to natural circulation of | high initial cost for fans and ducts to handle large mass flow rates, high electrical consumption, maintenance |

| | | | |
|---|---|---|---|
| | | air<br>• independent of wind direction and speed,<br>• higher mass flow rates than natural air circulation achieving high heat transfer rates,<br>• higher temperature reduction compared to natural air circulation | cost<br>noisy system,<br>difficult integration compared to natural air circulation system |
| Forced Water | Active | • Similar to forces air in addition higher thermal conductivity than air. | • Tank is required to store water and also needs pump and pipes.<br>• Electricity requires to operate pumps. in case of roof integration overall system increase the weight of the installation<br>• Pumping power requirement is higher than forced air |
| Nano fluid | Active | • high thermal conductive metal nano particle enhances the heat transfer | • Long term stability of nano particles in nano fluid is a complex work |
| PCM | passive | • higher heat transfer rate compared to both forced air and water circulation,<br>• higher heat absorption due to latent heating,<br>• no electricity consumption/ noise/ maintenance cost, on demand heat deliver | • Choice of suitable melting temperature is essential.<br>• If PCM is not able to release heat to ambient, combined system will be heat up further, PCM will behave as insulator.<br>• higher cost, toxic nature, fire safety issues, strongly corrosive, disposal problem after completion of life cycle |

It should be noteworthy that major thermal regulation work of BIPV/BAPV system was based on c-Si (Jia et al., 2019; Joshi and Dhoble, 2018; A. Shukla et al., 2017) while 2$^{nd}$ generation system is significantly less (Kalogirou and Tripanagnostopoulos, 2006; Ren et al., 2019), and third-generation is rare or no work has been performed. Large scale development using third-generation PV for BIPV/BAPV is the biggest challenge which limits the exploration of thermal regulation work. Also, thermal performance knowledge of third-generation PV is not well established.

### 4.3. Shading on BIPV and BAPV

Depending on the local climate BIPV and BAPV both can suffer from wind-driven dust, snow and shading from other building or construction or trees (Ilse et al., 2019). Deposited dust particle sizes vary between 1 to 50 μm which causes shielding effect on PV and thus decrease solar transmission through the PV surface glass which in turn decreases the power output (Appels et al., 2013; Toth et al., 2018; Weber et al., 2014). Curtailment of transmission also varies with dust deposition density, wind speed and humidity, particle diameter and PV tilt angle (Smestad et al., 2020). Dust particles include chemical, biological, electrostatic types, whereas its size shape and density are indispensable (Micheli et al., 2019, 2018b, 2018a; Micheli and Muller, 2017). A rough surface accumulates a higher amount of dust than a smoother one (Yusuf N Chanchangi et al., 2020). Electrostatically attracted inorganic materials are common in the desert location and salts and rain-driven dirt are common in a coastal area. Industrial and cooler location is subject to windblown organic dirt, deposits from evaporated rain and atmospheric pollutants from fossil fuels (Yusuf N. Chanchangi et al., 2020)(Ghosh, 2020a). The Middle East and North Africa have the worst dust accumulation zones in the world (Ghazi et al., 2014). Even in the cleanest region of the world UK, dust effect reduces the solar intensity by 5–6% after one- month continuous exposure (Ghazi et al., 2013). For a fixed period of exposure, the rise of tilt angle reduces the dust deposition density. For a constant tilt angle, dust deposition density increase with the number of exposure days (Hegazy, 2001; Xu et al., 2017). Wind directions and orientation of collector have an influential impact on dust deposition (Goossens et al., 1993). In Greece, the effect of 0.4 $mg/cm^2$ ash deposition reduced 30% of power output than a similar clear PV panel. Relatively small ash deposition (i.e. 0.06 $mg/cm^2$) reduced 2.5% of the generated power output (Kaldellis and Fragos, 2011). In another work, PV module efficiency drops by 33% for each 1 $g/m^2$ of dust accumulation (Al-hasan and Ghoneim, 2005). Heavy rainfall in any location reduces the soiling effect (Lopez-Garcia et al., 2016). Exposed PV on the third floor in the Politeknik Elektronika Negeri building in Surabaya, Indonesia (longitude of 112.533° and latitude of 7.2361°) during the dry season and the beginning of the rainy season in 2014, showed 2.05% power output reduction which increased to 87.29% compared to a clean module after a short period of drizzle (Ramli et al., 2016). **Figure 19**a shows the uneven soiling on PV array in Doha, and Figure 19b shows the heavily soiled modules on the Gran Canaria Island. Accumulated dust on PV enhances the electricity cost (Tanesab et al., 2018).

(a) (b)

Figure 19: (a) Uneven soiling on a PV array following a sandstorm in Doha, Qatar (Figgis et al., 2017), (b) Heavily soiled modules on the Gran Canaria Island (Schill et al., 2015).

Snow accumulation on the top of the PV modules (as shown in **Figure 20**) reduces the power generation due to a low transmission of incident solar radiation on the PV (Gullbrekken et al., 2015)(Borrebæk et al., 2020). When snow covering is light, and it melts easily, the generation losses are less; however, the impact is adverse when snow is heavy and does not quickly melt or shed (Brench, 1979). Snow is highly scattering optical medium at the visible range, which makes it white. Even a thin layer of snow is a bright and white colour, reflect the entire solar spectrum at the visible wavelength and transmit little (Perovich, 2007). Little 2 cm thick snow can reduce 90% of visible transmission whereas 95% reduction of visible and 99% reduction infrared transmission is possible from 10 cm thick layer (Perovich, 2007). However, some light still can penetrate through the snowpack. 2 cm snow can allow 20% of incident solar radiation whereas 10 cm thick allow 3-4%. Annual production losses from a snow-covered PVs are directly proportional to the amount of snow received and proportional to the squared cosine of the tilt angle of the panels (Powers et al., 2010). Annual losses from a snow-covered photovoltaic array in Ontario, Canada, varied from 1 to 3.5% (Andrews et al., 2013). Snow-covered BIPV can be considered as PV under low light condition. Mapped PV efficiency for irradiance levels as low as 2.9 W/m$^2$, were investigated which indicated a logarithmic correlation between incident solar radiation and efficiency for crystalline silicon cells, whereas the efficiency of amorphous silicon and gallium arsenide cells are less affected by this weak irradiance (Reich et al., 2005). However, snow-covered ground, in reality, enhance the reflection of solar radiation which in turn increase the total incident solar radiation on PV and thus yield of PV panels when tilt angles are optimal. Snow can increase local yield by 10% at snowy Switzerland location (Kahl et al., 2019). Mono-, poly-crystalline silicon, CdTe, CIS and CIGS modules (shown in **Figure 20 c, d**) were mounted on a platform at temperate mountain climate in Brasov, Romania (45.65°N, 25.65°E, 600 m above the sea level) where winters are snowy, and summers are warm. The best performing modules were of poly-crystalline silicon, whereas CIGS was the best thin-film modules having the highest output power and  CdTe had the steadiest efficiency (Visa et al., 2016).

Trees, tall buildings, bird droppings and passing clouds are the other most common shading on BIPV and BAPV systems. Tilted PV panels in a parallel row also limit solar radiation due to self-shading. Das et al classified shading as static and dynamic and soft and hard. Slow change soft solar angles are static shading while fast change due to moving clouds are dynamic shading. Shading due to flying birds or nearby trees is soft shading, whereas PV modules are blocked completely due to hard shading (Das et al., 2017).

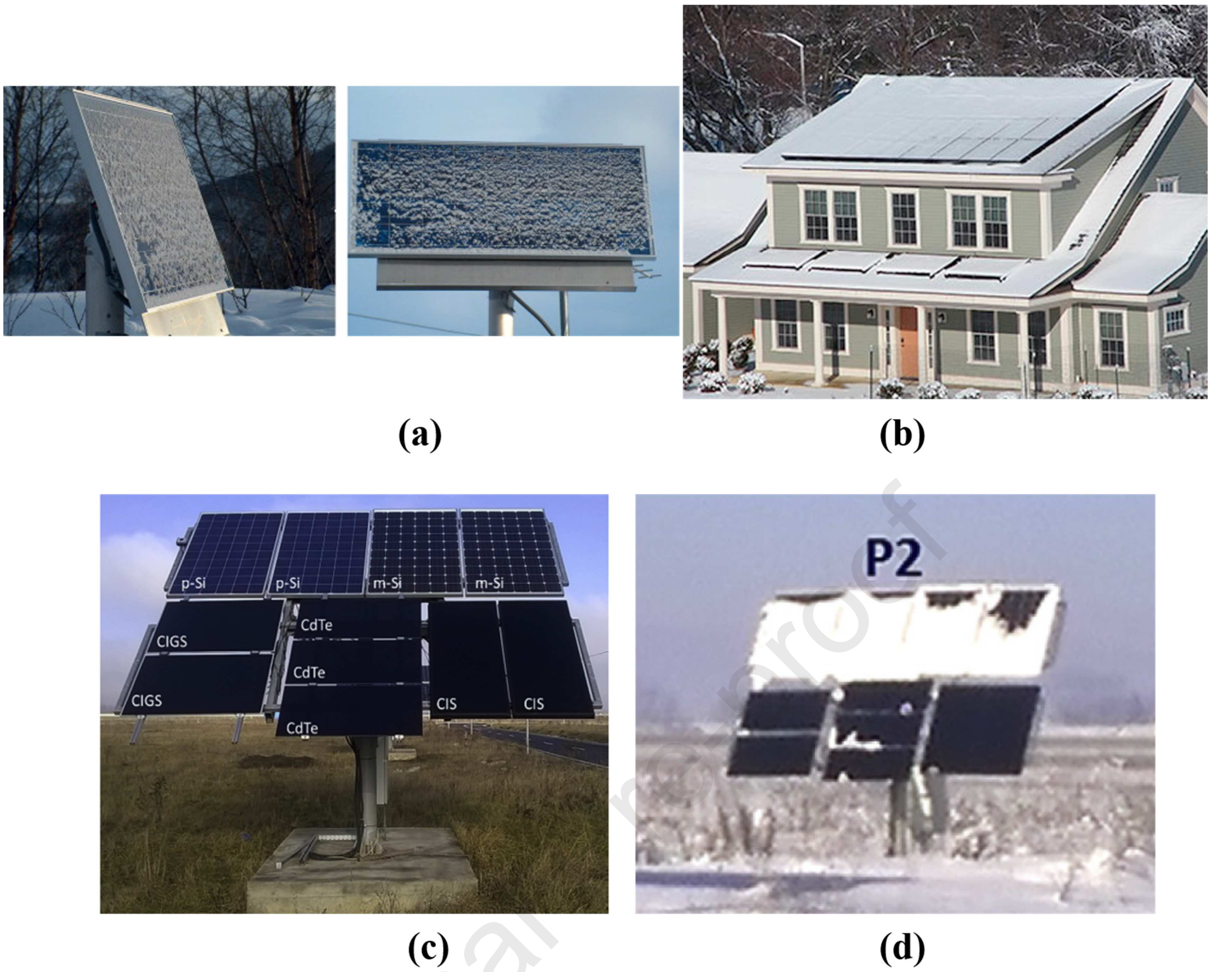



Figure 20: (a) Snow covering a solar cell panel at an inclination angle of 70°(Jelle, 2013) (b) Snow on photovoltaic modules mounted on pitched roofs (Andenæs et al., 2018), Mono, poly-crystalline silicon, CdTe, CIS and CIGS modules on platform (c) without snow covered, (d) with snow covered at Brasov, in Romania (45.65°N, 25.65°E, 600 m above the sea level) (Visa et al., 2016).

Cleaning off the dust from BIPV/BAPV module surfaces is possible by natural rainfall, wind or gravity, mechanical, electromechanical, electrostatic and self-cleaning methods (Said et al., 2018). **Table 5** listed the cleaning cycle and mitigation method based on different climate conditions and characteristics. Rainfalls are free of charge but seasonally volatile, thus highly unreliable when soiling is intensive, and rainfall is not enough either in quantity or in intensity to clean off the soil. Brushing, blowing, vibrating and ultrasonic driving are the mechanical methods to remove dust from PV. Broom or brush is generally used for brushing method which is driven by some machine. For small size and the strong adhesivity of the dust, this method is not very efficient. In a blowing method, wind from the blower is employed which needs high energy to operate. Electromechanical methods encompass shakes or vibrates the PV module array and use subsonic or ultrasonic waves to break the dust particle. The electrostatic approach has been proposed by NASA to mitigate the negative effects of dust on lunar-solar panels. Attached parallel or spiral transparent UV- radiation resistant plastic sheets repel the dust particle when a single- or multiple-phase AC voltage supply produces an electromagnetic field on the surface (Calle et al., 2009; Sharma et al., 2009; Sun et al., 2012).

Table 5 :Cleaning cycle and mitigation method based on different climate conditions and characteristics (Ghazi et al., 2014)

| Climate condition | Cleaning cycle | Mitigation |
|---|---|---|
| Humid cold temperature | Every six months | Wet type cleaning methods by using soap and warm water |
| Humid hot temperature | Every three months | Surface coating, self-cleaning hydrophobic |
| Humid equator | Monthly | Automatic cleaning systems for wiping snow and dust<br>Use a plastic mesh over PV panels to reduce the problem of bird droppings |
| Dry | Weekly | Dry type cleaning methods such as rotary brush, automated robotic device |

Self-cleaning methods can be categorized into hydrophobic and the photocatalytic hydrophilic (Ahuja et al., 2017) (Mehmood et al., 2016). Hydrophobic and hydrophilic are understood by water contact angle experiment where contact angle greater than $90^0$ possess hydrophobic and higher than $150^0$ possess superhydrophobic. On the other hand, the water contact angle less than $90^0$ are known as hydrophilic and less than $5^0$ superhydrophilic (Jang et al., 2019). Presence of hydrophobic coating, the water drops roll off the surface quickly due to the water repellent which also removes the contaminants from the surface. In the case of superhydrophobic which is also known as the lotus effect, ball-shaped water droplet, runs down the surface and collects the dirt with small sliding angle (Zhang and Lv, 2015). It is worth mentioning that superhydrophobic and hydrophobic are applicable for snow (A. Kim et al., 2015) and superhydrophilic and hydrophilic are suitable to clean dust covered BIPV/BAPV (Nundy et al., 2020). Superhydrophobic coatings include fluorocarbons, silicones, carbon nanotubes (Hanaei et al., 2016), polymeric materials such as polystyrene, polyurethane urea copolymer, poly (methyl methacrylate), polycarbonate, poly (vinyl chloride), organic materials and inorganic materials zinc oxide (ZnO) and titanium dioxide ($TiO_2$). Using UV treatment super hydrophobic and hydrophobic can be made as hydrophilic or super hydrophilic. $TiO_2$ is the most common super hydrophilic self-coating layer. Superhydrophobic fluorinated ethylene propylene (FEP) into a silicon PV enhanced the short circuit current density by 1.1% and 93.6% recovery ratio of short circuit current (Roslizar et al., 2019) (Vüllers et al., 2018). Superhydrophobic coating can improve 10% maximum power of c-Si-based PV module (Z. Huang et al., 2018). Addition of $TiO_2$ and KH550 superhydrophilic coated PV provided maximum 4.3% efficiency improvement (Zhong et al., 2017). Superhydrophobic nanostructure glass surface allowed only 1.39 efficiency drop while bare glass reduced 7.7% efficiency (Son et al., 2012). Potential of self-cleaning coating for PV surface cleaning is well documented elsewhere and shows its supreme applicability (Gullbrekken et al., 2015; Liu et al., 2019; Loh et al., 2013).

Further improvement from snow and ice challenges can be addressed by using icephobic surface coatings (Fillion et al., 2014; Hejazi et al., 2013). Icephobicity is related to superhydrophobicity, but superhydrophobic surfaces are not necessarily icephobic (Kulinich et al., 2011; Nosonovsky and Hejazi, 2012). Specific materials and coatings have achieved degrees of icephobicity, however, opaque nature makes them ineligible for BI/BAPV applications. **Table 6** summarised the advantages and disadvantages of different cleaning methods.

Table 6: Advantages and disadvantages of different cleaning methods

| Cleaning methods | Advantages | Disadvantages |
|---|---|---|
| Manual | Restoration of standard PV performance is possible. | Needs constant manpower, as frequent cleaning cycles require. Depends on location and dust intensity, intense cleaning needs weekly or monthly. |
| Mechanical | Less productive compared to manual cleaning | Requires electrical power, due to initial and maintenance cost suitable for large systems, |
| Electrodynamic screens (Bock and Robinson, 2008) | Removes 90% of soiling<br>Less power consumption; as low as 0.003% of generated power | Doesn't work properly under rainy condition and requires dry conditions for effective work. |
| Stowing of PV arrays | Protects from soiling when not in use (nighttime; dust storms) | Ineffective during daytime if sudden dust storm approaches (insufficient stowage time |
| Self-cleaning | Passive self–cleaning, no manpower, electrical supplies are required. | Depends on rainfall and long-term stability |

### 4.4. Scale up issues and lack of standard

Large-scale development for three different generations PV has its own issue. First-generation silicon-based crystalline-silicon-wafer PV modules have more than 90% of market share. First generation-commercial PV panels consume 100 mg/cell silver (ITRPV, 2015). Reduction in silver use for the rear contact of silicon PV cells with partial substitution by using aluminium is already standard practice but not for the frontal part yet. The rate of decrease in silver paste use in PV cells contacts metallization and the rate of increase in first-generation PV installed capacity can possess 70% of the variance of the yearly silver demand in the year 2050 (Lo Piano et al., 2019). Thus, the reduction in silver paste use for contact metallization needs meaningful pace, to ensure smooth deployment of PV power generation at a sustained pace.

Large scale deployment of CdTe PV technology requires two key elements which are cadmium and tellurium, by products of zinc and copper, respectively. CdTe is the fifth most expensive semiconductor material based on future extraction costs among 23 semiconductor materials (Wadia et al., 2009). Available tellurium reserves can support CdTe-based solar power production of 1438 GWp in 2020, 19149 GWp in 2050, and 20211 GWp in 2075 (Fthenakis, 2009).

Third generation type PV cells are particularly gaining interest in BIPV application due to their ability to tune the transparency. However, presently they are facing issue to fabricate in large scale primarily due to the material degradation under ambient exposure and drop of efficiency. Dyesol is working on large-scale DSSC installations in collaboration with Tata Steel in North Wales, UK. Exeger received a USD 20 million investment to build a 20 MW DSSC production line in Stockholm, Sweden (View, 2016).

Serially interconnecting different numbers (five, eight, or ten) of Perovskite PV cells (each cell made by a triple layer of mesoporous TiO2, ZrO2 and carbon as a scaffold for mixed cation lead halide) fabricated a large-area 100 $cm^2$ module (active area of 49 $cm^2$ ) that exhibited a PCE of 10.4% and stability till 1000 h. Later printable perovskite PV panel having 7 $m^2$ active area was fabricated for BIPV application (Hu et al., 2017). Recently scaled up perovskite (shown in Figure 8c) was achieved which had 108 $cm^2$ active area and 13.4% power conversion efficiency, stability till 1000hrs at 65°C

(Agresti et al., 2019) as shown in Figure 21a. Based on the techniques applied on the 5 × 5 $cm^2$ Perovskite cells 10.6% efficiency were used to increase the module size to 45 × 65 $cm^2$. A demonstration power station was made of 32 perovskite panels. No significant degradation was found after 140 days of outdoors testing as shown in Figure 21c (Cai et al., 2017). Presently perovskite based BIPV which was manufactured by Saule Technologies and installed in Skanska's Spark building in Warsaw (Wojciechowski et al., 2019), is shown in Figure 21b. The system consists of 52 perovskite modules, and its performance is monitored by a maximum power point tracker.

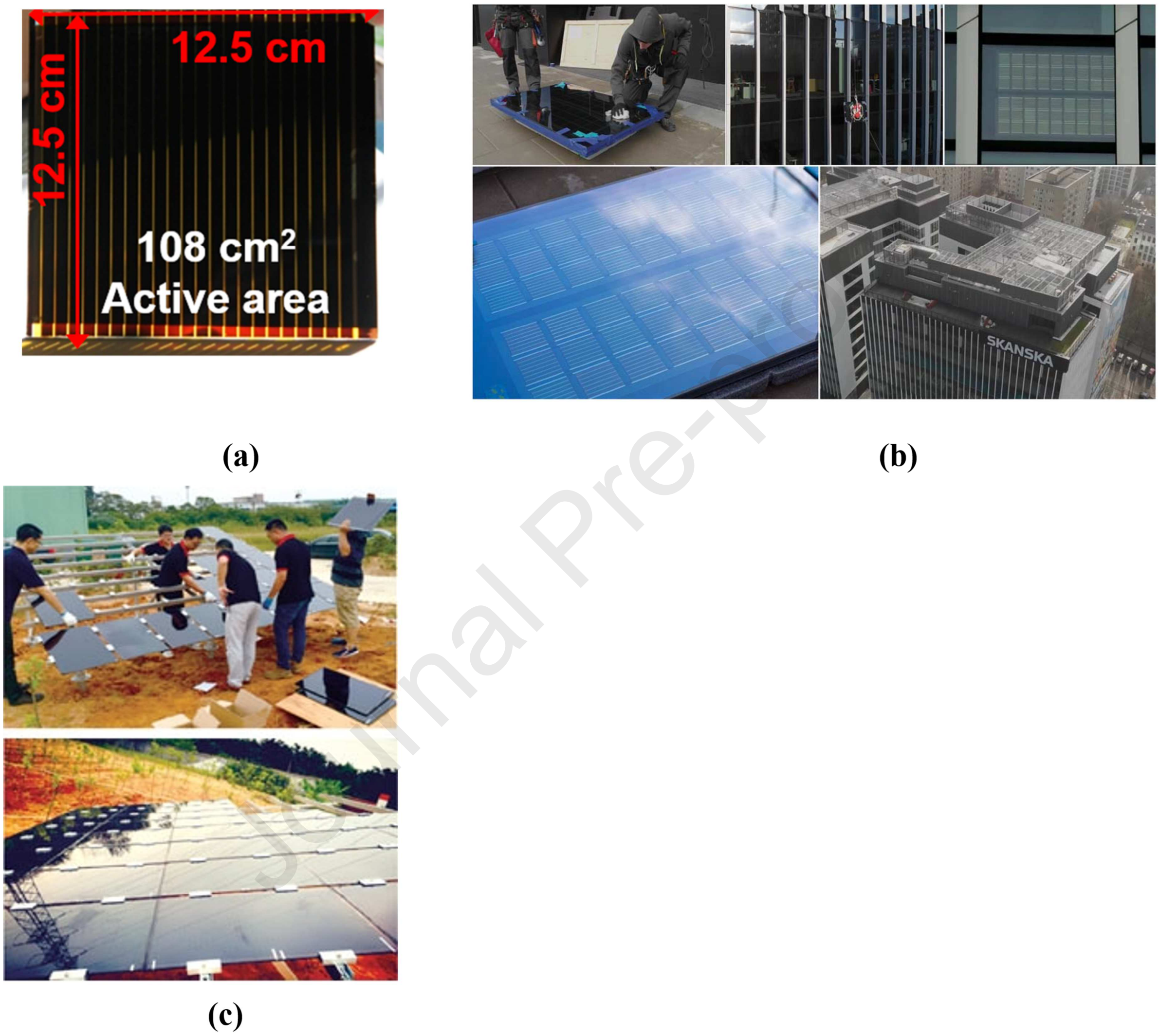



Figure 21 : (a) Photograph of a representative large-area Perovskite (108 $cm^2$ active area, 156.25 $cm^2$ substrate area ("Reprinted (adapted) with permission from, (Agresti et al., 2019) Copyright (2019) American Chemical Society") (b) Flexible perovskite solar modules laminated into a glass facade element and integrated into the Skanska's Spark building in Warsaw, Poland. Reproduced with permission. Copyright 2019, Skanska and Saule Technologies (c) Large area perovskite solar cell module Longhua (Cai et al., 2017) © 2017 Chinese Institute of Electronics

Standards, codes or guidelines for inclusion of PV in buildings are not available. Integration of the BIPV system into the building requires a large number of cable connections which may penetrate through the roof or under the layer of the roof (Agathokleous and Kalogirou, 2019). Thus, installation barriers, such as the cabling and connections, failure of fixings, islanding can create an issue after integration of PV into the building. Particularly replacement of BIPV system is more critical than

BAPV. Improper silicone waterproofing, can posses water penetration which is a serious drawback for a building. Thus, health and safety which can cover the cases of fire, electricity shortcut, wires failures play a major role while codes will be prepared. Noise control should be under examination as well. Standards for noise protection by integrating PV in buildings are not clear in the building codes. Lack of allowance of extra loads on BIPV from snow, ice, wind can cause BIPV system bending and this will lead to various failures requiring repairs or replacement (Yang, 2015; Yang and Zou, 2016). Thus standard test method is essential which can explain all details of the requirement for the combined building structure and BIPV cable connection (Gullbrekken et al., 2015). Ubiquitous standards are available for PV system but not for BIPV/BAPV systems (A. K. Shukla et al., 2017a). However, recently, for BIPV, only one standard EN 50583 is initiated (Ferrara et al., 2017).

### 4.5. Colour comfort evaluation

Presence of BIPV in a retrofit or new building has a significant impact on the behaviour of occupants. However, occupant comfort analysis for BIPV is the most underestimated area. In a building, occupant behaviour is complex and stochastic nature and primarily depends on comfort level at indoor space (Andargie et al., 2019). Occupant comfort hugely influences the cognitive activity of occupant, mental health, controls physiological reactions by maintaining melatonin production, core body temperature, heart rate, and cortisol production (Biswas et al., 2016). Occupant comfort includes visual and thermal both. For visual comfort glare and daylight analysis and for thermal indoor temperature and PPD-PVD methods are considered. However, for visual comfort, quality and quantity of light both are equally important (Smolders and de Kort, 2014). Daylight and glare analysis quantify the quantity of light where is colour properties indicates the quality of light. Thus, for BIPV glazed façade application evaluation of colour properties which includes colour rendering index (CRI) and correlated colour temperature (CCT) are essential to understand the visual comfort of building occupants. CCT and CRI provide the details of the quality and quantity of daylight (Hernández-Andrés et al., 1999; Prathap et al., 2016; Valencia et al., 2013). CCT near 6500 K and CRI above 95 indicates the comfortable daylight into space(Ghosh and Norton, 2017a) (Ghosh and Mallick, 2018). Variations of these may generate different CCT and CRI values that may not be suitable for indoor comfort. PV materials filter external ambient daylight while it is passing through it. Thus, penetrated daylight through a window in an indoor space has different wavelength dependent spectrum than the original daylight available outside. CCT and CRI both depend on full spectral than one single transmittance value (Ghosh and Norton, 2017a; Gunde et al., 2005). Similar average transmittance c-Si, a-Si, CdTe, CIGS, DSSC and perovskite PV will generate different CCT and CRI. Thus, before applying PV material for glazing or glazed façade, evaluation of CCT and CRI are equally essential.

## 5. Potential future application of BIPV and BAPV

### 5.1. Source for switchable window

Traditional static/ constant transparent windows are not thermally insulated and need shading device to control the daylight. Semi-transparent BIPV windows can replace those traditional ones but transparency cannot be modulated. Thus, rather integrating BIPV window, a switchable window can be introduced where BIPV can power those switchable windows (Gorgolis and Karamanis, 2016; Rezaei et al., 2017; Saifullah et al., 2016). Switchable windows include electrically and non-electrically actuated (Ghosh and Norton, 2018) types. However, electrically actuated switchable glazings are preferred for building application due to its controllable transmission (Ghosh et al., 2016a). Electrically actuated glazing includes AC powered suspended particle device (SPD)(Aritra

Ghosh et al., 2015)(Ghosh et al., 2017a) (Barrios et al., 2015) (As shown in **Figure 22a**) and liquid crystal (LC) (shown in **Figure 22b**)(Aritra Ghosh et al., 2018a) (S. Kumar et al., 2019)(Ghosh and Mallick, 2017) and DC powered electrochromic (EC) (Granqvist et al., 2017; Xiong et al., 2017).

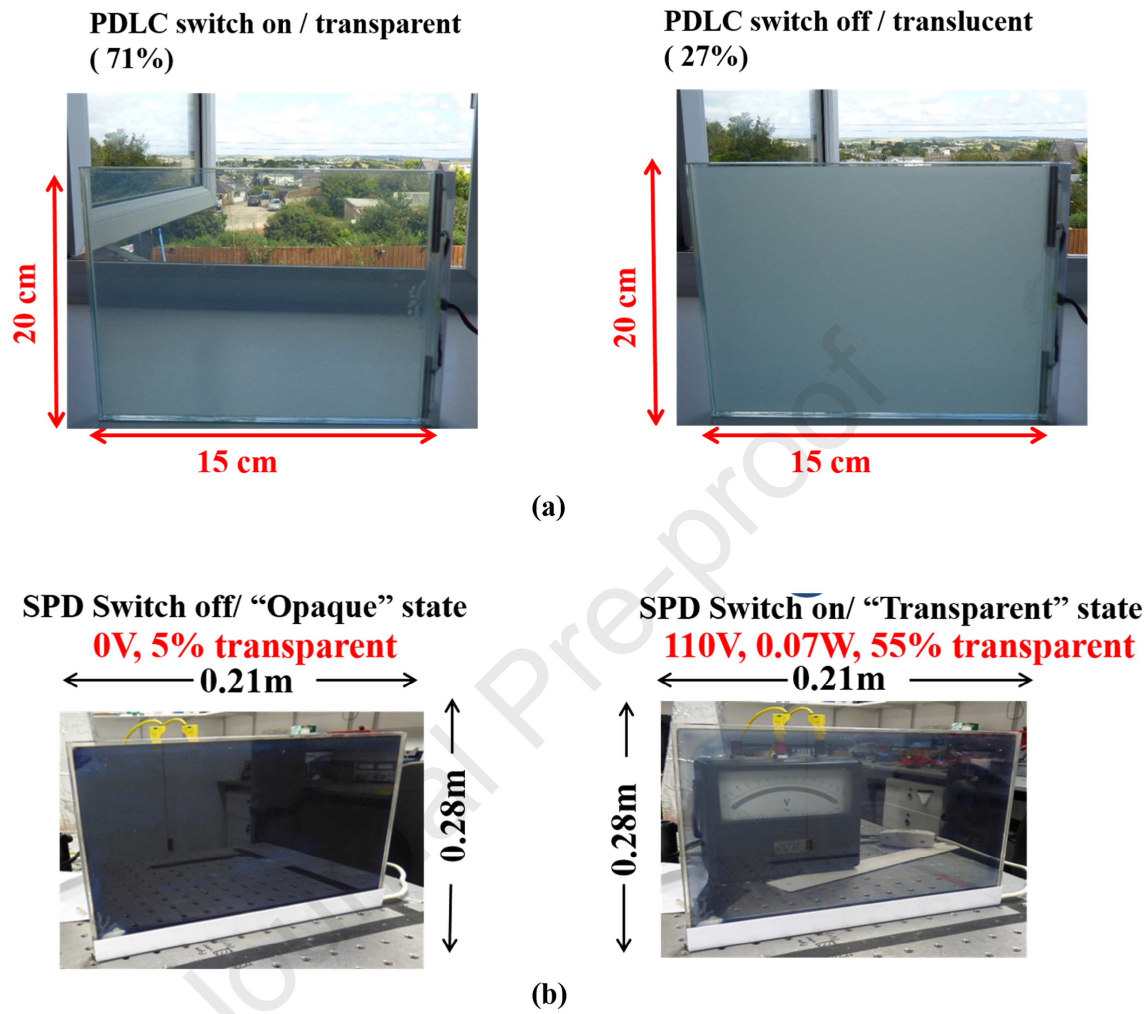



Figure 22: (a) Electrically actuated switchable glazing (PDLC type) (Taken from (Aritra Ghosh et al., 2018b) (b) Electrically actuated switchable glazing (SPD type) (Taken from(Ghosh et al., 2016b) )

Mitigation of external power requirement of those electrically activated glazings is possible by using PV devices which are shown in **Figure 23**. This novel system can be termed as self-powered glazing, switchable BIPV (Wheeler et al., n.d.), autonomous switchable glazing, photoelectrochromic (Cannavale et al., 2016) or photo-voltachromic which are suitable for less energy-hungry building. These combinations find solutions for seemingly impossible building problems. Powering from PV for AC powered SPD (Ghosh and Norton, 2017b) and LC(Hemaida et al., 2020) window needs an inverter for conversion as shown in **Figure 24a** (Ghosh et al., 2016b). An inverter increases the power losses which increase the required PV compared to EC powered glazing (Ghosh and Norton, 2019). However instant switching speed and no power requirement to control the solar heat gain can encourage using this type of combination (Ghosh et al., 2016b). Thus, building for hot arid climate SPD or LC type glazing is advantageous where power generation from BIPV or BAPV can be stored for night-time use(Ghosh et al., 2016c). PV powered EC glazing system has two-fold advantages. Firstly, EC glazing works with direct current (DC) power supply and PV produces DC power, thus direct coupling between EC and PV is possible where no need for power electronic conversion (Deb et al., 2001; Gao et al., 2000; Ma and Chen, 2012). Secondly, EC at high surface temperature requires less power to switch and PV at high ambient temperature generates less power than its standard rating (Bell and Matthews, 2001; Matthews et al., 2001). These two advantages make BIPV/BAPV power EC switchable glazing a potential candidate for future building integration. Dye-sensitized solar cell and silicon-based PV-EC device had already been investigated and found to be promising (Ahn et al., 2007; Santa-Nokki et al., 2007). Investigation showed that one 3.7% efficient perovskite PV powered an EC device which had an average visible transmittance of 26% (Cannavale et al., 2017a, 2017b). Solution type PV-EC material has been reported (Huang et al., 2012b, 2012a) where the electrochromic solution is located between the transparent non-conductive substrate and the silicon thin-film solar cell (Si-TFSC) substrate. The planarly distributed electrodes create a uniform electric field and due to solution type EC, the transparency of the overall device increase.

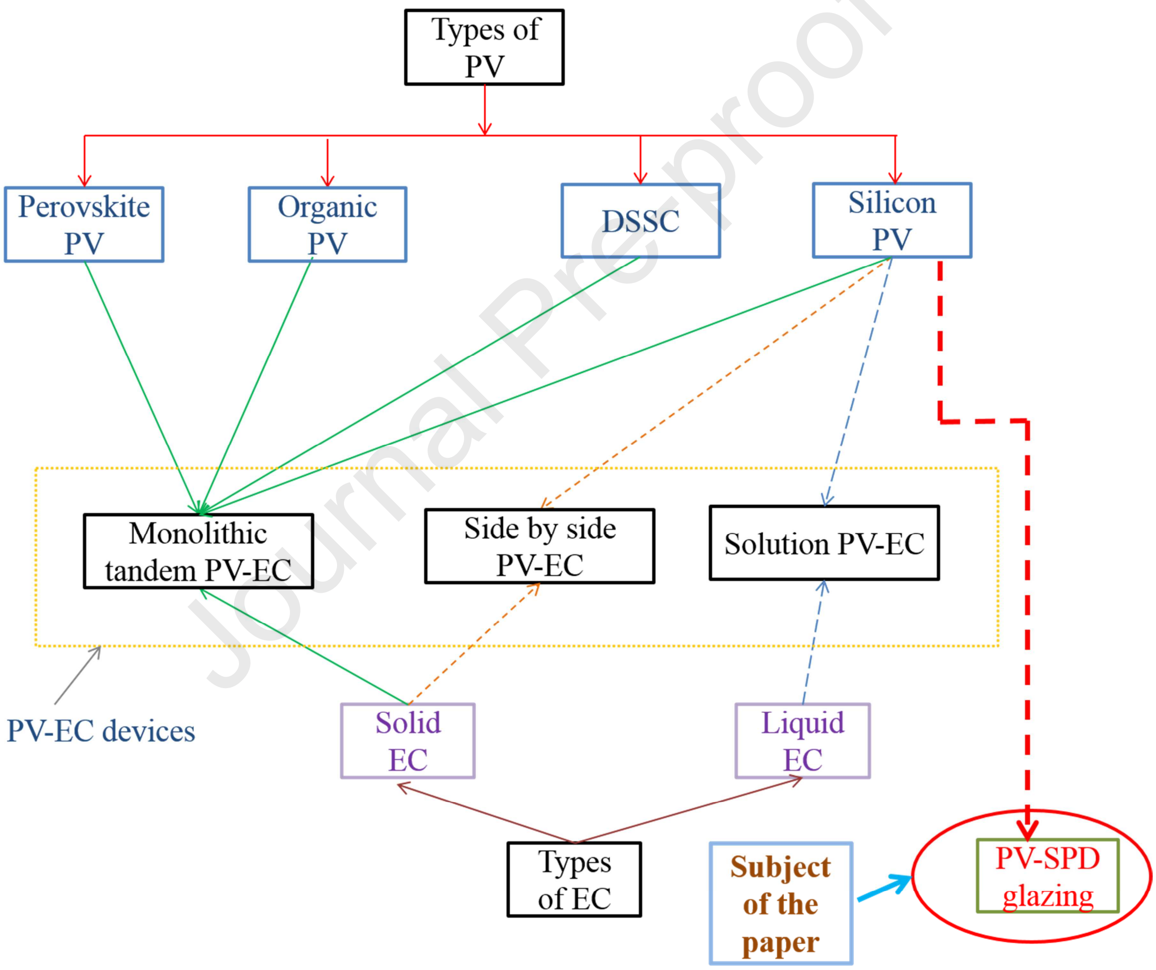
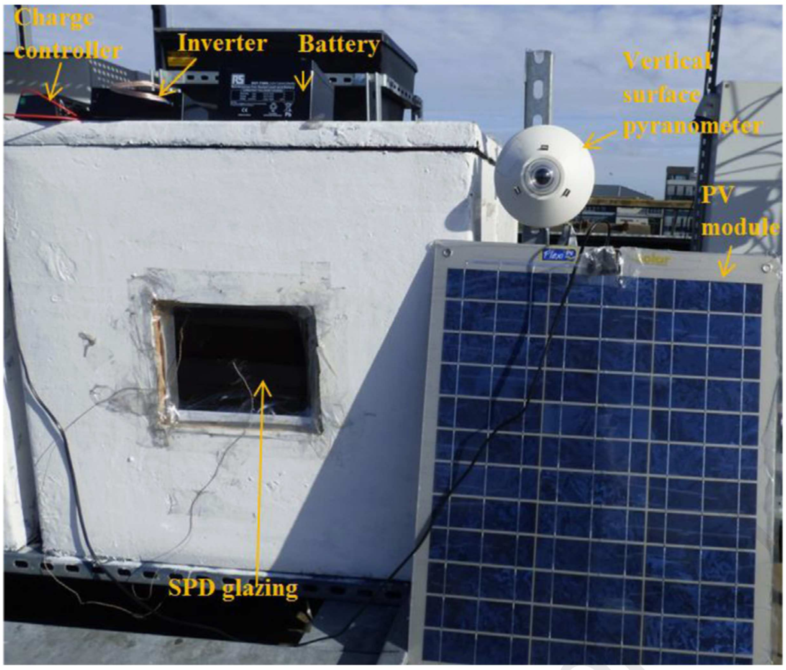



Figure 23: Types of PV powered switchable glazing. (Taken from (Ghosh et al., 2016b))




**(a)**

**(b)**

Figure 24: (a) Photographic view of PV powered SPD switchable glazing (Taken from (Ghosh et al., 2016b)) (b) 200 mm × 200 mm PDLC was powered by concentrator-type solar window used four parallel-connected edge-mounted $CuInSe_2$ modules of size 198 mm × 25 mm (Vasiliev et al., 2019)

Currently, LC-based glazing was also powered by DSSC based PV. However, the investigation was performed for a small scale, but the promising result confirms that PV integrated switchable glazing is future building architecture material (Kwon et al., 2015). Powering of PDLC glazing by a 13 nm thick a-Si PV cells was investigated for low (<0.8 mW/cm$^2$) intensity (Murray et al., 2017). Recently perovskite PV and a liquid crystal-based window were investigated where LC window switched from 3% to 79% transparent in the presence of 55V supply. Performance of perovskite was dependent on the thickness of the material. Higher thickness reduced the overall system transparency while reduced thickness enhanced the power conversion ratio (Xia et al., 2019). A PDLC size of a 200 mm × 200 mm was electrically driven using by concentrator-type solar window used four parallel-connected edge-mounted CuInSe2 modules of size198 mm × 25 mm in Edith Cowan University (ECU), October 2014 shown in Figure 24b. This is a patent work and not yet fully published academically (Vasiliev et al., 2019).

### 5.2. BIPV for highly insulating glazing

Available BIPV glazings are two glass sheets where PV materials are sandwiched between them. However, this double glazing has an overall heat transfer coefficient (*U*-value) which is near 2 W/m$^2$K. For less energy-hungry building, heat loss from window needs to be reduced and this is not achievable using double pane BIPV for cold climate. Highly insulating vacuum glazing has the potential to reduce the indoor heat by reducing the heat flow from indoor space to outdoor ambient (Fang et al., 2014)(Ghosh et al., 2016d). Vacuum glazing is two glass sheets where inside the space, the vacuum is created by using high-pressure air extraction (Ghosh et al., 2016e). To counteract the pressure from external ambient, small pillars are placed in regular order in the internal space (Figure 25a and b). Presence of vacuum reduces the conductive and convective heat flow and radiative heat flow is reduced by using low emission coating (Ghosh et al., 2017b). Low-e coatings are metals or metallic oxide based, transmit visible light in the solar spectrum and reflect the infrared (2000 nm - 50,000 nm)(Ghosh et al., 2017c). For double glazing, presence of a low-e coating on the internal surface of the inside glass pane reduces the heat loss from the interior room to an exterior environment (Jelle et al., 2015). Integration of vacuum glazing with BIPV (shown in **Figure 25 c**) can thus offer electricity generation, reduction of heat loss and control over admitting heat gain. Spaced type crystalline silicon attached with highly insulated vacuum glazing was also investigated for the temperate and cold climate which showed *U*-value of 0.8 W/m$^2$K (Aritra Ghosh et al., 2018d). Also, the light penetrated through space between cells allowed to maintain the external daylight at indoor space (Ghosh et al., 2019b). a-Si based BIPV-vacuum system (**Figure 25 b**) having *U*-value of 0.5 W/m$^2$K reduced up to 31.94% heat loss which saves net energy savings of 37.79% in cooling dominated Hong Kong (J. Huang et al., 2018).

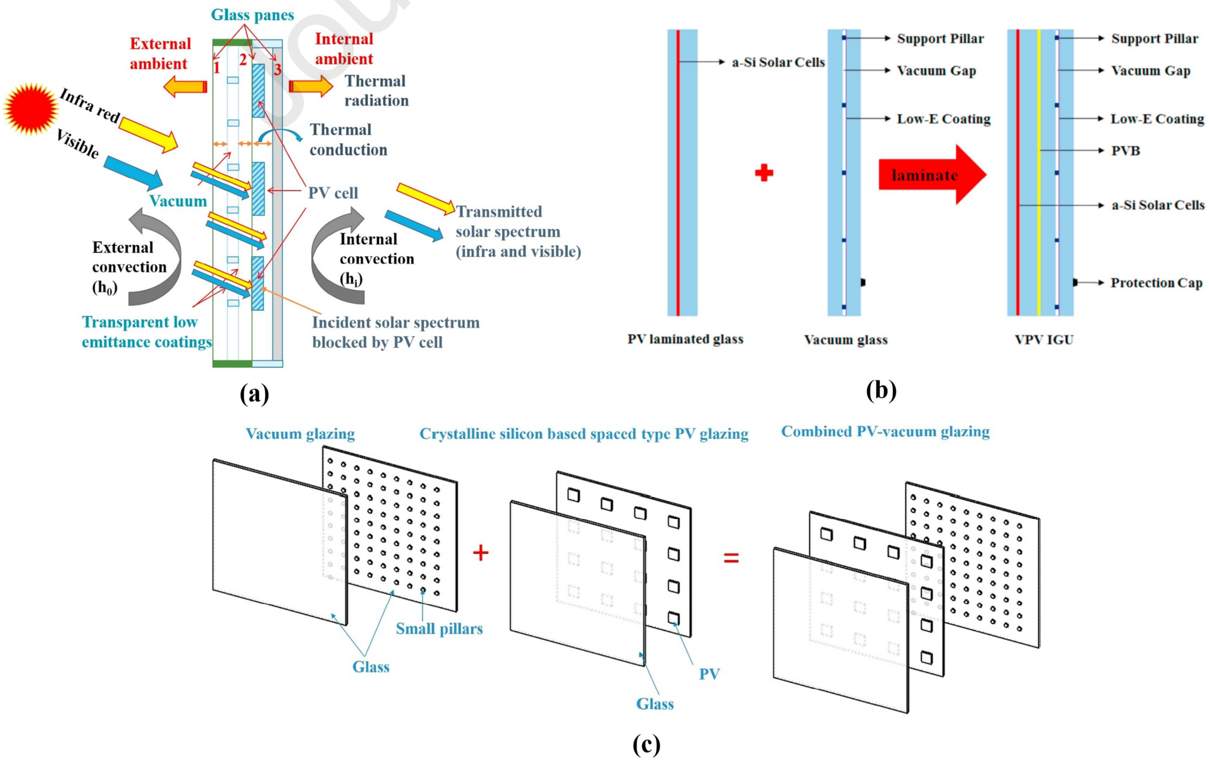


Figure 25: (a) Schematic of crystalline spaced type BIPV vacuum glazing (taken from (Ghosh et al., 2019b)), (b) a-Si based BIPV -vacuum glazing (taken from (Zhang et al., 2017)), (c) details of BIPV-vacuum glazing (taken from (Ghosh and Norton, 2018)).

In another work, BIPV-vacuum glazing's *U*-value was found to be 1.5 $W/m^2K$ and SHGC 0.14 from an indoor experiment. Combined these effects were employed in Energy Plus and WINDOW software and observed that cooling electricity reduction up to 25.4% and 16.5% was possible compared to single and double glazing (Qiu et al., 2019). Currently insulated BIPV was designed by using spaced c-Si and low e coated glass, as shown in Figure 19. The SHGC of the highly insulated BIPV was 0.25 and *U*-value was 3.5 $W/\ m^2\,K$. Low e coating was present in the third surface from exterior to interior, could not reflect longwave radiation into indoor space. Presence of low -e coating in the fourth surface could improve the result (Peng et al., 2019). Indoor thermal comfort using BIPV-vacuum system showed 39% enhancement than that of BIPV double glazing (Ghosh et al., 2019a).

### 5.3. Powering electric vehicle (EV)

One of the major applications of BIPV/BAPV can be in the field of transport which consumes 40% of fossil fuel energy worldwide and 90% transport sector is powered by oil-derived fuel (Chandra Mouli et al., 2019; Nunes et al., 2015). Consumption of expensive petrol and diesel for vehicles produces GHG, volatile organic air pollutant, PM10 and NOx (Van Vliet et al., 2011). The transport sector accounts for around 25% of EU greenhouse gas emissions. In Ireland, $CO_2$ emissions increased by 181% between 1990 to 2007 (Smith, 2010). In Switzerland, transport accounts for 31% GHG yearly (Smith, 2010). Deployment of electric vehicles (EV) over oil-powered vehicles can improve the situation. Electrically powered EV contains an electric battery that supplies the required energy to drive the car engine. Plug-in hybrid electric vehicles (PHEV), and battery-powered electric vehicles (BEV) are presently most investigated EV (Van Vliet et al., 2011) (Das et al., 2020; Tie and Tan, 2013; Yong et al., 2015). The conventional car uses gasoline or diesel fuel that create mechanical energy to move forward a vehicle. In a hybrid electric vehicle (HEV), small electric battery supply electricity to the drive train to optimize combustion engine's operating efficiency (Yong et al., 2015). HEVs are more fuel-efficient than conventional internal combustion engine (ICE) vehicle, but ultimately the vehicle is fully powered by liquid fuels. PHEV type works with the same principle to HEV, but they have large area high capacity battery that can be charged with a direct connection to the grid (Shamshirband et al., 2018). The high capacity battery also allows a car to drive the longer distance. Car model named PHEV 20 or 40 indicates car can travel with only the fully charged battery to 20 or 40 miles (Richardson, 2013). A battery electric vehicle (BEV) is fully powered by grid electricity stored in a large on-board battery. A lithium battery is the most used EV battery as they offer power density, energy efficiency and light and compact weight (Mahmoudzadeh Andwari et al., 2017; Zhou et al., 2020). The lead-acid battery is not preferable due to poor thermal performance, low specific energy and chemical leakage. BEV and HEV face a huge challenge as 45.3% of the EV cost is the battery's cost (Petersen, 2011).

EV can increase a household electricity consumption of an industrialised country by 50% (Van Vliet et al., 2011) which can be neutralized by powering EVs from PVs. Netherlands sets its targets to penetrate 200,000 EV in 2020 (Chandra Mouli et al., 2016). Nordic countries of Denmark, Finland, Norway and Sweden have planned to 100% penetration of passenger cars by 2050 (Graabak et al., 2016). Thus, the EV charging station can be powered from PV (Ghotge et al., 2020; Ma et al., 2014). Considering the potential of PV powered EV, currently, feasibility study using local solar radiation has been conducted in New Jersey (Birnie, 2009), Canada (Li et al., 2009), Brazil (Sorgato et al., 2018), Dublin (Esfandyari et al., 2019) and Australia (Islam and Mithulananthan, 2018). PV-grid and PV-standalone are the two most popular charging station. PV grid charging station gets supply during the insufficient sunshine while PV- standalone rely on PV only (Ghosh, 2020b). However, they are suitable for the remote area where utility supply is not convenient or costly or not available. A 6.5 kW PV standalone charging infrastructure, accommodated four EVs (Nissan Leaf), travelling 50 km throughout the day in Galway in Ireland. The control strategy was adopted to maximize the PV energy usage while meeting the demand of the EV batteries (Kineavy and Duffy, 2014). The parking area of any residential or commercial building can be covered with PV to form PV powered EV charging station, which will charge the battery of EV directly for the car during daytime as shown in **Figure 26a** (Fattori et al., 2014). These overhead canopies are built by PV and commonly referred to as solar carport. Due to variation of solar intensity in the summer and winter season, battery storage and provision for grid supply when requires are also suggested (Birnie, 2009; Codani et al., 2016; Esfandyari et al., 2019; Igualada et al., 2014; Li et al., 2009). **Figure 26b** shows India's largest carport in India, solarized by Tata Power Solar having 2.67 MW spread across 20289.9 $m^2$ area which Offsets 1868 tonnes of $CO_2$ annually (Power, 2019). Figure 26c shows solar carport for 22-vehicles at the parking lot located in Fort Lauderdale, Florida. This solar carport solution can produce up to 88, 357 kWh of clean energy with an average energy saving of $10,000 per year respectively. This charging while parking is a potential future option (Van Roy et al., 2014). Charging the EV directly from BIPV is possible for a commercial building where cars are parked during the peak office time and it matches with the sunshine period (Richardson, 2013).

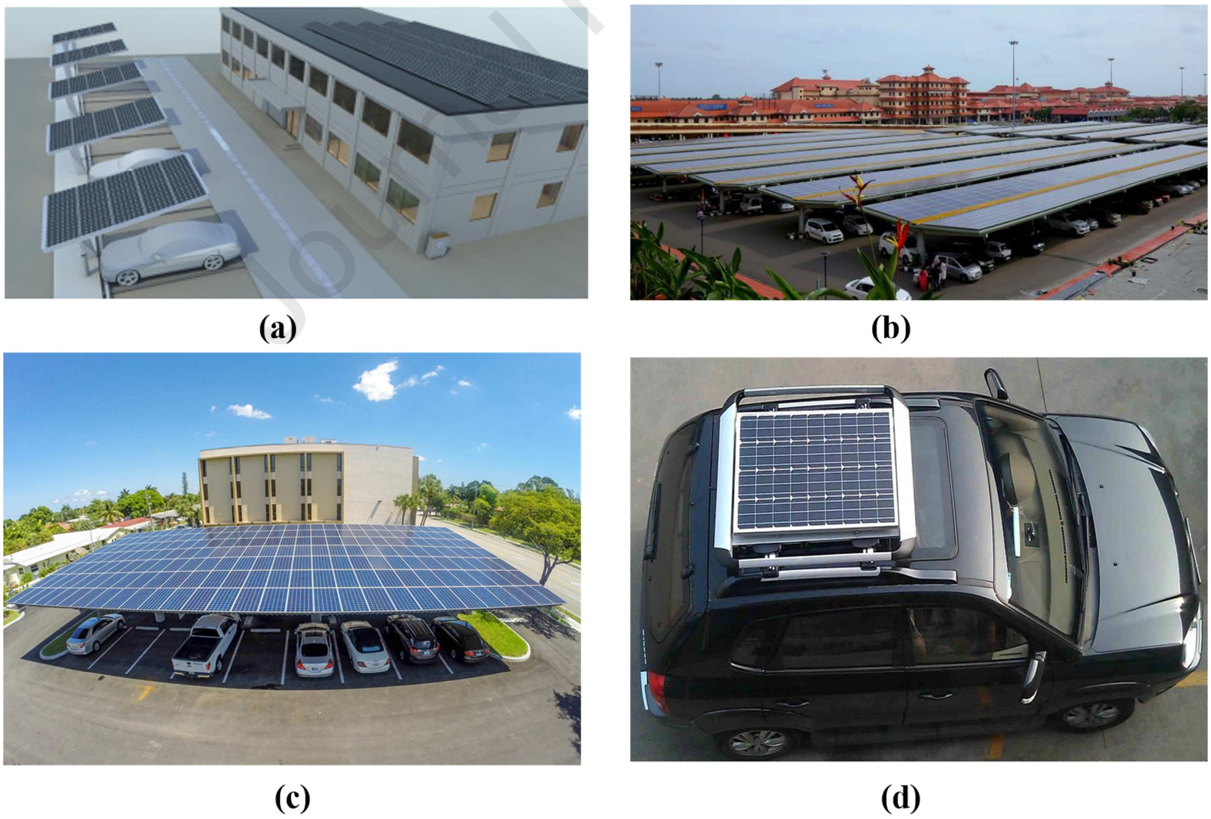



Figure 26: (a) Design of solar powered EV charging station (Taken from (Birnie, 2009)]; (b) Solar Car port In Cochin International airport (9.93606° N, 76.26145° E) India. Image Source ((Power, 2019) (c) 22-vehicles at their headquarters parking lot located in Fort Lauderdale, Florida. (Source &

image courtesy: solar carport installation at MOSS Construction by Advanced Green Technologies) (d) RV EV car roof-mounted PV module, (image courtesy: Giantour Corp Ltd)

Vehicle integrated PV (VIPV) is another elegant approach to power EV from PV (Bhatti et al., 2016; Richardson, 2013). Thin films or traditional c-Si based PVs (shown in Figure 26d) are attractive for VIPV to mount on the roof of the EV and converter fitted battery will be there for back up. VIPV using brushless permanent magnetic DC motor was also proposed (Rattankumar and Gopinath, 2012). This integrated can also be used for the air conditioning or heating purpose inside the car. Thus, VIPV systems can be suitable to run an auxiliary device such as fan, audio players, and switchable window or for racing cars. A mixture of silicon crystal with fixed quantum points can be painted on the car body for VIPV application (Kadar and Varga, 2013). Despite the low efficiency (less than 2%), the future of this technology is exciting.

### 5.4. Emerging future BIPV/BAPV technology

**Light weight BIPV-**BIPV and BAPV both are often installed or integrate on an existing building which can affect the building structure as the weight of glass-blacken sheet PV modules vary from 12 to 16 kg/m$^2$ and glass-glass modules vary from 16 to 20 kg/m$^2$. This extra load was not taken into account during the building design phase which crates obstacle. Therefore, for BIPV application, specific power (power/weight =W/kg) gets higher priority than conversion efficiency. Flexible amorphous silicon and c-Si have a specific power of 16 Wp/kg and 12-17 Wp/kg respectively (Ransome, 2009). Flexible and lightweight, emerging PV technologies enable novel building applications over traditional type PV modules (Ramanujam et al., 2020). Flexible type PV modules do not need any ballast which makes easy integration. PV module with a weight of 5 kg/m$^2$ substitutes the typical front glass with a thin polymer sheet and the standard back sheet by a composite sandwich structure using stiff ionomer (Martins et al., 2018a) adhesive and polyolefin (Martins et al., 2018b). Varying substrates for CIGS PV, specific power can be achieved between 0.2-0.4 kW/kg (steel, titanium and polyimide foil) for light weight BIPV integration (Feurer et al., 2017). First 250 m$^2$ flexible OPV fabricated by a roll to roll process had 4.3% average efficiency was installed in the solar trees at German pavilion in 2015 Universal Expo in Milan for investigation of future BIPV (Berny et al., 2015). **Figure 27** shows that higher specific power is possible from emerging technologies which broke the myth that the highest efficiencies are necessary for BIPV application (Reese et al., 2018). Third-generation PV technology offers further lightweight high power generation because of their low-temperature solution-processable fabrication (Xie et al., 2019).

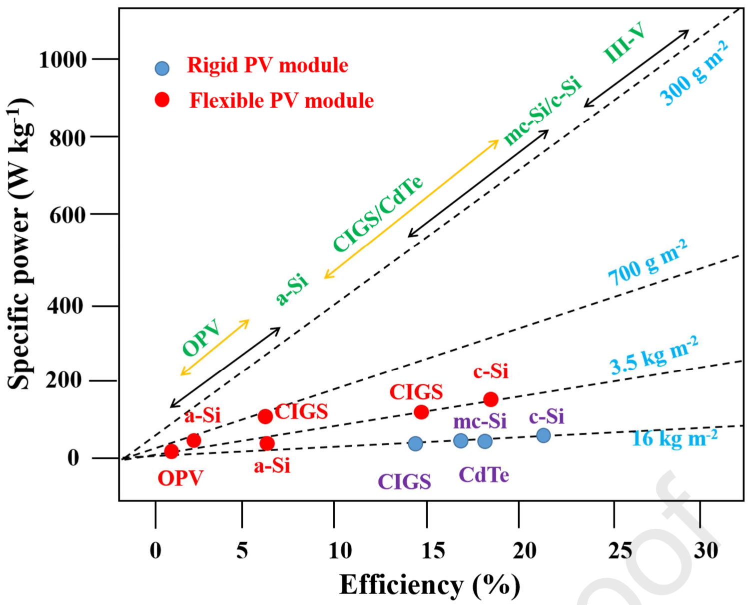
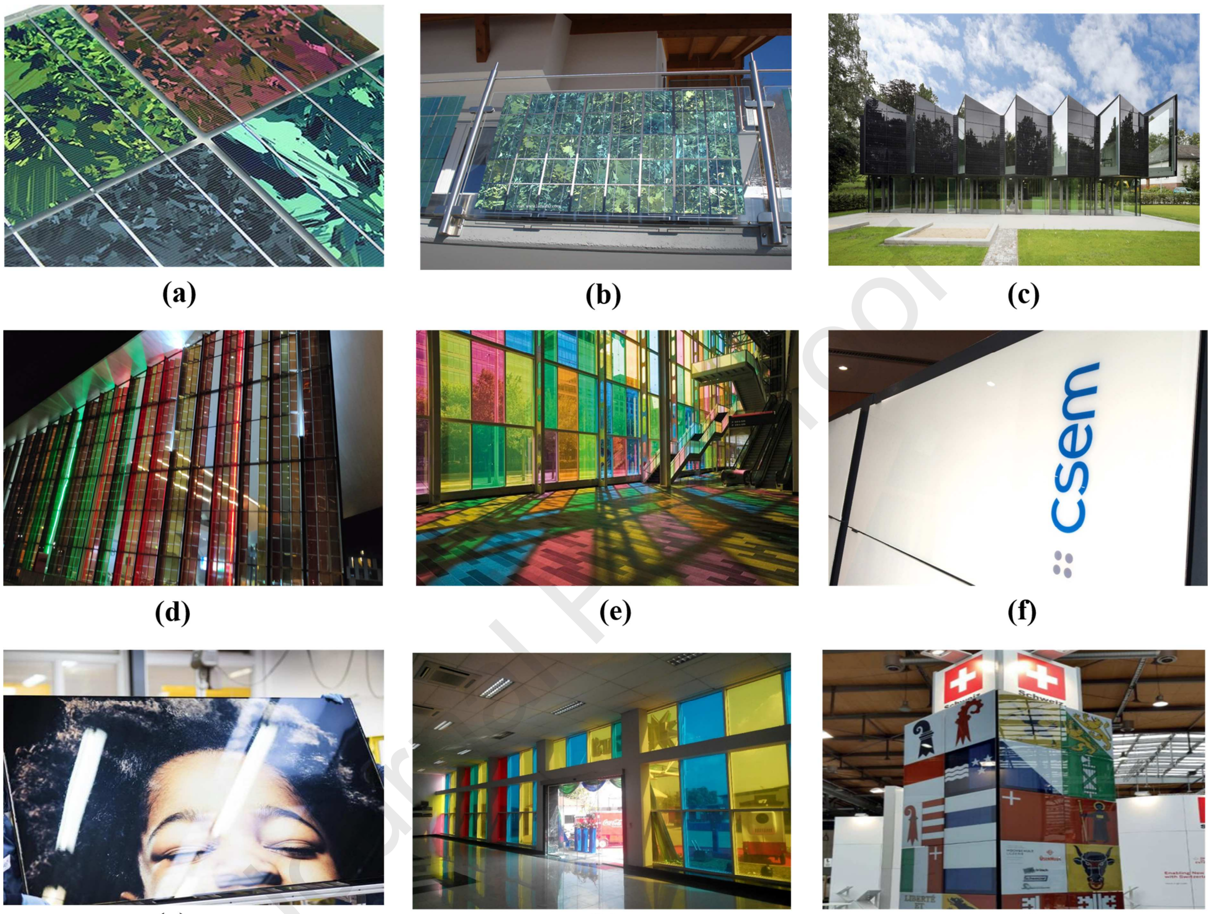



Figure 27: Specific power as a function of AM1.5G module efficiency (Redrawn from (Reese et al., 2018))

**Coloured or invisible BIPV**

Coloured BIPV is a new technological solution for the inclusion of coloured PV in modern and heritage type building. Coloured PV technology includes traditional and new all new type of PV e.g. blueish silicon, DSSC, Organic type while they can be installed as façade, roofing shading or balcony glazing (Eder et al., 2019). The prime target is to hide the PV functionality from and treat them as invisible PV. Bare c-Si (both monocrystalline and multi-crystalline) offers reflectance around 30 %, which can be reduced by introducing antireflective (AR) coatings on their surfaces (Soman and Antony, 2019). Varying AR coating thickness gives blue or other colour to the PV cells which also influence the PV cell efficiency. AR coated modified colour-based PV cells can be purchased directly from the cell manufacturer. Presently few developers are in the market with coloured BIPV. Kameron Solar produce Sparkling Gold, Disco Pink, Emerald Green, Stone Elegance, Diamond Blue type coloured PV (as shown in Figure 28a). LOF solar built a residence with balcony glazing in Black forest Germany where this colour blends seamlessly with surrounding forest and trees as shown in Figure 28b. In addition, coloured BIPV is possible to achieve from any semi-transparent type a-Si, CdTe, CIGS and third generation DSSC (as shown in Figure 28d), perovskite, organic PV and LSC (as shown in Figure 28e) technology.

A certain colour/pattern-based interlayer can be sandwiched as an encapsulant layer between upper glass and module or can be introduced at the back also produce coloured BIPV. Such system is commercialized by the Centre Suisse d'Electronique et de Microtechnique commercialized (CSEM) by Solaxess SA where an elective filter on the front of the glass cover reflects and diffuses solar radiation within the visible spectrum, offering a white appearance (Figure 31f), whilst the transmitted infrared part is converted into benign electricity. Kaleo-Solar developed (Figure 31g) an integrating coloured BIPV system where high-resolution photo printed on a film with special inks is laminated between cells and the cover glass. After the module lamination, only the printed photo is visible while PV cells are no longer visible. Amorphous silicon technology can be combined with coloured polyvinyl butyral as the back encapsulant is shown in Figure 33h for coloured a-Si technology. Lucerne University of Applied Sciences developed multi-coloured ceramic digital printing on BIPV glass (shown in Figure 28i) where ceramic paste can be introduced to the glass prior to the tempering of the glass which bonds strongly to the glass. The printed dotted pattern allows sufficient light to reach the PV cells; offers inhomogeneous shading and losses up to 20% (Mertin et al., 2014, 2011). Use of coloured BIPV requires optimization of colour perception, as mentioned in section 4.4. Also, it must be kept in mind that reduced PV efficiency is achievable from coloured BIPV since there is a reduction of the incident light on the PV cells.




(a) (b) (c) (d) (e) (f) (g) (h) (i)

Figure 28: (a) Colourd PV (Image courtesy: KameleonSolar), (b) Blacony glazing by LOFT solar, (c) Black BIPV façade on a children's day-care centre in Marburg; project realized by ertex-solar (d) SwissTech convention centre at EPFL campus, Lausanne Switzerland (Image courtesy: EPFL), (e) Striking facade of the Palais des Congrès in Montreal, Canada,(Debije, 2015) (f) Elective filter based white BIPV (image courtesy: CSEM) (g) High resolution photo integrated coloured BIPV (Image courtesy: Kaleo-Solar (h) Amorphous silicon with coloured polyvinyl butyral (Image courtesy: AppleSun) (i) Multi coloured BIPV modules developed by the University of Lucerne (Image courtesy: Envelopes and Solar Energy Competence Centre within the Hochschule Luzern)

**Sensor application-**BIPV can act as a sensor for an intelligent building energy management system. Voltage is proportional to the temperature and current directly depends on the solar intensity. Mapping the response of a specific PV power- generating BIPV is attractive as over a variety of illumination and temperature condition, output parameters from it can be engaged as input data for intelligent building energy management system. Most often PV arrays incorporate a large number of PV module which can replace the engagement of a large number of sensors. Installed BIPV for a smaller area can also work as sensor and can offset a smaller amount of building energy needs by producing modest power. BIPV window sensor can inform how to operate the HVAC system which is necessary to operate electrically actuated shading or electrically actuated chromic window(Abe et al., 2020) (John and Conklin, 2017).

**Emerging product-**

Solar squared is a product from BuildSolar, spin-out company from the solar lab, University of Exeter. In this product, the spaced typed structure is present. Low concentrator CPC on crystalline silicon generates power while they are sandwiched between transparent glass blocks. One block is able to produce 1 W DC power while *U*-value is 1 W/m$^2$K (Baig and Mallick, 2018). This product (shown in Figure 29a) has prodigious potential for building integration specially for less-energy hungry, zero energy, sustainable, green, and aesthetic building integration.

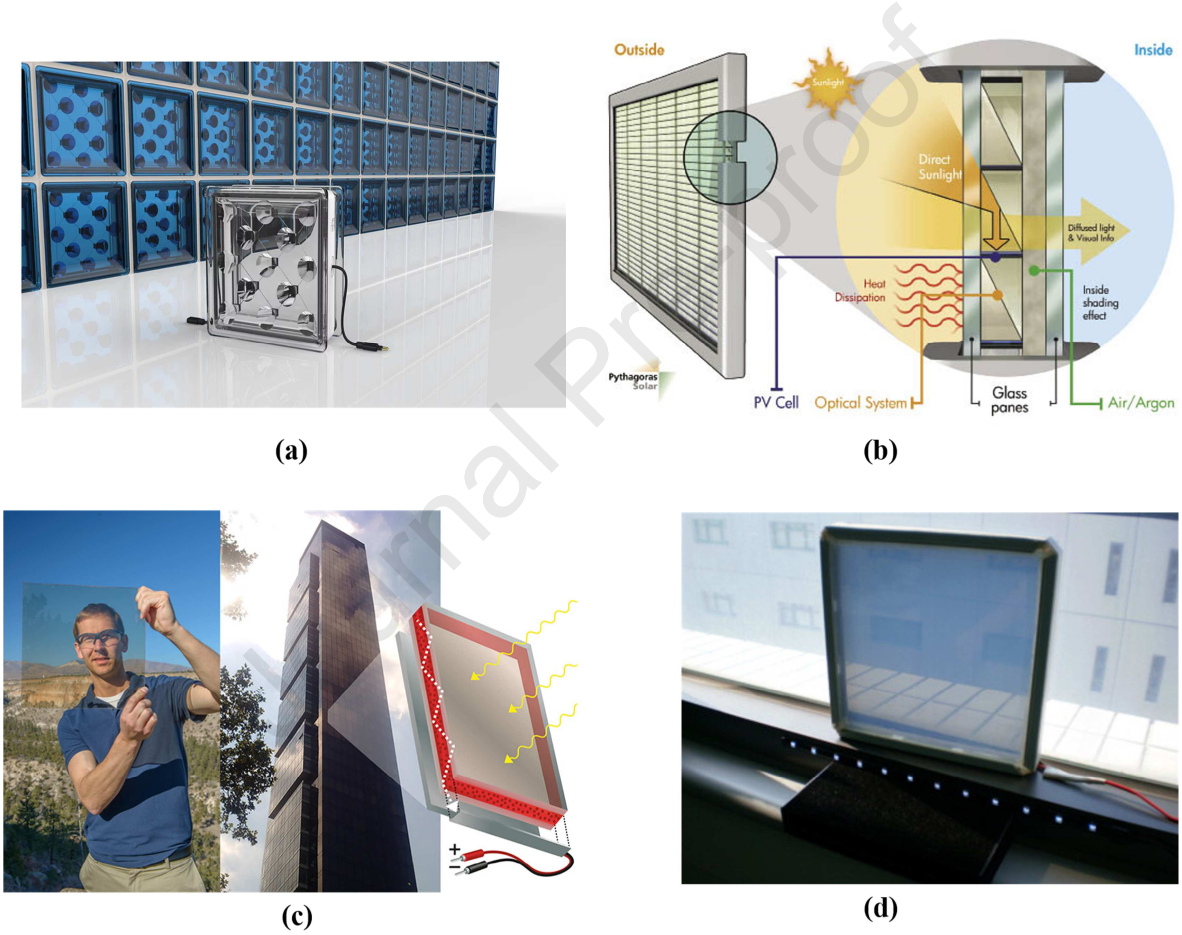



Figure 29: Solar squared (Image courtesy Build Solar (taken with permission)) (b) Pythagoras Solar (Image courtesy: Pythagoras Solar) (c) CuInS2 Quantum dot LSC BIPV Window (taken with permission (Bergren et al., 2018) (d) Transparent PV- window module (17 cm$^2$) for LED lightning application (Chau et al., 2010).

Pythagoras Solar as shown in Figure 29 b was conceived in Petach Tikva, Israel, with offices in Taipei, Taiwan and San Mateo, California, specializes energy efficient building by harnessing energy from the sun, generate power directly from it. This aesthetically pleasing BIPV product was employed in Chicago's Willis Tower, formerly known as the Sears Tower. It was founded in 2007, however currently not in operation (Closed from Apr 2013). Figure 29c shows LSC-BIPV window which has high quantum yield (>90%), NIR-emitting CuInS2/ZnS quantum dots into the polymer interlayer between two sheets of low iron float glass, a record optical efficiency of 8.1%. A 10 cm × 10 cm device is ∼44% transparent is the visible spectrum and with silicon solar cells this device converts 2.2% and 2.9% solar to electrical power conversion while substrates are a black background and reflective type respectively (Bergren et al., 2018). Presently it is commercialized and ready for sale in the brand name of UbiQD. Figure 29d shows a 17 $cm^2$ transparent PV based window for LED lighting application which was fabricated by integrating traditional silicon PV cells and organic–inorganic nanocomposite material. A window having 8 $cm^2$ active area had an efficiency of 3.4% while measured under AM1.5 conditions (Chau et al., 2010).

### 5.5. BIM embedded BIPV/BAPV performance

Optimized building design, construction and operation are required to obtain an energy-efficient less-energy hungry building. For a new building, this task can be performed before the construction phase (during the design phase), and for retrofit building, this is possible using the historical data of the building. Building energy modelling is currently gaining high importance which can compare the different building components and prescribe the efficient and suitable components for a particular location complying with the energy standards. Incorporating of PV particularly BIPV/BAPV is now common practice for analysing the self-sufficiency of less-energy hungry/low energy/ zero energy/ adaptive building (Gao et al., 2019; J. Li et al., 2020).

Successful integration of PV into a building (BIPV/BAPV) requires architectural building design, and engineering knowledge to integrate the photovoltaic suitably. Both architecture and engineer need software tools to perform the design and analysis of the overall results. Building information model (BIM) gives a platform where architecture, engineer and construction people gets benefitted by solving the multiphase complex building scenario. BIM contains parametric computable data, such as building geometric descriptions, construction typology, and thermal properties which are required for building project and particularly applicable for rapid design, generation, planning, and decision-making, document creation, cost estimation, and vital project data in a digital format through the course of a building life cycle (Sanhudo et al., 2018). For the architectural design, required software tools are AutoCAD, MyArchiCAD, Auto Desk Revit and Sketchup while for PV design PVSYST. However, for building energy model (BEM), a complete package is required where this drawing software will provide the 3d building geometry, PV design will provide the PV parameters for particular location and properties of building envelopes e.g. window, roof, wall, door. Currently building energy software includes DOE-2, eQuest, DesignBuilder, Ecotect, Energy-10, Green Building Studio, IESVE, HEED, and EnergyPlus (J. B. Kim et al., 2015). For EnergyPlus graphical user interfaces (GUI) are AECOsim, CYPE-Building Services, DesignBuilder, Demand Response Quick Assessment Tool, Easy EnergyPlus, EFEN, Hevacomp, OpenStudio, Simergy, and SMART ENERGY. OpenStudio uses SketchUp plug-in to create building geometry editor; an OpenStudio application as a main energy modelling interface; RunManager as a simulation interface; and the ResultsViewer. BIM based building energy model (BEM) is a potential tool for less energy hungry building simulation. Information data stored in BIM need a seamless translation from BIM to BEM. However, BIM information does not always need to be translated into BEM or all the required parameter always come from BIM. For example, a room in an architectural model does not always indicate a zone in an energy simulation model and neither boundary conditions nor thermal zone information is stored in BIM.

Input parameters of BIM-BEM for BAPV are different from BIPV. For BAPV, the required input parameters include location, PV specification (efficiency, rated power), tilt angle and inverter details. For BIPV technology, including the previously mentioned parameters, the additional requirements are the transmission of PV, daylight transmission, solar heat gain factor or solar energy transmission, thermal transmission, or overall heat transfer coefficient. EnergyPlus (Buildings energy simulation tool) requires input parameters of PV module area, efficiency, open circuit voltage, short circuit current, voltage at the maximum power point, current at the maximum power point, power temperature coefficient, thermal conductivity, infrared emittance, *U*-value, solar heat gain coefficient, and visible light transmission, daylight illuminance inside a room due to BIPV, (Ng et al., 2013) (M. Wang et al., 2017)(Peng et al., 2016)(Jakica, 2018). BIM for optimizing BIPV tilt angle (Xuan, 2011) and BIM API program in Autodesk Revit (Dixit and Yan, 2012) (Kuo et al., 2016) was previously employed to simulate production of PV electricity (Gupta et al., 2014).

# 6. Discussion and perspective

## 6.1. Environmental, economic and societal viability of BIPV/BAPV

Environmental benefits from BIPV/BAPV is the essential study as during the processing, purification and production of raw PV materials, PV system and other BOS fabrication, operation and maintenance, and also during the dismantle of BIPV system there is a provision of power consumption which come from traditional fuel sources (Parida et al., 2011). Life cycle analysis (LCA) of PV system reveals the benefits of using a PV system. LCA analysis indicates for 1kWh energy generation, PV emits only 35 gCO2eq while 1138.8 gCO2eq for coal. This data clearly indicates the positive environmental impact of PV (Sierra et al., 2020). PV system's energy payback time (EPBT) indicates the electricity balance or net zero gain from PV over its lifetime. Adaptive BIPV window system has ability to enhance the environmental impact up to 50% higher than traditional window (Jayathissa et al., 2016). EPBT of c-Si based BIPV window for Singapore climate was 1.98 years (Ng and Mithraratne, 2014b) while 2.1 kWp domestic BIPV in Southern England showed EPBT of 4.5 years (Hammond et al., 2012). In Hongkong climate, roof top BAPV system's EPBT was 7.3 years however variation of azimuthal and inclinational angle this time changes. However, greenhouse payback time was only 5.2 when PV faced south direction and kept an optimal angle (Lu and Yang, 2010). Low concentrating BIPV system showed 13% improvement of an environmental impact compared to without concentrating BIPV system (Menoufi et al., 2013). In another work, asymmetric lens-walled compound parabolic concentrator based BIPV showed EPBT which varied between 2.82–4.74 years depends on the different location in China (Li et al., 2018). For BIPVT system EPBT varies between 7.3 to 16.9 years. Cost of energy production for BIPVT varies from 1.61 to 3.61 US$/kWh (Tripathy et al., 2017). For Taiwan climate, EPBT took 10 years (Wu et al., 2018). Hence it is clear that EPBT within 10 years is possible for BIPV/BAPV integration in less energy-hungry building.

Building's construction cost reduction potential using BIPV/BAPV system is one of the most engrossing topics of discussion. It is evident from reported work that cost of BIPV building envelop is higher than the cost of the traditional building envelope. BIPV tiles can increase 2% cost than conventional tiles (Hammond et al., 2012), BIPV window can add \$350–500 per $m^2$ (Benemann et al., 2001), while in a commercial building, BIPV can add 2-5% of overall construction cost (Eiffert, 2003). Also, in some cases, it was found that BIPV façade can reduce 20% cost than polished stone facades (Koinegg et al., 2013). For BIPV tiles, standing seam products and shingles, require additional adhesives and framing and flashing material while for BAPV roof, PV is attached on the existing construction materials. Thus, BIPV actually offset the construction cost of a building. Hence, the higher cost can be expected for BAPV compared to BIPV (Verberne et al., 2014). Other costs for BIPV/BAPV systems arise from BOS and transportation and installation. Most often, this BOS counts only 10-16% from the overall project cost, where inverter and storage systems are the leading cause of this cost during installation and operation time. Transportation cost is very dynamic, and few reports are available for information. In Italy, transport and installation cost was 19% (Cucchiella et al., 2012) while in Greece mounting cost was only 2.5% and 3% transportation cost (Bakos et al., 2003). However, for BIPV, cost should include building envelope cost and additional benefits from electricity generation (Oliver and Jackson, 2000)(Pagliaro et al., 2010; Sozer and Elnimeiri, 2007). BIPV/BAPV has potential to satisfy the building energy demand by generating the green electricity and reducing the electricity consumption by lowering heating, cooling, and lighting load, and excess energy can be exported to the grid. Thus BIPV/BAPV shows a positive cost-effective over traditional construction cost.

Deployment of BIPV/BAPV has high societal impact and benefits to wider society. Currently, because of the rapid urbanization, 55% of the world population lives in urban areas and it is projected that in 2050 this will be 68% (Sampson et al., 2020). This urbanization consumes a considerable amount of electricity while most of the country depends on the imported fossil fuel energy sources to generate that electricity (Foster et al., 2020; Luo et al., 2020; Su, 2019; Xie et al., 2020). Also, the economic growth of a nation increases with urbanization (Gasimli et al., 2019). Hence, to maintain economic growth and urbanization, and to become an energy secured country, BIPV is the key solution. Traditional coal based power plant emits particulate matter (PM) which has a dimension between 2.5 micrometre ($PM_{2.5}$) to 10 micrometre ($PM_{10}$) and also $SO_2$ and NOx, $CO_2$ and CO (Clark et al., 2020; Karplus et al., 2018; Song et al., 2020). While these gasses create a greenhouse effect, PM also has a direct adverse impact on human health as $PM_{2.5}$ influences asthma. In 2015, 24.6 million people had asthma represented nearly 8% of the population in the USA. In the USA, between 2008 and 2013, per head asthma treatment cost was $3266 annually (Williams et al., 2019). Replacement of the coal plant with BIPV can displace this PM2.5 and save the medical cost, which can be employed for countries development and also help the growth of the energy economy without polluting the environment. Also, transmission and distribution losses reduction gives an opportunity to the energy provider to reduce electricity tariff (Byrnes et al., 2013) (Yang and Zou, 2016).

### 6.2. Limitation and progress towards BIPV/BAPV

Inclusion of PV in building still is not excitingly triggered due to several factors such as lack of public awareness, missing professional knowledge, low communication between designers and engineers, no proper knowledge of maintenance. End-users of BIPV technologies are still in the dark about the capital and installation cost, ongoing repairing and maintenance cost for BIPV/BAPV systems throughout the lifetime of buildings. They have knowledge about the cost of the system but have no knowledge about the long-term benefits. Hence, a clear cost-benefit analysis should be there to make helpful for users. Although since 1980, 10 fold price dropped for PV modules but concrete data of energy payback time is rare (Yang and Zou, 2016). In addition, long payback period, high upfront capital cost, low efficiency of BIPV may possess high electricity tariff. BIPV policies are not well documents and government supports particularly for small industries are not available in the same order (Biyik et al., 2017; Jelle, 2016; Osseweijer et al., 2018; A. K. Shukla et al., 2017b; Shukla et al., 2016b, 2016a). Low PV cell efficiency is also another barrier for widespread BIPV/BAPV adoption. Low efficiency decreases the power conversion which increases the capital cost and delays the EPBT. Lower electricity price from fossil fuel energy sources also creates a barrier for BIPV technology (Alnaser and Flanagan, 2007). Hence to promote BIPV technology, an incentive for PV and increase the traditional electricity should be implemented. At the end of 2017, global installed PV capacity was 400 GW which is expected to reach 4500 GW by 2050. If the average PV panel lifetime is considered to be 25 years, the worldwide solar PV waste is anticipated at around 78 million tonnes by 2050.

Therefore, the disposal of PV panels, by using environmentally benign waste recycling, recycling technology, recycling policies are also pertinent (Bogacka et al., 2017)(Chowdhury et al., 2020).

Though the presence of so many barriers, many countries including UK, USA, Asia and EU's zero-carbon or decarbonisation in 2050 has escalated the BIPV penetration in the building sector. This is envisaged because of the attractive aesthetic and flexible nature of BIPV (Osseweijer et al., 2018; A. K. Shukla et al., 2017b). Specific region wise BIPV growth is listed in Table 7. Present global BIPV market size is about 2.3 GW where Europe constitute the largest market size (42% of global market ), particularly because of attractive incentive in Germany, Italy, and France. Globally, Europe and the USA dominate the BIPV market than that of Asia. The continuous growth of global BIPV market is happening while compounded annual growth rate (CAGR) is higher for ASIA pacific (Osseweijer et al., 2018). Incentive plan has already been taken by different countries. In Germany, "The thousand Solar Roofs Program" was initiated in 1995 to promote BIPV/BAPV, while in the USA, "Ten Million Solar Roofs Program" was started in 2010 and in China, "enforcement advice for promoting solar energy applications in buildings" and "interim procedures" was started to promote the BIPV/BAPV technologies (Zhang et al., 2018). Indian government has also set target to achieve 40 GW rooftop solar PV integration by 2022 (Reddy et al., 2020). Because of these initiatives, present market growth of BIPV is very promising which shows close to 40% per year in the next decade, from US$1.1 billion in 2017 to over US$2.7 billion in 2021 shown in Figure 30 (Ballif et al., 2018). Later on, the BIPV market average annual growth rate for 2023 is expected to reach 11200 million $. Positive media coverage regarding environmental and economic benefits from BIPV/BAPV can increase public awareness as without public support, the whole concept and project will be in jeopardy (Azadian and Radzi, 2013).

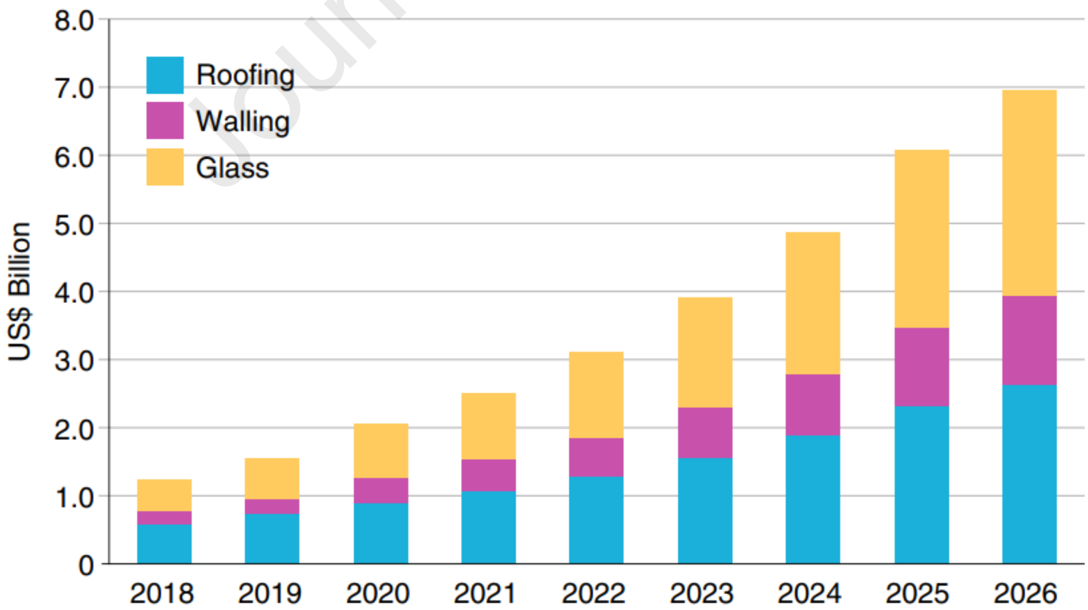



Figure 30: Worldwide annual revenue from BIPV (Reprinted with permission from (Ballif et al., 2018) Copyright © 2018, Springer Nature).

Table 7: Global BIPV market development and forecast for 2020 in MW and compounded annual growth rate

| **Region/Country** | **2014** | **2015** | **2016** | **2017** | **2018** | **2019** | **2020** | **Compound annual growth rate (CAGR %)** |
|---|---|---|---|---|---|---|---|---|
| **Asia/Pacific*** | 300 | 492 | 772 | 1159 | 1672 | 2329 | **3134** | 47.8 |
| **Europe** | 650 | 967 | 1441 | 2103 | 2929 | 3807 | **4838** | 39.7 |
| **Rest of world** | 81 | 125 | 184 | 263 | 355 | 451 | **561** | 37.9 |
| **USA** | 319 | 476 | 675 | 917 | 1200 | 1491 | **1766** | 33.0 |
| **Canada** | 42 | 61 | 86 | 119 | 157 | 190 | **228** | 32.6 |
| **Japan** | 143 | 201 | 268 | 349 | 434 | 520 | **612** | 27.5 |
| **Total (GW)** | 1.5 | 2.3 | 3.4 | 4.9 | 6.7 | 8.8 | **11.1** | |

*Asia/Pacific excluding Japan

Hence a smooth entry of BIPV in energy market of any country needs a support from all BIPV stakeholder which includes government (central/national government, energy Review Committees), BIPV industry (BIPV manufacturers/suppliers/wholesale), construction industry (contractors; material suppliers; PV-module installation; architects); academia (Universities; Research institutes), end users (Housing associations and their tenants; Business Rental (office spaces); private homeowners (Osseweijer et al., 2018).

## 7. Conclusions:

The work reviews the available and future application potential of PV systems in a building being part of building-integrated (BI) PV (BIPV) or building attached (BA) PV (BAPV) while they are separated by their integration and purpose of uses. Building wall, roof and window application using semi-transparent PV types are gaining interest because of their multifunctional behaviour such as replacing structural material, provides high insulation, allows daylight, and generates power. To enable BIPV in a colder climate, vacuum integrated BIPV is suitable. BIPV and BAPV both can also be a source for autonomous switchable glazing to change its state based on occupant's requirement. BIPV/BAPV has the ability to be a source of power supply for an electric vehicle (EV). Along with this advantageous, BIPV/BAPV both suffer from temperature issues, dust, and snow accumulation on the devices. Elevated temperature effect can be minimised by using active or passive thermal regulation while shading effect requires a cleaning mechanism. Gaining the interest of photovoltaic technology integration in the building, forced to impose an international standard or country wise standard for installation. In future BIPV and BAPV has a possible application in mainly three application, autonomous switchable glazing, low heat loss glazing and BIPV as a source of EV.

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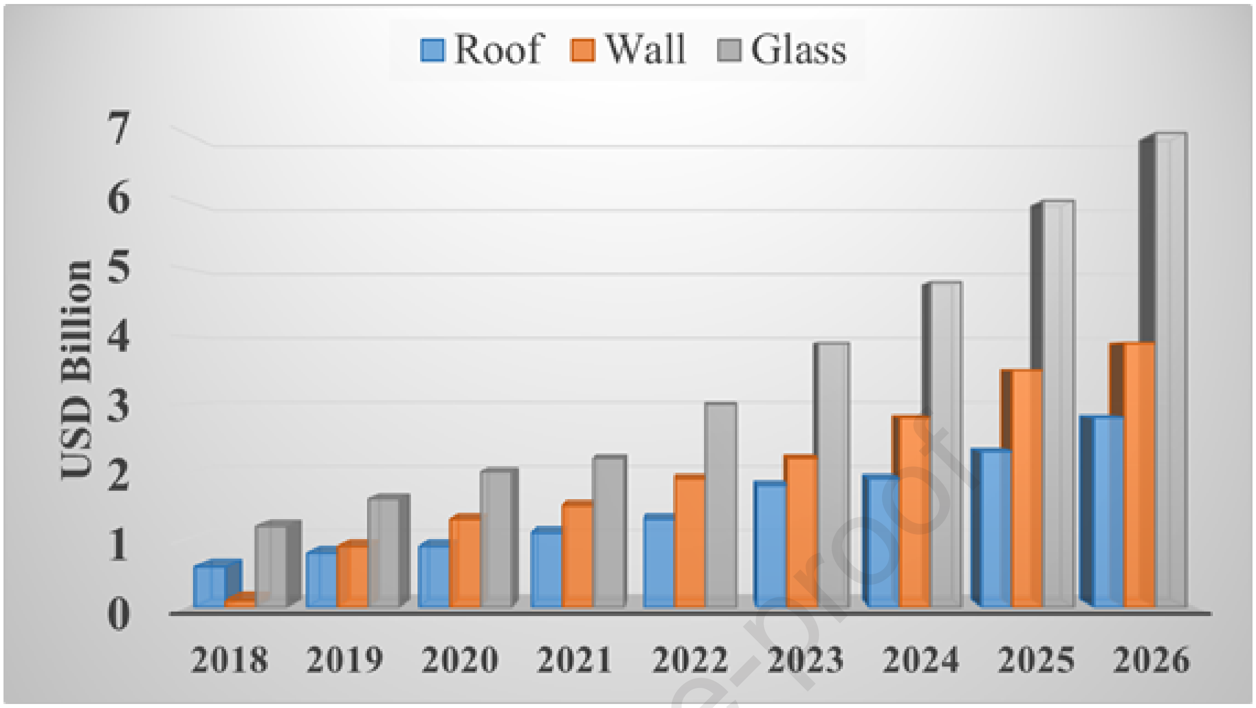
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**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: