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Building Integrated Photovoltaics: Technical and Aesthetic Prospects

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Abstract: The energy demand in the world is expected to exceed 740 million TJ by 2040 and our dependence on fossil fuels needs to be switched to sustainable and renewable energy sources like solar energy. Building Integrated Photovoltaic (BIPV) is one of the best approaches to extracting solar energy. There are more than 200 BIPV products in the market currently but when it comes to integrating these products into the technical aspects such as buildings' structural integrity, thermal, daylight retainment and aesthetic prospects to be considered. The share of BIPV integration potential of different building types in the world of residential, agricultural, industrial, commercial and other buildings account for 66%, 4.8%, 8.1%, 19.9%, and 1.2% accordingly. Many solar technologies developed to achieve architectural requirements, but the main problem is the trade-off between efficiency and aesthetic appeal, which is less than 10% in coloured and transparent solar modules. This paper discusses the different applications of solar photovoltaics (PV) in building architecture, technical requirements, and different module technologies. The article provides a comprehensive guide for researchers and designers working on the development of BIPV integrations.

Keywords: Building integrated photovoltaics (BIPV), Aesthetic, Rooftop, Façade, Solar module, Color

1. INTRODUCTION

The world's energy demand is expected to exceed 740 million TJ by the year 2040 and approximately 22.7 billion tons of coal need to burn to meet the demand using thermal energy [1]. But fossil fuels are depleted day by day and their extraction and combustion lead to negative environmental impacts due to the release of greenhouse gases such as CO_2 [2]. The total CO_2 emission in the world is expected to exceed 10 billion tons by 2030 [3]. For CO_2-neutral energy systems, there is no question about the need of switching to renewable energy sources in the future [4].

Solar energy is the Earth's most abundant source of energy, and it is inexhaustible and clean [5]. Therefore, the development of solar photovoltaics has become one of the most talked about energy extraction modes [6]. Ground-mounted solar PV has been implemented and developed in many countries for several years [7]. But it requires a significant amount of land which is scarce and expensive mostly in urban areas where energy is highly consumed [8]. Therefore, it is necessary to move to other methods of integration of solar PV. The development of Building

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Integrated Photovoltaics (BIPV) is crucial for the transition to renewable energy, where solar photovoltaics are integrated into the building infrastructure [9]. Solar PV modules can be added to the building infrastructure such as roofs, facades, and windows. A BIPV product is effective and can be used when it meets the basic requirements of a building product and replaces it [10]. In other words, it should be able to perform the task of building materials while generating electricity.

When integrating solar PV into the building, several aspects must be considered. Some of these aspects are: application on the building, availability of BIPV products and possible technologies, aesthetic aspects, and light, thermal, acoustic, and other comfort parameters retainment inside the building [11]. There are several major BIPV installations in some significant architectural buildings around the world. Among these installations, roof and shading devices in Dubai Expo Pavilion, photovoltaic canopy in the main entrance of a total of 27,986 sq ft of area, semi-transparent curtain walls in office buildings in Slovakia, semi-transparent facade in Coca-Cola Femsa headquarters in Mexico, BIPV skylights in a university building in Malag, skylight in Bell Works USA covering 60,000 sq ft, and integration of residential roofs in Sweden show the wide varieties of architectural structures in which BIPV products have been installed [12,13]. Many research and development activities are carried out to optimize the tradeoff between aesthetic appeal and module efficiency. Some significant areas of improvement are thin film solar cells, dye-sensitized solar cells, organic solar cells, perovskite solar cells, and Luminescent Solar Concentrators, which have many applications, but have efficiencies mostly less than 10% and low lifetime [14]. The theoretical efficiency of silicon solar cells in colour and aesthetic appeal was recorded between 15.4% and 20.4% [15]. Upon integrating solar BIPV, it is important to consider geographic distribution, surrounding architecture, heat and sound insulation, and daylight retention [4,16]. This review paper discusses the possible application of solar modules in the different infrastructures of the building and the technical requirements of the buildings like retaining the structural integrity, thermal and daylight retainment, possible solar module technologies to develop different aesthetically appealing solar cells, commercially available BIPV products, and Research and Development (R&D) activities in this field.

2. APPLICATIONS OF SOLAR PV IN BUILDING ARCHITECTURE

Figure 1 shows the categories of applications of the BIPV system in the building architecture. When it comes to integrating photovoltaics in building, the aesthetic appeal as well as the maximum possible power generation at the least possible cost is important [17]. In building architecture, the designs are not fixed. Therefore, it is possible to meet aesthetic requirements while reducing power gain and increasing cost. However, the tradeoff must be within an acceptable range unless the purpose of replacing a building product with a BIPV

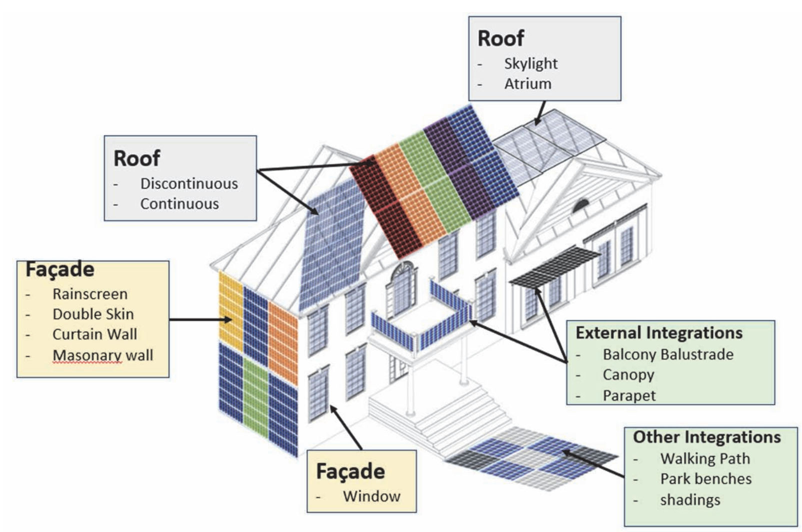


Fig. 1. An example of BIPV system applications (the main categories are roof, façade, external and other integrations).

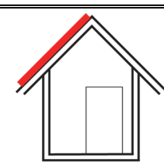
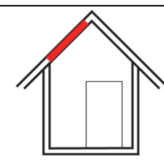
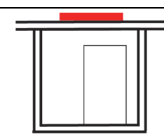
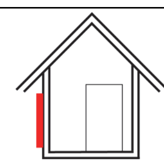
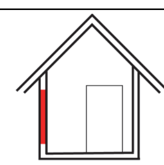
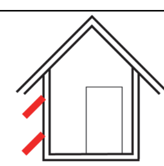
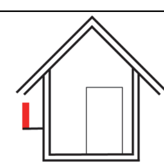
cannot be achieved. Therefore, understanding the technical and material properties of the module is important for designing BIPV modules [4].

Table 1 shows the categories of building integrations according to the international standards IEC63092 [18] and European standards EN50583 [4]. According to standards, basic building categories can be divided into four main components roof, façade, external integration, and other structural integration.

2.1 Roof

Rooftops are ideal for solar PV integration due to less shadowing due to building heights [19] Rooftops with continuous roofs or discontinuous roofs and skylights can be used to install BIPV products [20]. The largest part of the installation of BIPV products is rooftop integration which represents approximately 80% of all BIPV installations [21]. For light diffusion, semitransparent modules can be used [22].

Table 1. Categories of installation according to IEC63092 and EN50583 standard.

Category	Building application	Title angle (from horizontal plain)	Accessibility from inside	Sketch
A	Roof	Slope/horizontal 0~75°	Not Accessible	
B-1	Roof	Slope/horizontal 0~75°	Accessible	
B-2	Roof	1) Slope/horizontal 0~75° 2) Vertical 75~90°	Not accessible	
C	Facade	Vertical 75~90°	Not accessible	
D	Facade	Vertical 75~90°	Accessible	
E-1	External integrations	Slope/horizontal 0~75°	Accessible or not accessible	
E-2	Balcony balustrade	Vertical 75~90°	Accessible or not accessible	

Shingles and tiles add more aesthetics to roof integration. Flexible laminators are another option that can be used for flat and curved surfaces [19]. It is lightweight and has the advantage of not needing rack mounts as it can be directly pasted onto the building, but the efficiency is low. Skylights replaced by BIPV components add an extra benefit of thermal comfort as most IR and UV rays are absorbed by the silicon-based modules [23]. A significant example is the Bell Laboratory skylight, using amorphous silicon photovoltaic glass planes by Onyx Solar, which is the largest photovoltaic skylight installation in the USA [13].

2.2 Façade

Facades are of several types according to Fig. 1 which are rain screen facades, double-skinned facades, curtain walls, windows, and masonry walls. The façades with ventilations can have a range of 10~30 cm between the wall and the facade where thermal envelope is prioritized [24,25]. On the other hand, double-skin facades focus on properties such as daylight savings and maintenance work where the distance between the façade and the wall is approximately 1~1.2 m [26]. Integrating solar PV into walls, it can be used as a cladding element [19].

2.3 External integration

The canopy function is to protect against weather conditions. By integrating solar PV in canopies, it adds electricity generation combined with protection against solar radiation. For designing the slope of canopies, the solar PV dimensions and wind and snow loads must be considered [26].

2.4 Other

PV walkable floors where solar tiles with laminated protection can be used to replace tiles in walkable floors. The ability to withstand loads and anti-slip properties are two important factors to consider when designing walkable floors [26]. Parking space integration can be used to charge electric car batteries using on-site electricity generation. Protection against extreme weather conditions is an important factor to consider in parking lot integration of solar PV. In addition to these BIPVs on park benches, tables, and shadings can be used as remote charging points for passers [26].

3. TECHNICAL REQUIREMENTS OF THE BUILDINGS IN SOLAR PV INTEGRATION

There are several factors that affect the efficiency of solar PV components in building integrations, such as operating temperature, solar irradiation, shadow effects, spectral changes, and optical losses [27]. When the temperature of the component increases, the efficiency decreases. If the modules are installed in close contact with other building material, such as walls or roofs, it further increases the temperature due to low air circulation [28]. Solar PV also should be compatible with existing insulating materials of the building [26].

If a solar module replaces a building block of construction, it should be able to retain the integrity of the building structure even if the module breaks or reduces the energy output [4]. It is necessary to consider the fact that it is possible to replace units without damaging the building infrastructure while planning the integration of the building. On the other hand, if the unit cannot be replaced by a new will affect the overall energy output of the building which will negate the purpose of installing solar PV products as a part of the building. This should especially be considered when installing the façade, windows and balustrades areas of the building.

The purpose of adding semitransparent modules is not only aesthetic, but also for light diffusion to the structure [26]. The desired light intensity inside the building can be controlled by the dimensions of the solar module, the spacing in crystalline cells, and the thickness of the films by controlling the transparency in the manufacturing process. But when a module is more transparent, it converts less energy [29].

Cooling in summer and heat retaining in the building during winter is important when designing the BIPV systems [30]. Thermal envelope depends on the design and PV glass configuration. Thermal comfort inside a building can be measured using predicted mean vote (PMV), which includes factors such as air temperature, relative humidity, air velocity, mean radiant temperature, cloth insulation, and person metabolic rate of the person. The thermal comfort range $-0.5<PMW<0.5$ is the comfortable range for 90% of people. Protection against weather conditions is one of the basic factors considered when designing a building. If the application is ventilated or has double-skinned facades, then the impact of inverse weather conditions can be mitigated [26]. In addition to the said features, the acoustics inside the

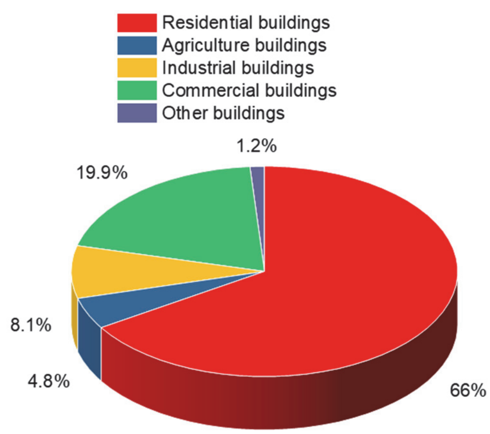


Fig. 2. BIPV integration potential in the world according to the building type (type of buildings are residential, agricultural, industrial, commercial and other building categories).

building will be no different from the traditional glass façade [26].

Figure 2 gives the percentage of BIPV integration potential of different types in the world. The share of residential, agricultural, industrial, commercial and other buildings account for 66%, 4.8%, 8.1%, 19.9%, and 1.2% accordingly [31]. It was also found that half of the potential for BIPV installation is rooftops, one fourth are façades, and the remaining are of other types of BIPV installation. The preference for building integration is mainly rooftop followed by south orientated facades [32].

4. SOLAR TECHNOLOGIES TO DEVELOP DIFFERENT AESTHETICALLY APPEALING SOLAR MODULES

Developers from industries, universities and research institutions make efforts to produce novel BIPV solutions, which are more architecturally pleasing [33]. The module is the element of construction in the building integration [19]. When it comes to the aesthetic aspect of BIPV transparency and the color properties in a solar module, the following are important aspects to consider. Making a totally transparent module is practically impossible using available technologies, since solar photovoltaic energy should capture sunlight to generate electricity. [14] The application of colors to modules reduces overall efficiency due to reflections of solar radiation resulting from the optical and physical features of the colored layers [34]. The efficiency of colored layers ranges between 7~10% [35]. There are several technologies to produce colored and transparent solar modules.

The modules that are available in the market can be customized using five different techniques namely 1) solar cell antireflective coating, 2) PV- active layers that are semi-transparent/or colored, 3) colored or patterned solar filter layers, coatings and interlayers, 4) colored polymer films 5) front glass with prints, coats and other finishings [36]. Figure 3 shows the components of a solar module where the combination creates the total solar module, while Fig. 4 shows the components which can be altered to add colors and transparency to the module.

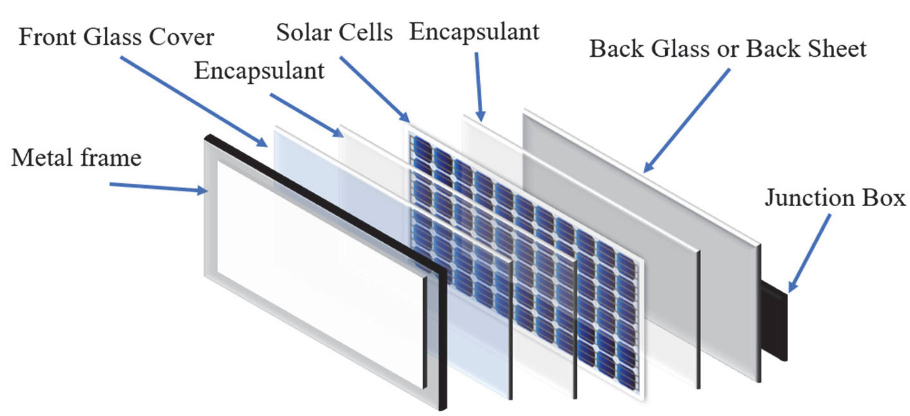


Fig. 3. Components of a solar photovoltaic module (the module components from the front to back are as metal frame, front glass cover, encapsulant, solar cells, encapsulant, back glass or back sheet and junction box).

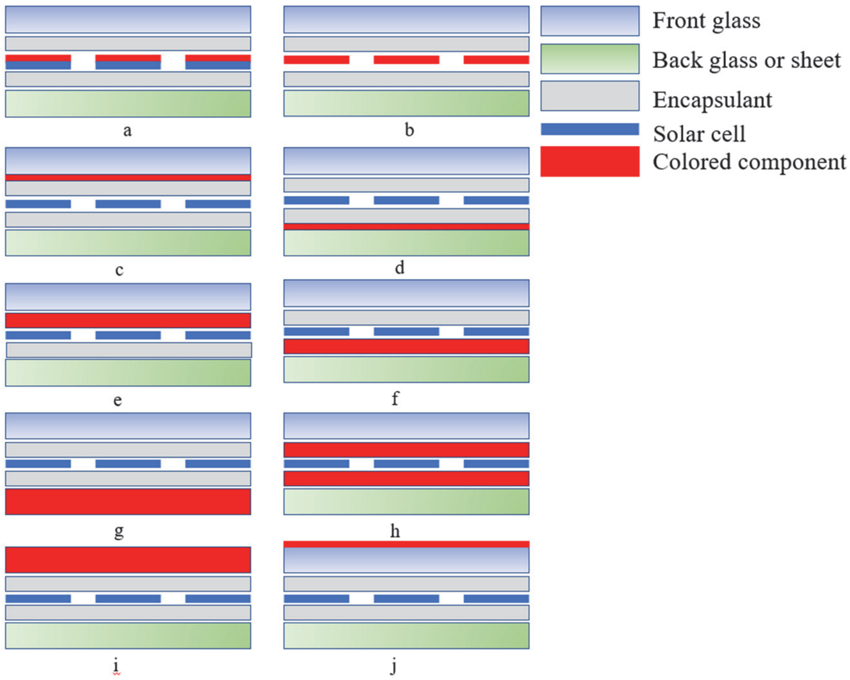


Fig. 4. Colored module combination according to the component of the module that are colored.

4.1 Solar cell antireflective coating

In conventional crystalline silicon solar cells to reduce reflections and enhance the power conversion efficiency, antireflective coating is used which gives solar cells their signature blue and black color [36]. Usually hydrogenated silicon nitride SiNx:H is deposited on the cell surface, which acts both as a passivation layer and an antireflective layer [37]. Silicon dioxide (SiO_2) is another type of anti-reflecting coating that can be used. Using thickness variation, reflection minimum shifts the reflection to the near-infrared range, thus reflecting the visible spectrum. By changing and optimizing the thickness of the antireflecting coating, a wide range of colors can be produced, such as blue, yellow, green, purple, pink, and orange [38].

4.2 PV- active layers that are semi-transparent or colored

The transparency and color in a solar cell depend on the absorption spectrum of the active layer material [33]. Amorphous silicon or thin film solar cells can achieve transparency by removing material using different treatment methods but it leads to reduction of efficiency by significant levels [36,39]. Among other cell technologies that can achieve transparency and color in the active layer are organic solar cells, dye-sensitized solar cells (DSSC), and perovskite solar cells [40,41]. In 2007, a highly transparent DSSC cell was produced with 60% transparency and 9.2% efficiency with titanium dioxide nanoparticles containing paste printed on fluorine-doped tin oxide [14], which shows the possibility of improving more aesthetically pleasing modules using these technologies.

4.3 Colored or patterned solar filter layers, coatings, and interlayers

Adding and interlayering solar modules is another option in obtaining colored BIPV products such as solar filter, or coating, which is patterned or colored [42]. In addition to that, the encapsulant and the back sheet can also be altered by colors or semi-transparent materials. Using these methods, a wide array of customizations can be achieved which are relatively economical than using special treatment methods [33,36].

4.4 Colored polymer films

Polymer films such as polyvinyl butyral (PVB), ethylene-vinyl acetate (EVA) can be altered to different colors and shades, and can be used as encapsulant or back sheet of an amorphous or crystalline solar modules [43]. Using this a large array of colors and degrees of transparency can be achieved. Using colored layer as back sheet will help to decrease the efficiency reduction due to reflections and absorption in colored polymer films [33].

4.5 Front glass with prints, coats and other finishings

The front glass of the modules can also be printed, coated, or textured for different finishes for aesthetic appeal [44]. Among the techniques, spectrally selective glasses, mass-colored glasses, mineral coatings, digital glass printing, sandblasting, enamel coloring, have more potential [45]. The difficult task in this method is to find the best balance between the aesthetic and efficiency [46].

5. COMMERCIALLY AVAILABLE BIPV PRODUCTS AND DEVELOPMENTS IN THE RESEARCH FIELD

Availability of BIPV products in the market is important when it comes to BIPV designs. Many solar industries are trying to innovate more aesthetically appealing BIV products into the market. Even the solar market leaders like LONGi introduce new products for rooftop and façade installation with variety of color options. Their latest products include LONGi roof with 20.57% efficiency and LONGi BRIGHT for facades with an efficiency of range 10~20% available on 14 colors [47]. The roof products consist of rooftop tiles and shingles, flat and curved rooftop products, and roof lights. It can be observed that the maximum efficiencies can be seen in monocrystalline silicon products compared to others, while the maximum power is higher in multicrystalline silicon solar products [21,48]. Thin film products like amorphous silicon, CIS, CIGS show low efficiencies compared to crystalline silicon solar products [33].

Figure 5 shows the potential generation of BIPV energy yearly and average potential irradiation according to the country [31,52]. The BIPV potential and the average potential

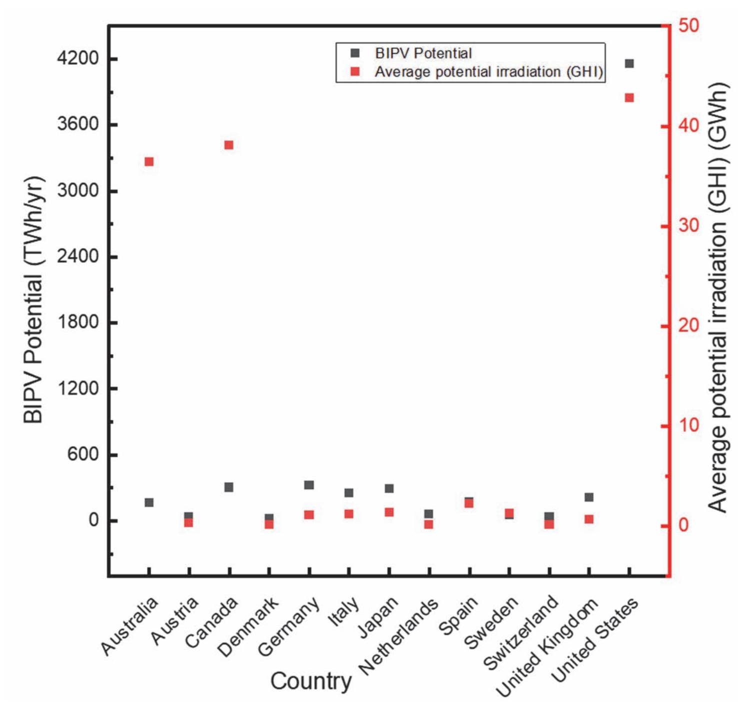


Fig. 5. BIPV potential according and average potential irradiation according to country (GHI global horizontal irradiation).

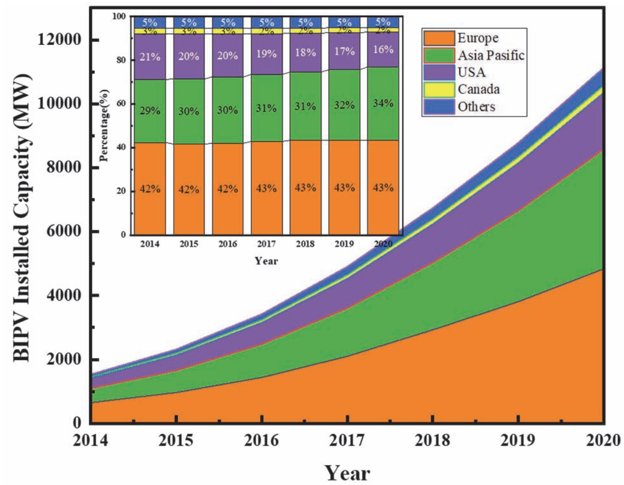


Fig. 6. BIPV installed capacity according to the countries and regions.

irradiation show a similar variation, except for Australia and Canada. For Australia and Canada, excess land area that cannot be utilized for human habitat is larger compared to other countries. Therefore, potential irradiation is wasted in these areas and thus shows a difference between the BIPV potential.

Figure 6 shows the share of total BIPV installations in the world according to region and countries. The current largest share of BIPV installations is in Europe [49,50]. This is due to the availability of many BIPV products in European countries such as Sunovation, onyxsolar, Ertex Solar, Soltech and many others, which offer a wide array of BIPV products with different colours, customisable sizes and transparency working hand in hand with architects for BIPV installations [51]. The percentage of market share in Asia-Pacific has shown significant growth compared to other parts of the world due to more BIPV products in countries such as Japan, China, and Korea. Europe maintains a steady growth in the market share. In 2020 the market shares in Europe, Asia-Pacific, USA, Canada, and others were 43%, 34%, 16%, 2%, and 5%, respectively [49]. It is assessed that the BIPV market value will reach to 45,000 million Euro by 2024 [12].

6. CONCLUSION

The BIPV technologies and markets are developing and improving day by day. New industrial products are launched with a variety of color, transparency, and flexibility properties, which can also be customized at different aesthetic needs. While installing photovoltaic products in the building many technical properties such as maintaining building integrity, replaceability, daylight saving, heating and cooling ability, and maximum energy generation need to be considered for the comfort and success of the BIPV as part of the building.

When it comes to customization of solar modules for different needs using five different techniques namely 1) solar cell antireflective coating, 2) PV- active layers that are semi-transparent/or colored, 3) colored or patterned solar filter layers, coatings and interlayers, 4) colored polymer films 5) front glass with prints, coats, and other finishings can be used.

BIPV market, industries and customers are expanding. Many companies including major solar PV producers launch new and improved BIPV products, which shows the possibility of market expansion in rapid growth in the future.

For the future development and enhancement of BIPV integration there are four areas to be considered: Efficiency enhancement of BIPV modules which are relatively lower than conventional solar PVs, feasibility of BIPV application, cost reduction in the system integration, and improvement of storage systems.

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