CHAPTER 3

BIPV products

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3.1 Introduction

This chapter describes the BIPV products from their components to their final layout as part of the building envelope construction systems. The BIPV module technologies mainly differ in the PV cell type and the front and back cover materials, but also important for the BIPV design may be the additional layers, such as the encapsulant or the coatings on the front and backsheet, and the variations in the density and distribution of the PV cells, which lead to different looks and a variety of transparency levels. The manufacturing techniques also allow variations in the module characteristics to fulfill the construction requirements. Currently, more than 95% of BIPV products on the market are based on crystalline silicon glass laminates, which allow a large variety of customisation levels to accomplish various architectural applications. The chapter shows the BIPV product design possibilities, challenges, and development trends for their integration into roofs, façades, and shading devices.

3.2 Components and assembly of a BIPV module

3.2.1 Photovoltaic cell types

The standard "IEC 63092 Photovoltaics in buildings – Part 1: Requirements for building-integrated photovoltaic modules" defines a BIPV module as follows:

> *A BIPV product or BIPV module is the smallest (electrically and mechanically) non-divisible photovoltaic unit in a BIPV system which retains building-related functionality. At the same time, it represents a functional unit of the building envelope satisfying the primary functions of the construction: if the BIPV product is dismounted, it would have to be replaced by an appropriate construction product.*

A BIPV module is a photovoltaic (PV) module and a construction product at the same time, mainly designed to be a multifunctional component of the building skin.

PV modules generate renewable electricity by directly converting solar radiation into direct current (DC) using semiconductor materials. PV modules are made of PV cells, which represent the principal elements responsible for the energy conversion in a BIPV product. They can be classified according to the cell or film technology, each one having different solar energy conversion efficiencies, design and appearance.

3.2.1.1 Crystalline silicon solar cells

Crystalline silicon PV cells (c-Si) have dominated the market for years. They are based on crystalline silicon wafers. Depending on the type of crystallisation, these wafers and the cells manufactured from them can be multicrystalline or monocrystalline. Multicrystalline silicon (mc-Si, also called polysilicon) wafers show crystals directed to different angles with a structure comparable to granite stones. Oppositely, monocrystalline silicon wafers show homogeneous surfaces because they come from the cut of large cylindrical single crystals. During cell manufacturing, the crystalline wafers (mono or multi) run through chemical and physical processes. The last step is the application of an anti-reflective coating, which turns the naturally occurred metallic grey-coloured surface of a silicon cell into the typical blue-to-black common appearance of c-Si PV cells.

Today, monocrystalline silicon PV cells, with conversion efficiencies exceeding 24% (and modules with over 20% efficiency), dominate

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the photovoltaic market. This trend is expected to continue in the coming decade [1]. Whereas conventional solar cells are designed to harness solar energy from only one side, the current trend for utility-sized PV applications is rapidly shifting towards the use of bifacial PV cells (and modules), which are capable of harnessing solar energy from both sides, front and rear. In 2023, about 50% of produced PV cells were bifacial[12]. Typically, their rear side is about 20% less efficient than their front side. This trend brought a change as well in the solar module construction: while earlier standard modules had a white foil as a backsheet, nowadays, bifacial standard photovoltaic modules are mostly framed glass-glass-laminates to allow the entry of sunlight from both sides of the module.

3.2.1.2 Thin-film solar cells

In 2021, approximately 5% of the total PV modules in the market utilised thin-film technologies [13]. Unlike crystalline wafer-based modules, thin-film PV modules are composed of layers of transparent and opaque conductive PV materials, typically coated or sputtered onto a substrate. The manufacturing process for thin-film PV is similar to low-emissivity (low-e) hard-coated window glass. Thin-film PV cell materials are applied to a substrate – mostly transparent conductive oxide (TCO) glass – in several layers, with the coating order being from the front glass ("superstrate") or the back cover ("substrate"). Beyond TCO, stainless steel or aluminium can also be used as a substrate.

Thin-film PV can be made from different semiconductor materials such as amorphous silicon (a-Si), copper indium gallium selenide/sulfide (CIGS), and cadmium telluride (CdTe). While a-Si PV cell efficiencies are significantly lower than crystalline silicon, CIGS and CdTe efficiencies are already comparable to multi-crystalline silicon ones. In the early days of PV, amorphous silicon was the first and most widespread thin-film material. Its appearance, versatility regarding its properties, and lower manufacturing costs made this technology attractive. However, its low efficiency (6–8%), when compared to other commercialised technologies, has become a market barrier.

Typically, thin-film PV is opaque. For the film to become semi-transparent, layers of the PV material are removed by laser etching, widening the thin lines between cells. This way, the transparency is usually set between 10–20%. Although this process leads to a decrease in module efficiency, their visual appearance of homogeneous greyish semi-transparent elements makes thin-film technologies an appealing product for skylights and façade applications. Organic photovoltaic (OPV) is expected to also contribute to thin-film semitransparent BIPV solutions.

3.2.1.3 Heterojunction and multijunction PV cells

Most commercial PV cells are homojunction, meaning that they are made of just one semiconductor to form the cell junction that creates voltage. Alternatively, heterojunction PV cells include two semiconductor materials to form the cell junction. The silicon heterojunction (SHJ) technology combines the advantage of monocrystalline silicon and thin-film materials, which are coated on top. Typically, these thin-film layers are composed of amorphous silicon or perovskite. SHJ PV cells can achieve efficiencies above 24%. It's important to note that SHJ cells are classified as a type of crystalline photovoltaic cells.

A multijunction solar cell (MJSC) consists of several individual cells (sub-cells) stacked together and connected in series to obtain higher performance by combining different solar radiation wavelength sensitivities (spectral responses). An MJSC made of two cells is commonly named a tandem cell. Mostly, MJSCs are used in PV concentration systems.

3.2.2 PV modules manufacturing

Today, crystalline silicon PV modules have the largest market share, accounting for over 95%. Consequently, this section provides a detailed description of this technology. It is important to note, however, that thin-film modules share many common features with crystalline silicon ones.

Crystalline PV module manufacturing starts with the electrical connection of several PV cells in series, making up a "cell string." In a string, the same current goes through all of the cells (there is no current intensity addition), and cells add their voltages to sum the final voltage of the module. Usually, PV modules are made of more than one string to also increase the output current (several strings in parallel add their currents). All of the strings are connected at the junction box of the PV module, which also contains bypass diodes. These electronic devices allow PV current to "bypass" shaded cell strings or even the whole module. The issue with shaded solar cells is twofold: not only do they cease to produce electricity, but they also create hotspots. Figure 3.1 shows the main steps from the PV cell to the module, to the BIPV system.

To set up a BIPV system, the solar modules are connected in series to form "module strings." The module strings are then connected either in series or in parallel at the PV array combiner box. The BIPV system may also contain overcurrent protection and disconnection devices. Its output is the DC BIPV array (or BIPV generator) output, which can further be connected to a power conditioner equipment such as an inverter. Inverters transform direct current (DC) into alternating current (AC). More information about inverters can be found in Chapters 2 and 4.

Thin-film module manufacturing technologies differ from c-Si ones. In thin-film modules, the PV material layers are created by different techniques, such as printing, sputtering, or chemical

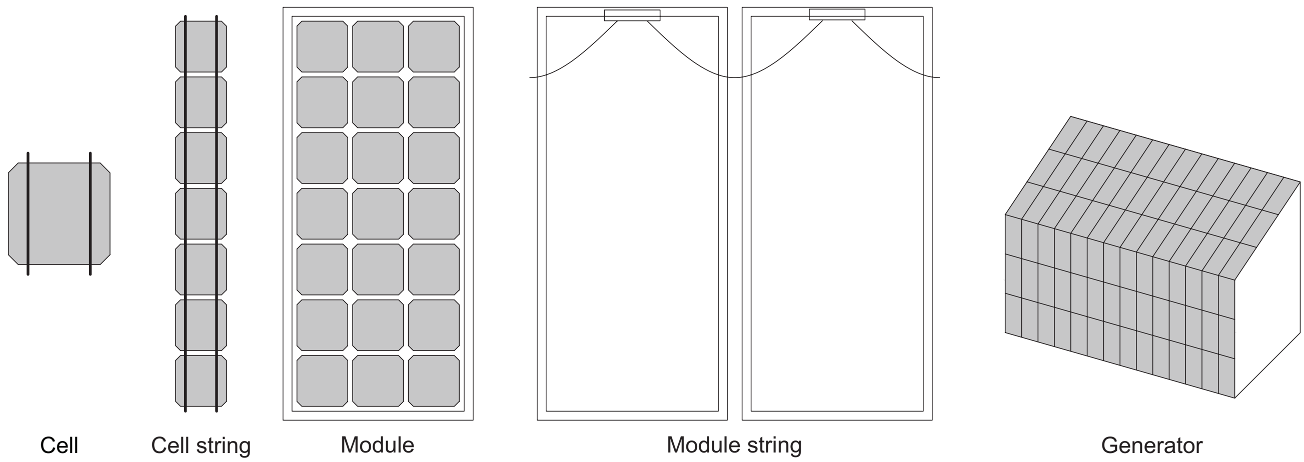

Figure 3.1 From PV cells to BIPV generator.

vapour deposition. Then, by laser ablation, PV cells are formed and interconnected, resulting in the appropriate module voltage and current values.

The common manufacturing process of a conventional (mass produced) PV module consists of the following steps (Figure 3.2):

- *Preparation of the raw material*: The various raw materials used for the assembly process are prepared and controlled.
- *Stringer machine and layup for PV module stringing*: The PV cells are placed in a solar stringer that interconnects the cells in series by soldering a coated copper wire, called ribbon, on the bus bar of the cell. The result is a PV cell string.
- *Placement on the glass*: PV cell strings are automatically or manually placed on the glass previously prepared with the first layer of encapsulant material.
- *Buses welding*: The bus ribbons for interconnecting PV cell strings are welded. This phase can be automated or customised according to the desired application.
- *Pre-lamination preparation*: The second encapsulation layer and a foil of electrically insulating material called backsheet are applied. Then, the terminal ribbons are kept out to be connected in the junction box in a subsequent step. At this point of the manufacturing process, it is important to perform some electrical tests and possibly an electroluminescence test to verify that there are no short circuits or broken PV cells inside the module. At the pre-lamination stage, it is still possible to correct potential deficiencies.
- *Lamination*: The multi-layer sandwich is transformed into one single unit thanks to the polymerisation of the encapsulating material. Laminators work at high temperatures and vacuum levels. The resulting product is called PV laminate.
- *Junction box application*: Junction boxes in BIPV modules have special designs and placement to facilitate architectural integration and facilitate the connections between modules.
- *Framing (optional)*: If requested or needed, a frame is applied around the PV module, directly with tape on the laminate or using silicone in the aluminium channel frame.
- *Final test*: After assembling, the PV module is inspected and tested.

3.2.3 BIPV modules manufacturing: standard sizing or customisation

There are different ways to design, construct, and manufacture BIPV modules. However, all of the methods share the need to encapsulate and protect the PV cells, mainly from oxygen and moisture, to avoid corrosion. Most available BIPV products use laminated glass to protect the solar cells on both sides and, at the same time, to give the modules the mechanical strength required to perform as construction products. Other cell types and architectural applications can lead to additional encapsulation layers, different module materials, and construction designs.

There are three main approaches to manufacturing BIPV modules:

1. **Mass production for standardised products:** The layering of BIPV products remains fixed, allowing only one module layout per production line. It involves a series of consecutive operations performed by automatic machines dedicated to optimising each production phase, transforming raw materials into finished products. The process typically comprises the eight or nine steps presented previously.
2. **Full customisation for custom designs:** BIPV modules can be produced in various sizes, shapes, and with various layers of materials, for example, with different glass types and colour layers. In this case, several steps in the manufacturing line are manual with machine support.

Figure 3.2 (from left to right and top to bottom): "Half-cut" crystalline silicon PV cells; PV cells prepared for stringing; preparation of the cell layout of the module; standard high-efficiency PV modules with backsheet foil (left), and with black backsheet foil for "all black" appearance (right). Photos taken at the Sonnenkraft GmbH facility in Austria (credits: Astrid Schneider, TU Wien).

The level of customisation impacts the final cost of the product.

3. **Mass customisation:** The mass customisation approach aims to minimise material and size variations while employing a semi-automatic assembly line capable of producing most of the solutions required in the market. Automated steps alternate with manual work.

Overall, the manufacturing and assembly of BIPV modules involve a variety of techniques and options that cater to different design requirements and market demands, considering factors such as functionality, aesthetics, and sustainability.

The following simile can be made between the effort and cost of these PV production methods and fashion: readymade mass-produced jeans in a big store are cheaper than tailor-made ones. However, specialised shops such as sport shops might offer specialised pants for reasonable prices. This might help to understand the differences between PV and BIPV markets.

Large PV manufacturers – with about 95% located in China – produce "standard PV modules" produced and optimised for utility-scale PV plants or large rooftop applications. In PV plants, about 60% of modules are currently larger than 2.5 m^2 (e.g., PV modules with nominal power of around 700 Watts are up to 3.1 m^2), whereas for rooftop installations, module sizes are smaller than 2 m^2 because of manual installation limitations [3] and restrictions by building authorities such as the German Institute for Construction "DIBT-Deutsches Institut für Bautechnik."

In earlier times, it was easier than today to differentiate BIPV modules from PV modules with a quick look, because standard PV modules were always equipped with a frame and a white backsheet. Nowadays, due to the innovative bifacial PV cells, which can receive solar radiation and produce solar electricity from both sides, most advanced and highly efficient standard PV modules use glass as a backsheet to allow maximum exploitation of back-reflected solar radiation. As those modules are optimised for maximum electricity production with minimum use of materials, the frontsheet and backsheet glasses are extremely thin with 2 mm thickness. In this case, the structural strength of the module is normally provided by an aluminium frame. The producers deliver the modules with an installation manual, which specifies where and how to fix them to guarantee wind and snow load resistance.

3.2.4 Differences between standard PV and BIPV modules

In most building rooftop PV installations, standard PV modules are commonly used. This is primarily because these installations are categorised as building-attached photovoltaics (BAPV), where the modules are affixed to an existing building envelope without serving any other function than renewable electricity generation. The use of PV in buildings, including both BAPV and BIPV, is on the rise. In 2020, the SolarPower Europe Association reported that 44% of the global installed PV power was mounted on buildings, presenting a significant growth opportunity for BIPV.

Now, the key question is: what differentiates a BIPV module from an ordinary standard PV module? The answer is easy: a BIPV module is designed, constructed, and certified according to both electrotechnical and building construction requirements [3].

Most BIPV modules are based on glass-glass PV laminates. Additional attributes that differentiate BIPV from standard PV modules are as follows:

- Frameless: The module strength is provided by the laminate.
- Thicker frontsheet and backsheet glasses of both 3 mm, 4 mm, or even 6 mm thickness and more, depending on the project and construction requirements
- Wider cell-free borders to avoid cell shading by the construction profiles
- Certified as a laminated safety glass and as a construction component by public construction authorities to allow the installation in building skin (e.g., overhead installation or even point fixings)
- Designs do not always prioritise module efficiency but rather aesthetic requirements (e.g., transparency, colour, thermal insulation, see Chapter 2).
- Junction box located on the edge of the module to allow an invisible wiring during installation.

As discussed in Chapter 2, the BIPV product requirements derive from:

- Electric safety requirements, based on low voltage electrotechnical regulations
- Laminated safety glass standards for products containing at least one glass pane
- Building requirements, as introduced by construction product regulation and building codes (e.g., fire safety requirements for roofs and façades, heat retention, mechanical safety, etc.)

Moreover, depending on the BIPV application, other requirements can apply, such as mechanical resistance and stability, health and the environment, safety and accessibility in use, protection against noise, energy economy, and heat retention. An example is the rain tightness for BIPV roofing elements such as PV roof tiles.

The question about which standards must be fulfilled is strongly dependent on the use case and the function the PV modules shall fulfil, the building type and height and, especially, the local and national construction codes, regulations, and guidelines, which define the required qualifications and relevant certificates.

In the European Union, the reference standard for BIPV products and systems is EN 50583–1 and –2, respectively. In 2020, a similar international standard was also introduced:

IEC 63092–1 and –2, adopted by several countries across the globe.

3.2.5 Design options regarding colour, transparency, and reflectivity

BIPV modules tend to be installed on the "sunny side" of buildings, mostly highly visible, when it comes to façades, shading elements, or canopies.

When incorporating photovoltaics as building components, designers and architects seek various options to properly integrate them into the building's surfaces. An important question is how far the designer can influence the appearance of the solar modules regarding colour, shape, and reflectivity to fit the building's design qualities. To enrich BIPV products, from standardised manufacturing approaches to flexible and customised options, the industry has developed different solutions by modifying one or more of the typical layers of the module:

- Front cover (*frontsheet*)
- Encapsulant
- Crystalline solar cell strings
- Encapsulant
- Back cover (*backsheet*)

Each of the layers – and inner and outer surfaces of the front and back glasses – can be varied to change the module design and appearance. Photovoltaic cells can differ in colour, shape, dimensions, and placement, while other layers can be modified using different types of printings and coatings for front glasses, interlayers, or backsheet materials, leading to a variety of colours and transparency levels (see Figure 3.3). Several sophisticated solutions combine measures on different layers of the module to achieve the desired appearance.

3.2.5.1 Frontsheet

The frontsheet of a c-Si module or a thin-film module typically features a 2 mm to 6 mm glass cover with high solar transmittance, allowing maximum solar radiation to pass through and reach the photovoltaic layer. Known as low-iron (or solar) glass because of its low iron oxide content, the frontsheet is always heat-treated or tempered. To reduce the frontsheet reflections, an anti-reflective coating (ARC) can be implemented, featuring a macroscopic surface texture in the form of micro-pyramids or micro-domes that act as a "light trap." Using ARCs, the solar transmittance of the frontsheet glass can reach up to 95%, which compares favourably to approximately 92% for low-iron glass without ARC of the same thickness [4]. Note that ARC will increase soiling for BIPV installations that are not vertical (e.g., roofs, solar shading), due to surface texture and the hydrophilic nature of the ARCs currently used in the market.

In recent years, spectrally **selective coloured films and coatings** and **glass treatments**, such as **digital printing, etching, or frit**, have been applied on the glass frontsheet to provide a colour finish or pattern on the BIPV module. In these cases, module efficiency is sacrificed for aesthetics, due to shading of the PV layer, when compared to a clear frontsheet module [5]. When a colour or a pattern treatment is applied, the photovoltaic layer is fully or partially "camouflaged" behind the BIPV frontsheet. This opens new architectural possibilities that enhance building aesthetics and turn building surfaces into renewable energy generators. Note that other dated methods exist for producing coloured BIPV methods, some of which are discussed in the following sections.

Frontsheets for flexible photovoltaic modules can be made from transparent plastic materials, such as fiberglass-reinforced plastic (Figure 3.4). The same material can also be used as the backsheet. Other backsheet options used to manufacture

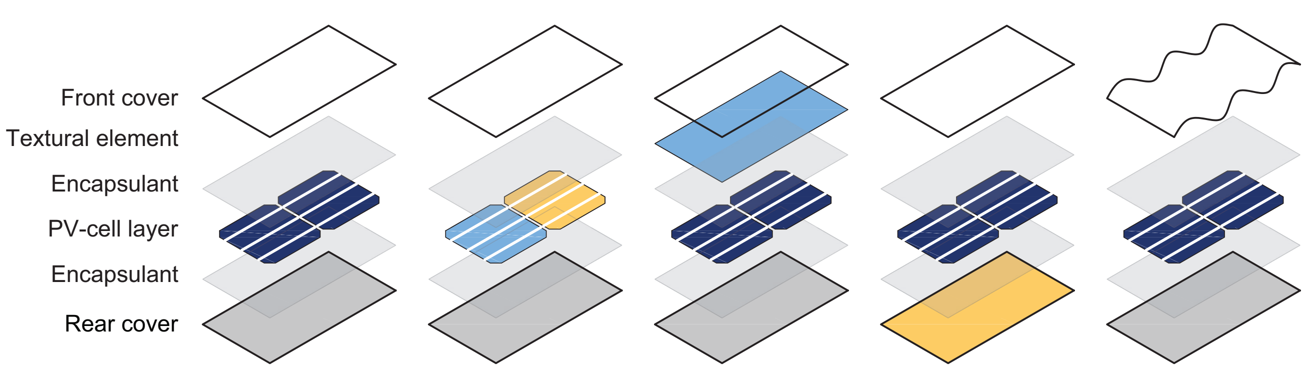

Figure 3.3 Schematic layer representation of a conventional PV laminate (left) and four alternative BIPV designs.

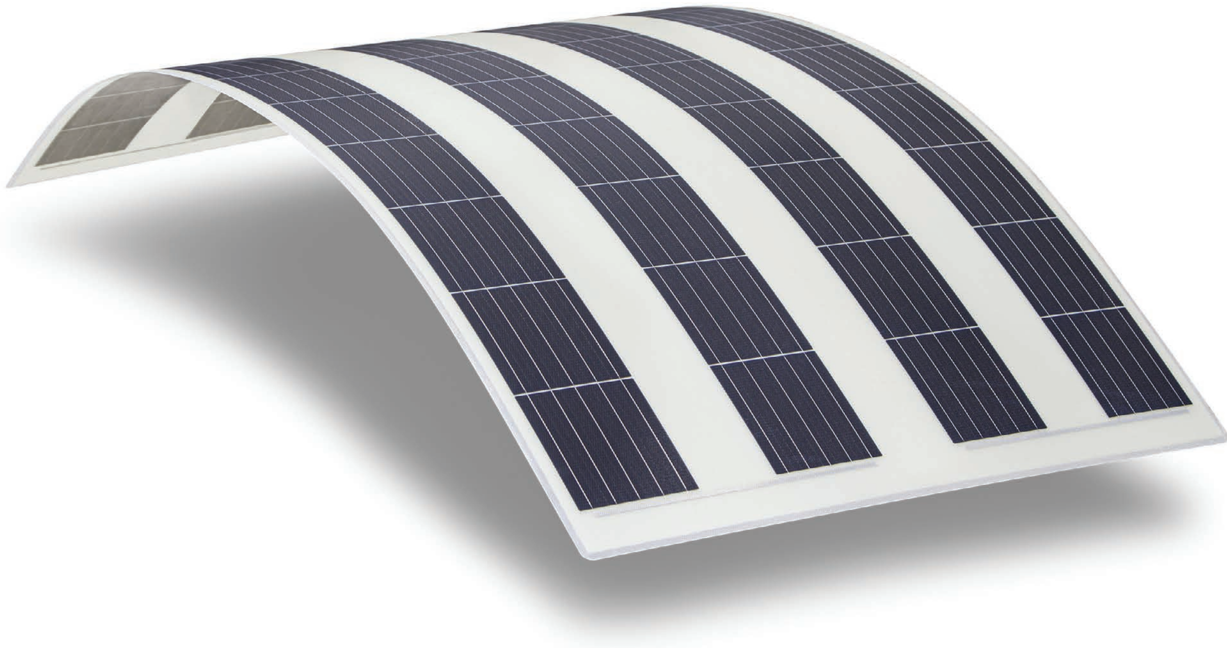

Figure 3.4 Lightweight flexible photovoltaic module with thin monocrystalline solar cells encapsulated between two fibre-reinforced plastic sheets; see the roof project in Figure 3.7. Photo: DAS Energy, Austria.

flexible thin-film PV modules or super-thin c-Si modules are flexible metal sheets or synthetic substrates.

3.2.5.2 Encapsulation

The encapsulation layer serves multiple crucial functions, including providing structural integrity between the frontsheet, PV layer, and backsheet, as well as protecting against the intrusion of humidity and oxygen into the PV laminate, as it would cause corrosion to the sensitive solar cells. Common encapsulation materials include ethylene vinyl acetate (EVA), primarily used in glass-laminate modules, and polyvinyl butyral (PVB) that is commonly used for glass-glass modules. Poly olefine elastomer encapsulants (POE) is a newer encapsulant material used in bifacial and thus glass-glass-laminates, as it is more resistant to chemical changes and degradation. Less commonly, silicone gel is used as an encapsulant. Some of the key attributes of encapsulation materials are to maximise solar transmission, achieve strong adhesion and cross-linking, and ensure long-term stability, especially under UV light exposure. To prevent moisture infiltration, which could lead to issues such as delamination and potential semiconductor device degradation, a sealant can be applied along the module's edges to effectively block moisture penetration.

Coloured encapsulants can be used to provide colour to semi-transparent thin-film technologies, but also to c-Si modules. The coloured encapsulants can be semi-transparent or opaque. Some only appear opaque in front of the solar cells but are indeed semi-transparent. Opaque encapsulants behind the cell layer are used to create, for example, a homogeneous black appearance of the overall solar module.

3.2.5.3 Photovoltaic layer

The photovoltaic layer consists of the solar cells and their interconnections. To obtain "full black" solar modules, it is necessary to hide the metal interconnectors between the cell strings. This can either be done by screen printing on the inner side of the front glass or by covering the metal connectors with small pieces of black foil. Another option is the use of so-called back contact silicon solar cells, which are connected behind the cells and do not show visible metallic grid and buses from the front side.

Crystalline silicon solar cells can be coloured by varying the thickness of the anti-reflective coating, from regular bright blue to gold, green, or a range of other colours. Nevertheless, the use of coloured cells results in a reduced module efficiency between 5% and 15%. The highest efficiency is attained with the optimised blue/black anti-reflective cell coating, which gives the well-known appearance to conventional PV modules.

Solar cell layout: different densities, transparencies, and patterns in PV cell distribution

In general, the lower the PV layer density and the higher the transparency, the lower the PV module efficiency. There are no transparent high-efficiency PV modules. Some novel near-transparent BIPV products use the frontsheet to concentrate sunlight onto the module edges where the PV layer is. So far, the efficiency of these novel products remains low (5% or less).

PV cell distribution density in BIPV modules can vary from maximum dense packing to lower cell densities, leading to 10%, 20%, 30%, or more daylight penetration. Furthermore, the solar heat gain coefficient of the BIPV will rise with its transparency. Customised solar cell patterns can be tailor-made (Figure 3.5). In this case, the cell strings have to be connected manually. Finally, the BIPV module shape can be varied by using different glass formats and geometries, such as circular, triangular, or free-form glasses.

3.2.5.4 Backsheet

Glass is the most common material used also as a backsheet in BIPV modules. Another common material is polyvinylidene difluoride (PVDF), a thermoplastic fluoropolymer-based foil. In the case of a PVDF, the backsheet tends to be opaque, and it is used in Si-based modules. In standard PV modules, PVDF is white to reduce the amount of solar irradiation absorbed by the backsheet and, thus, reduce the operating module temperatures.

Figure 3.5 BIPV skylight at the Schönbrunn Zoo, in Vienna, using customised solar cell patterns. Photo: Costa Kapsis.

For BIPV applications, PVDF can be coloured, creating from an all-black (e.g., black cells/black backsheet) to a plaid look (e.g., blue cells/red backsheet). The use of coloured opaque backsheets tends to marginally increase the operating module temperatures. Glass-foil BIPV products have less mechanical strength.

For opaque BIPV modules, coloured glass is often used as a backsheet to produce a coloured appearance. The colouring can be made by different means: by opaque enamelled screen printing on the outer surface of the glass or by coloured glass itself. Coloured and all-black designs are primarily used for rainscreen façades where no solar irradiation can be gained from the rear side. However, in the case of BIPV products for solar canopies and shading devices, that use bifacial solar cells to benefit from, e.g., ground albedo to increase annual electricity yield, the use of low-iron clear glass is preferred.

3.3 BIPV envelope solutions

3.3.1 BIPV roofing products

Roofs have the highest solar potential of buildings and are therefore not only the preferred place of installation for PV systems but also usually the most economical solution to generate solar electricity. Several BIPV systems have been developed for all kinds of roof construction types. As identified in the IEA-task 15 report "Categorisation of BIPV Applications" [7], the main roofing systems can be referred to as discontinuous roofing, continuous roofing, and skylights.

3.3.1.1 BIPV discontinuous roof

A pitched or sloped opaque roof is commonly covered with tiles or slates. This is a widespread roof construction method, referred to as a "discontinuous roof," due to the presence of small elements (tiles, slates, etc.), with the main function of water drainage. Pitched roofs are areas of the building envelope where PV deployment has been particularly successful. This success is attributed to various factors, such as high sun exposure or the ease of installing PV products with standard mounting systems on roofs, showing a consequently good economic payback. Many "in-roof" solutions have been developed in recent years, in which BIPV modules replace the traditional roof tiling layer. Solar tiles, metal sheets, shingles, slates, and prefabricated roofing modules that constructively replace traditional roof components are some of the possible applications. Although a solar roof is in the public imagination – a pitched simple roof of a single-family house with a few solar modules – more and more elaborated and innovative solutions are entering the market and are used in complex and ambitious designs. Some of the current main trends of innovation are related to:

- Aesthetic evolution of solar roof tiles due to different colours such as black, grey, red (terracotta), and different glass treatments, such as anti-reflective surfaces (see Figure 3.6) or structured glazing
- Availability of many different roofing tile typologies and sizes
- Customisation of solar tiling in complex roofs
- Availability of dummies without any electricity production (see Figure 3.6)

3.3.1.2 BIPV continuous roof

A planar or low-slope roof, often referred to as a "continuous roof," is distinguished by its continuous water-resistant layer, typically utilising membranes or metallic roofing. BIPV products have been used for these applications. BIPV continuous roof applications can be found in industrial

Figure 3.6 Left: Renovation featuring terracotta BIPV roof tiles on a historic farm in Ecuvillens, Canton of Fribourg, Switzerland; middle: solar shingles in a discontinuous roof; right: special roof parts for the Umwelt Arena in Spreitenbach, Switzerland. The modules are in an "all black" appearance with a black backsheet and covered interconnectors between the cell strings. Architect: Rene Schmid. Photos courtesy of Patrick Heinstein, CSEM (left) SUPSI; Flisom-Schweizer (middle); P. Bonomo (right).

halls, shopping centres, and airports, where flat roofs cannot carry heavy loads but offer large unshaded areas with high solar potential (Figure 3.7). The main products today are crystalline solar cells integrated into a laminate, where the front and backsheets are made from fibre-reinforced plastic that is flexible and can be used for flat or curved surface installations. Similar flexible solar modules are made with thin-film solar cells as well as encapsulated in plastic. This module type is then attached to either metal sheet roofing elements or roof membranes.

Additionally, there are innovations such as solar floors, which enable the installation of PV as a walkable roof, as illustrated in Figure 3.8.

Specific challenges are related with this application typology, such as anti-slippery treatments, user safety against falling and breakage, shading tolerance (if the roof is accessible), etc., so that components are specifically designed for the application field both in construction and electrical terms. Main market targets are multifamily or commercial buildings, and all buildings with available roof space that don't want to fully occupy the roof with solar modules but leave the possibility of using the roof.

3.3.1.3 BIPV skylights

Skylights or glass roofs are ideal places for the integration of PV modules, either as the main glazing for single-glazing roofs or as the outermost pane of an insulated glazing unit (Figure 3.9). The solar cells allow better control of important comfort parameters, such as solar gains and daylighting. The solar heat gain coefficient and the roof's insulation are important planning parameters. In both crystalline and thin-film technologies, the thermal/acoustic insulation and the transparency can be adjusted according to the indoor environmental requirements, depending on the climatic zone, the building typology, the internal functions, etc.

3.3.2 BIPV façades

Façades present a compelling option for PV integration, offering both advantages and disadvantages compared to roof installations. One notable drawback is that façades are more susceptible to shading, whether from surrounding buildings, self-shading, or trees. Furthermore, façades typically receive between 35% to 45% less irradiation than an optimally oriented roof would, depending on the geographic location. In regions with latitudes of 45 degrees or higher, BIPV façades demonstrate significant potential due to the consistently low sun angle throughout the year. Closer to the equator, the sun's path becomes more extreme, moving vertically over buildings and affecting the efficiency of façade-based PV installations. Another aspect to consider is that BIPV façades are intensively intertwined with the design of the building and its structural and design grid patterns, which are mostly determined by the height of the storeys and the width of the rooms. Typically, standard-size PV modules are usually not designed to meet the grid and design requirements of a building. For this reason, custom sized and designed BIPV modules are often chosen for façades, making them more expensive than conventional PV modules. Key reasons why façades are becoming an increasingly attractive option for BIPV applications can be summarised as follows:

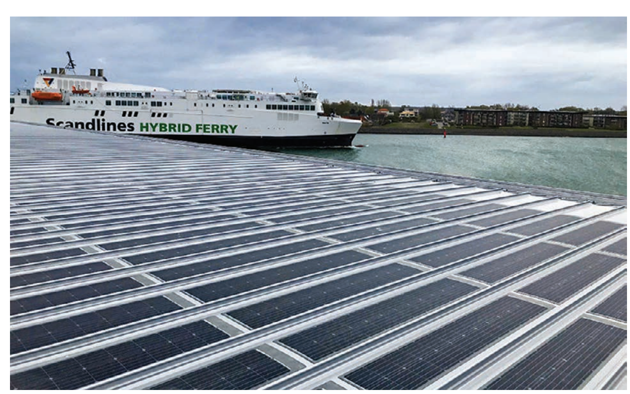

Figure 3.7 Flat inclined roofs of the company "Trumpf" in Germany at the Rostock harbour. The crystalline solar cells are integrated into plastic laminates, incorporated in aluminium sheet roofing. The PV modules' weight is less than 4 kg per m^2. Picture: DAS Energy Ltd., Wiener Neustadt, Austria.

Figure 3.8 Walkable BIPV floor and balustrade realised with laminated safety glass and c-Si solar cells. Source: BIPVBOOST.

Cost-Competitiveness with Conventional Façade Systems: For many modern façade typologies, such as rainscreen, curtain walls, and double-skins, the costs of conventional systems (using materials like metal, fibre cement, ceramic, natural stone, or glass) are often on par with, or even exceed, those of BIPV systems. In this case, BIPV façades become cost-effective, as the marginal extra investment is quickly offset by energy savings.

Energy Generation Profile Aligned with Self-Consumption Needs: BIPV façades are particularly effective in terms of self-consumption. They can better align the energy generation profile with the building's load profile throughout different seasons and times of the day, unlike roof-based systems.

Some of the current main trends of innovation in façades are related with:

Cladding customisation: custom sized and designed BIPV modules are produced in a project-specific manner.

Camouflage BIPV elements: in the first "age of integration" of BIPV modules, a "showy" type of integration of the PV modules was preferred due to a mix of both: the wish to show the pretentious PV elements and a lack of preferable design options. Furthermore, it was generally the wish to maximise the solar gain. Today several technologies have become trendy: the BIPV cladding became "invisible" thanks to the use of coloured coatings and treated outer glass surfaces, allowing the full disappearance of the solar cells in the BIPV modules. Such a "camouflaged" and "designed" approach allows hiding the PV cells behind opaque and coloured patterns (Figure 3.10) [5].

Other trends of innovation focus on the future coupling of active PV claddings with sandwiched façade systems, including

Figure 3.9 BIPV skylight application using insulated glazing with lower cells density for daylight transmittance at the "house of choice" designed by White Architects in Stockholm.

Photo: Jesper Westblom.

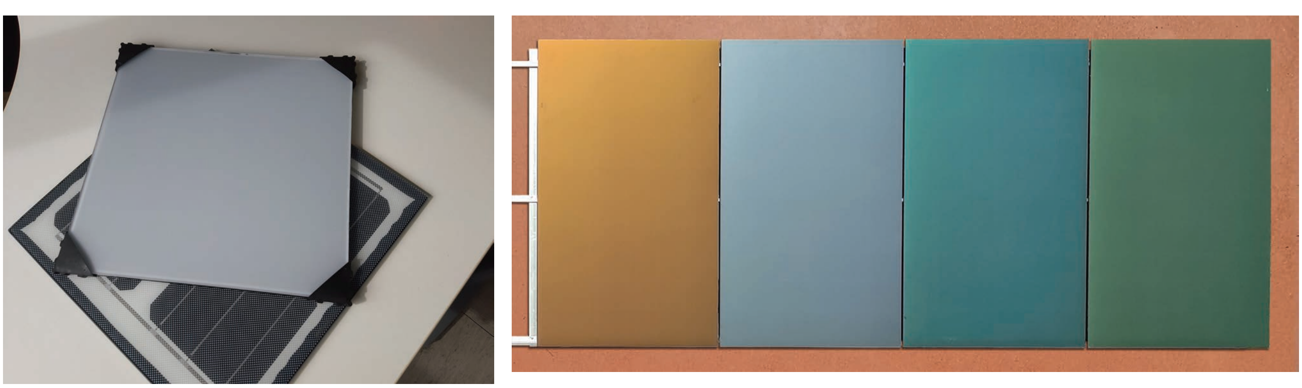

Figure 3.10 Examples of coloured BIPV cladding for a façade where coloured glass is used to partially or fully cover the solar cells behind. Photo: courtesy of SUPSI.

thermal insulation layers, which are aimed at obtaining a totally dry installation, ensuring simplicity and efficiency of mounting for a unitised kit with thermal protection, fire prevention, and sound insulation [7].

3.3.2.1 Ventilated façades or rainscreen cladding systems

A ventilated façade or a rainscreen cladding system (also called "cold" façade") typically comprises a load-bearing building structure, insulation followed by an air gap, and an outer cladding system.

In a BIPV façade, the conventional cladding elements are substituted with PV modules (Figure 3.11). The market offers a multitude of construction models and technological solutions, each featuring various fixing options.

Typical market segments are multi-storey residential, commercial, and institutional buildings, both in new or renovation cases. The market offers a multitude of construction models and technological solutions, each featuring various joint types and fixing options.

3.3.2.2 Double-skin façades

A double-skin façade consists of two layers, usually made of glass, wherein air flows through the intermediate cavity. This space (which can vary from 20 cm to more than 1 meter) acts as a buffer zone against extreme temperatures, winds, and sounds, improving the building's thermal efficiency for both high and low temperatures. BIPV is applied similarly to a curtain wall even though the outer façade, in this case, does not require thermal insulation. Thus, it is often a glass laminate rather than an insulation glazing. A particular application of this technology is represented by bifacial solar cells. Bifacial façades take advantage of the recent development of bifacial PV cells, which can harvest sunlight from both sides (front and rear).

One of the current main challenges for PV elements integrated in high-rise buildings is fire safety. Ongoing research and normative developments are addressing aspects related to the possible reduction of some critical risk of electrical fire ignition, fire spread due to the combustible parts of PV modules and other parts, and regarding safety questions for both the maintenance and the rescue teams (Figure 3.12).

3.3.2.3 Curtain walls

A curtain wall is an external and continuous building skin fenestration system, totally or partially glazed, composed of panels supported by a substructure in which the outer components are non-structural. A curtain wall refers to its construction since the façade is hanging (just as a curtain) from the top perimeter of the building and is locally fixed to resist air and water infiltration. It is typically designed with extruded aluminium frames (but also steel, wood, etc.) filled with glass panes. The façade satisfies multiple requirements, such as a load-bearing function, acoustic and thermal insulation, light transmission, waterproofing, etc. In the case of a "warm façade," it divides, as a unitised skin layer, outdoor and indoor environments. It can be realised according to different construction systems such as stick-system, unitised curtain wall, Structural Sealant Glazing (SSG), and point-fixed or suspended façade. PV is typically part of the outer cladding layer, in the form of glass-glass elements, with both crystalline (Figure 3.13) or thin-film technologies and with various transparency degrees and visual appearance possibilities. Usually, the glass is an IGU (double or triple glazing) to ensure adequate thermal insulation. In the basic cases, it can be assimilated to a window. Thus, in windows, PV can be integrated into conventional PV glazing similarly to a curtain wall or also into some innovative applications.

3.3.3 BIPV shading

Photovoltaic cells and modules can be used as external photovoltaic shading systems to control light and reduce solar heat gain in curtain wall and double-skin façade solutions,

Figure 3.11 Rainscreen cladding with coloured modules in a multi-family house in Zurich, Switzerland, designed by Kämpfen Zinke + Partner AG. Photos: courtesy of I. Zanetti, SUPSI.


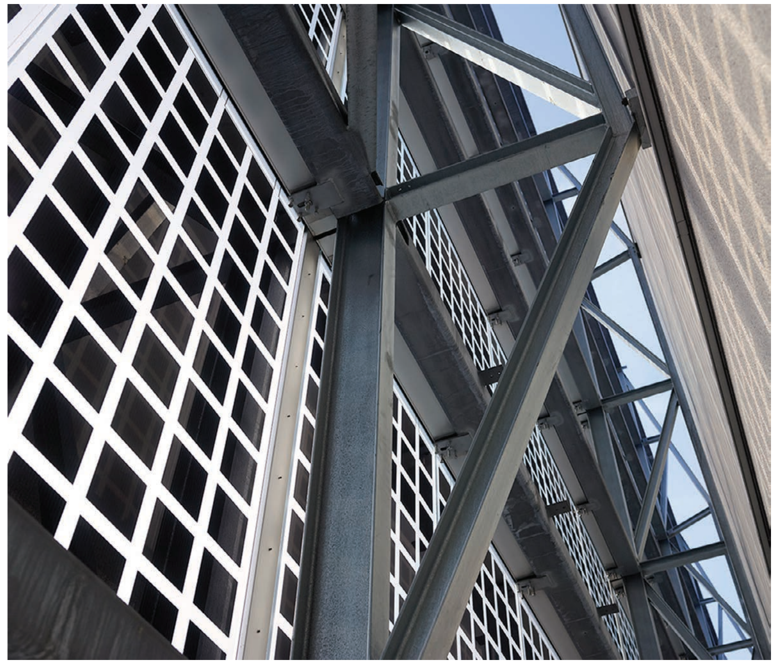

Figure 3.12 Double-skin façades featured in a new office building in Milan, Italy, and the renovated CSEM building in Neuchâtel, Switzerland. Photos: courtesy of P. Bonomo, SUPSI.

either as fixed elements or movable devices to adapt to dynamic solar conditions. Accurate simulation studies are crucial for designing these systems effectively, avoiding overshading, optimising solar harvesting, and ensuring desired thermal and visual comfort.

Large shading systems have been commonly used, as demonstrated in previous projects and studies such as [8–10], which analysed different south-facing shading solutions in office buildings. Movable BIPV shading systems (Figure 3.14) are also employed to control solar radiation and allow solar energy to enter the interior, based on cooling and heating demand. Various architectural shading devices that incorporate photovoltaic technologies have been invented, indicating the growing interest in integrating renewable energy generation into shading systems.

Lightweight photovoltaic materials such as CIGS offer flexible and curved shapes, making them suitable for dynamic shading systems. Although CIGS has lower energy conversion efficiency compared to traditional c-Si modules, it is advantageous for buildings with large, glazed areas or multi-storey structures that require shading systems and have sufficient transparent area. Integrating PV modules into dynamic shading systems enables the fine-tuning of different functions, such as generating electricity, balancing energy performance, and expressing architectural design while ensuring visual and daylight comfort.

Currently, several innovative concepts represent the frontier of dynamic active shading devices. One concept is external movable shading developed by the Polytechnic of Zurich ETHZ, which utilises a soft-pneumatic actuator to adapt blind positions based on user needs and desired comfort (Figure 3.14). Another concept, developed by SUPSI, involves integrating the photovoltaic blind into an insulating glazing unit, providing long service life and improved visual comfort while protecting the lamella from outdoor weather conditions. Other opportunities are available using conventional c-SI cells or organic photovoltaic modules.

To effectively utilise dynamic shading systems, intelligent algorithms are essential to orientate blinds for optimal energy efficiency. These algorithms help find the balance between PV generation and daylight control, minimising heating, cooling, and lighting demands.

Another solution is user-operated low-tech systems, which follow traditional architectural patterns. The “Solar Window Shutter” (Figure 3.15) is a product developed and patented by the German architect Astrid Schneider [11].

The “Solar Window Shutters” can be moved by hand to either fully shade, be in a ventilation position, or on the side to allow full sunshine into the room, while producing solar electricity. Due to a parallel opening mechanism, the active solar cell side is always oriented towards the sun so that the inhabitant can choose freely and depending on the actual weather conditions and their needs between fully open or fully closed shutters.

Figure 3.13 Semi-transparent thermally insulated BIPV façade in an office building. Photo: Sunovation GmbH, Germany.

Figure 3.14 The movable BIPV solar shading system, Solskin, installed at HiLo, NEST building, in Dübendorf. Photos: courtesy of Roman Keller (left) and Chair of Architecture and Building Systems (A/S) Group (right).

Figure 3.15 Residential building in Nechlin, Germany, with "Solar Window Shutters" designed and patented by Astrid Schneider. Photo: Astrid Schneider, Solar Architecture, Berlin.

In conclusion, semi-transparent and translucent solar façade concepts with solar cells integrated into the façade glazing itself have limitations in adapting to dynamic solar conditions. However, the integration of PV modules into movable shading systems offers opportunities to combine shading benefits with solar energy harvesting. Lightweight PV materials like CIGS provide flexibility and enable fine-tuning of functions while ensuring visual and daylight comfort. Innovative concepts, including external movable shading and integrated windows, control sunlight and solar gains, contributing to both energy efficiency and architectural appearance. Intelligent algorithms play a crucial role in optimising the performance of dynamic shading systems by balancing PV generation and daylight control.

3.3.4 Other BIPV applications and designs

From innovative façades or roofs that generate electricity to elegantly designed shading devices discussed in the previous chapters, BIPV is redefining the boundaries of architectural creativity and sustainability. Some other BIPV applications and designs have been developed to push forward renewable energy production in buildings. These possibilities include:

Balustrades: BIPV modules can be integrated into balustrades or guardrails, providing safety and generating solar energy simultaneously. These solutions often prefer bifacial technologies to harvest sunlight from both sides (Figure 3.16).

Parapets: Solar modules can be incorporated into parapet walls, which are low protective walls at the edge of a roof or balcony. This application combines aesthetics with energy generation, using surfaces that normally protrude from the façade of the building.

Winter gardens: BIPV can be incorporated into winter garden structures, providing a dual function of growing plants and generating energy.

Pergolas and gazebos: BIPV modules can be integrated into pergolas and gazebos, offering shade and energy generation in gardens and recreational areas.

Figure 3.16 From balustrades to solar benches, BIPV can take several forms within the built environment. Photos: courtesy of Isa Zanetti (left) and Costa Kapsis (right).

Solar benches and tables (Figure 3.16): These elements can integrate BIPV modules and thus provide seating and device charging capabilities.

Shading elements for public spaces: Due to the ongoing climate change, more and more cities want to provide shading elements for public open spaces.

Finally, different **artistic designs** can be proposed where BIPV can be used in artistic or decorative installations, allowing architects and designers to create unique and functional art pieces.

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