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Review of technological design options for building integrated photovoltaics (BIPV)

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ABSTRACT

This paper reviews and analyzes technological design options, which have become available to date for BIPV systems on roofs and facades, independently of specific products or building projects. This means that this survey does not analyze existing products or realized buildings, but provides an overview of the technologies for BIPV. The starting point is an analysis of the relevance of BIPV technologies for the decarbonization of energy systems, providing energy for direct use of electricity and sector coupling together with an analysis of the German BIPV market. The paper presents the wide range of technical design options for BIPV systems and categorizes and analyzes them to provide a structured overview. This comprises a detailed analysis of the design options for BIPV modules, in which not only the design options for the PV cell layer were comprehensively investigated, but also the different variants of embedding materials, front and rear cover materials, additional interlayers and electrical module layout. Two fundamental module-level design options were investigated in particular detail: The use of PV cells as basic elements of patterns and the use of color to conceal the PV cells. Subsequently, options for the design of complete electrical systems are reviewed, ranging from sub-module level design parameters to building energy systems. Design options for the constructional integration of BIPV modules in the building envelope complete the review of technological design possibilities.

Contents

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Nomenclature

BIPV	building-integrated photovoltaics
W_p	Power of a PV system under standard test conditions (STC)
W_p/m^2	Power of a PV system under STC, relative to the module area
$€/m^2$	Net or gross cost of a BIPV system/module/PV-cell/..., relative to the module area
$€/kW_p$	Net or gross cost of a BIPV system/module/PV-cell/..., relative to the power under STC
$€/kWh$	Electricity cost per kWh
EVA	Ethylene vinyl acetate, used as embedding material bonding the cell layer to the cover layers
PVB	Polyvinyl butyral, used as embedding material bonding the cell layer to the cover layers
c-Si	Crystalline silicon solar cell technology (wafer based)
CIGS	Copper indium gallium selenide solar cell technology (thin-film)
CdTe	Cadmium telluride solar cell technology (thin-film)
MPP	The maximum power point (MPP) for a PV-system corresponds to electrical load conditions with maximum power output.

1. Introduction

Photovoltaic modules are considered to be building-integrated, if they have been designed following the basic requirements for construction works in order to form and/or replace a construction product (see Fig. 1 with examples). If the integrated PV module is dismounted, the PV module would have to be replaced by an appropriate conventional construction product [1]. A discussion of variants of BIPV definitions can be found in [2]. However, these details are not relevant for this paper, since the technological design options discussed here are also applicable to PV modules on buildings that are not "integrated" into the building envelope in the strict sense.

In this introductory section, the following key framework conditions for building-integrated PV systems (BIPV) are analyzed:

- How many PV and BIPV systems are needed in a CO_2-neutral energy system? Section 1.1 analyses the required installed PV power [kW_p] considering sector coupling between electricity, heat and transport using Germany as an example. The relevance of the results for other countries is discussed afterwards.
- How large is the potential area that can be used on roofs and facades for PV and BIPV installations? A full analysis of the existing German building stock is used as basis for the analysis in Section 1.2. This includes a discussion of the relevance of the conclusions for other countries.

module geometry	standard size	custom size	standard width, adaptable length	custom size
appearance	close to conventional appearance, frameless modules, mounted with clamps	partially transparent, close to conventional appearance	surface texture, uniform color	sophisticated artistic design
constructional integration	additional ventilated layer	glazing-integrated	module-integrated backrail system for ventilated facades	glazing-integrated

Fig. 1. The figure presents a first overview of BIPV systems based on examples. Important aspects are the type of constructional integration of the modules, the possibility to adjust the module size and how the aesthetic appearance can be designed by using colors, surface textures or partially transparent surfaces. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- Section 1.3 analyzes the current BIPV market and future trends based on the statements from Sections 1.1 and 1.2 and a market study for Germany commissioned by Fraunhofer ISE in 2020. The relevance of the results for other countries is also discussed.

Section 2 explains and justifies the approach for the review of the technical design options, which is followed for the rest of the paper. Sections 4 and 5 deal with options for BIPV modules and the electrical system. Section 6 contains an in-depth analysis of two very important fundamental module-level aesthetic design options: Patterns formed by PV cells or invisible PV-technology. Chapter 7 deals with options for the constructional integration of the BIPV modules into the building envelope.

1.1. Importance of BIPV for energy system transformation

In November 2016, the Paris Climate Change Agreement was signed by heads of more than 150 countries [3]. With the agreement, they have committed themselves to drastically reduce greenhouse gas emissions by 2050 in order to limit global warming to below 2 K. This implies a transformation of the present energy system (including the heat and cooling sectors, electricity and transport) into a CO_2-neutral energy system. Many studies have analyzed possible pathways for this transition (see for example [4], [5] [6–10]).

The following discussion is based on a study [10,11] published by Fraunhofer ISE in 2020. The energy system model REMod (Regenerative Energy Model), developed at Fraunhofer ISE, was used to simulate and optimize different scenarios. REMod takes into account the coupling between the transport, electricity, process heat and building heating sectors. On the basis of an hourly analysis of the next 30 years, the study examines development paths of the German energy system that will lead to a reduction of energy-related CO_2 emissions by between 95 and 100 percent by 2050. Despite a very high proportion of fluctuating renewable energy, the study shows that a secure supply of electricity can be achieved every hour and in all consumption sectors. At the same time, the results show that electricity generated from renewable energy sources will become the most important primary energy form and that a strong increase in electricity demand can be expected due to sector coupling - the results range from 2 to 2.5 times higher than today. To achieve this, the installed power $[kW_p]$ of wind and photovoltaic systems must be increased by a factor of 5 to 10 compared to the total capacity installed today. The study took into account not only the development paths of the energy system, technical feasibility and costs of energy system transformation, but also the influence of diverse social behavior and attitudes. Four main scenarios were calculated for this purpose: the "persistence" scenario (strong resistance to the use of new technologies in the private sector), the "inacceptance" scenario (strong resistance to the expansion of large-scale infrastructures) and the "sufficiency" scenario (changes in social behavior significantly reduce energy consumption) - these scenarios were compared with a scenario in which the achievement of objectives is neither promoted nor impeded ("reference" scenario). The results are easily accessible via the Energy Charts [11]. Fig. 2 shows the evolution of installed PV capacity over the next 30 years for the reference scenario. It can be seen that the installed PV capacity rises to 413 GW_p by 2050, of which 275 GW_p must be installed on buildings. Even in the best-case scenario, in the "sufficiency" scenario, 176 GW_p must be installed on buildings by 2050. All other scenarios require significantly more than 200 GW_p of installed PV capacity on buildings by 2050. It can be concluded that the installed PV capacity in Germany on buildings must be increased drastically to probably more than 200 GW_p, regardless of how social behavior and attitudes may change. To estimate which area is required to install 200 GW_p of PV power, it can be assumed that modern c-Si modules have a power output of 200 W_p/m^2 under standard test conditions (STC) and that therefore 5 million m^2 of PV module area is required to install 1 GW_p. For 200 GW_p one therefore needs 1,000 million m^2 of PV module area. With a total number of about 53 million buildings in Germany [15], an average PV module area of about 19 m^2 is required per building. If the module area is compared to the 82 million inhabitants in Germany, this results in a roof-mounted or facade-mounted PV module area of around 12 m^2 per inhabitant. If one neglects the already installed systems and the replacement of systems after 20 years of use, then one has to install an average of 6.7 GW_p or 33 million m^2 per year on buildings for the next 30 years. This is about three times higher than the total PV capacity currently installed per year (ground-mounted plus roof- and facade-mounted). Germany is a country with limited areas for ground-mounted PV systems. It is important to integrate PV modules into existing, already exploited and/or impervious surfaces, especially on buildings, in order to avoid additional land use. This also applies to many other highly industrialized countries such as e.g. Japan [12], the Piedmont Region of Italy [13] and Switzerland [14]. In these countries, too, it is to be expected that the installed PV capacity on buildings will have to be increased drastically. With such a

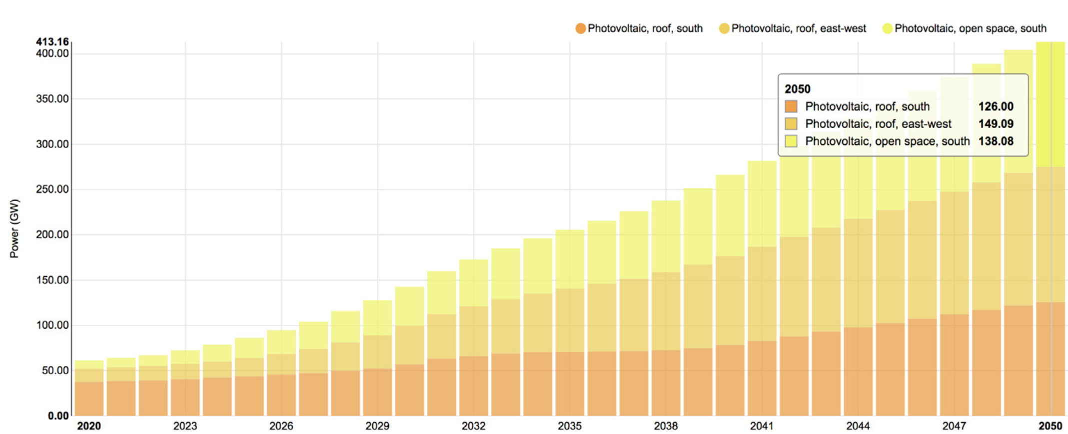


Fig. 2. Fraunhofer ISE Study 2020: Towards a climate-neutral energy system [10]. Installed capacity of PV-systems for electricity generation in Germany (reference scenario with minimal costs). Graphs for other scenarios can be found in the Energy Charts [11].

significant expansion of PV areas, it is particularly important to ensure that PV systems have sufficient architectural integration quality in a given urban environment, to ensure high acceptance by the general public. Functional and aesthetic integration of the PV modules into the building envelope, i.e. the use of BIPV modules or standard modules with improved aesthetics instead of standard modules with a conventional appearance, is particularly important and supportive for high public acceptance.

1.2. Solar potential of the building envelope

As explained in Section 1.1, a significant expansion of PV areas is necessary for the decarbonization of the energy system.This expansion must be realized with limited additional consumption of land areas in several countries. Fortunately, there are economically viable areas available on roofs and facades of new and existing buildings to install PV. The higher the buildings, the more relevant the facade area becomes. In high-rise buildings, where the roof is often required for the installation of heating, ventilation and cooling systems, the roof area is often very limited and relatively small. This means that facade surfaces become increasingly relevant with the height of a building. Furthermore, as the height of taller buildings increases, facade surfaces are often less shaded by plants or neighbouring buildings, except for megacities (e.g. NYC or Toronto) where high-rise buildings are commonly surrounded by neighbouring high-rise buildings. For Germany, it was shown that building envelopes have a large potential of profitable areas to install the PV systems required in a renewable energy system and that the economic potential is several times greater than the necessary 200 GW_p mentioned above. A first step towards validating this statement was the thesis by K. Fath, written under joint supervision by KIT and Fraunhofer ISE [23] [24]. In this dissertation, the solar potential of roofs and facades of representative city districts was analyzed in detail on the basis of 3D building and city models and the results were extrapolated to cover the whole of Germany using cluster analysis. An economic potential on roofs and facades of more than 1400 GW_p was determined, whereby window areas, balconies, chimneys and dormers etc. were neglected in the building models, which means that a geometric detail of the buildings was LOD2.1 according to the level of detail (LOD) concept [26]. The study is currently being extended in the Standard-BIPV project [27]. In this project, a complete survey of all building envelope areas of the complete German building stock, including facades, is carried out. Also in this project, initial results confirm that sufficiently large areas are available on buildings [15], showing that there is a very high potential for the installation of PV modules on buildings, which exceeds 200 GW_p by far. Other studies for other countries show similar trends [12] [13] [14].

Obviously, not all PV systems have to be integrated into the building envelope or installed on buildings. However, the conclusion from what has been written is that very large profitable areas are available on buildings for the installation of PV modules, which should be used due to the limited space for ground-mounted systems in many countries. It is important that PV in the built environment (including BIPV) is technically and aesthetically well integrated to allow broader acceptance from the building industry and the general public. This is especially true for all facade installations.

1.3. Analysis of the BIPV market

Today's BIPV market is relatively small and prices for BIPV facade products are high compared to non-BIPV facades. Fig. 3 provides the historical development and the forecast of the BIPV market in Germany for the roof, facade and other segments, as determined in a market survey performed by B + L Marktdaten GmbH for Fraunhofer ISE [16].

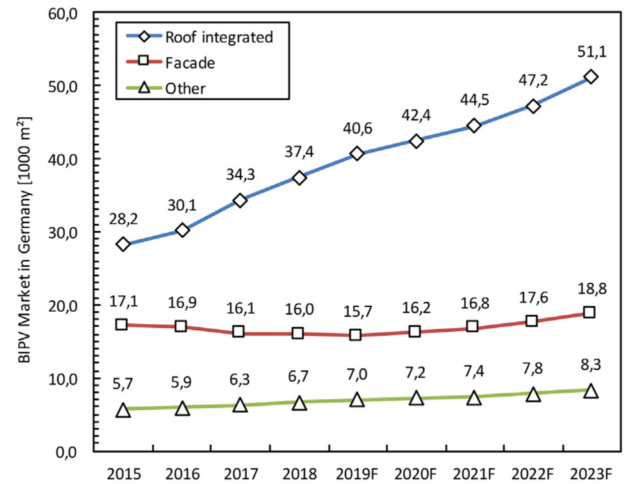


Fig. 3. Historical development and forecast of the BIPV market in Germany in the segments roof, facade and others [16]. An "F" was added to year dates if forecast data was used.

In 2019, the total BIPV market in Germany was estimated to have a size of 63.300 m^2 corresponding to around 12 MW_p installed module peak power. This was only 0.3% of the total German PV market with new installation of 3.94 GW_p in 2019 [18]. The market survey anticipated strong growth for roof integration, a stable market for facade integration and a moderate growth for other BIPV applications. However, there are strong arguments that the BIPV market will grow much faster in the future than estimated in the B + L market survey [16]:

- Photovoltaics and wind power are the main cornerstones in the transition of the German energy supply system with strong further growth for PV installations expected for Germany, as already discussed in Section 1.1. The further expansion is also supported by a high level of social acceptance for photovoltaics.
- Limited areas for new ground-mounted installations in Germany and several other countries (see Section 1.1).
- Today, there are numerous design options available that give thin-film as well as wafer-based modules an optically very appealing appearance. We will present and discuss these options in the following sections.
- The high prices of BIPV modules present a major obstacle to stronger growth. One main component of the BIPV modules is the solar cell. The prices of solar cells have dropped dramatically in recent years. Today, solar cells cost less than 20 €/m^2, whereas they cost around 65 €/m^2 just five years ago. This makes BIPV on the basis of crystalline silicon solar cells much cheaper today (calculated from Fig. 3 of [19])
- Another reason for the high manufacturing costs of BIPV modules is that they are manufactured manually, and equipment and factories are underutilized. Therefore, the cost of equipment, personnel and overhead dominate the manufacturing costs. A modern, highly automated production line with a manufacturing execution system (MES) for planning, steering, controlling and monitoring the production processes with a large variety of products/formats will allow high equipment and factory utilization with minimal personnel resources required. For BIPV, factory digitalization offers great potential to significantly reduce manufacturing costs in the future, despite the large variety of products and highly individual customer requirements. The integration of glass processing and module production will enable additional cost savings and significantly reduce manufacturing time.

The question arises as to how much more expensive a BIPV facade can be compared to a non-BIPV facade if the power generation is still intended to be economically viable. Table 1 shows the price for a 1 kW_p PV flat roof system. This system covers an area of 530 m^2. Both the total price as well as the breakdown into all individual cost items (modules, inverter, cables, mounting system, grid connection, meter, expenses for roof and electrical installation) is given. Such a system with a gross price (including German VAT of 19 %) of 1.070 $€/kW_p$, installed in Germany, with a feed-in tariff of 7.1 c$€/kWh$ and a self-consumption rate between 0 and 30% over 20 years will generate an annual interest rate of 5 to 11%. Together with the fact that the service life of glass-glass modules with crystalline Si PV cells significantly exceeds the required service life of 20 years and warranties of even 30 years are beeing currently offered (see [17] and Section 3.4), this interest rate can be considered a very interesting investment opportunity today.

A BIPV facade with its vertical orientation generates typically only 65% (55% facing east or west, up to 75% facing south) as much electricity as a south-facing roof system with a tilt angle between 20° and 50°, as discussed in Section 6.1. However, this also means that such a BIPV facade system may only cost 65% of the price of a rooftop system if it is also to be economically viable, i.e. in our case, the gross costs must not exceed 131 $€/m^2$. This calculation is given in Table 1 as well. Here we refer to the price may be added to that of the non-solar facade in order to convert it into a BIPV facade (including the entire electrical part such as cabling, inverter, grid connection, meter and the entire electrical installation effort). If we are interested in the maximum additional price that the actual BIPV facade element (as constructional element, not the entire system) may have, then we have to subtract the costs for the electrical installation, whereby it was assumed that the electrical installation effort corresponds to the effort for a roof system. The result is a maximum additional gross price of 55 $€/m^2$ as shown in Table 1. Today, a non-solar facade element without its mounting system costs 95 $€/m^2$ on average [16], which then means an average total gross price of 150 $€/m^2$ for a BIPV facade element where the electricity generation of the facade is as economically viable as a rooftop system. In comparison, the conventional PV module for a rooftop installation would have gross costs of 67.07 $€/m^2$ (357 $€/kW_p$). Note that the price of the facade element is still low compared to the price of the mounting system and the actual work involved in installing it. For a non-BIPV facade, the market survey has determined an average gross prices of 95 $€/m^2$ for the actual facade element, 280 $€/m^2$ for the mounting system and 900 $€/m^2$ for the installation work on the insulating or ventilated glass facade [16].

Fig. 4 provides an overview of the additional price to convert a facade installation into a solar electricity generator for different levels of customization. The y axis shows the level of individual, customer-specific adaptation. The x axis shows the additional price to have a BIPV facade instead of a non-BIPV facade (including cabling, inverter, brackets, mounting system, grid connection, meter, installation cost, etc.). At the present, most BIPV manufacturers manually produce customer-specific modules with a low degree of automation. Solar building envelope components are therefore more expensive than comparable non-solarized building products, resulting in a significant difference in investment costs labeled "handcrafted BIPV modules" in Fig. 4. Only a few manufacturers produce standardized BIPV mass products with fixed dimensions. The green dotted line at a level of 131 $€/m^2$ (justified by Table 1) indicates that there is a certain allowable additional price

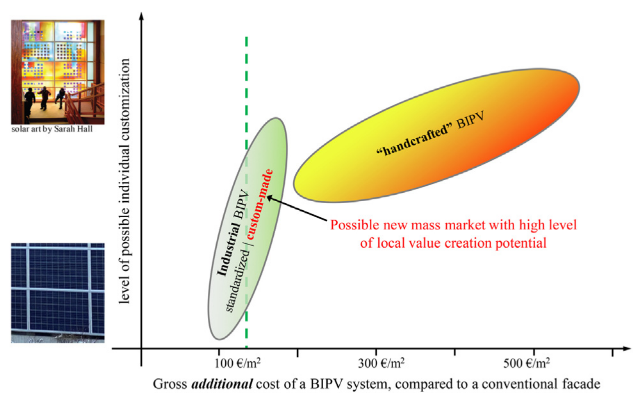


Fig. 4. Additional price, compared to a conventional facade, to make a BIPV installation, for different levels of customization. The green dotted line at 131 $€/m^2$ refers to the German market and is justified by Table 1, it is intended to indicate that there are certain additional investment costs for the BIPV building products, up to which the additional price pays off.

Table 1
Total selling price in Germany and breakdown into all individual cost items for a 1 kW_p PV flat roof installation [20] and the calculation of the supplementary price a facade can have if it generates electricity to pay off the additional cost.

	Gross Price (€/kWp)	Gross Price (€/m²)	Net Price (€/m²)	Price	Part of Facade Installation
100 kWp rooftop system (= 530 m²)	**1071**	**201**	**169**	**100%**	
• Modules	357	67	56	33%	yes
• Inverter/cables	167	31	26	16%	no
• Mounting system	131	25	21	12%	yes
• Mechanical installation	179	34	28	17%	yes
• Electrical installation/grid connection/meter	238	45	38	22%	no
BIPV facade system					
	Relative electricity yield of BIPV (vertical installation)			65%	
	= > **Allowable additional cost for BIPV System** (PV cell layer & junction box, inverter & cables, etc.)	**696**	**131**	**110**	
	– Electrical Part (inverter, cables, grid connection, meter, labor)	405	76	64	
	= Allowable additional cost for BIPV facade module (for PV cell layer, junction box etc.)	292	55	46	
	+ Average price for non-BIPV facade element (without mounting system)		95	80	
	= Allowable average price for profitable BIPV facade module		**150**	**126**	
Standard modules (for comparison)			67	56	

for solar active building products, up to which the additional prices pay off. If the BIPV system prices are to the left of the green line, then the solar building envelope is cheaper over its lifetime than the conventional one. A highly automated, flexible production process for customer-specific modules (i.e. with customer-specific dimensions and design) with an output of around 300.000 m^2 per year (55 MW per year) will provide the required cost structure to offer products for additional gross prices of less than 131 €/m^2 (including cabling, inverter, brackets, mounting system, grid connection, meter, installation cost, etc.). Such a next-generation BIPV facade production facility will allow an interesting profit margin for end users, the manufacturer and investors. Such a production process would offer an enormous new opportunity for smaller local production facilities in Europe, since proximity to and coordination with the final customer are essential.

Note that the derivation of the additional allowable price that still allows profitable installations was carried out for vertically installed BIPV facades. BIPV roof installations with a higher electricity yield can compensate higher additional prices. The same applies to facade installations that result in higher electricity yield e.g. by using tilted modules, as explained in Section 6.1.

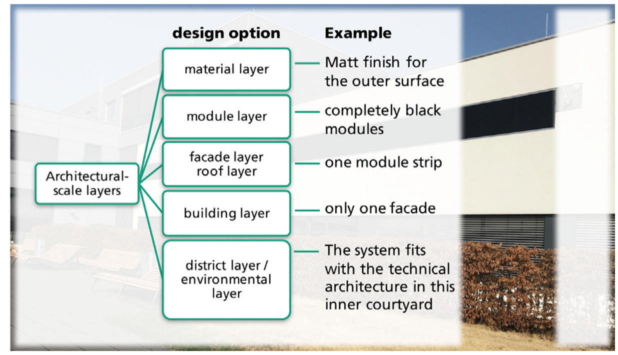


Fig. 5. Illustration of different architectural-scale layers for BIPV-modules [116]. The picture in the background shows a facade with a black stripe made of BIPV modules with a matt antiglare surface texture at a Fraunhofer ISE building in Freiburg, Germany.

2. Approach taken for the review of the technical design options

Previous BIPV reviews usually focused either on an overview of existing BIPV products [109,172,61,36,35,34] or on the analysis of already realized building projects [167–170]. A large and well-documented collection of successful projects, for example, is presented by the Swiss Solar Prize publications [167]. They comprise 429 construction projects that were awarded the Swiss Solar Prize from 1989–2019.

Other publications address the BIPV topic holistically, including construction aspects and the legal and economic framework [32,171,33,110,108].

Standards provide an overview of the valid technical rules that must be complied with when manufacturing and using BIPV products. There is a two-part European standard, the EN 50583 [128] [129], and a draft for a two-part international standard, based on this European standard, the IEC 63092 [1]. Large parts of the pre-normative scientific work for the international standard are currently the subject of activities in subtask E of IEA PVPS Task 15 [168]. An important function of these standards is that they refer to all other standards relevant to BIPV from the construction sector, the PV sector and the general electrical sector.

Publications [106,109] aim to propose objective acceptability criteria for the evaluation of building integration. These criteria are intended to be used in (Swiss) building regulations as a basis for minimum requirements to ensure that BIPV systems are integrated sufficiently well into a specific urban environment.

UNstudio architects present a BIPV design strategy based on architectural-scale layers [116] (see Fig. 5). The first level represents material-layer design options such as colored layers or surface textures. The next level encompasses module-layer design options, where the design of individual modules is determined. Here, for example, it is decided whether the modules are to be uniformly covered with PV cells or whether the cells form a certain pattern. The third level addresses facade-layer design options, in which it is decided, for example, whether the entire facade is to be covered with equally patterned PV modules or with different patterns on different parts of the building. The fourth level refers to the entire building and includes the layout for the different facade orientations and the roof. Finally, there are the environmental-layer or district-layer design options, where the building is put into the context of other buildings in the surrounding area. This categorization or layering approach is especially helpful when designing a particular building. The architectural-scale layers are less suitable for a BIPV technology overview, because many technological features (such as the distance between PV cells) can be applied at several architectural-scale layers.

This paper therefore takes the approach of reviewing and analyzing the different technological design options, independently of specific products or buildings. In particular, a structure for the design options is presented. This structure is intended to provide a comprehensive overview of all technological design options. Technological design options can be understood as points in a multidimensional "design parameter space" [40]. The structure for the technological design options can be interpreted as a "coordinate system" in this design parameter space. A BIPV system consists of modules, inverters, cables, possibly additional string diodes between the PV-modules or power optimizers, and the constructional integration of the modules into the building envelope. These parameters are therefore used as the basis for the structure (or the co-ordinate system) for the design parameter space (see Fig. 6). The following chapters address the different dimensions. Chapter 3 provides a review of the technical design options for BIPV modules. Chapter 4 analyzes design options for the electrical system at the sub-module, module, BIPV-system and building levels. Chapter 5 describes two fundamentally different approaches for the aesthetic design of BIPV modules. Chapter 6 analyses options for the integration into the building envelope, including the positioning of the modules and their constructional integration.

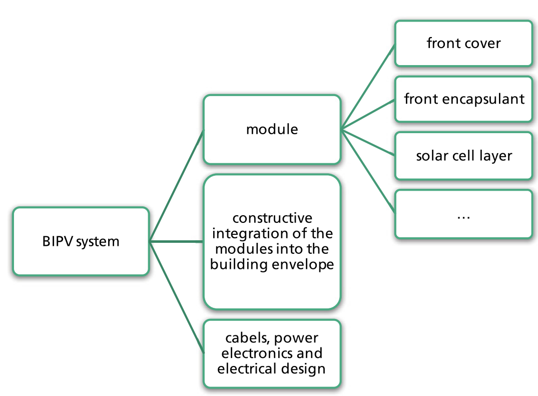


Fig. 6. Technological dimensions of a BIPV system, used as the structure for the following discussion of the different technological design options.

3. Technical design options for BIPV Modules

The design of a BIPV module needs to fulfill aesthetic requirements but should also be able to generate the maximum possible electricity yield at reasonable cost [78,79]. However, the aesthetic design is usually not fixed and small alterations are feasible if a higher power output or reduced costs can be reached. Therefore, the prerequisite for a good module design is the knowledge and understanding of the variety of technical design options for the different components comprising a module. This section provides a generalized approach to explain the varieties of components and map out options to achieve aesthetic design beyond the standard module layout. Section 6.2 discusses the building and constructional integration of the modules.

Section 3.1 introduces the module configuration by differentiating between the laminate and the additional components, i.e. the junction box and the mounting system. In Sections 3.2 and 3.3 the design options for the cover materials and for the embedding materials are discussed. Section 3.4 discusses the design options for the cell layer by also looking at different solar cell and interconnection technologies.

3.1. Generalized module configuration

PV Modules essentially consist of a solar cell layer, two encapsulation layers completely surrounding the cell layer, and a front and rear cover. This configuration is also often called a laminate. Fig. 7 shows the structure of a PV module. Additionally, in the case of a standard module, a frame (as part of a mounting system) and a junction box are connected to the laminate to allow mechanical and electrical connection, respectively.

The junction box contains the bypass diodes. In certain cases a junction box may not be used. For these cases the module is an integral part of a complete system and is usually used in device-integrated PV (e.g. solar street lights [46]). The junction box provides either connectors or cables for electrically connecting the modules. To reduce the size of the junction box, the bypass diodes can be integrated into the laminate [47,48]. In this case the junction box only serves as a connection box.

In the case of a standard module, the frame provides connection to the racks, in the case of a BIPV module more complex mounting systems are used. The mounting system provides mechanical connection to the building and provides additional mechanical stability if required. Visible mounting systems are sometimes undesirable for aesthetic reasons. Section 6.2 discusses different types of mounting systems for glazing which are commonly applied for BIPV. Further examples are module-integrated, rear-mounted complex structures providing insulation [49], ventilation or cooling [50] or easier mounting on standard substructures [45,51,52]. The mounting system can also function as rear cover, replacing the rear cover material entirely or partially while providing a mounting structure [53].

While the laminate usually consists of the front cover and encapsulant as well as the rear cover and encapsulant, a combination of cover and encapsulant as a single material seems feasible. Examples are front covers with low-reflective module surfaces used for high-efficiency applications [54] or some device integration examples using a very thick polymer layer [55]. However, due to the usual high sensitivity of the embedding material to humidity, moisture, mechanical stress, UV light and chemical reactions, it is usually more cost-effective to use a separate impermeable cover layer.

The following discussion applies to flat but also to curved modules. While the application of curved modules is mainly in the vehicle-integrated sector [91], some examples for BIPV also exist [57]. Depending on the curvature, additional adaptations may have to be made (e.g. using smaller wafer-based solar cells). However very strong curvature leads to differences in the irradiation on individual cells, which creates a mismatch between the current generated by the cells and thus a significant drop in overall power output.

3.2. Design options for front and rear cover materials

The cover materials for the front and rear cover can be completely different (e.g. glass as the front cover and layered polymer films as the rear cover). However, they can be categorized according to the same configuration: external surface, bulk material and internal surface (see Fig. 8).

The surfaces (both, outdoor and inside the module) can be structured, coated or even finished with additional layers. Combinations of structuring and coatings are also possible. All options can be functional [58,59] or aesthetical [28]. Coatings can be various additive layers on the bulk material of the cover layer. These include sputtered coatings [29], enamel coatings or printed coatings [157] but also different varnishes and lacquers are possible. Fig. 9 allows the appearance of flat glass surfaces and structured glass for transparent and opaque modules to be compared.

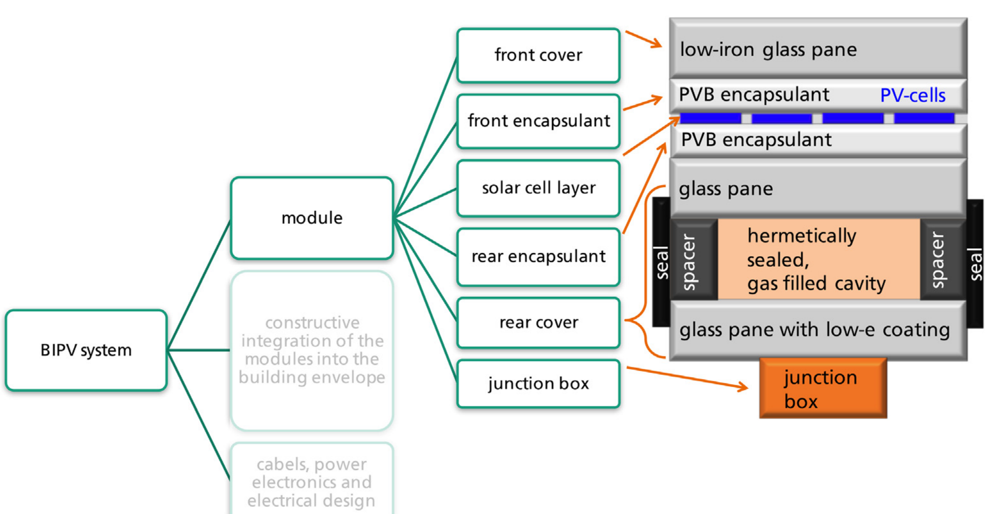


Fig. 7. Overview on technical design parameters for BIPV modules as part of a BIPV-system. To illustrate the structure on the left side, a schematic of a BIPV double glazed unit (DGU) is shown on the right hand side. Common material classes for this setup are mentioned. A double glazing is mounted on the rear side (interior side), creating a double glazed unit. A junction box provides the electrical connection of the modules.

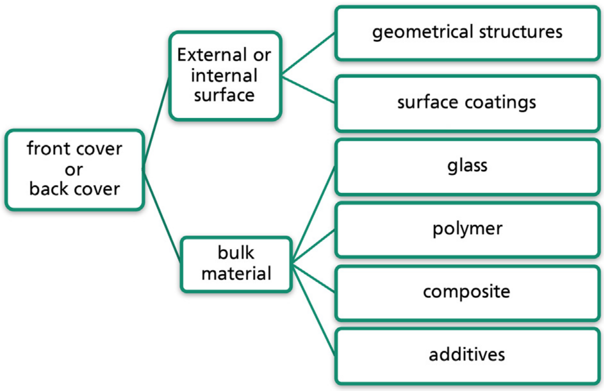


Fig. 8. Overview on design parameters for the front and back cover.

Structures on the outside surface change not only the appearance but also the reflection behavior and can thus, for example, prevent glare caused by specular reflection of the sun. However, glare control of the surface cannot be achieved by classic flat anti-reflective layers alone, e.g. interference layers or nanoporous structures ($\lambda/4$ layers), because the luminance of the sun can only be reduced by 99% (i.e. a factor of 10^{-2}), which makes virtually no difference to perceived glare due to the logarithmic sensitivity of the human eye and the high luminance of the sun of 10^9 cd/m^2. Very good antiglare properties can be achieved by using diffusing surface textures. Diffusely reflecting surfaces can reduce the luminance of the reflected radiation by up to 10^{-5} (with isotropic diffuse scattering), whereby very good glare control can be achieved. However, with diffusely scattering surfaces, care must be taken to ensure that they still have the highest possible degree of transmission in order to reduce electricity yields as little as possible. The matt surfaces of the colored modules in Fig. 24 are examples for light-scattering highly transmitting, anti-reflective surfaces.

Additional glazing components are usually added behind the rear cover material or replace it entirely. An example is shown in Fig. 7. Here, the module is integrated into a double glazing unit (DGU). In this case, the rear cover is not a single polymer film or glass pane but a complete glazing unit.

Functional coatings or structuring can be applied to the external or internal surface (e.g. AR coating on the external surfaces, adhesion strengthener on the internal surface). Aesthetic coatings are usually on the internal surface since environmental conditions have less impact there. The design options and possibilities for coloring by coatings are discussed and compared in more detail in Section 5.2.

The bulk materials can be manifold. Glass is most commonly used and offers several advantages for BIPV: highly transparent, mechanically stable, low thermal expansion coefficient, non-combustible, sustainable and recyclable and a material which is well known within the building industry. Additionally, when glass is used as the bulk material for the front and rear covers, it often can be classified as laminated glass, or even laminated safety glass, which is beneficial for constructional integration, safety, sound insulation and long service life with warranties of up to 30 years [17]. Therefore, many BIPV modules use glass for the front and rear covers [61]. Other common materials for the front and rear covers or sheets include polymers or polymer compounds such as ethylene tetrafluorethylene copolymer (ETFE), polyamide (PA), polypropylene (PP), polyethylene terephthalate (PET) and polyvinyl fluoride (PVF). Even thin metal layers such as aluminum foils can be integrated into a polymer layer compound [62,63]. Modules with at least one non-glass cover are typically used for lightweight applications such as roofs of industrial buildings or for building-applied photovoltaics, where requirements regarding fireproofing and structural support may not be as strict [64]. Additionally, composites including glass fibers are manufactured and used as an alternative to glass for the front or rear covers [65]. Here, many benefits of glass such as a high stiffness are combined with a more

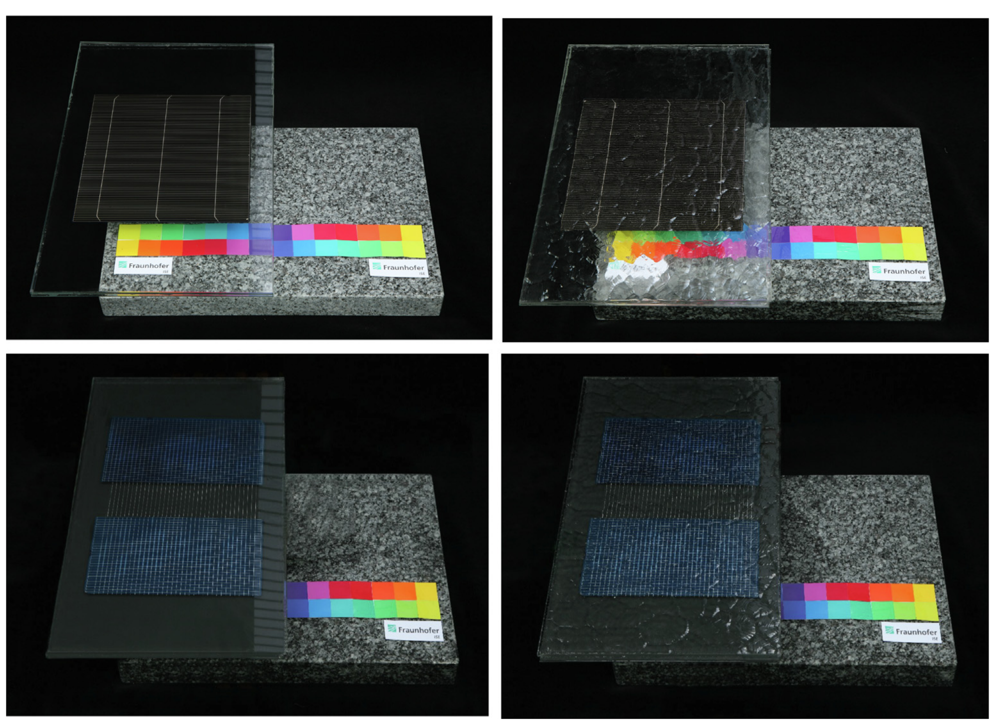


Fig. 9. Comparison of glass-glass modules without (left column) and with (right column) macroscopic surface textures for transparent (top row) and opaque modules (bottom row). Along the right edge of the modules the reflection of a bright white block with dark stripes is visible. On the smooth glass pane (left column) the reflections are sharp and clearly visible, whereas on the structured module they are smeared out. Structuring of transparent modules (top row) influences not only the light reflection, but also the view of the background.

lighter-weight material. However, the costs of glass fibers are usually also higher. Additives can be used, especially for polymer bulk materials, to achieve certain properties. Examples of such additives, especially for the rear covers are TiO_2 to achieve higher reflectance [85,86] or pigments, to achieve a coloured impression (e.g. black backsheet). Additives can also be incorporated into glass such as to reduce abrasion of the glass surface [66].

3.3. Design options for embedding materials and additional interlayers

The embedding material of a solar module provides an airtight surrounding for the solar cells and adhesion to the cover material. The embedding material has to accomodate the possibly different thermal expansion coefficients of the various materials (i.e. the metal contacts, the solar cells and the cover materials) and maintain an impermeable seal over the lifetime of the module. Possible alterations to the embedding material for BIPV applications are shown in Fig. 10.

Commonly, the embedding material is a cross-linking polymer such as ethylene vinyl acetate (EVA) or a thermoplast such as polyvinyl butyral (PVB) which bonds the cell layer to the cover layer [67,68]. EVA is most commonly used for standard module production due to its low costs. PVB is commonly used for laminated glass within the construction industry and is therefore also often used for BIPV applications [69]. Both material groups are usually laminated as interlayer between the cover and the cell layer. Alternatively, a casting resin (mostly silicone) can be used for embedding as well. The production process is fundamentally different since here the liquid resin is poured into the cavity between the cover layers and subsequently solidifies [70]. Another fundamentally different approach is the use of gases as the embedding material, such as in the case of the TPedge module design [143,75].

The properties of the embedding material can also be altered by adding additives. Functional agents are commonly used, for instance, to improve UV stability or processing speed. Regarding aesthetic design, two options have been observed, one is adding light-scattering particles, which create a colored impression while maintaining a high transparency of the layer [164] and the second approach is using pigments which provide a colored impression by absorption and reflection [42].

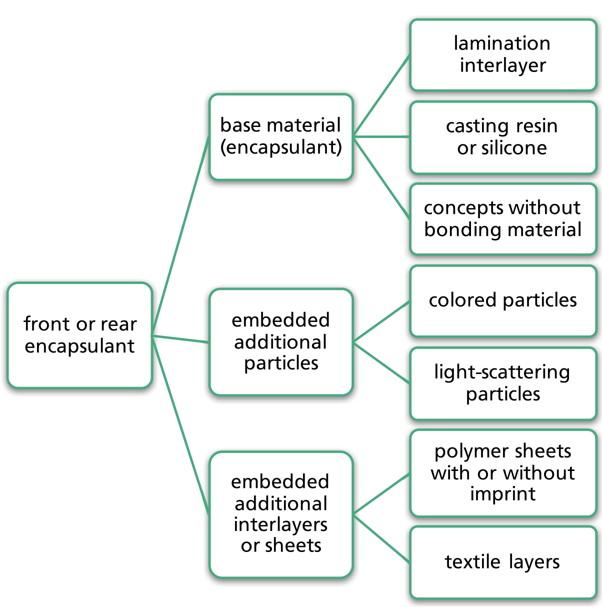


Fig. 10. Design options for front or rear embedding materials.

Additional sheets/interlayers can be embedded within the encapsulation layer. The primary aim of embedding is to achieve a desired color, light diffusion or light reflection. An example are colored nets, which can be incorporated into the module production process by adding them during the layup [92,38]. Fig. 11 shows an example. Various options and realization possibilities for adding color to a module are discussed in detail in Chapter 5.2.

3.4. Design options for the PV cell layer and electrical module layout

The PV cell layer is the decisive factor for the electricity yield, the service lifetime and in most cases for the optical appearance of the module. The main differentiation is between the cell technologies, which split into two main categories. Firstly there are wafer-based technologies such as crystalline Si, or tandem solar cells (III-V, Si-perovskite or Si-III-V) and secondly, there are thin-film technologies. Thin-film technologies are usually active layers grown or applied onto substrates (such as a-Si, chalcogenic, organic or perovskite solar cells), which offer a homogeneous impression and are therefore, in principle, beneficial for aesthetic module design. However, the market share for standard modules with thin-film technology is much lower than for crystalline Si solar cells and shows a further decreasing trend [145]. Therefore, thin-film technologies for BIPV applications cannot benefit from a supporting mass market where technological advancements and cost reductions are pursued by a large number of companies for a specific cell technology.

Table 2 shows a comparision between the relevant or most promising solar cell technologies with regards to BIPV. The symbols "+ +", "+", "o", "-" and "- -" indicate comparable advanteges or disadvantages between the different cell technologies. The selection is based on technologies which are currently actively followed in market and research. Further solar cell concepts such as amorphous silicon solar cells (a-Si) or tandem cell technologies exist but they currently are either followed purley academically or there are no manufacturers available for the BIPV market. As an example there are many research activites on perovskite or III-V on Si solar cells at the moment. The concept which is currently closest to commercialization and therefore is also considered here as potentially relevant for BIPV applications is "perovskite on Si solar cells".

Fig. 11. Solar module with an integrated interlayer (woven fabric) to provide a colored impression (left) and closeup view of the module (right). The woven fabric is placed in front of the solar cell layer and conceals the cells with blackened interconnectors and a black backsheet completely. Depending on the mesh size, the power losses due to the absorption of the woven fabric can be varied but also the appearance of the module changes. A larger mesh size reduces the intensity of the color impression and darkens the overall module. Here, the mesh size results in an absorptance of 35%.

Table 2
Rough overview of different solar cell technologies for building-integrated photovoltaics. The column heading Efficiency considers the currently achieved efficiency in industry or in pilot lines. Cost is the typical or expected price range for standard module products. Long-term stability considers the intrinsic stability of cells without covers or encapsulants. Temperature and irradiation dependence indicates strongly temperature and irradiation influences the efficiency of the cells, respectively. (However, a stronger dependence may still result in a higher efficiency at a given temperature if the efficiency at STC is higher). Hazardous components identifies the potential risks in relation to the contained hazardous components. Market penetration reflects the annual production capacity.

	Factors influencing LCOE						
Cell Technology	**Efficiency**	**Cost**	**Long-term stability**	Temperature dependence	Irradiation dependence	Hazardous components	Market penetration
Wafer-based technologies							
Crystalline silicon (monocrystalline/ multicrystalline)	**+**	**++**	**++**	o	o	o	++
III-V cells (single-/ multi-junction)	**++**	**- -**	**++**	+	+	-	o
Perovskite Si tandem	**++**	**o**	**-**	o	o	-	-
Thin-film technologies							
Chalcogenide cells (CIGS, CdTe)	**o**	**++**	**+**	o	+	-	+
Organic/ dye-sensitized cells	**- -**	**+**	**- -**	+	+	++	o
Perovskite cells	**+**	**+**	**- -**	-	-	-	- -

- **Crystalline silicon (c-Si) solar cells** represent the most commonly used cell technology for PV systems in general. Since the beginning of the 1980s cells have been specially developed for terrestrial use and the current efficiency record is 26.7% [93]. While this efficiency record has been reached in the laboratory, the market is not far behind. The different solar cell technologies provide different efficiencies but also costs. With the current standard technology PERC (passivated emitter and rear cell), module efficiencies above 20.5% are achieved commercially. Currently emerging technologies such as the TopCon technology and heterojunction technology (HJT) provide module efficiencies of around 21% or 22% respectively. Modules with even 22.8% efficiency are available based on interdigitated back contact (IBC) solar cells [80]. In December 2018, the price for standard modules was 40 €/m^2 (21.4 c€/W) and 21 €/m^2 (11.5 c€/W) for the PV cell layer. Prices for c-Si PV modules have decreased by around 30% each year over recent years. Of course, these prices only apply to standard modules and for large quantities. However, the low cell prices in particular demonstrate, that the costs for the raw materials for BIPV modules have fallen dramatically in recent years. The lower material prices therefore also had a positive effect on BIPV modules manufactured to customer specifications. Si-wafer based PV technology accounted for about 95% of the total production in 2017 [145] [148]. A warranty period of 30 years is possible with c-Si glass-glass modules [17]. Si-wafer based solar cells can be integrated into curved modules with a low curvature, such that the individual cells remain almost flat. This applies to all wafer-based cell technologies. Additionally, the cells can also be cut into smaller sizes, which allows for stronger curvature and provides a benefit for the module efficiency. The temperature and irradiation dependendcy for c-Si solar cells depends on the cell architecture but is generally considered to be a weak point for this solar cell type. However, different Si solar cell technologies also show a different temperature coefficient such as heterojunction solar cells, which have a strongly reduced temperature effect [76], and the efficiency for low light conditions and higher temperatures is usually still higher than for other cell technologies due to the higher efficiency under standard test conditions (STC) [74]. Most Si-wafer based solar cell technologies contain lead for cell metallization and interconnection but in small quantities and as a constituent of chemical compounds or alloys, not as free lead [94].
- **III-V cells** show the highest record efficiencies with 29.1 % for GaAs single junction cells and multi-junction cells featuring 38.8 % [93]. Due to the usage of rare materials and the higher material costs, the overall cost is around one to two orders of magnitude higher than for c-Si solar cells. III-V cells were developed for space and terrestrial concentrator applications and have an existing albeit small market. The long-term stability is similiar to c-Si solar cells and even better suited for space applications, where high energy particles degrade the materials and lead to performance losses. Temperature and irradiation dependence is slightly lower than for c-Si solar cells. Most III-V cells contain As a toxic component but in very small quantities and in a bound form. The III-V cell technology has been discussed as wafer based technology, however, it can also be applied as thin film on (flexible) substrates.
- **Perovskite on Si tandem cells** have shown a record efficiency of 28% on large size wafers [95]. However, since sales and production have not started yet, a price cannot be provided. The price range is expected to be somewhat higher than crystalline silicon solar cells and other single-junction concepts. Market penetration is non-existent as of now, but there is great interest in this technology and the first companies are ramping up production. The long-term stability is intrinsically much lower due to the high sensitivity of the perovskite layer to humidity. The temperature and irradiation dependence may be similar to c-Si solar cells. Due to the currently used lead-based perovskite layer, the amount of lead in the module is slightly higher than for c-Si technology. Additionally, it is contained in a non-bound form which is soluble in water.
- **Chalcogenide thin-film solar cells (i.e. CIGS, CdTe)** represent the second-most relevant technology after c-Si solar cells for BIPV applications. Due to their homogeneous black appearance, they provide a more aesthetically pleasing appearance for architects and building owners. The record efficiency of chalcogenide solar cells (currently at 22–23 % [73]) has also increased in recent years. Still efficiency and prices favour c-Si technology, due to the much higher market penetration (currently available module efficiencies are in the range of 16–17%). Long-term stability is not an issue, but a 30-year warranty as for c-Si technology has not been observed. While curved modules could be provided more easily with these thin-film technologies in principle, processing and cracking of the cell layer prevent the application of strong curvatures. This also applies to all inorganic thin-film solar cell types. The temperature dependence is similar to c-Si technologies, but the irradiation dependence is weaker for CdTe but stronger for CIGS [72,114]. All currently relevant technologies also contain hazardous components such as Cd and lead in small quantities [94].
- **Organic (OPV) cells or dye-sensitized cells** are currently undergoing a rapid development. Important alliances have been formed between material manufacturers and OPV module producers. BIPV modules have been realized [39,173] and installed in pilot buildings [43]. The record efficiency of organic solar cells is currently 17.4 % and of dye-sensitized 12.3 % [73]. However, available module efficiencies are around 8%. The potential cost could be lower than for c-Si technology, but since there are only very few companies in the market, the cost-reduction potential cannot be fully activated. A major concern is the long-term stability of organic materials, so additional measures have to be taken to encapsulate and cover OPV solar cells successfully [39]. Still UV light degrades this cell technology more strongly than all other cell technologies. The bendability however, is much better and curved modules can be easily manufactured. It is even possible to bend the modules several times without significant degradation of the cells. Additionally, temperature and irradiation dependence is much weaker than for all other types of solar cells, but as the efficiency under STC conditions is also much lower, the efficiency for higher temperatures and under low light conditions is still significantly lower. Unlike other cell technologies only the environmental effects of solvents have be considered with respect to hazardous components [94].
- **Perovskite solar cells** are an upcoming new cell technology which is currently at the stage of research projects. Efficiencies even higher than for chalcogenide solar cells have been demonstrated (currently 25,2 % [93]). The cost-reduction potential is also promising. However, no modules have been offered commercially to date. The long-term stability also suffers from the high sensitivity to humidity and additional steps such as glass solder-

ing have to be included to seal the modules [71]. For the bendability the same effects apply as for chalcogenide solar cells. However, temperature and irradiation dependence could potentially be slightly worse. Since currently promising perovskite solar cells contain a large amount of soluble lead, significant encapsulation measures have to be taken.

Fig. 12 provides an overview of the technical design options of the PV cell layer for BIPV applications. For all wafer-based technologies the cell size, cell shape (contour and perforation), cell position and spacing as well as cell color can be altered. Changing the cell size and shape, is fairly difficult and requires additional processing steps within module production (usually a laser process for cutting the cells), so it is currently seldom used. However, due to the rise of half-cell technologies for standard modules, a laser cutting process is becoming increasingly common throughout the industry [80,81]. Changing cell position and spacing, on the other hand, is fairly simple and therefore often used to achieve some adjustable transparency of modules [82]. Changing the cell color is also possible but the efficiency will be reduced [83].

The interconnection of wafer-based technologies influences module aesthetics significantly. Fig. 13 shows an overview of the different interconnection technologies. For conventional busbar/ribbon interconnection, bright metal ribbons are usually highly visible and disturb an otherwise more homogeneous impression. The

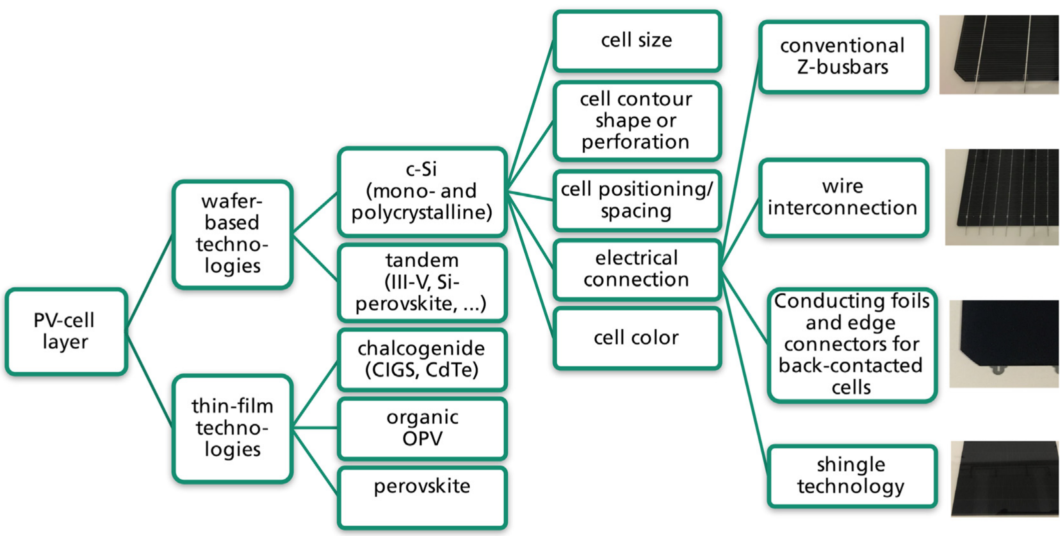


Fig. 12. Design options for the solar cell layer. See also Fig. 13 for an overview of the electrical connection options.

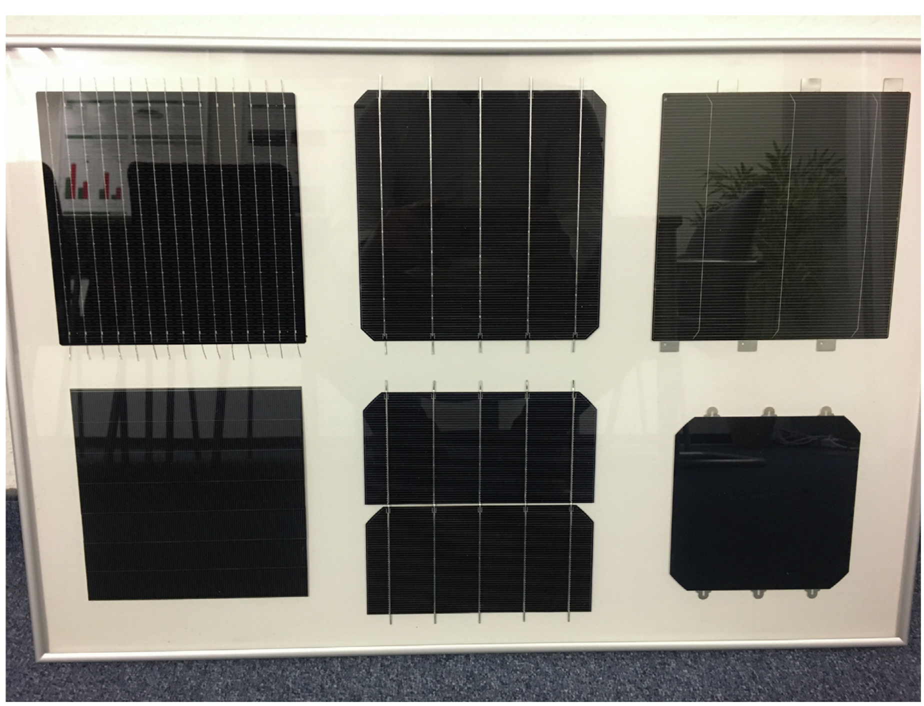


Fig. 13. Comparison of the different interconnection technologies. Top left: wire interconnection, Bottom left: shingled interconnection, Top middle: standard busbar interconnection, Bottom middle: half-cell busbar interconnection, Top right: metal wrap-through interconnection, Bottom right: interdigitated back contact interconnection.

conventional design a with few thick silver ribbons in front of black cells and a black back sheet does not meet the requirements of architects in several cases (see Fig. 13, middle column). Therefore, techniques have been used to conceal the ribbon interconnection. Three approaches can be observed in the field: (1) covering the ribbons with a black sheet, tape or film after interconnection, (2) aligning the ribbons behind a black print on the inside of the front cover and (3) using ribbons which have been blackened. All techniques reduce the efficiency of the module since the total internal reflections of the light reflected by the bright ribbons contribute around 0.5% of the power output of a solar module [84]. Additionally, approaches (1) and (2) also shade the solar cell near the ribbons since a certain overlap is needed for alignment and complete coverage of the ribbons. For approach (3), the cell interconnection tool needs to be able to handle these ribbons.

A second option for the interconnection of solar cells is the wire interconnection, which is increasingly observed in the market, since it also offers efficiency benefits for standard modules [87]. Here the wafers are interconnected with thin round wires, which are not as prominent as the flat ribbons, especially from a distance. From a distance the impression is more subtle or the wires are even not visible at all. From a closer viewpoint connection pads on the cells may disturb a homogeneous impression (see Fig. 13 top left). However, the illustrated connection pads are not required for all wire interconnection technologies and can be avoided [77]. For the wire interconnection, no interconnection concealing technologies are used, since the required overlap in relation to the number of wires is too large and the blackening of round wires is difficult to achieve if a good electrical contact is needed.

Back-contacted solar cells are also commonly used to achieve highest efficiencies and black or homogeneously colored modules. There are several options available for back-contacted solar cells available. One is the IBC solar cell technology [88] and the emitter or metal wrap-through (EWT/MWT) solar cell technologies [89]. In both cases the interconnection of the solar cells is on the back surface and the interconnectors visible only in the spacing between cells (see Fig. 13 right column, top for MWT and bottom for IBC). Here coating of the interconnectors and alignment is easier to achieve and this technology is currently most commonly used when a black or homogeneous appearance of the module is required. Additionally, for the IBC technology even the metal fingers of the solar cell are not visible, creating the possibility to have a completely black module design. However, the main drawback for this technology is the significantly higher cost of the solar cells compared to the conventional busbar design.

An emerging approach to achieve a homogeneous module appearance is the shingled interconnnection technology. In this case, solar cells are cut into smaller strips, which are then contacted in series by placing each cell on top of a small section of another cell, as with roof shingles (see Fig. 13 bottom left). Conductive adhesives are used to achieve an electrical contact between the two cells. This approach was initially investigated as a method to increase the efficiency of standard modules since smaller cells generate lower currents which reduces resistive losses [44]. It was patented by Schmidt and Rasch already in the early 1990s [21] further developing a basic patent from 1960 by D. Dickson [21]. In addition to the potential higher efficiency, the shingled interconnection technology does not need any interconnectors so the impression is by default more homogeneous and only the fingers of the solar cells are visible. Additionally, the matrix interconnection configuration can be applied, where the solar cells are interconnected with a parallel offset such that one cell connects with the halves of two other cells, as in a brick wall, see Fig. 14. In this case the appearance of strings of cells is resolved and by adjusting the offset different kinds of patterns can be formed and modules of different sizes can be filled more effectively. The matrix interconnection also increases the yield of solar modules in the case of partial shading [90]. Due to the smaller cell size, greater module curvatures with Si-wafer based technologies can be achieved and the size of the cell layer can be more easily adapted to BIPV modules of different sizes. It is also possible to adjust the output voltage and current to external requirements within a certain range due to more options regarding series or parallel interconnection within the module (see Fig. 15).

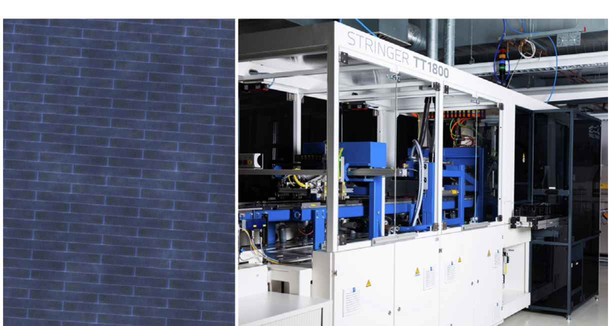


Fig. 14. The figure shows a matrix shingle BIPV module [44] on the left side. On the right side is an industrial stringer for manufacturing shingled solar cell strings.

4. Design options for the electrical system

Conventional PV systems - on roofs or ground-mounted - are typically designed for maximum electrical output at minimum cost. In contrast to this, BIPV systems are required to fit into the geometry, design and structure of an existing or a specifically designed building. Unavoidably, the orientation of many BIPV modules is not only far from the optimum, but different sizes of modules can be required to fit into the given architectural design and the modules can be prone to shading either by adjacent buildings or by other parts of the building itself. Therefore there is simply no all-purpose BIPV module that meets all financial, technical and aesthetic requirements. These conditions require not only specific module solutions but also a special electrical design of the BIPV system [152]. To understand this, one should consider that the number of generated charge carriers and thus the power generated in the individual cell depends on the irradiance. Since all PV cells in a cell string are connected in series, an electrical mismatch occurs if the irradiance on the individual cells is inhomogeneous. This means that the current in the entire string is limited by the most heavily shaded cell, which can lead to overproportionately high losses. Thus, heavily shaded cells may be operated as electrical loads (reverse bias) and may be heated up considerably. The actual operating point of the individual cells depends on the wiring and the maximum power point (MPP) tracking of the inverter. In order to prevent such overproportionate losses, a multitude of electrical design options is available. Especially the MPP tracking can be realized at different levels. This section analyses a range of design options with respect to the electrical design of BIPV systems. The analysis of the technical design parameters is divided into four different levels as depicted in Fig. 13: the substructure inside individual modules including module-integrated electronic components (sub-module level), the individual module with its external connections and possibly further external electronic components such as DC/DC converters or micro-inverters (module level), the BIPV system with several modules and further power electronic components like inverters (BIPV system level) and the whole building including consumers, batteries and grid-connection (building level).

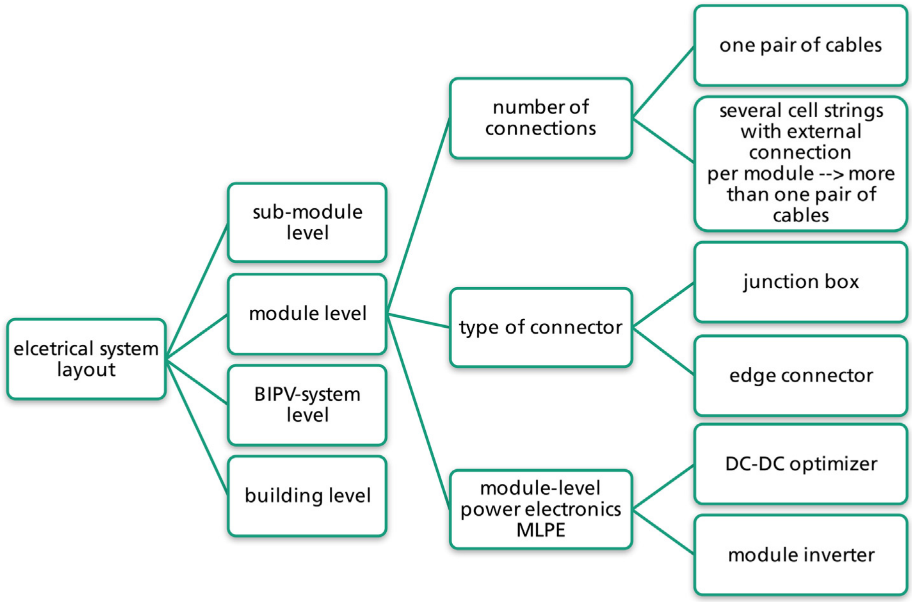


Fig. 15. Overview of the design parameters for the electrical BIPV system layout. The parameters on the module level have been further detailed as examples.

4.1. Sub-module level

The sub-module level comprises options within the PV module. The most important component of course is the PV cell itself. The PV cell technology has a major influence on all electrical properties of the PV system. The type of semi-conductor (crystalline silicon, amorphous silicon, CIGS, CdTe, organic etc.) and the method of solar cell processing strongly influence the final output and important parameters such as temperature coefficients and low-light behaviour. These fundamental properties of photovoltaics are beyond the scope of this work. Apart from choosing the solar cells themselves, one can choose the number of cells in the horizontal and vertical direction within a module, the distances between adjacent cells and between cells and glass edges, the orientation of cells (e.g. parallel, perpendicular or rotated with respect to the glass edge) and the cell interconnection technology. It is important to note that the solar cells behind a single glass cover can be part of several electrical subsystems. This is e.g. the case when a module is shaded regularly and thus the cell array is subdivided into areas that are each homogeneously illuminated although the adjacent areas see other illumination levels. This is illustrated in Fig. 16, where the vertical wooden fins regularly shade the cell columns that are closest to the fins. For this reason, the PV module is subdivided into three electrical sub- systems. All cells along the left-hand edge of all solar modules in that system are connected to each other in series. All cells in the central columns of all solar modules in that system are connected to each other in series and all cells along the right-hand edge of all solar modules in that system are connected to each other in series. This takes account of the recurring shading situations in the morning and the evening, such that the shaded areas at the left or right edges of the module do not limit the output of the complete module. Furthermore, an adequate number of suitably positioned bypass diodes or more complex electronic components can be integrated within the module. As such components are not yet typically highly integrated within the module, but are added externally to the module, they are described primarily in the following Section (module level). One example of highly integrated power electronics are integrated circuits that do MPP tracking already at the sub-module level [96].

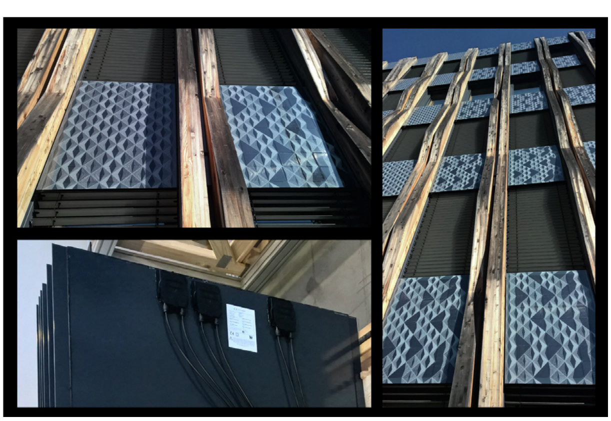


Fig. 16. The picture shows the Z3 building of Ed. Züblin AG in Stuttgart, Germany. Since the vertical wooden lamellas of the existing facade often shadow the edge areas of the BIPV modules on the right and left, each glass panel was divided vertically into three modules (left, middle, right).A typical partial shadow can be seen on the upper left picture. The three junction boxes on the rear side are shown in the bottom left picture. Pictures Ed. Züblin AG 2019.

4.2. Module level

Also at the module level, power electronic components can be useful when the complete BIPV system is designed and optimized. Typically, junction boxes with bypass diodes are mounted directly on each module. Different types of junction boxes (e.g. edge-connected junction boxes or conventional ones mounted on the back cover of the module) are available, which is especially important with respect to the mechanical mounting/framing and can have an influence on the aesthetic appearance of the modules. The typically used passive bypass diodes can short-circuit the circuit of a sub-string and protect its cells against reverse voltage and hot spots. Passive bypass diodes can cause problems of heat dissipation, leakage current and defects due to overvoltages. Therefore, instead of passive Schottky bypass diodes, also active bypass diodes can be used. They apply transistors to reduce conduction losses and heat dissipation, thereby increasing efficiency and achieving active overvoltage protection, see e.g. [98]. In addition to passive or active bypassing of shaded modules or substrings, every system requires MPP tracking at one of the levels described here. "Standard" PV generators use central MPP tracking (see following section about system level). For BIPV, due to the usually more complex geometrical configuration and different orientations of modules and due to partial shading, decentralized MPP tracking can be beneficial. This can be done e.g. by module-level DC/DC converters or micro-inverters. In particular, DC/DC converters have become a very interesting option for BIPV systems. Depending on the system concept, different topologies could be used (buck, boost, buck-boost converter), realizing local MPP tracking while still connected to a central string inverter. Alternatively, micro-inverters could be used that are directly connected to the AC grid or could achieve local MPP tracking even at the sub-string level with new topologies [99]. In general, the advantages of module-integrated power electronics include higher yield and additional monitoring functions. For benefits and drawbacks of decentralized MPP tracking, see e.g. [97]. Whether module-level power electronics or string inverters are preferable depends on many specific system parameters and requires detailed understanding of the system, e.g. by simulation. For a comparison of these options in specific cases, see for example [147]. The number of DC connections is a further degree of freedom that is directly related to the number of electrical subsystems, as explained in the previous section about the sub-module level. While most modules feature two DC connectors (+ and −), dividing the module into two or more sub- modules and having four or more DC connectors can be a further option to reduce the effect of partial shading.

4.3. BIPV system level

At the BIPV system level, there is design freedom to choose how modules are interconnected. Usually a number of modules is interconnected in series to strings, and sometimes modules or strings are connected in parallel. One or more inverters usually convert DC into AC electricity. The inverter is the central component of the electrical system and controls and operates the complete system. By maximum power point tracking, it usually determines the operating voltage of the system. It has to be chosen carefully with regard to its topology. Some special cell and module technologies require inverters with a transformer to ensure galvanic separation between DC and AC circuits or to avoid PID effects. In some cases, the galvanic separation is also a requirement of the regulations of public authorities. However, most modules on the market today can be operated with transformerless inverters, which are typically smaller and more efficient. Choosing an inverter with appropriate electrical parameters is also crucial, especially considering that BIPV systems often operate under low-light conditions or higher temperatures. Therefore, sufficiently low start voltages and rated powers that are not too high are important. Connecting strings of different orientations (e.g. east facade and west facade), which provide their maximum power at different times, to a single inverter can help to reduce the number and cost of inverters and to increase self-consumption rates. One extreme example was the plus-energy renovation of an art noveau villa in downtown Zürich, Switzerland [27,76] , where a BIPV system with 198 modules of 112 different sizes and 19 different module orientations has been planned and realized. One further option, which might become important in the future, is to realize a local DC grid, e.g. in the building, thereby eliminating the DC/AC conversion and connecting the BIPV system directly to a DC system, e.g. a battery or DC loads. In this case, as there is no inverter, the MPP tracking has to be done independently, for example by a charge controller or power optimizer. For such an option, a detailed comparison is needed of the advantages and disadvantages of the DC or AC grid connection, taking the given system parameters into account. Another option is shown in Fig. 16 for the case of the Z3 building of Ed. Züblin AG in Stuttgart, Germany. In this building, frameless structural sealant glass panels on the south facade were replaced with frameless structural sealant BIPV modules as part of the EU project construct-pv [107]. A frit print, designed by UNStudio, is applied to the rearside of the front glass. Since the vertical wooden lamellas of the existing facade often shadow the edge areas of the BIPV modules on the right and left, each glass panel was divided vertically into three modules (left, middle, right). This reduces the negative influence of partial shading on the electrical yield. For more details see [31,25,102].

4.4. Building level

Sometimes BIPV systems are connected to the public AC electricity grid and are just used for feed-in. In this case, the BIPV system level is the highest level for an individual building and everything else is taken care of at the grid level. However, more and more often, BIPV systems are forming an important part of building energy systems, including aspects of self-consumption and self-sufficiency. In this case, the electrical design of BIPV systems also has to consider the demand side and possible storage capacities. Having a BIPV system with various orientations can help to match supply and demand better. At the building level, degrees of freedom include the choice of installing a battery, integrating electric vehicles into the system and introducing and controlling large electrical loads like heat pumps. As there are interdependencies between BIPV, batteries, heat pumps and other electrical loads, the system and the size of its components should be optimized holistically.

5. Module-level aesthetic design options: Patterns formed by PV cells or invisible PV-technology

If one wants to make BIPV modules visually appealing, there are basically two fundamentally different options:

- One can leave the cells visible and consciously use them as a design element. The cells are then used as basic elements of patterns. This design option is examined in Section 5.1.
- One can try to design the modules in such a way that the pv-technology becomes invisible by coloring all components of the module uniformly in the cell color or by using a colored or light-scattering front cover, which is often associated with a considerable loss of efficiency. Different technical options for colored modules are analyzed in detail in Section 5.2.

5.1. Using PV cells as a basic element for the design of patterns

Leaving the cells visible and consciously using them as a design element means that the cells are used as basic elements of patterns. PV-modules with transparent areas between the PV cells provide stationary solar control, partial transparency and reduced daylighting compared to a clear glazing unit. It is important that the cell connectors should also be included in the pattern (e.g. by using colored connectors) or be designed to be less obvious and disturbing by using many thin cell connectors instead of a few thick ones. This is illustrated in Figs. 17 and 18.

For thin-film PV-technologies, transparent conductive oxide (TCO) cell-connectors are used, whereby the different solutions vary in the degree of light scattering in the transparent area between the cells. PVShade, a special angle-selective solution with

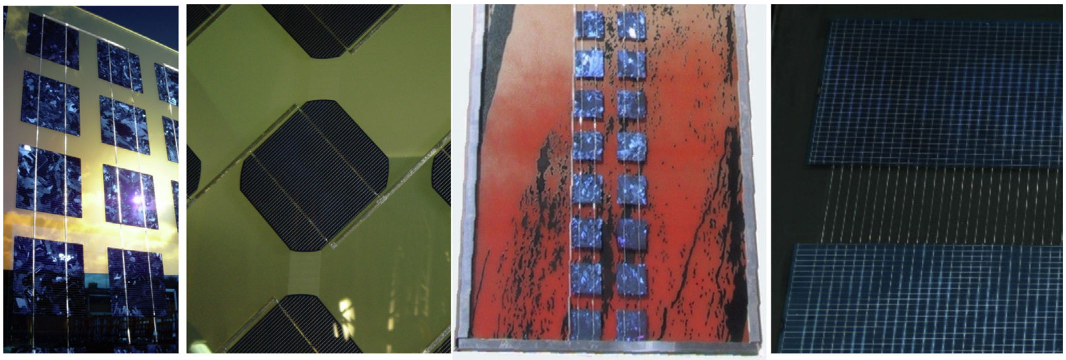


Fig. 17. This Figure shows various BIPV modules using c-Si PV cells as the basic elements of patterns. In the three illustrations on the left, the cells are connected by two busbars, where nowadays more and thinner busbars would be used. The right Figure shows two cells connected according to a multistring concept. Pictures © Fraunhofer ISE and Christoph Erban.

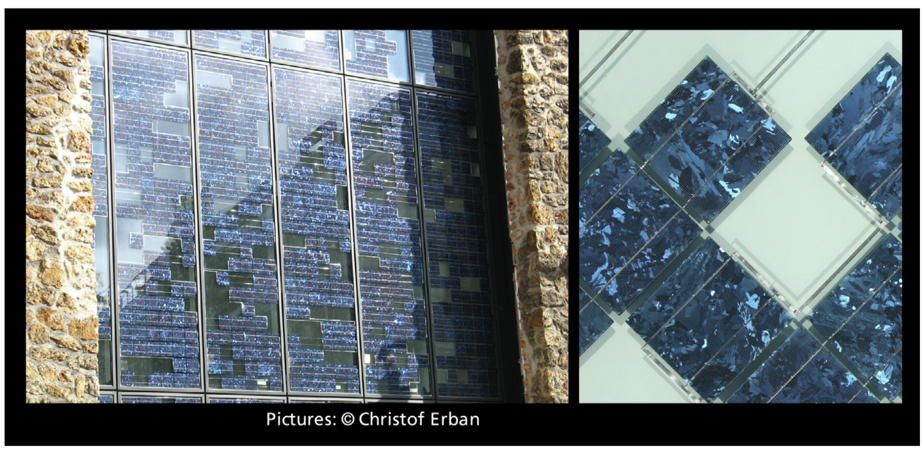


Fig. 18. Designing with patterns of conventional PV cells. Compagnie Parisienne de distribution d'TlectricitT, Rue Raymond Losserand, Paris, France.

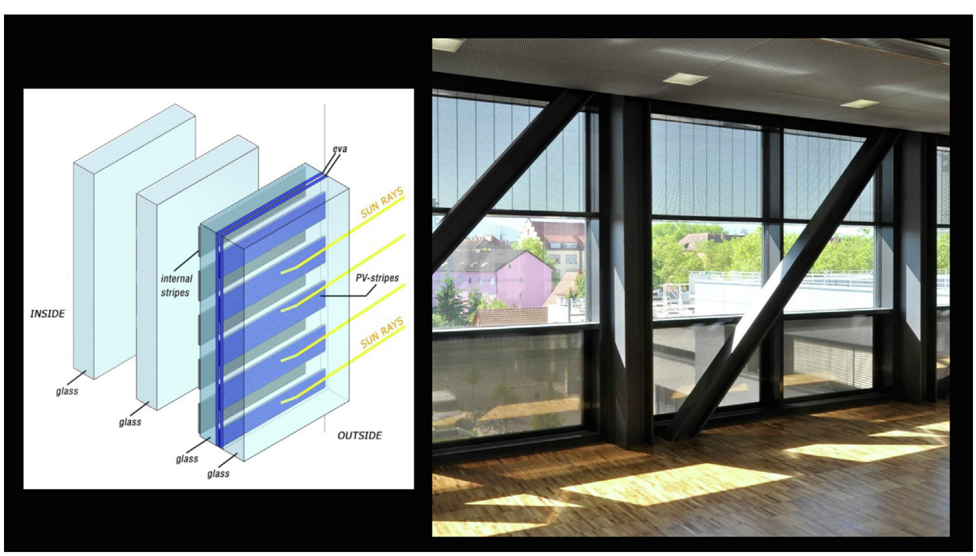


Fig. 19. The Figure shows the angle-selective PVShade glazing unit based on a-Si thin-film PV cell technology. Two layers of PV cells are integrated into the outer pane. On the left side, a cross-section of the glazing unit can be seen [111]. The right side shows the element as installed in the spandrel zone of a seminar room in Freiburg, Germany.

two layers of a-Si thin-film PV cells is shown in Fig. 19. The PV glazing was installed only in the spandrel zone, as this zone is almost irrelevant for the supply of daylight in areas of the room distant from the facade. However, the view that it allows downward of the outdoor surroundings increases the feeling of "transparency" indoors. Over the course of several research projects, the technical,

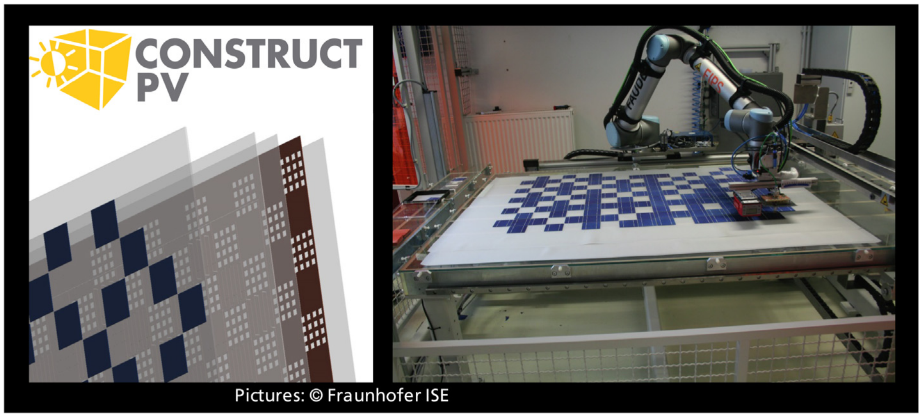


Fig. 20. The illustration shows a so-called Mosaic Module [101,142] [107]. The concept allows higher degrees of freedom by using freely positionable MWT solar cells of different sizes. For the pick-and-place module production process, a six-axis robot was used as shown in the photo on the right.

energy-relevant and economic properties of PVShade glazing were investigated by measurement and model-based simulation [112].

Fig. 20 shows a so-called Mosaic Module [101,142] [107]. The concept of the Mosaic Module allows significantly higher degrees of design freedom than the typical pattern that can be realized with conventional crystalline silicon PV cells, by using freely positionable solar cells that are flexible in size from 2 $\times$ 2 cm^2 to 156 $\times$ 156 mm^2. For this purpose back-contact metal wrap through solar cells (MWT) are used, which have a higher cell efficiency because no front contacts are applied which would shadow the cell surface. The cells are contacted via an electrically conductive backsheet, consisting of a polymer backsheet with a copper layer. A pick-and-place production process based on a six-axis robot was used to ensure accurate placement of the cells, which is important because of the high sensitivity of the human eye to small deviations in regular patterns.

Fig. 21 shows the Design2PV module concept [103,41,100]. The basic idea is that a PV cell does not have to consist of one continuous surface, but that instead a "cell cluster" of several distinct cell segments that are connected electrically in parallel can be used. The cell segments can have any shape as long as all cell segments are correctly contacted and as long as the sum of the segment areas is identical for each cell cluster. Each cell cluster occupies a certain base area, which also includes the area between the cell segments. The size of the base area can be different for the different cell clusters, which means that even gradients in the coverage density of cell segments can be realized. This gives architects a high degree of design freedom. A software tool based on image recognition can be used to automatically check whether a pattern complies with the aforementioned design rules [103].

5.2. Using color to conceal the PV cells

BIPV modules with invisible PV technology can be realized either by monochromatic dark modules in cell color (e.g. black) or by colored layers, behind which the also necessarily dark cell layer cannot be seen [42,157,158,162,154]. In the case of black or dark modules in cell color, the fact that the solar cells themselves are dark is used and all other surfaces in the module are masked by darkening them to same color. This applies, for example, to the busbars or the white backsheet of conventional modules. This means that there is no need to apply an (absorbing) painted layer in front of the cells in dark modules, such that the efficiency is only slightly affected by the darkening of the module (0% to 3% relative losses [104]). Fig. 22 shows the example of the 21-storey high-rise building Grosspeter Tower [165,159], with a complete BIPV glass facade with black modules.

Another technical option to achieve invisible PV technology is to place semitransparent, colored layers in front of the PV cell layer. The visual effect of such semitransparent colored layers generally improves when the color of the dark cell layer becomes more homogeneous. In order to reduce the impact on the efficiency of

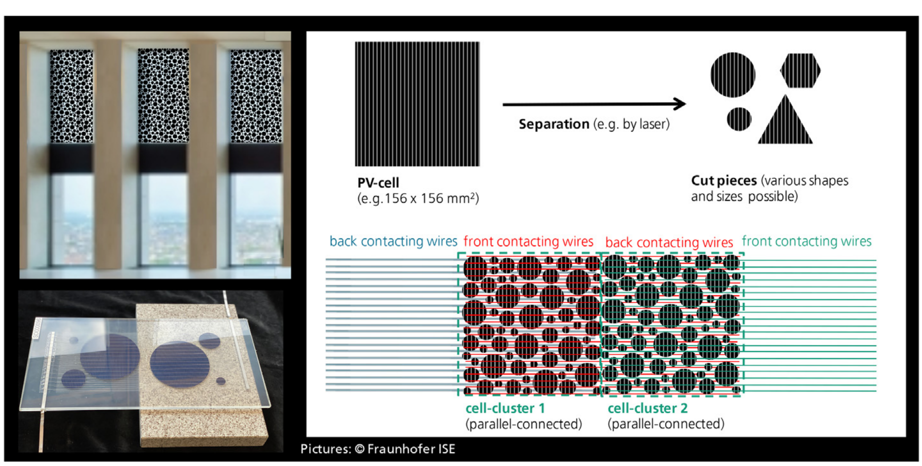


Fig. 21. Design2PV module concept [103,41,100]. The illustration on the right explains the basic principle. The idea is that a PV cell does not have to consist of one continuous surface, but that instead a "cell cluster" consisting of several distinct cell segments that are connected electrically in parallel can be used. The cell segments can assume any shape as long as they are all correctly contacted and as long as the sum of the segment areas is identical for each cell cluster. The Figure on the lower left shows a first fully functional prototype module. The Figure on the upper left shows the initial visualization of a BIPV application using Design2PV modules.

Fig. 22. Großpeter Tower, Basel, Switzerland. Around 10,000 thin-film solar modules in 450 different sizes were installed in this building. All facade orientations are covered with BIPV. The facade-integrated solar system has a total output of 440 kWp. Architecture: Burckhardt + Partner AG, Basel, Switzerland. BIPV Modules manufactured by Nice Solar Energy GmbH, Germany. Pictures ©NICE Solar Energy.

Table 3
Analysis of options to realize colored BIPV modules.

Category	description	durability	design freedom	loss of efficiency
Coloured coatings on surfaces exposed to weather	Ceramic pigments, which are fused into the glass during tempering, can be applied evenly with a roller coater, by screen printing or in the form of high-resolution digital printing.	High durability since inorganic pigments are integrated into a glass matrix.	Can be applied evenly with a roller coater, by screen printing or in the form of high-resolution digital printing.	Often large loss of efficiency, which can be up to 50% with light-colored modules [156].
Colored bulk materials for front and back covers	Bulk colored polymer materials or glass are sometimes used as the back cover and rarely also as the front cover [56].	A long service life is possible if inorganic pigments are used.	Usually monochromatic layers.	Spectrally selective pigments could limit efficiency losses to a moderate level ($\leqslant$20%) [164].
Colored coatings on internal surfaces (not exposed to weather)	Colors can either be realized with ceramic colors, with spectrally selective interference coatings or other photonic structures [28] [150,151].	A long service life is possible if only inorganic materials are used for the coatings [158].	Usually monochromatic layers are applied. Patterns are possible if the coloring layer is not applied over the entire surface [158,163].	Relative losses compared to a black module can be limited to less than 15%, in some cases even to less than 7% (see Fig. 24).
Colored encapsulants	Black opaque interlayers are often used behind the cells in glass-glass modules to realize a black background [32]. Pigments can be incorporated into colored front encapsulants such as PVB, EVA or TPO [42].	A long service life is possible if inorganic pigments are used.	Usually monochromatic layers, but (photorealistically) printed encapsulants are also possible [148].	With front encapsulants, relative efficiency losses (e.g. 6–20% [42]) depend strongly on color saturation and brightness. Little effect by colored back encapsulants [104].
Additional encapsulated colored interlayers	Mainly printed films or colored, semi-transparent, perforated (e.g. woven) textile structures are used [105] 38,37] (see also Fig. 23).	The service life is strongly dependent on the selected technology.	All types of colored meshs and textiles (see Fig. 11). One can print photos on interlayers, even white modules are possible [105]	Especially with light colors, there are often high efficiency losses of more than 40% compared to uncolored modules [38,105,166].
colored PV cells	Colors are realized by additional coatings on standard PV cells or special anti-reflective cell-coatings [32,161].	Long service life possible, if inorganic materials are used for the coatings	design freedom is limited to the coloring of the cells, multi-colored cells have been realized.	Relatively high efficiency losses (17–44% [160,83]), depending on the color saturation and brightness.

the BIPV modules and thus the energy yield, a high transmittance of the colored layers is necessary . This is achieved by applying a pigmented layer to the surface only at certain points or by making the coloring layer itself transparent. The different technical design options for implementing colored modules are analyzed in Table 3 and illustrated in Fig. 23. Fig. 24 shows an example of a spectrally selective colored photonic structure located on the inside of the front cover (position 2). The MorphoColor coloring layer is based on the morpho butterfly effect [153] for spectrally selective coloring of the front cover, applying photonic 3D structures. The effect is

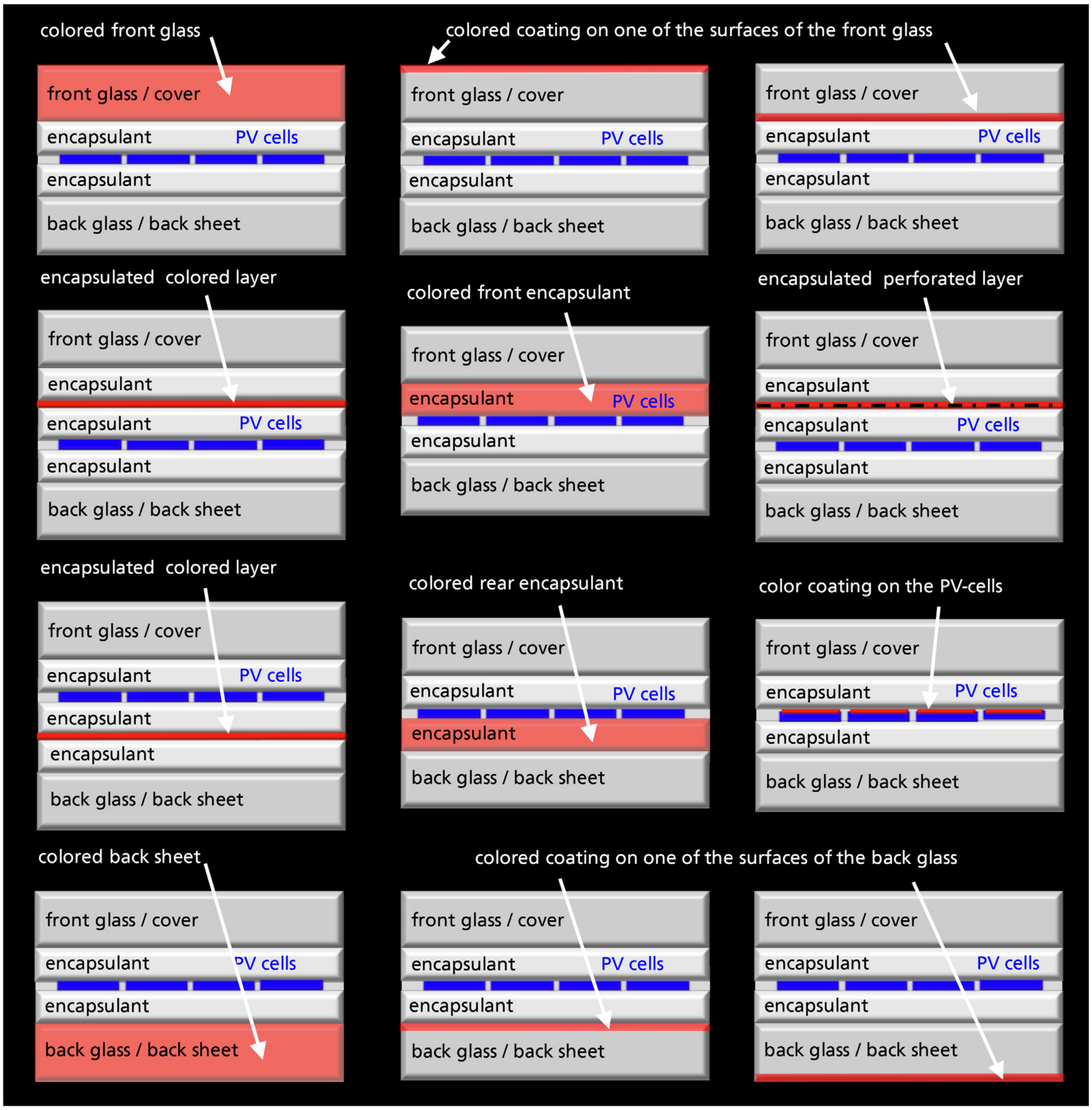


Fig. 23. Colored BIPV module options. The various technical design options are shown in the figure sorted from the outside to the inside, with the outermost layer on top. The colored layer or surface is always highlighted in red.

Fig. 24. The figure shows PV modules with the spectrally selective MorphoColor structure located on the inside of the front cover (position 2). The effect is illustrated on the upper left side of the figure, where a black solar cell was placed on a white table and partially covered with a front cover with a green MorphoColor layer. The schematic diagram in the lower left corner shows the structure of a MorphoColor module.

illustrated on the upper left side of the figure, where a black solar cell was placed on a white table and partially covered with a front cover with a green MorphoColor layer. It can be seen that the coloring layer is only visible above the black solar cell. Over the white table, the green reflection is almost invisible because of the higher intensity of the radiation transmitted by the coloring layer and reflected by the white table. The MorphoColor layer, developed by Fraunhofer ISE, features a relatively stable color impression from different viewing angles, high color saturation and less than 10% relative electrical losses compared to a black BIPV module [28,29,158].

6. Important options for the constructional integration

6.1. Positioning of the modules

Possible shading, the orientation of the modules in azimuthal (compass) direction and the tilt of the BIPV modules are decisive for the annual yield and the time pattern of solar power generation. If a BIPV system is planned to consist of several differently oriented sub-systems facing in different directions, then a more uniform electricity generation profile can be achieved over the day, which can help to minimize the load on the electricity grid and lead to a higher self-consumption of the generated electricity.

One important reason for the dependence on orientation is the angle-dependent distribution of the direct and diffuse irradiance incident on a module. This is caused by the relative orientation of a module surface to the position of the sun, with its daily and annual variation, and the influence of shading, e.g. by neighbouring buildings, plants or protruding parts of the building itself (see also Fig. 16). The influence of shading is not limited to the reduction of the irradiance. Partial shading of BIPV-systems or parts of modules can significantly increase the negative effect on the electricity yield. The influence of partial shading should therefore be minimized by a suitable electrical design, if relevant, as already discussed in Section 4. Fig. 25 illustrates the angular distribution of annual solar radiation [$kWh/(m^2a)$] for an unshaded area in Freiburg, Germany. The figure not only illustrates the influence of the orientation of the modules but also shows the temporal shift in the time of day for the maximum irradiance [30]. One can see from the graph that the time of maximum irradiance for a SW facade (+45°) is shifted by about 7 h compared to a SE facade (-45°). Consequently, if a building is oriented in such a way that the corner of the building faces south and if the SE and SW facades are then covered with BIPV modules, the yield is much more evenly distributed over time than with a purely south-facing system on a facade or roof. Another influencing factor is the angular dependence of the module efficiency, which is mainly determined by optical losses due to the angle-dependent reflectance of the front cover and the PV cells. A detailed analysis of the angular losses can be found in [113], where both the annual losses and their monthly distribution were analyzed. However, there are also possible electrical loss effects, e.g. when PV modules are operated at irradiance levels lower than standard test conditions (STC), which may result in decreased module effciency due to internal losses in the PV cells (see also Section 3.4). A comparison of low-irradiance losses of different PV-technologies based on field measurements can be found in [114].

It is important to bear in mind that BIPV-modules can be inclined relative to the building skin (roof or facade) in order to increase the yield. Especially facade-integrated systems can be tilted with respect to the vertical wall. An example of this is shown in Fig. 26.

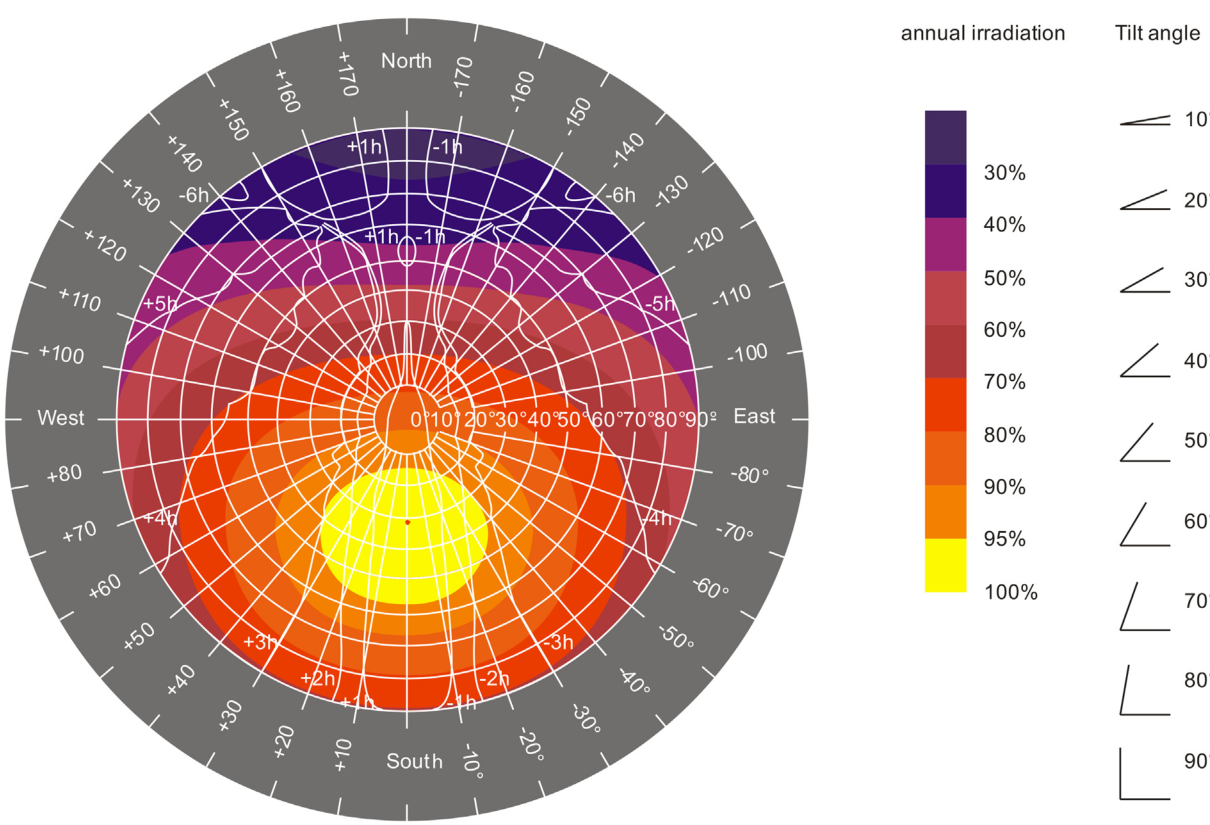


Fig. 25. Annual total solar radiation and shift of the time of maximum irradiance as a function of the azimuthal orientation and tilt of an unshaded surface relative to that for a surface with the orientation for maximum annual yield in Freiburg, Germany [30]. The isolines show the shift in the time of maximum irradiance - and thus the maximum electricity generation - compared to a south-facing area. The irradiance was calculated with the RADIANCE program [155] [149] using the Perez sky model [144].

Fig. 26. Renovation of the Hanwha Headquarters building in Seoul, South Korea. The facade has been designed by UNStudio. This building shows an example of a facade in which the BIPV modules were not arranged vertically. The inclination of the modules increases the electrical yield. The concept and the ideas behind the design are explained in [115,116]. Pictures UNStudio, Amsterdam, the Netherlands.

6.2. Constructional integration of the modules into the building envelope

The front cover of BIPV modules can be made of either glass or polymer material. Products with a polymer front cover are often used in roofing membranes or firmly bonded to other components. In most BIPV applications, however, glass front covers are used and the module is often designed as a glass-glass module. Therefore, this chapter focuses on constructional integration of BIPV modules with a glass front cover.

In general, there are no fundamental technical difficulties with the constructional integration of BIPV systems into the building envelope. Technical solutions are commercially available. The challenge is that BIPV systems have to be planned interdisciplinarily across trades, that consequently responsibility is often spread over several shoulders and that some actors are not yet familiar with such components. Hence, the planning and installation of a BIPV system is not always fast, reliable or cost-effective. Conflicting requirements originating from guidelines and regulations issued by different independent institutions are another aspect that can lead to difficulties in planning, manufacturing and installation. Important requirements and corresponding organizations are:

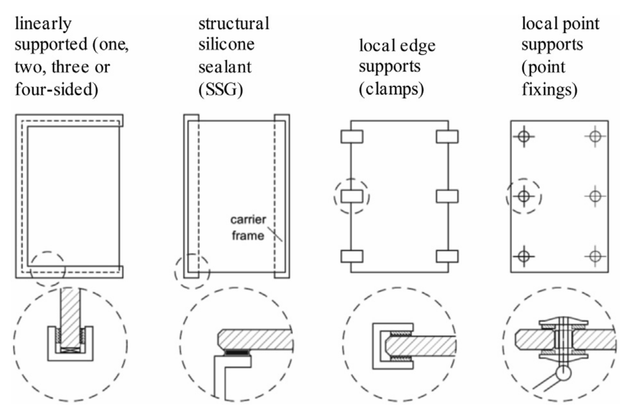


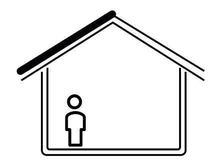
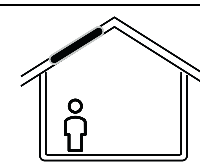
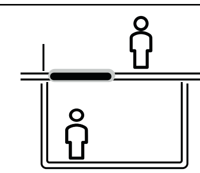
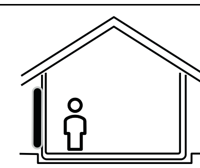
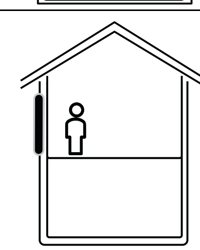
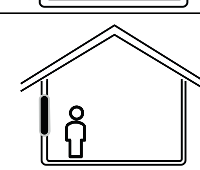
Fig. 27. Common support types for glazing elements [119], pictures ©Haldimann. The single glass pane shown in the figure is to be replaced by a BIPV-module. Additional requirements may have to be considered for the case of structural sealant glazing (SSG) or point fixings to ensure mechanical safety (e.g. front cover and back cover bonded separately to the sub-structure) and electrical safety (sufficient safety distance between holes and electrical components).

- Minimum requirements for the **service life** of (BI) PV products are defined in the international standard IEC 61215 [120,126]. They are *de facto* binding in many cases since banks often require this IEC certificate as security when granting a loan.
- Minimum requirements for the **electrical safety** of (BI) PV products are defined in the international standard IEC 61730 [121,122]. The electrical system is treated in IEC 62446 [123]. These requirements are internationally agreed and accepted: normally no additional local electrical product safety regulations are added (see e.g. Low Voltage Directive 2014/35/EC [124]).
- A precondition for the **marketing of construction products** is the proof of conformity with the corresponding **standards for construction products** and the documentation of conformity with these standards and the specification of performance metrics via product labelling (see e.g. the rules of the US National Fenestration Rating Council (NFRC) or the European Construction Product Regulation CPR 305/2011 [125] for "CE-marking" in Europe).
- The **permission to use a construction product** at a specific location for a specific construction type is determined by national or local (e.g. federal) **construction authorities** [139]. Examples of specific local requirements are post breakage integrity requirements. While several glass-glass BIPV modules meet the product requirements for laminated safety glass according to EN ISO 12543 [134], some of them do not meet local requirements (e.g. [135–138] in Germany) for post breakage integrity, which must ensure that no one can fall out of the building, even if the product was already broken before impact. Hereby, the post-breakage integrity is strongly influenced by the support system, the breakage characteristics of the glass and the stability of the embedding material (e.g. laminating interlayer) used, together with the processing conditions during manufacturing. Glass qualities, which break into large pieces, such as (partially) heat-strengthened glass [130], are particularly important here.
- **Additional safety guidelines** are often defined by **insurance associations**, e.g. by employer's liability insurance associations, which are part of mandatory insurance policies for employers. In some cases, this adds e.g. indoor post-breakage safety requirements, even for category D-2 of Table 4.
- Additional characteristics might be required for **Environmental Product Declarations**, for the assessment of the environmental performance of buildings and for the **certification of the sustainability of buildings** (see e.g. LEED [138], BREEAM [132], and DGNB [133]).

Well-known support systems for glass elements can be used to mount BIPV-modules. Fig. 27 provides an overview of common glass support types. National and local (e.g. federal) technical rules for the use, design and construction (e.g [135–138]) have to be followed for each of the support types. These not only include product characteristics for BIPV modules and support systems, they also includes rules for the assembly of construction products to form construction works (so-called 'construction techniques'). This is especially the case, when important features of the construction work result from the interplay between different construction products. Some countries issue general permits (e.g. [118]) or project-related approvals for 'construction techniques' (e.g. [117] for Berlin) for specially designed combinations of BIPV modules and support systems which do not necessarily have to follow all the general rules because of this individual approval. These individual approvals are very important for innovative products, which are not covered by product standards or general technical rules.

In many cases, the constructional integration of BIPV modules requires project-specific customization of the modules. Very often this concerns the size of the modules or the aesthetics. Difficulties arise from the fact that product characteristics may change and thus certificates and approvals may become invalid. For example: Custom module sizes with special PV cell coverage of the module surface or individual colors often affect the efficiency and the electricity yield, which in turn affects the environmental building assessment and the product labelling according to IEC 61215 and construction product regulations. One possible solution for this dif-

Table 4
Installation categories (extending the categories specified in [1,128].)

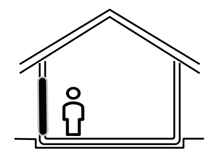
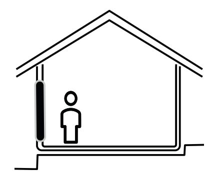
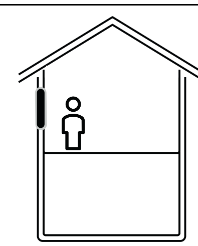
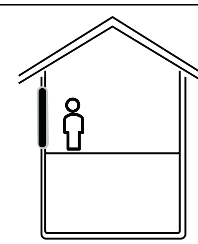
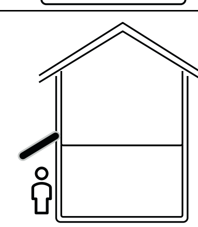
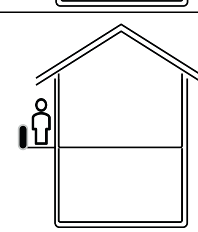
Category	Tilt angle of glass surface	Indoor post-breakage integrity*	Protection against falling through**	Outdoor post-breakage integrity***	Examples	Illustration
A	Sloped or horizontal	No	No	No	integrated in external roof surface, not accessible from indoors	
B-1	Sloped or horizontal	Yes	No	No	integrated into roof window, skylight or saw-tooth roof	
B-2	a) Sloped or horizontal b) Vertical	a) Yes b) Yes	a) Yes b) Yes	a) No b) Yes	roof accessible from outdoors, integrated into roof window, skylight or saw-tooth roof, glazing temporarily or accidentially accessible or walkable in general	
C-1	Vertical	No	No	No	integrated into external surface, ground story, not accessible from indoors	
C-2	Vertical	No	No	Yes	integrated into external surface, higher story, not accessible from indoors	
D-1	Vertical	No	(No)	No	glazing-integrated, glazing above conventional spandrel area, ground story	

This categorization generalizes various regional, national and international regulations.
Vertical: angle of glass surface $90^\circ \pm 10^\circ$ [135] or $\pm 15^\circ$ [1] [128] [138] from horizontal.
Sloped or horizontal: $0^\circ \leqslant$angle of glass surface $< 80^\circ$ [135] or $< 75^\circ$ [1] [128] [138] from horizontal.
*: broken glass fragments must not fall into the building.
**: the glazing must prevent people from falling through the (horizontal, sloped or vertical) glazing.
***: all components of the BIPV glazing must remain in place, even if broken.

ficulty is to certify several sub-categories for a product and to characterize each of the sub-categories with a limited number of parameters. For the case of custom module sizes, the number of PV cells per module area could be a good parameter.

When approaching planning, design and construction it is helpful to distinguish between several different types of installation with fundamentally different *requirements*. Installation typologies can be found in the European BIPV standard EN 50583 [128] [129] and the draft two-part international BIPV-standard IEC 63092 [1] [127], which has been prepared on the basis of EN 50583 by IEC Technical Committee 82 (solar photovoltaic energy systems) in collaboration with ISO Technical Committee 160 (glass in building). This paper extends these standardized installation typologies in Tables 4 and 5. The goal is to provide a quick overview together with graphical icons to highlight the main differences between the categories. Three aspects are highlighted in the table since many planning difficulties are caused by interdisciplinary requirements for indoor post-breakage integrity (broken glass fragments must not fall into the building), protection against falling through (so that no one can fall out of the building or fall into the building when standing on the roof) and outdoor post-breakage integrity (so that all components of the BIPV glazing remain in place, even if broken). Particularly for these topics international (e.g. EN ISO 12543 [134]) or European product-related requirements are often not aligned with national or local installation or application requirements.

Table 5
Installation categories - continued.

Category	Tilt angle of glass surface	Indoor post-breakage integrity*	Protection against falling through**	Outdoor post-breakage integrity***	Examples	Illustration
D-2	Vertical	(Yes)	(No)	No	glazing-integrated, glazed spandrel area, ground story	
D-3	Vertical	Yes	(Yes)	No	glazing-integrated, glazed spandrel area, floor slightly above ground level, fall-protection measures required	
D-4	Vertical	No	Yes	Yes	glazing-integrated, glazing above conventional spandrel area, higher story	
D-5	Vertical	Yes	Yes	Yes	glazing-integrated, glazed spandrel area, higher story	
E-1	Sloped or horizontal	Yes	Yes	(No)	integrated into additional external elements	
E-2	Vertical	Yes	Yes	Yes	integrated in balcony balustrade	

It is far beyond the scope of this paper to discuss all relevant requirements in detail. IEC 63092 and EN 50583 attempt to compile all relevant requirements from standards for construction products and PV systems. Furthermore, for BIPV systems in general, the fire-safety behavior of the modules has to be proven with regard to reaction to fire, if the building authorities require the use of non-combustible materials or materials that are difficult to ignite. For a complete fire-protection concept or the fire-safety behavior in general, the requirements in the building context must also be considered. For more detailed information on the fire-safety risk of PV systems and how to minimize it, see for example the PV Fire Safety Fire Guidelines [140,141]. The German firesafety report [141] was officially translated into English by the US Department of Energy DOE.

The constructional integration of BIPV modules requires also the constructional integration of cabling and electronic components like junction boxes or optimizers that are mounted on every module. This can have implications especially for the mounting structures, the aesthetics and the fire safety of the installation. For all installation categories, various solutions for dealing with these additional electric components exist and can be chosen or adapted for the specific situation. The greater the implementation detail of technical rules in a particular country, the lower is the individual responsibility and the freedom of design that lies with the planners, product manufacturers and construction companies.

7. Conclusion and outlook

This paper reviews and analyzes the different technological design options for BIPV components and systems, *independently of specific products or buildings*. A survey of the relevance of BIPV technologies for renewable energy systems and an analysis of the German BIPV market demonstrates that BIPV systems are very important for the transformation of the German energy system. Strong further growth of PV installations on buildings to more than 200 GW_p installed capacity is to be expected. A cost analysis shows that additional costs of 131 €/m^2 are allowable for profitable BIPV facade systems. From this it can be deduced that an average price of 150 €/m^2 leads to economically viable BIPV facade modules (without the mounting system, cables and inverters). Such price levels should be possible with highly automated production lines for customized BIPV modules that offer great potential for local value creation potential. The paper provides a structured overview of the wide range of technical design options for BIPV systems and categorizes and analyzes them and compares the different available solar cell technologies. It is concluded that crystalline silicon-based solar cell technologies currently offer the greatest advantages for BIPV applications, in particular due to their long service life and because they benefit from a utility-scale PV mass market with price pressure, availability and rapid technological advances which can be transferred to the BIPV market.

Two fundamental module-level design options were investigated in particular detail: The use of PV cells as basic elements of patterns and the use of color to conceal the PV cells. Both options are available for architects to either highlight the use of renewable technologies or to blend the technology with the overall building and surroundings. The analysis of options for the electrical system design and options for the constructional integration of BIPV Modules in the building envelope complete the overview of the technical design possibilities. With the given technological design options, BIPV systems can be tailored to a large variety of building projects and contribute significantly to renewable energy systems.

Important future steps would be: Increasing numbers of flagship demonstration projects that increase visibility and long-term experience with BIPV, facilities for customized but highly automated production, innovative business models in the framework of future renewable energy systems, simplified and harmonized regulations, and generally increased digitalization. Especially the digitalization of the entire value chain would be very helpful for the construction sector in general and BIPV technology in particular, as it requires a smooth and quality-assured communication between the different trades and throughout the entire construction process.

Declaration of Competing Interest

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.

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