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Aesthetic and functional aspects of BIPV – an architectural outlook

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Abstract

The growing interest in the application of photovoltaics in construction results in solutions based on the concept of integration with the architecture of the building. This means that the challenge lies not only in the technical integration itself but in accordance with the concept of building integrated photovoltaics (BIPV), integration results in closer ties with architecture.

The following article aims to determine the current possibilities with regard to the integration of PV technology with the building (narrowed down to the use of PV cells and PV modules) and, consequently, the role of BIPV in modern architecture in terms of aesthetics and functionality, including the relationship of the building with the environment. The paper offers an architectural perspective on the problem while omitting detailed technological issues.

To illustrate the considerations, carefully selected design examples (including those developed by the author) are used, which enable these possibilities to be defined across a broad spectrum.

Research prompts the conclusion that the development of BIPV strengthens the relationship between PV technology and architecture, both in terms of aesthetics and utility. This relationship is synergistic and stimulates the parallel development of PV technology as architectural solutions.

Keywords: BIPV, photovoltaics, architecture, PV façade, PV roof

1. Introduction

The increase in the popularity of PV technology in architecture has its origin in the fuel and energy crisis of the nineteen-seventies. At that time, attention was drawn to the fact that construction, which consumes almost half of the world's energy, cannot be based on non-renewable and environmentally harmful energy sources. The concept of sustainable development emerged. In architecture, it took the form of so-called "green buildings" which comprised several terms, depending on the focus on the main goal they were to meet in this regard (e.g. energy-saving, bioclimatic, smart buildings) (Zielonko-Jung, 2013).

1.1. BIPV – definition

Until the early nineteen-nineties, the use of PV technology in architecture mainly consisted of adding PV elements to the building structure as a separate device, not aesthetically integrated into the building. In the nineteen-nineties, limitations in the aesthetic and formal selection of PV systems began to be seen as the main obstacle to them being accepted by architects. A general history of PV is included in Table 1 below.

Currently, PV technology is increasingly being treated as a fully-applicable building element and an alternative to traditional finishing materials. Thus, emphasis is placed not only on technological considerations (efficiency) but also on aspects of form (shape, size, colour, transparency) (International, 2018).

Further development has either already occurred or is anticipated due to thin--film cell technology and third-generation PV cells, mainly DSSC (Parasuraman, 2023), organic (Prasad et al., 2013), perovskite (Park, 2015), as well as tandem solutions that combine more than one semiconductor material (Saif et al., 2023), such as graphene-based PV cells, which are known as fourth-generation cells (Pastuszak & Węgierek, 2022).

Table 1. The history of the development of photovoltaics (by the author)

1839	photovoltaic effect discovered by Antoine Becquerel
late nineteen-fifties	application in space technologies
nineteen-sixties	application in terrestrial technologies (beyond architecture)
nineteen-eighties	application in architecture (based on adding a PV installation to an existing facility)
nineteen-nineties	**integration with the requirements set by architects**

The term 'building integrated photovoltaics' refers to the integration of a photovoltaic system with a building in technical, functional, and aesthetic terms (Reijenga, 2011; Strong 2005). Generally, the term refers to applying a set of PV cells as a constructional element integrated with the building, such as the façade or roof cladding, external glazing, or shading systems (Ballif & Perret-Aebi 2013; Tabakovič, 2016). This feature of BIPV is distinguished from the application of monofunctional PV modules, defined as building--added photovoltaics (BAPV).

The concept of BIPV has yet to be clearly defined. From the construction point of view, it refers to physical integrity, consisting in the integration of photovoltaics (usually PV modules) with the building structure. From an architectural point of view, it means aesthetic integration.

Thus far, no separation of the concepts of building and architectural integration has been made. The former concept is commonly used and is believed to cover both ways of understanding the term BIPV; however, various examples can be provided where the lack of literal physical integrity results in interesting architectural solutions and, conversely, integration with the building structure causes an architectural disorder.

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Three conditions that should be met when considering BIPV have been specified (Reijenga, 2011):

- the technical quality of the PV system (e.g. inverters, cabling);
- the building quality of the PV system: PV modules treated as a building element;
- the aesthetic quality of the PV system, as the least measurable evaluation criterion, but nevertheless crucial from the point of view of social acceptability and the most critical criterion from the architectural point of view.

1.2. BIPV – an architectural outlook: the state of the art and the originality of the paper

BIPV constitutes a frequently discussed scientific topic. It can primarily be divided into research-related areas:

- general development trends, such as opportunities, potential, limitations, and barriers, e.g. (Heinstein et al., 2013);
- implementation of new technologies of PV cells and modules in terms of energy, usability and aesthetics (e.g. Pelle et al., 2023);
- individual applications, e.g. glazing (Uddin et al., 2023), shading elements (Zhang et al., 2018), within roofs (Pabasara Upalakshi Wijeratne et al., 2022), façades (Uddin et al., 2023) and skylights (Li et al., 2009);
- BIPV in various types of buildings, e.g. historical (Rosa, 2020) and high-rise buildings (Xaing & Szybińska-Matusiak, 2022);
- BIPV in a context other than the mentioned problematic issues, e.g. urban planning (Costanzo et al. 2018), cultural heritage (Lucchi, 2022) and fire protection (Yang et al., 2023).

The present study reviews the possibilities and limitations of introducing BIPV in modern buildings with regard to aesthetic aspects. It also considers the utility aspect related to creating the thermal and visual environment as well as urban planning. This multidisciplinary view responds to the basic tasks faced by architects. The study, therefore, offers a purely architectural view in which energy and technological aspects are only considered in a certain context – they provide the background required for the understanding of the discussed design issues. Thus, the originality of the article lies in the joint consideration of the following issues:

- exposing the aesthetic aspect in shaping the architectural form with the use of BIPV;
- testing the functional characteristics of BIPV in terms of the heating, ventilation and lighting of the building;
- taking into account the broadly-understood relationship between the building and its environment as an element;
- discussing problem issues supported by selected examples of buildings for the fuller illustration thereof.

This article can be seen as part of the body of research on general development trends, although the field of study is narrowed down to aesthetic and functional aspects in the architectural context. The article concerns designing the spatial form, façades, roofs and the relationship between the building with its surroundings while taking the technological features of BIPV into account as well as its requirements resulting from the fundamental energy role of photovoltaics.

Table 2 (below) lists the scientific studies with which, according to the author, the article is most closely related; the article aims to supplement the knowledge contained in the studies listed below.

Table 2. Selected articles thematically related to the subject of the article (by the author)

Authors	Title	Year	Short characteristics (elements closely related to the present article)
Urbanetz J. Zomer C.D. Rüther R.	Compromises between form and function	2011	Searching for the proper geometry of the building envelope for low latitude locations as a balance between the spatial form and the energy requirements of the PV installation. Principal conclusion: recommendation for curved BIPV installation.
Heinstein P. Ballif Ch. Perrer-Aebi L.-E.	Building Integrated Photovoltaics (BIPV); Review, Potentials, Barriers and Myths	2013	Overview of PV-cell technology and how it should be applied in buildings. Discussion on the attractiveness of BIPV in relation to traditional solutions as a separate installation (BAPV). Determination of barriers and threats. Major conclusion: cost-effectiveness and social and psychological factors must be overcome.
Byiyk E. Araz M. Hepbasli A. Shahrestani M. Yao R. Shao L, Essah E. et.al.	A key review of Building Integrated Photovoltaic (BIPV) System	2017	Comprehensive review of the BIPV applications in terms of energy generation amount, nominal power, efficiency, type and performance-assessment approaches. Major conclusions: two fundamental research areas in the BIPV systems are observed to be i) improvements in system efficiency by ventilation, thus obtaining a higher yield by lowering the panel temperature ii) new thin-film technologies that are well suited for building integration.
Amo S.A., Sukki F.M. Bennadji A Sellami N	Myth or Gold? The Power of Aesthetics in the Adoption of Building Integrated Photovoltaics (BIPVs)	2021	Aesthetic issues connected with building design: elements and principles of BIPV design connected with colour, texture, rhythm, variety balance, contrast and proportion. Major conclusion: aesthetics is a major driver of BIPV development.
Ghosh A.	Fenestration Integrated BIPV (FIPV): A Review	2022	Detailed review of new technologies and their applications in façade glazing as well as their impact on the appearance of individual parts of the building. Major conclusion: second-generation and third-generation PV cells are suitable for fenestration. One of the main challenges for the broad adoption of BIPV windows lies in the optimisation of both daylighting and electricity.
Taşer A., Koyunbaba B.K., Kazanasmaz T.	Thermal, daylight, and energy potential of building-integrated photovoltaic (BIPV) systems: A comprehensive review of effects and developments	2023	Overview of PV-cell technology and how it should be applied in buildings. Discussion on the attractiveness of BIPV in relation to traditional solutions as a separate installation (BAPV). Determination of barriers and threats. Major conclusion: Cost-effectiveness and social and psychological factor must be overcome.

2. Materials and methods

The article is based on observation methods as well as on analysis and critique of the literature (Pieter, 1970). Based on observations and the literature review, fourteen examples of buildings were selected in which various approaches to the aesthetic and functional integration of photovoltaics with the building are reflected. These examples were considered representative with regard to the issues raised in the article. The examples cover both roof and façade applications. The selection was made from buildings erected from the nineteen--nineties to the present, i.e. since BIPV has been observed (see Table 1). High--rise and historic buildings, being separate issues, were not included in the present study. The comparative method, a method which enables studying the evolution of BIPV over thirty years, was rejected as it was also seen as

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a separate research issue. The selection was facilitated by a review of articles entered in the Scopus and Web of Science databases, as well as the author's design experience (one selected building is an original concept by the author and the author worked at the planning stage of another chosen example). Due to the extensive nature of the subject, the research is related to synthesis with elements of the analysis of selected buildings being a tool with which the discussed issue is illustrated.

The research was conducted in two ways; research activities were divided into aesthetic and functional aspects on the urban and the scale of the building. The two aspects were discussed separately and conclusions defining the aesthetic and functional role of BIPV were drawn from the resulting observations (Fig. 1).

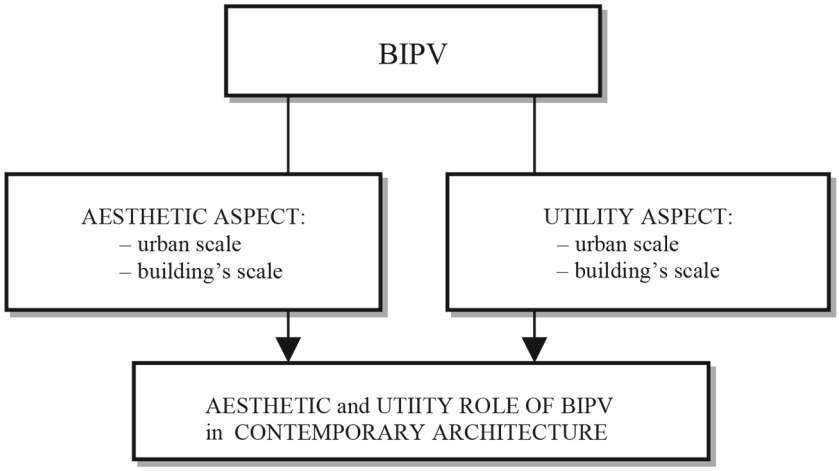


Fig. 1. Scheme of methodology adopted by the author

3. Results and Discussion

3.1. BIPV and the environment

3.1.1. Utility aspect

The process of integrating photovoltaics with the building begins as early as the pre-design phase. From the utility point of view, it is essential that favourable conditions for obtaining solar energy are ensured. Studies conducted in the Czech Republic for various layouts of urban fragments (conducted in different periods) have demonstrated a strong correlation with potential solar gains (Matuska & Zhral, 2008). It has been confirmed that this relationship also occurs on a smaller scale, e.g. on a campus scale (Costanzo et al., 2018).

The process of integrating photovoltaics in this context includes:

– the analysis of climatic and topographical conditions;
– the analysis of the urban context.

A. Climatic and topographical conditions

It should be assumed that the efficiency of the photovoltaic system is directly affected by the degree of insolation. The analysis of climatic and topographic conditions is essential when the degree of solar radiation intensity is to be determined in the given area (Skandalos et al., 2022a, Skandalos et al., 2022b). Their most significant elements include the degree of sunlight diffusion, the path of the apparent movement of the sun, the outside air temperature, the amount of precipitation and the lay of the land.

B. Urban context

The relationship between urban planning and PV technology is based on the feedback principle. This means that not only do environmental conditions influence the choice of PV technology, but PV technology also plays a role in shaping the facility's environment.

An example of this is the fact that the location of an object in a shady urbanised urban tissue may deem the application of a PV system useless or force its specific placement within the building (Matuska & Zhral, 2008).

Installing a PV system may affect the creation of the environment (e.g. the removal of elements that hinder the system's operation, such as vegetation and elements of small architecture).

The design of the Doxford Solar Office building in Sunderland (Northern England, arch. Studio E Architects, 1998) offers an interesting example of how the surrounding conditions may be accounted for and adjusted in terms of development in order to optimise the use of solar energy. The facility features one of the most prominent photovoltaic façades in the world.

The project was preceded by an analysis of the area insolation and the impact of wind as a cooling factor. The cool wind blowing from the southwest, from the North Sea, exerts a positive impact on increasing the efficiency of the PV modules within the façade. The façade has a southern orientation, which is optimal for solar energy use. Any obstacles that could cause shadowing of the façade have been removed from the facility's foreground. It now consists of a scarce strip of low greenery and a carpark for passenger cars. It should be emphasised that the PV façade and foreground design constitute part of a broader energy strategy based on the integration of the building with elements of passive architecture (Jones, 1999) (Fig. 2).

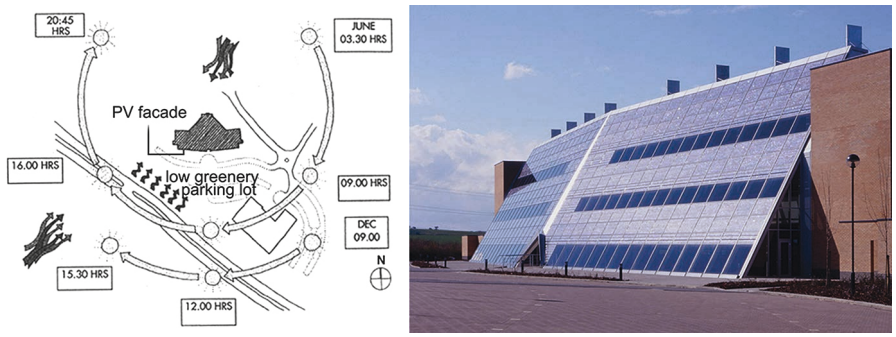


Fig. 2. Urban concept and PV façade of the Doxford Int. Office Building (photo by Dennis Gilbert©)

3.1.2. Aesthetic aspect

Buildings in which BIPV is used require an analysis of aesthetic integration on an urban scale, i.e. the adequacy of aesthetic solutions with regard to the context of the place. This mainly refers to large-area façade applications in an environment with strongly defined style features (e.g. old town buildings). Such an environment can undoubtedly influence design decisions related to the location and selection of PV modules in the aesthetic aspect (Hermannsdörfer&Rüb, 2005).

Such a problem as that described above was encountered with regard to the concept of the Solar-Copper House in Wrocław (arch. author, 2013). The facility is erected on an exposed plot in the historic part of the city. The surroundings, especially the neighbouring buildings, are of high historical value. The original variant, inspired by the architecture of the Solar Fabrik building in Freiburg, referred to the high-tech trend in which technological elements (in this case, mainly PV modules and their structure) are strongly exposed and give the building an industrial, technological image. This design was intended to create connotations with modern ecological technology. The dynamic and rhythmic spatial form with a powerful appearance has not

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only become an artistic means of expression but has also been optimised in the context of the passive and active use of solar energy and the energy aspect has become a key factor that shaped the design.

The proposed building layout described above was rejected. The historical context of the place served as a verifier of the proposed design solutions. The juxtaposition of the industrial, technological architectural form with the historic and traditional buildings of the surroundings were deemed to be too much of a formal and aesthetic mismatch. Despite the attempts to clearly individualise the architecture of the designed structure, its high-tech character was considered too 'rough' and not corresponding with the building substance of the surroundings, both in terms of aesthetics and architecture as well as urban planning and composition (Marchwiński, 2015) (Fig. 3).

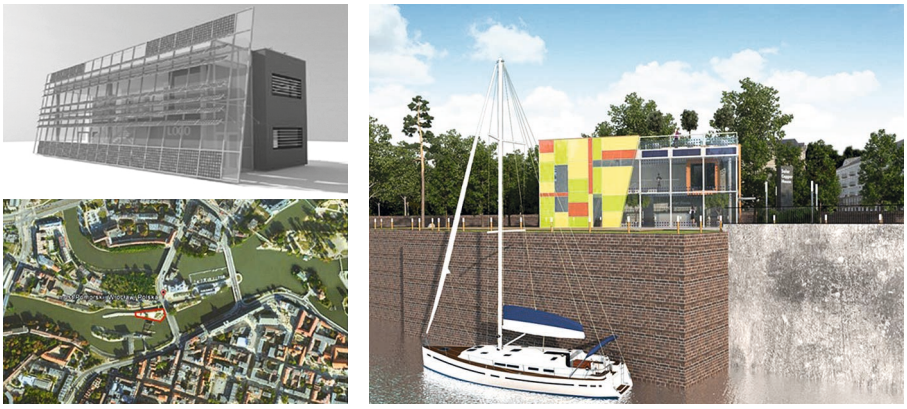


Fig. 3. The concept of the Solar-Copper house: top left – initial rejected design; right – final concept; bottom left – urban context (by the author)

To sum up, the integration of photovoltaics with the surrounding environment in terms of utility and aesthetics requires examining the relationship between environmental factors and the impact of BIPV on the environment (Table 3).

Table 3. Relationships between PV technology in a building and elements of the environment (by the author)

Elements for analysis:	Actions to improve efficiency:	Impact of PV installation:
– the shape of the building plot	– the rule of maximum exposure to southern solar radiation should be followed	– plot selection: plots elongated along the east-west axis are more advantageous
– the place and degree of plot shading by neighbouring objects (other objects, trees, small architecture, etc.)	– places selected for the use of PV technology in the building or its vicinity should feature as low a degree of shading as possible	– in the vicinity of the place where the PV technology is used, the design of objects that can cast a shadow on it is avoided
Elements for analysis:	**Actions aimed at the aesthetic matching of PV technology**	**The shaping role of PV installations**
– the context of the place (type of surrounding buildings, dimensions, colours, type of building material, style, etc.)	– in the case of traditional buildings in the surroundings, the excessive dominance of PV technology can be questionable – in the case of contemporary and modern buildings in the surroundings, PV technology can be a dominant feature (further studies required)	– this concerns the architectural aspect and manifests itself in the selection of size, shape, colour, articulation, degree of transparency, the method of integration with traditional building materials and the place and method of location within the building (e.g. roof, façade) or in its vicinity

3.2. BIPV and the aesthetic function of the building

3.2.1. The influence of BIPV on shaping the building envelope

A. Façade and roof geometrical composition

The geometric composition of the building envelope created by PV modules is a broad issue, but in short, it refers to spatial, planar and linear divisions.

The aesthetic potential of photovoltaics in this context lies in the fact that the geometric composition of the building envelope, especially the façade, can be shaped by the simultaneous introduction of all the aforementioned divisions. The resulting design may consist of the creation of regular or irregular rhythms, intentional disturbances of the horizontal and vertical directions along the compositional grid, façade endings, and the introduction of hierarchisation and directionality of divisions, all of which consciously blur or emphasise the human scale (Photovoltaic Design, 2001; Marchwinski, 2012).

Spatial divisions

They are created using façade PV modules (rarely roof modules) as shading elements. In the Budomierz border crossing office building (arch. n.d., 2013), this effect was achieved by installing PV shelves on the external supporting structure on the southern façade of the building. The façade was spatialised. The shelves protrude from the face of the external wall, making it more spacious and introducing new façade divisions in the foreground. The façade background is created by traditional window divisions (Fig. 4, top left).

Plane divisions

They are usually created using façade cladding PV modules or photovoltaic glass and result in the creation of a visually separate façade strip (e.g. between windows); the more significant the visual separateness of the PV modules, the stronger this influence is. In the building of Wydział Inżynierii Środowiska Politechniki Warszawskiej (The Faculty of Environmental Engineering, Warsaw University of Technology-WIŚ) (the first PV façade in Poland, 2006; with the cooperation of the author at the investment planning stage), rows of PV modules were installed in the planes between the windows as part of the modernisation of the building. They emphasised the plane horizontal compositional orientation of the building. Generally, PV modules made in various technologies of PV cells are visually distinguished from the plastered façade, owing to which factor, the aforementioned effect was possible (Fig. 4, top right).

Linear divisions

They are produced by tangential edges of adjacent PV modules within the building envelope. They generally create a grid of horizontal and vertical lines on the façade and frame PV modules with strongly exposed frames have the most substantial impact. However, these divisions are also visible in the case of frameless modules. The architectural language is especially enriched in this field by roof modules (photovoltaic tiles). Covering the roof slopes, such tiles create different linear divisions compared to traditional coverings by means of solutions such as ceramic tiles, shingles or sheet metal. This approach is illustrated by a school building in Kagoshima, Japan (arch. Shimomai Architectural Design, 1997), in which the sunlit areas were covered with PV tiles and other parts of the roof with less sunlight were covered with imitations of PV tiles with the same appearance (Fig. 4, bottom).

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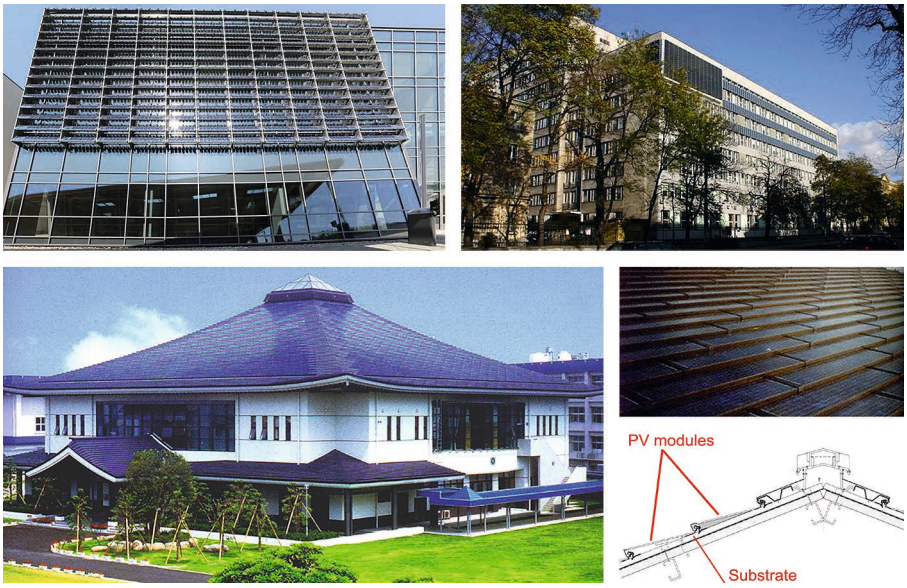


Fig. 4. Different influence of BIPV on the geometric divisions in the building envelope: top left – spatial divisions, PV façade of the Budomierz border crossing building (photo by ML System); top right – plane divisions, modernisation of the WIŚ building in Warsaw with the first PV façade in Poland (from the author's collection); bottom right – linear divisions, PV roof (photo by Jiro Ohno©)

B. Artistic effects

The pursuit of the aesthetic integration of PV technology with the building architecture results in increasing opportunities to create visual effects with its application within the building envelope. Due to highly visibile nature, the discussed impact mainly concerns building façades, although it can also be applied to roofs. The plastic effect depends on the technology and construction of PV modules and their components (Taşer et al., 2023; Amo et al., 2021).

Given the unlimited palette of artistic solutions, the discussed issue is complex. However, each solution is based, either jointly or individually, on the use of three basic artistic elements, namely colour, texture and chiaroscuro 'play' (Marchwiński, 2015).

The development of PV technology offers new ways of laminating PV modules and makes it possible to create PV cells with different visual properties. Thus, almost unlimited plastic effects related to texture, colour, and translucency are attainable (Amo et al., 2021; Pelle et al., 2020; Heinstein et al., 2013; Muszyńska-Łanowy, 2011).

New aesthetic possibilities are brought by the development of the third--generation cell technology, which in a way emerged in response to aesthetic and pro-environmental needs. As yet, these solutions remain, however, not competitive enough in terms of efficiency or durability (Pastuszak&Węgierek, 2022; Park, 2015), despite the enormous progress in recent years (Mirabi et al., 2021).

The building of the Swiss Tech Convention Center in Laussane (architect Richter Dahl Rocha & Associés, 2014) was a flagship example and a kind of manifestation of these new achievements. The building features semi--transparent PV modules made of multi-coloured DSSC cells (so-called Grätzel cells) on the front façade. Modules in the form of vertical shelves create the external cover of the building that defines its aesthetic function both from the external body of the building and from the internal spacious hall (Barraud, n.d.) (Fig. 5, left).

Modules of different translucency and colours that use lamination technology and the laser cutting of amorphous silicon cells were used in the Solar-Copper House building by the author of the present article. The novelty of this concept consists in the use of modules of various shapes and translucency, which resulted in creating a kind of artistic mosaic (Marchwiński, 2021). (Fig. 5, middle)

Another manifestation of BIPV's artistic potential is expressed in the case of the photovoltaic façade of the Xicui Entertainment building in Beijing

(architect Simone Giostra, 2008). In this case, semi-transparent PV modules are made in such a way that each module comes with a different sequence of PV cells, thus forming a specific pattern called "sea scape". These modules are set at a certain distance from the actual outer wall. The mentioned effect is also obtained by varying degrees of twist of the modules along the vertical axis so that the pattern resembles sea waves. However, the most characteristic artistic feature of the façade is its illumination from the back with LCD lighting (powered by PV cells), which creates original light and colour effects – a form of changing billboard (Roberts&Guariento, 2009 pp.82-5) (Fig. 5, right).



Fig. 5. Artistic effect potential created by BIPV: left – coloured PV façades made of 3rd generation PV cells-Swiss Tech Convention Centre (photo by Swiss Tech Convention Centre); middle – semitransparent a-Si modules in Copper solar house (author's collection); righ – interactive PV-LED façade of the Xicui Entertainment Hall (photo by Simone Giostra©)

At this point, limitations in the use of BIPV as an artistic material need to be discussed. Buildings with strictly defined style features, especially historical forms or traditional local architecture, may not adopt photovoltaics as an element of aesthetic function (similar to the relationships with the urban environment discussed earlier). Although many examples of the successful integration of BIPV with a historic substance can be provided, as well as examples of BIPV integration in such a way as to cultivate a centuries-old tradition (Hermannsdörfer & Rüb, 2005), the issue still requires research in relation to local conditions, including the identity of the place (Lucchi, 2022). Exposed BIPV may not be assimilated in the architectural expression of either the aforementioned building types or in those that are considered to be ultra--modern. Such a case is illustrated by the Museum of Tomorrow in Rio de Janeiro (arch. Santiago Calatrava, 2015), in which PV cells used on longer façades, although visible on the façade, play a subordinate aesthetic role. As in the case of other projects by Calatrava, this extremely expressive object designed in white brings an organic skeleton to mind – the skeleton of a marine animal in this case. In the building, PV cells were placed on the long side slats, ensuring favourable insolation conditions, but without exposing the fact of their existence (Fig. 6).



Fig. 6. BIPV in the Museum of Tomorrow as a "supplementary" element of aesthetic function (photo from author's collection)

Additionally, it should be mentioned that modern PV technology can adapt the appearance of PV modules to the high adaptation requirements related to making the modules similar to the plastic features of the façade wall (Hermannsdörfer & Rüb, 2005). Therefore, the complete masking of PV cells can be achieved by, for example, selecting a colour that does not contrast with the white of the façade (although this is done at the cost of decreasing the efficiency

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of PV) (Marchwiński, 2015). However, the PV cells in a common navy blue colour used in the described building increase the spatial effect of the façade, enhancing the chiaroscuro effects through contrast.

C. Kinetic envelope

Kinetic façades are becoming the domain of our times. This term is used to describe interactive façades that are responsive to the characteristics of the environment (Haghighat & Sadeh, 2023). One such type of façade is dynamic façades, including mobile façades, also called adaptive photovoltaic façades (Orhon, 2016).

The use of BIPV may be associated with the variability of the image of the entire building envelope, which is not only of the façade but also of the roof (Humm & Toggweiler, 1993, pp. 32-3). This effect is achieved by applying tracking devices, known as trackers, the main purpose of which is to track the apparent path covered by the sun in order to increase the efficiency of power generation by the PV installation. The variability of the building's image over time is generated as a side effect; it becomes an artistic outcome giving the architecture a fourth dimension. Owing to visual responsiveness, associations from the area of semiology arise, namely the symbolic dialogue between the building with the natural environment. Probably due to the high cost of these devices, relatively few examples of such design approaches can be found. One such example is the Japanese office building Shibua Passage Garden in Tokyo (arch. Nikken Sekkei, 1998), in which PV modules in the form of external vertical sunshade shelves rotate along the vertical axis. This solution resulted from the desire to position the modules more effectively due to unfavourable location conditions, i.e. the possibility of installing PV modules on the less favourable western side (Fig. 7).



Fig. 7. Western PV façade with mobile PV modules in Shibuya Passage Garden and the scheme examining the insolation time of a PV module due to its rotation (photo: Jiro Ohno ©)

In a way, solutions having a variable plastic image can be treated as those with a kinetic casing, although they do not involve a vector change, as in the case of the Xicui building.

3.2.2. Direct and indirect impact of PV on shaping the spatial form

Although PV modules, being flat elements, are generally not associated with having an impact on spatial shaping, in the broader sense of the integration of PV with the building, this issue can be questioned. This is because the use of PV modules is associated with providing the building envelope (façades, roofs) with three-dimensional features. This impact may be either direct or indirect (Marchwiński, 2012).

A direct impact occurs when the spatialisation of the façade or the roof is achieved by the physical characteristics of the PV modules and their construction. In the case of façades, the strongest influence is exerted by

PV modules in the form of shading strips mounted on a structural frame independent of the building structure (shadowvoltaic system), which gives them the appropriate inclination angle. The frame itself is also sometimes set at a certain distance away from the external wall of the building, thereby defining a new geometry of a part of the building.

In the Itoman City Hall office building on the island of Okinawa, Japan (architect Nikken Sekkei, 2002), an independent openwork wall made of PV modules somehow defines the building's geometry (Tochigi & Tsukamoto, 2005) (Fig. 8).



Fig. 8. The influence of shadowvoltaic system on the buildings form: three variants of Itoman City Hall, from the left – basic volume, volume with traditional lamellas, volume with sloped shadowvoltaic system-implemented variant (source: Tochigi & Tsukamoto, 2005)

Similar solutions characterise the roof shaping. In this case, however, PV modules are not always referred to as shading elements. A quite common architectural solution is the creation of spatial roof shelves, independent of the geometry of the roof itself. Yet another illustration of the discussed impact is created by the densely embedded PV modules located on the roof, which create a spatial image of the "fifth elevation". It should be noted that in this situation, although the physical integration of BIPV is not the case, the undoubted impact of such solutions on the aesthetic function allows the PV modules to be perceived as an element of the BIPV concept in the architectural sense. This approach is evidenced by a school building of Annie E. Fales Primary School in Westborough, Massachusetts, USA (arch. HMFH Architects, 2022) (Fig. 9).



Fig. 9. Shaping of the building's form with the use of roof PV shades in Annie E. Fales Primary School building (photo HMFH Architects©)

The indirect impact results from the need to adapt the façade or roof planes to the energy requirements of the PV installation, so that the PV cells are exposed to the sun as much as possible. This is manifested in the inclination of roofs and façades to the optimal angle at which the PV installation is planned. This approach may result in the creation of unusual spatial building forms (Marchwiński, 2023).

The office and production building "Solar Cell Plant" Gelsenkirchen (architect Hohaus, Hinz & Seifert, 2002) is an interesting example that illustrates this influence. Cladding modules were used on the entrance façade on the southern side of the building. They form the skin of an administration and office facility.

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The desire to create favourable sunlight conditions resulted in a characteristic curved profile of the façade. The shape of the building's body, together with the cladding PV modules, creates an unusual, innovative architectural expression. Additionally, the arched façade was glazed in the central part – the impact of the modules integrated with the glazing is discussed in the following section of this article (Fig. 10).

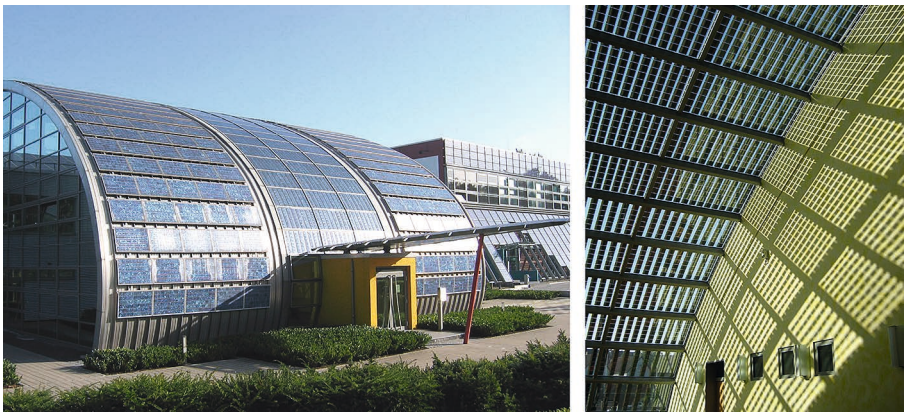


Fig. 10. The indirect influence of BIPV application on the building form – "Solar Cell Plant" (photo from the author's collection)

It should be emphasised at this point that shaping the body of the building by giving it an unusual profile under the influence of energy-related premises resulting from exposing PV modules has its rational limitations. Greater freedom is enjoyed when using lightweight outer coatings. One of the most pronounced trends refers to the integration of PV with foils to be used within building envelopes, including ETFE foil in two- and three-layer structures (Yin et al. 2020, Hu et al., 2017).

3.3. BIPV and the utility function of the building

The utility function of BIPV, excluding the obvious function as a generator of electric current, is mainly related to shaping the light and thermal environment of the building in a passive strategy of controlling these environmental factors. This effect is mainly observed due to BIPV in the form:

- glazing in the building envelope;
- external solar shelves.

3.3.1. PV modules as glazing and cladding elements

The development of PV modules as glass coverings of the façade is also aimed at improvements to their functional and utility aspects. Semi-transparent PV modules in which cells of the second and third generation are used, combined with the glazing pane, function not only as a generator of the electric current but also, as is the case with covers made of solar protection glass, as a light diffusing element and a transparent partition simultaneously.

In the atrium roofing of the aforementioned Solar Cell Plant building, popular PV modules were used with thin-film PV cells spread within the module (Fig. 10, right). These modules are semi-transparent – the gaps allow natural light to enter the interior. The spacing of the cells determines the degree of PV module translucency (Transparent, 2023). However, it should be mentioned that in conditions of strong sunlight shining onto the façade, modules of such construction produce strong chiaroscuro effects. For this reason, in the absence of other solar protection elements, such modules are not recommended in spaces where a high-quality light environment is required (e.g. office spaces). Additionally, spreading the cells further apart reduces the potential power of the module.

In this aspect, the development of PV technology is aimed at unifying the surface of PV modules – DSSC, organic and perovskite cells are conducive to unification, thereby to the creation of homogeneous surfaces. Similarly, inorganic PV cells technology as well as quantum dot cells (QD cells) seem to be promising solutions for the future (Romani et al., 2022). Photovoltaic glass is not much different from the traditional glass used on façades and roofs (Marchwiński & Starzyk, 2021).

In addition to issues related to the light environment, the utility role of BIPV is also expressed by the tendency to include PV technology in the strategy of the passive use of solar energy for heating the building through the so--called thermosyphon effect. This effect is possible due to the creation of an air gap, which functions as a circulation channel within the double façade. Namely, PV modules constitute a component of the double skin elevation, creating its outer layer (Roberts & Guariento, 2009, pp. 124-7; Photovoltaic, 2001, pp. 34-5). This layer is moved away from the inner plane of the glazing. As a result of the heat emission which occurs as a side effect of the photovoltaic conversion, the air in the space between the layers is heated. As is the case in traditional double glass façades, the thermal energy obtained in this way is used for the passive heating of room spaces and as natural displacement ventilation. Thus, this solution constitutes another step in the development of this type of façade. In this solution, the façade PV modules play not only the role of an electricity generator and an external partition but also serve as a component of a passive solar heating system.

A similar effect to that described above was obtained in Solar Building XXI in Lisbon (by architect Pedro Cabrito, 2005), where PV modules were introduced as façade cladding. This proves that the passive use of solar energy requires no sophisticated glass façade solutions. In this building, PV modules are attached to the spaces between the windows. Through the thermosyphon phenomenon, the heat collected from their surface is used for heating or 'dragging' warm air out of the room, depending on the season. The use of PV modules, depending on the season, serves both passive solar heating and natural ventilation (Gonçalves et al., 2008) (Fig. 11).

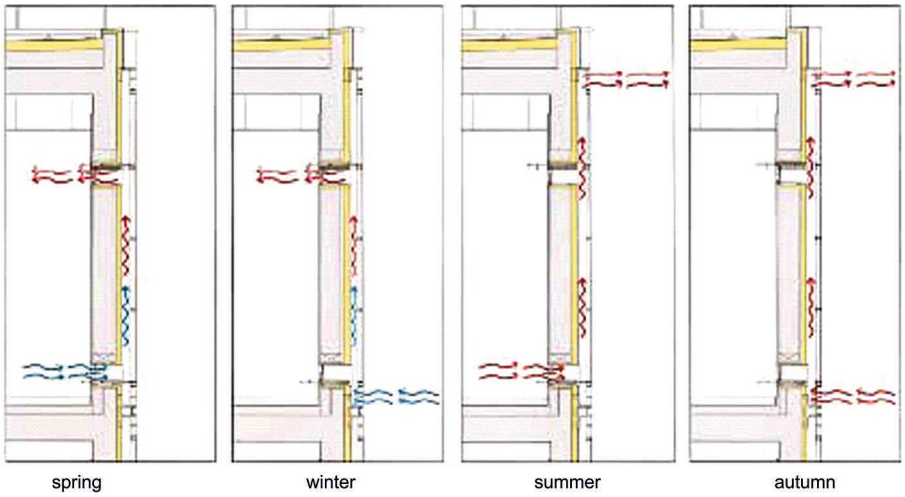


Fig. 11. The use of the thermosyphon effect with the use of PV cladding elements in Solar Building XXI (source: Goncalves et al.)

3.3.2. PV modules as 3-d shading elements

In their standard form, PV modules are not transparent, so they cannot be applied as lighting elements, nor can they exert an influence on the visual contact with the environment. For this reason, when PV modules are to be used on a significant scale or on the entire surface of the building envelope, it is generally necessary to 'mix' them with traditional glass panels. However, opaque PV modules are better suited to the role of solar ledges or shading lamellas;

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they may even be applied in the form of integrated shadowvoltaic systems. For this reason, PV modules are located in the vicinity of glazed partitions or other transparent walls and roofs that let the sun's rays through. In order to maximize exposure to the sun, it is rational to place these modules on the outside of the partition. This placement is also due to thermal reasons, i.e. to avoid the greenhouse effect and cooling the PV modules in order to increase their power generation efficiency (Sarniak, 2008).

A system of unregulated PV modules serves as the basic solution. In such a solution, it is important to adjust the inclination angle of the modules so that it is optimal with regards to the direction of the sun's rays in the summer, i.e. during the period of the highest solar gains.

More technologically advanced solutions (but also more expensive options) are based on the use of the mobile PV modules mentioned above when discussing the kinetic casing. These modules can be regulated individually (manually) or automatically. The automatically regulated shadowvoltaic system is usually connected to a central building management system (BMS). Such solutions are rational in the case of glass roofs due to difficulties to access them (Humm & Toggweiler, pp. 32-3). Higher investment expenditures are compensated for by the increase in the energy efficiency of such modules, as well as their greater efficiency as elements with which to control the flow of light and solar heat to the rooms of buildings (cf. Shibuya). However, due to financial constraints, compromise solutions are often introduced. With dense arrays of solar shading modules, a selected part of the system is established as a regulated element. This often comprises a row of PV modules, located at the user's eye level. In this way, employees are given the possibility to individually adjust the PV modules (e.g. to improve lighting conditions and maintain visual contact with the environment). Mixed solutions are also introduced to enable both manual and centrally controlled automatic regulation (Reijenga & Kaan, 2000).

3.3.3. Hybrid solutions

One of the manifestations of further research into expanding the usable role of BIPV is combining the concept of PV modules used as spatial shading elements with the idea of using them as glass elements. PV integration is based on the use of PV elements that, while acting as a glass cover, also serve as a sun shelf. This integration mainly concerns the profile of the façade and the location of the PV modules. This is facilitated by the use of double glass façades, in which the outer layer may come in the form of a profile suitable for the role of the PV module. The sawtooth cross section of the façade allows the PV module to be placed as an inclined sunshade shelf (usually above the eye level) which also acts as a component of the glass façade. The implementation of such a solution is presented by the Energy Base building in Vienna (architect POS Architekten, 2006). In this facility, the façade slope is optimised for solar protection in summer and, simultaneously, for energy efficiency of the module's operation as well as a passive solar heating strategy in winter. Additionally, the lower, larger plane of glazing serves as a partition responsible for lighting the interiors and providing visual contact with the surroundings (Fig. 12).

At this point, it is also worth mentioning a separate research path, namely the technology of combining PV with switchable glazing. Although being part of the hybrid nature of solutions, it has not yet found widespread construction applications. In these solutions, the mutual cooperation of the two technologies, i.e. PV and switchable glazing, is observed. Switchable glazing plays the main role of a responsive sun barrier, whereas the PV is the electricity generator required to power the glazing. Additionally, PV can play an auxiliary role in the solar protection of rooms (Marchwiński, 2021b). Future cooperation is expected mainly with the use of electrochromic glazing (Huang et al., 2016) but also with SPD (Gosh & Norton, 2019). Commercialisation is hindered by technical

and usability-related limitations, e.g. the long time of phase transformation, and non-uniformity of the glass colour.

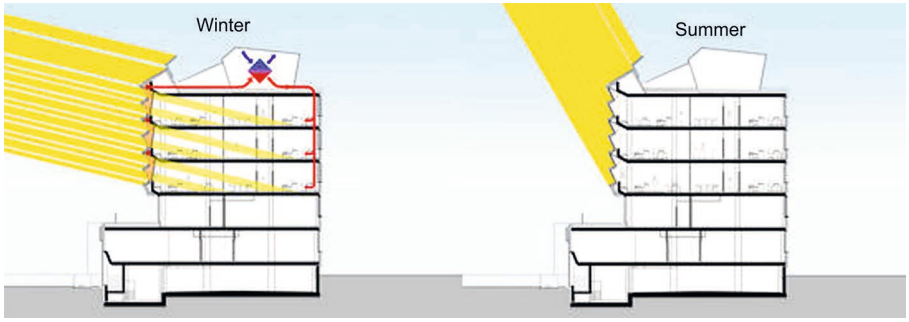


Fig. 12. Winter and summer strategy with the use of sawtooth BIPV double elevation in Energy Base office building (source: POS Architekten)

These problems increase with the increase of the glazing surface. Undoubtedly, however, the current progress is leading to overcoming these barriers. Furthermore, combining both technologies gives new possibilities for the aesthetic creation of façades (Marchwiński, 2022).

Combining PV with ETICS façade insulation systems may prove another promising technology. Research is underway with the use of phase change materials (PCM) materials and methods to remove moisture from the inner surface of such hybrid systems (Talvik et al., 2023). Overcoming technological barriers will likely exert a revolutionary impact on the development of BIPV once PV is introduced in the area of insulation materials used each time thermomodernisation of buildings and their façades is conducted.

3.4. The role of BIPV in the aesthetic and functional aspect – summary

The review of the possibilities to integrate photovoltaics with the architecture of the building and the related issues of designing buildings with BIPV contained in Sections 3.1-3.3 enables an attempt to determine the role of BIPV in modern architecture in terms of aesthetics and utility. This role is discussed below in Table 4.

Table 4. The role of BIPV in the context of assessing the impact of its use on the aesthetic and functional aspect (by the author)

Type of BIPV impact	BIPV façade	BIPV roof
AESTHETIC FUNCTION		
Impact on the aesthetic coherence of building complexes	• – in the case of large-area façades in buildings with strongly developed formal and style features (further research required)	○ – in the case of roofs with an extensive support structure exposed in the body of the building – in buildings with strongly developed formal and stylistic features (further research required)
Shaping the spatial form of the building	• – in an indirect aspect that consists in adapting roofs and façades to maximise solar exposure (tilting, bending) ○ – in the direct aspect as a result of the introduction of extensive support systems for BIPV (e.g. support for the shadowvoltaic system, creating sawtooth roofs for BIPV)	
Spatialisation of the building envelope	• – in the case of extended façade support for the shadovwoltaic system – in the case of double glass façades with BIPV	○ – in the case of extended roof support for the shadowvoltaic system

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Table 4. cont.

Creating a flat-plane composition within the envelope (rhythms, compositional directions, etc.)		○ – as in the case of the façade, but due to the fact that the roofs are less exposed in the body of the building – the impact is limited
Creating a linear composition within the casing (rhythms, compositional directions, etc.)		
Impact through artistic effects	● – in the case of creating the aesthetic function of PV façades with the use of colour, texture, graphics and transparency degree of PV modules and cells, shape, size and framing (or lack thereof) of PV modules – in the case of the use of chiaroscuro effects by affecting the spatialisation of the façade, combining with other technologies (e.g. LED lighting) (this impact is growing due to the development of second and third generation cell technology)	
Creating the expression of architecture by influencing the kinetic envelope	● – through the effect of the variability of the façade image over time: in the case of large-area mobile shadowvolaic systems as well as façades with variable artistic (color, texture etc.) features > – due to the development of PV-switchable glazing technology	
UTILITY FUNCTION		
Impact on the plot selection and its arrangement	● – in the case of PV glazed or PV cladded façades with PV modules installed at low levels above the ground	
Passive solar heating and stimulating natural interior ventilation	● – with the use of double glass façades with BIPV and façade cladding modules attached to a passive solar system	● – with the use of roof glazing with BIPV (e.g. atrium glazing) attached to a passive solar system
Natural lighting of the interior	● – due to the development of the technology of PV cells and transparent and semi-transparent PV modules; (influence on such aspects as brightness, colour, contrast, including chiaroscuro effects)	
Solar protection	● – in the case of PV modules as PV façade glazing and spatial shading elements, including shadowvoltaic systems on windows and glass curtain walls (shelves, slats); – in the case of hybrid solutions (glass-sun-shield) within the glass façades	● – in the case of PV modules as PV roof glazing and spatial shading elements (shelves, slats), including shadowvoltaic systems with glazed atria covers and skylights

Table 4. cont.

Controlling the inflow of solar radiation to the interior	• – with the use of movable solar shelves and their systems	
Warming of the building envelope	o – in the case of double glass façades with BIPV > – due to integration with the ETICS external wall insulation technology	

• Strong impact o Weaker impact > Anticipated impact

4. Conclusions

This article has analysed the aesthetic and functional aspects of BIPV; it illustrates the current state of achievements and possibilities. It can be said that combining PV technology with architecture creates a synergistic relationship. Under the influence of architectural needs, PV technology is developing towards meeting aesthetic and functional requirements significant from the architectural design point of view. Furthermore, BIPV enriches the 'language' of contemporary architecture; it results in interesting, sometimes innovative implementations in terms of the spatial form rather than only the building envelope (elevations and roofs), as it is sometimes mistakenly believed. Further scientific research is required on the relationship between BIPV and the urban context, especially in the often overlooked aesthetic context.

A comparison of the assessment of the impact of façade and roof applications of BIPV suggests that the former play a priority role in terms of creating the aesthetic function of the building. In the case of the discussed utility function, the role of BIPV façade applications is more equal to that of roof applications.

Taking into account the fact that from the energy point of view, roofs provide a more sunlight-exposed location (Humm & Toggweiler, p.97), and are therefore a more attractive location for PV modules, the question should be asked of where the optimum that reconciles the architectural and energy requirements is. Is it even possible to determine it at all in a universal sense, and if not, what are the main factors that determine it? Or perhaps it is the role of priorities in each case? Does the fact that roof applications account for 80% of the total of PV applications in buildings (Shukla et al., 2017) mean that non--energy aspects, such as aesthetics and utility, fail to provide sufficient reasons for the use of photovoltaics within the façade?

Observations of contemporary buildings with BIPV prove that the aesthetic limitations that accompanied BIPV at the beginning of its path are disappearing slowly. The variety of products (different colours, textures, graphics, shapes, translucency, size, etc.) offers the possibility for BIPV to be better matched to the architect's vision to meet architectural needs.

Further global development of photovoltaic technology in architecture seems certain. Progress will be directed towards both further increasing the architectural attractiveness of PV modules and improving their efficiency (manufacturers' efforts will also focus on reducing economic and ecological production costs). The future lies in multifunctional applications, e.g. PV as an electricity generator, a building element and a component of a solar heating and lighting concept at the same time. The solutions of PV-switchable glasses may be seen as the first manifestations of this trend. The development in this field will aim at maximizing usability and then aesthetic values, with the greatest construction simplification of these technologically advanced solutions. It seems that this trend will accompany all new building materials and that BIPV is now a tangible example.

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To sum up, the goals that currently seem to be the most important from the point of view of further BIPV development in the context of the discussed aesthetic and functional role can be defined as follows:

- searching for BIPV solutions as full-fledged glass covers associated with the improvement of PV efficiency;
- maintenance and further development of the aesthetic diversity of PV cells and modules along with the increase in their efficiency and independence from direct solar radiation;
- searching for common BIPV solutions, such as a combination thereof with an insulation system;
- searching for synergistic forms of PV cooperation with other façade and roof technologies, such as switchable glass technology.

In general, the most important challenge should be seen in a context much broader than the scope of this article, namely the challenge to create hybrid solutions that fulfil the role of a power generator as well as the aesthetic, and functional role without compromising any of these roles in favour of the others. Furthermore, such a solution should be safe, trouble-free, pro--environmental and generally available.

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