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ARCHITECTURAL ANALYSIS OF PHOTOVOLTAIC (PV) MODULE APPLICATIONS ON NON-FLAT ROOFS

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ABSTRACT

Due to the growing importance of renewable energy sources (RES) technology, a noticeable increase in interest in photovoltaics can be observed. Roofs most often provide the places where photovoltaic (PV) modules are installed. In many cases, ill-considered decisions concerning the selection of PV modules and their installation lead to unfavourable architectural effects. The article aims to examine the possibility of integrating PV modules installed on non-flat roofs with the broadly understood building architecture. An observational method based on case studies was applied to the study. Not only aesthetic aspects but also functional and technical aspects were considered while paying attention to energy issues. The conducted analysis indicates a good level of possibilities for integrating PV modules with architecture and these possibilities vary depending on the geometric features of the roof. Applications within full and glazed roofs are also rather distinctive.

Keywords: photovoltaics, PV modules, solar architecture, roofs, BIPV

INTRODUCTION

Placing photovoltaic (PV) modules on a building's roof generally guarantees a maximum level of exposure to the sun and a reduced risk of shadowing by the surrounding objects. With regards to climatic conditions and a latitude similar to Polish conditions, in the case of southern exposure – which is considered most advantageous – PV modules inclined at an angle of 35° to the horizontal ground generate approx. 28% more energy per year than modules placed along the vertical plane. In the case of eastern and western orientation, the difference is 44% and 43%, respectively (Roberts & Guariento, 2009).

Hence, roofs with such or similar inclinations and orientations provide a conveniently shaped surface upon which PV modules can be applied.

According to research conducted in 2017, the use of PV systems within the roof reached almost 80%, as compared to 20% within the facade (Shukla, Sudhakar & Baredar, 2017).

The application of PV modules on non-flat roofs requires a separate discussion, as significant differences can be observed in this case compared to PV applications on horizontal roofs. These applications were discussed in a separate publication (Marchwiński, 2022). First of all, the use of PV modules on non-flat roofs is characterised by a greater dependence on the exposure to the cardinal directions – differently oriented roof planes receive various amounts of insolation. As already mentioned, southern exposure is generally considered the most favourable annually; it is followed by eastern and western exposure (Chwieduk, 2011). Apart from some PV technologies and flat roof applications, northern orientation is not recommended for PV installations (Waseed, 2014).

From an architectural point of view, the exposure of the PV modules in the building's body is another significant difference. Horizontal roofs are naturally subject to weaker visual perception, which is why the rank of PV elements as a tool of aesthetic creation is potentially reduced. The flatter the roof is, the

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weaker the visual perception. Larger free space also results in less sublime forms of integrating photovoltaics with architecture – PV elements are more often installed as a monofunctional installation, which plays no other role than being an electricity generator. Unfortunately, this phenomenon also applies to non-flat roofs, mainly gable roofs, which often exert a negative impact on the architectural form of the building, especially when the use of PV modules was not originally planned. With the launch of government programmes and the resulting growing interest in photovoltaics among individual consumers, disastrous aesthetic effects are increasingly experienced.

This article aims at exploring the possibility of integrating PV modules within non-flat roofs with the broadly understood building architecture. Not only aesthetic aspects were considered, but also those related to the architectural and construction design, namely regarding utility and technical-construction aspects. Efforts were made not to lose sight of the energy issues, as these provide the primary reason for reaching for PV systems and should be considered together with the above-mentioned aspects (Lucchi, Baiani & Altamura, 2023).

MATERIAL AND METHODS

The observational method (Pieter, 1975) of a quantitative character was used in the article. The research is descriptive and based on the selected examples of buildings; it is an overview of solutions for PV applications within non-flat roofs subjected to architectural analysis. This analysis was conducted according to a general division into solid and glazed roof applications. The analysis has been supported by eight case studies – these are the non-residential buildings that have been selected to illustrate different approaches to the issue of PV integration with non-flat roofs in architecture. Roofs being tensile structures with the use of textile and foil coverings were excluded from the considerations; this case was discussed in more detail in a separate article (Milosevic & Marchwiński, 2022).

The insights resulting from the analysis were collected in a summary of the discussed PV applications, which provides the research synthesis. The synthesis made it possible to reach conclusions, the content of which provides the execution of the aim of this article.

ANALYSIS OF APPLICATIONS OF PV MODULES WITHIN NON-FLAT ROOFS

No definition of a flat and non-flat roof can be found in the legal regulations. According to the Polish PN-B-10425:1989 standard, which is commonly used to separate these concepts, the non-flat roof is a roof inclined at an angle of greater than 12° (Polski Komitet Normalizacyjny [PKN], 1989). However, for the purposes of this article, intuitive perception was applied. Non-flat roofs were treated as all roof planes whose geometry is visually perceived as non-horizontal.

Solid roofs

Photovoltaic modules applied on solid roofs come in the form of non-transparent modules. As elements added to the existing roofing (so-called building-added photovoltaics – BAPV), they are shaped as frame modules in thick-layer PV cell technology. In the case of building-integrated photovoltaics (BIPV), these modules act as cladding elements that replace these coverings (e.g., roof tiles). In the case of more sophisticated shapes (e.g., strongly bent elements), PV modules in thin-film PV cell technology may be the only possibility.

Gable roofs

The use of PV modules within traditional, existing gable roofs as BAPV, e.g., in single-family houses covered with tiles, generally brings few positive aesthetic effects. The modules applied upon the roof cover differ in both size and plastic features (colour, texture, shine), which makes them perceivable as a foreign, artificially added installation element. Replacing traditional roofing with PV modules is a difficult task, as, unlike tiles or other traditional roofing, the surface of the PV module requires ventilation from the inside. In general, solutions that do not adhere to the roof slope also look unfavourable. These, however, are less common solutions; they are only applied in such cases as when the roof slopes are unfavourably oriented.

These disadvantages are mitigated or disappear when PV modules are applied as roofing, e.g., tiles (BIPV), as well as when their application was planned before the roof was installed. This approach brings interesting and original aesthetic effects. The new tile equipped with PV cells and covered with glass with a metallic texture gives the surface a shiny, modern look while maintaining the familiar divisions. Manufacturers generally provide for appropriately prepared construction systems. This is another advantage of a system solution. The base surface is adapted to ensure the optimal operation of the modules, e.g., it provides adequate ventilation space, which positively affects the cooling of the module from the bottom and thus leads to maintaining its power generation efficiency.

In the Ho-Oh High School gymnasium building (arch. Shimomai Architectural Design) in Kagoshima (Japan), the roof slopes were covered with small rectangular PV modules as roof tiles (Fig. 1). The installation's peak power equals as much as 151 kW. The shiny roof surface, combined with the overlapping module layout analogous to the layout of traditional tiles, creates an innovative combination of tradition and modernity. As is characteristic of Japanese architecture, the roof slope has a curved profile. Its inclination angle varies from 27° to 11° to the ground. The PV modules were placed on a specially prepared steel construction frame.

The problem with this type of application lies in the aspect of aesthetic unification of all slopes, including the shaded ones, where it is irrational to apply PV modules. In such cases, the introduction of imitation elements may be required, such as glass end caps whose appearance is similar to that of the PV module.

Shed roofs

Another type of non-flat roof which provides a common base surface for PV modules is shed roofs, including the so-called saw-tooth roof. Both in newly designed and modernised buildings, these types of roofs are willingly used as a base surface for PV modules, as long as they are orientated towards the south and are not shaded. The main advantage of this solution results from the fact that the favourable inclination of the modules is obtained with no need for a structural frame. This translates into financial savings and ease of assembly. In general, the slope of the shed roofs is in line with the functional premises. The southern roof surfaces are covered with PV modules, while the northern surfaces can be glazed and thus provide diffused daylight access. Such solutions are beneficial in

Fig. 1. Photovoltaic modules integrated with the gabled roof – Ho-Oh High School gymnasium building in Kagoshima, Japan

Source: the author's elaboration on the basis of the New Energy and Industrial Technology Development Organization [NEDO] (2011).

buildings where top-down natural lighting is required or desired. At the same time, chiaroscuro contrasts, and the direct solar radiation access that can cause interior overheating are avoided. An example of such buildings is industrial halls (Szparkowski, 1999). Moreover, such solutions occur more and more frequently in such types of buildings as sports halls, art galleries, and residential or educational facilities.

The building of the Annie E. Fales Elementary School in Westborough Massachusetts, erected in 2021 (arch. HMFH Architects), has a rather unusual saw-tooth roof whose area equals 1,900 m^2. The sheds are arranged in eleven irregular rows (Fig. 2). A total of 1,350 PV modules with a total capacity of 507.75 kWp were installed on their southern slopes. The northern planes have been glazed. The layout of the sheds has been adapted to optimise solar energy gains and to illuminate the classrooms. The eleven saw-tooth rows have a total length of 19.8–57 m. On the southern side, the slope of the roofs ranges from 21° to 30°, whereas on the northern side – 54°–90°. The individual heights of each "saw-tooth", from the roof level to the top, range from 2.13 m to 3.66 m.

The cell technology used in the PV modules (manufacturer-REC) is interesting. High-efficiency PV cells (21.4%) with a power of 3.1 W each were made in the "half-cut" technology, which helps to improve the energy efficiency of the PV system. Half-cut modules are designed in such as way that the top and bottom half of each panel operate independently for maximum output. The use of light and reflective waterproofing materials on the roof is also beneficial in this case (RoofingAdmin, 2022).

Roofs with untypical geometry

The layout of PV modules on traditional roofs of existing buildings may be faced with several problems. The basic problem results from the need to arrange the modules in such a way that their surface remains unshaded throughout the year, at least in the summer, late spring, and early autumn periods when insolation is the strongest. Usually, however, despite the significant "free" roof area, it is periodically shaded by various elements existing there, such as gravitational, smoke, and exhaust chimneys, telephone exchanges, air-conditioning centres, antenna masts, superstructures, high cornices, and parapets, etc.

The construction requirements regarding the maximum loads that the flat roof can carry should also be considered. Another limitation results from the technical conditions and construction standards concerning such aspects as height relations between chimneys or air-conditioning outlets and other elements of the building's roof.

Fig. 2. Photovoltaic modules on the shed roof – Annie E. Fales Elementary School in Westborough, Massachusetts, USA

Source: ®HMFH Architects.

The search for the best location and exposure for the PV modules can lead to interesting architectural solutions. The business promotion centre office building in Duisburg (architect Norman Foster) was provided with a southern slope thanks to its body being "chopped" (Fig. 3a). The slope was used to accommodate a set of PV modules and solar thermal collectors. As a result, the building gained an unusual spatial form. These elements are not visible from the ground floor level, so there is no direct aesthetic role of these elements. However, if the shape of the building's body is considered a consequence of their application, the indirect impact is significant.

An analogous case, although completely different in its aesthetic expression, is the building of the solar cell plant in Gelsenkirchen (arch. Hohaus, Hinz & Seifert) – a manufacturer of PV modules (Fig. 3b). The office part, which is located in the front part of the building on the southern side features an original spatial shape. Its profile is curved into an arch, which creates a smooth transition from the roof part to the facade. Full fragments of the partition over its entire surface were clad with frame PV modules made of polycrystalline silicon cells. It has been shown that even thick-film technologies can be used in BIPV on curved surfaces in some cases. The modules were mounted on a trapezoidal sheet metal base. The cross-section of the sheet creates a convenient base to provide air-flow under the module for cooling, which increases the efficiency of the PV system (ATB Becker, 2006). The front of the building clad with PV modules is complemented by a greenhouse structure whose laminated glazing is also equipped with PV cells. The use of PV modules on the most exposed part of the building provides the most advantageous feature in terms of energy; open foreground, orientation to the south, and the arch, which offers a convenient inclination to the sun's rays, and ensures the effective operation of the PV system. This solution was also dictated by aesthetic considerations; it aimed to create a sort of advertisement for the company's products.

Glazed roofs

Apart from being located on traditional roofs, PV modules are increasingly used within glazed roofs. This is another step in the development of PV technology in construction and architecture.

Photovoltaic modules can replace traditional glazing panels. They create laminated glazing, in which the inner layer is made of PV cells, as in the case of modules to be used within facades, except that roof modules usually require different technological solutions, e.g.,

a b

Fig. 3. Photovoltaic modules on curved roofs: a – business promotion centre office building in Duisburg, Germany; b – solar cell plant in Gelsenkirchen, Germany

Source: the author's collection.

glazing with increased resistance to mechanical loads. They are also available in the form of shading systems, the so-called shadow-voltaic systems.

Coverings of greenhouse structures

One of the most interesting implementations of a glazed roof where PV technology is used is the ECN-42 office and laboratory building in Petten (the Netherlands), designed by BEAR Architecten, a well-known Dutch design office.

Photovoltaic modules from "BP Solar", whose total area equals approx. 400 m^2, with a power of 42 kWp, were used in the upper part of the greenhouse, which forms a kind of winter garden in the building (Fig. 4).

The greenhouse was shaped as a dynamic volume with an arched profile. This curvature not only enhances the architectural expression but also helps to obtain a convenient inclination angle for the PV modules. The glazing has a favourable south orientation. Each PV module contains 32 offset monocrystalline silicon PV cells. The layout of the cells causes light to pass between the gaps. The separation is from 1–2 cm, depending on the module, whereas the light transmission amounts to 30%. In this way, the modules play the role of shading elements; they filter sunlight and introduce it into the interior in a diffused form. This prevents the effect of excessive luminance and overheating of the greenhouse in the summer. In winter, when the sun is low above the horizon, the sun's rays can penetrate directly into the interior through fully glazed panels located in the lower part of the partition. Passive solar gains are possible.

Being a temporarily used space, the greenhouse is not heated traditionally. It acts as a thermal buffer or solar heat collector.

The greenhouse has a wooden structure, which is yet another manifestation of holistic pro-ecological thought in shaping the building's architecture. Material from renewable sources with low demand for so-called embodied energy, that is, the energy needed for its manufacturing, is used. The structure comprises bent beams made of laminated timber. The repeating structural element called the main beam is composed of two individual wooden beams connected by steel profiles. Aluminium profiles are attached to the upper outer surface of the beam, which constitutes the structure for both the glass panels and the roof of the PV modules. Particular effort was required to obtain the curvature of the module surface in accordance with the geometry of the beams. Each element was cut and bent every 120 mm to create an impression of a smoothly curved plane. The modules are 575 × 1,175 mm. Thus, the modular division has been preserved, which introduces harmony and order in the facade (BEAR Architecten, 2011).

Coverings for atriums – atrium skylights

In the office and laboratory building of the Fraunhofer Institute in Freiburg, Germany, designed by Dissing+Weitling, a glass roof with PV technology

Fig. 4. Glazed BIPV as a covering for a winter garden in the ECN-42 office building in Petten, the Netherlands

Source: BEAR Architecten (2011).

covers the inner atrium (Fig. 5a). The roof geometry, which is characterised by a "saw-tooth" cross-section, is interesting. Semi-transparent PV modules that form the roof are arranged in series and inclined at a certain angle. The vertical surfaces, which are created as a result of the modules' inclination, have been filled with transparent glazing.

Despite the introduction of vertical glazing and spreading the PV cells apart within the modules, the intimate atrium is poorly lit, which may make its space perceived as cramped and gloomy. On the other hand, the roof solution introduces an artistic "play" of light and shadow. Since the atrium serves as a communication space and does not require high illumination standards, the level of natural lighting can be considered sufficient in the functional context.

Limitations regarding the use of PV modules in the glass coverings of central atriums (surrounded by walls on four sides) become apparent when the covering is arranged in the form of a roof, dome, barrel vault, or other spatial forms that introduce a division into planes with different orientations regarding the cardinal directions. As the PV modules should only be installed on the sunlit parts of the roof, it is not rational to distribute them fully or evenly across the entire structure. In the building of the Technical University of Munich, the glass covering of the central atrium has the form of a barrel vault (Fig. 5b). Photovoltaic modules occupy only the lower part of the southern plane of the cradle. The remaining surface is filled with glass panels. This solution allows for significant use of daylight but fails to protect well against strong summer radiation when the sun is high in the sky. In winter, the semi-transparent modules serve as a barrier to sun rays that fall at a lower angle, which is desirable during this period. It should also be pointed out that the use of modules in this type of cover is limited in terms of area, thus, in the total power of the PV installation. In the Munich building, the total peak power is less than 19 kW (New Energy and Industrial Technology Development Organization [NEDO], 2011).

A different approach to the use of PV modules within glazed roofs is presented in the building of the European Headquarters of Digital Equipment Corporation in Geneva (arch. Lecouturier & Caduff). The pyramid-shaped glass roof that covers the inner atrium is equipped with densely spaced PV modules in the form of horizontal shading lamel-

a b c

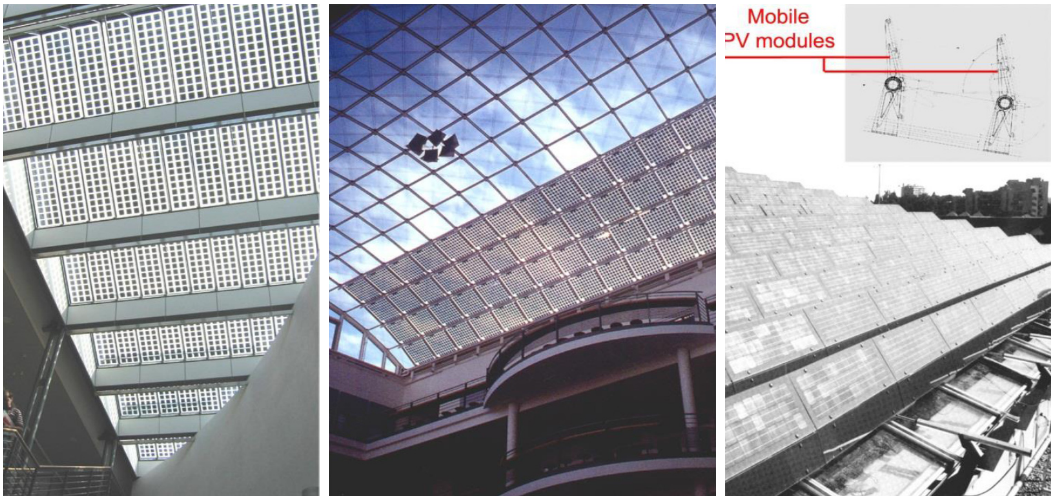

Fig. 5. Glazed BIPV as a covering for atriums in: the office and laboratory building of the Fraunhofer Institute in Freiburg, Germany (a); Technical University building in Munich, Germany (b); building of the European Headquarters of Digital Equipment Corporation in Geneva, Switzerland (c)

Source: [a]the author's collection; [b]NEDO (2011); [c]Humm & Toggweiler (1993).

las (Fig. 5c). These modules were attached to the glazing structure from the outside. The elements cover three surfaces of the glass roof, except for the northern part, where traditional external slats have been introduced. The PV modules were equipped with follow-up devices. They can change their position by adjusting the angle of inclination to the direction of the sun's rays. This solution is of great importance in terms of obtaining solar heat in winter and protection against overheating of the interior in the summer. It also helps to optimise the use of natural light. Finally, the variability of the position of the modules increases the aesthetic value of the atrial space (Humm & Toggweiler, 1993).

RESULTS

The following section includes a summary of the PV module applications within solid and glazed roofs. The list concerns the most crucial aspects from the architectural point of view, namely aesthetic, functional, and technical (Table 1).

Table 1. Comparison of the PV modules application within solid and glazed roofs

Aspect	PVs – solid roofs	PVs – glazed roofs
Aesthetic	Relatively strong direct impact on the building's architecture when used on sloped roofs (impact through colour, texture, roofing divisions); the influence increases with the growth of slope deviation from the horizontal axis. Applications of BAPV generally do not offer beneficial aesthetic effects (visual distinctiveness); it may require the imitation of modules in less sunny areas in order to obtain a homogeneous aesthetic expression of the entire roof. In the case of newly designed buildings, an indirect aesthetic impact may be achieved, i.e., the impact of energy considerations related to maximising the operation of PV modules on the roof geometry. In the case of gable roofs, the direct influence on the building's aesthetic function is limited, due to the relatively poor exposure in the entire building's body. In the case of arched profiles, the effect is potentially much stronger; the boundary between the roof and the facade is blurred, which makes it possible to use PV modules in creating expressive architectural forms.	Elements of PV provide a component of external glass partitions or solar shading systems. For this reason, they generally result in favourable effects in terms of architectural integration. From the outside, shadow-voltaic systems on arched roofs, if the boundary between the roof and the facade is blurred, potentially exert the strongest impact. However, what should be considered is the direct aesthetic impact on the internal space when the PV elements are visible from the inside. It concerns the plastic and compositional features of the glass roof (texture, colour divisions). Indirectly, the impact on internal space is exerted through the impact on internal lighting (change of light intensity and even a colourful chiaroscuro effect can be an element of aesthetic creation). Indirect impact, as in solid roofs, may consist in adjusting the geometry of glass roofs to the energy needs of PV modules, i.e., creating the most favourable solar exposure (e.g., glass roofs).
Functional	Limited impact. Indirectly, it is related to the restrictions on the introduction of roof elements that could shade the modules, as well as elements that limit the PV modules' total area (e.g., numerous and large roof windows). South-oriented shed roofs create favourable conditions to meet the aspirations for favourable natural lighting of interiors while meeting the energy conditions related to the requirements of the PV modules' operation.	Potentially significant impact on shaping the visual and thermal environment of the space under the PV glass roof. The possibility to use PV modules as shading elements (solar glazing and shadow-voltaic systems). Semi-transparent modules with distanced PV cells may be inadequate in spaces that require diffused natural light, devoid of chiaroscuro contrasts. For this reason, they are more suitable for covering public spaces (e.g., courtyards, and entrance halls). Another problem may be related to the need to reconcile the efforts to create high-power PV installations with the premises regarding effective natural lighting.
Technical	PV modules require a base surface that provides effective cooling from underneath (e.g., a trapezoidal sheet). System solutions tailored to a specific manufacturer are recommended. It may also be important to adjust the roof covering in terms of reflecting light (albedo); bright, glossy materials can increase the influx of solar radiation (especially in shed roofs).	In the case of glazing-integrated PV elements, the impact is limited – these elements use support systems for glass roofs. The profiles of the glass systems should make it possible to conceal the wiring and connection sockets. Shadow-voltaic systems require a base surface analogous to traditional external solar protection systems.
	Indirect impact consists in adapting the structure to the roof profile, which results from energy conditions related to the PV elements' inclination.	

Source: own elaboration.

DISCUSSION AND CONCLUSIONS

The conducted analysis indicates a good deal of possibilities to integrate PV modules used on non-flat roofs with the broadly understood building architecture. These possibilities vary depending on the type of roof. The differences concern all three aspects: aesthetic, functional, and technical. It should also be noted that a difference in the use of PV technology within solid and glazed roofs is likely.

Further detailed research is required. The glazing application of BIPV in the energy context seems especially interesting. The search for balance between energy gains from photovoltaics and the use of natural light is a crucial issue. Other issues that require more attention are: the potential of BIPV in shaping flat roofs, regarded as the "fifth facade", and the influence of glazed PV roof elements applications on the thermal and visual internal environment of the building.

The following general conclusions can be drawn from the analyses:

– Photovoltaic technology should be taken into account during the design phase. This mainly applies to its applications within solid roofs. Then, the possibilities for successful integration of PV modules with architecture increase, both in the aesthetic and technical context. These modules are used within glazed roofs and generally serve as elements that are strongly integrated into the building's architecture, as they are a building component rather than a separate installation.
– In addition to the direct impact of PV modules on the building's architecture, activities involving shaping the building body under the influence of their application should be considered an interesting manifestation of the integration of PV technology with architecture.
– The problem of the lack of architectural visibility of roof-based PV modules applies only in some cases (e.g., roofs with a small slope and the majority of shed roofs).
– The impact of PV modules on the aesthetic aspect is more related to the building's body in the case of applications within solid roofs and the internal space in the case of applications within glazed roofs.
– Compared to solid roofs, the use of PV modules within glass roofs offers greater possibilities to take advantage of these elements while shaping the thermal and visual environment. These modules should be seen as part of the strategy of coupling with solar architecture, also in order to increase their role in the building.
– The use of PV modules within roofs should form a consensus between the desire to maximise energy gains and the utility requirements in terms of ensuring natural lighting of interiors, also in terms of energy benefits.

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ANALIZA ARCHITEKTONICZNA APLIKACJI MODUŁÓW FOTOWOLTAICZNYCH (PV) NA DACHACH NIEPŁASKICH

STRESZCZENIE

Za sprawą rosnącego znaczenia technologii z wykorzystaniem odnawialnych źródeł energii (OZE) obserwuje się wzrost zainteresowania fotowoltaiką. Dachy budynków często stanowią miejsce montażu modułów fotowoltaicznych (PV). Nieprzemyślane decyzje o doborze i sposobie zamontowania modułów PV niejednokrotnie prowadzą do niekorzystnych efektów architektonicznych. Artykuł ma na celu zbadanie możliwości integracji modułów PV w obrębie dachów niepłaskich z szeroko rozumianą architekturą budynku. Wykorzystano metodę obserwacyjną z zastosowaniem analizy przypadków. Pod uwagę wzięto nie tylko aspekty estetyczne, ale także funkcjonalne i techniczne, rozważono również aspekty energetycznych. Przeprowadzona analiza wskazuje na duże możliwości integracji modułów PV z architekturą. Możliwości te są zróżnicowane w zależności od cech geometrycznych dachu. Odrębnością cechują się również rozwiązania techniczne tego typu stosowane na dachów pełnych i przeszklonych.

Słowa kluczowe: fotowoltaika, moduły fotowoltaiczne PV, architektura słoneczna, dachy, BIPV