

Article

# Investigation of the Effective Use of Photovoltaic Modules in Architecture

Waclaw Celadyn <sup>1,\*</sup>  and Pawel Filipek <sup>2</sup>

<sup>1</sup> Faculty of Architecture, Cracow University of Technology, 30-084 Krakow, Poland

<sup>2</sup> Architecture Studio Filipek, 31-423 Krakow, Poland; paulusfilipek@gmail.com

\* Correspondence: wceladyn@pk.edu.pl

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**Abstract:** The application of photovoltaic systems is becoming a dominant feature in contemporary buildings. They allow for the achievement of zero-energy constructions. However, the principles of this strategy are not yet sufficiently known among architects. The purpose of this study is to enhance their expertise, which cannot be widened due to the shortage of targeted publications. The issue presentation was structured in a way that follows the typical design stages, beginning with large-scale urban problems up to the scale of building forms and components. Different types of photovoltaic (PV) systems are considered, based on their efficiency, relations with building fabrics, potential for thermally protecting buildings and their impact on esthetic values. The focus was mainly on the most popular PV modules. The application of these systems requires in-depth analyses which should be carried out by designers at the initial stage and through the next stages of the design. A method to analyze zoning plan regulations and site planning in view of PV modules' efficiency is novel. This paper also contains considerations with regard to some other untypical applications of these systems. There is need for changing attitudes in architects and investors regarding the issue of promoting the systems through further elucidations.

**Keywords:** architecture; architectural design; photovoltaic modules in architecture

## 1. Introduction

Among the few methods of gaining energy from renewable sources set in the paradigm of sustainable architecture, it is the photovoltaic (PV) modules (further termed PV panels) which have become the most promoted and used in contemporary buildings. Of the solar electric systems currently available, photovoltaic technology is the most advanced and mature [1] (p. 75). The relative simplicity of installation, skyrocketing electric rates and a comfortable accessibility of generated electrical power for household appliances make PV technology a reasonable option for homeowners as well as for an array of facilities to solve energy problems. Solar panels are becoming gradually more popular as their costs are falling, and this form of electricity generation is growing fast [2] (p. 260). Another reason for the increasing use of this technology in the building market is because solar thermal electricity costs more than PV electricity [3]. The green electrical generating systems, because of their sustainable and ecological nature, are classified as a nonmaterial tecnofact [1] (p. 68). They bring many ecological advantages not only for using renewable energy, but also for reducing carbon dioxide emissions and fostering a recommended decentralized electrical power production, which thereby achieves a higher security level, e.g., because of an increased resilience to power outages.

Architecture based on a solar energy concept is sometimes called regenerative. A regenerative system provides the continuous replacement, through its own functional process, of the energy and materials used in the operation [4] (p. 10). The energy is replaced primarily by incoming solar radiation; thus, photovoltaic systems make buildings ecological. The processes for converting solar energy to

electrical power are the most efficient regenerative energy-conversion processes. Most regenerative technologies are modular in nature, just like photovoltaic cells [4] (p. 74).

Given the constant increase in thermal requirements, PV panels have become an indispensable element of nearly zero-energy buildings (NZEBs), which will shortly be a pervasive standard model. However, the application of photovoltaic systems to buildings requires in-depth analyses to make this energy option perform well in terms of its energy efficiency, economic issues, spatial effects, as well as the esthetic values of buildings, their components, and even the plot layout.

The basic and detailed knowledge of solar systems is ample and constantly increasing. New solar technologies concerning PV panels and other electricity generating systems are extensively covered in publications. However, the complexity of the related problems is rarely considered in publications in a way that is useful for architects. Therefore, architects' viewpoints, hardly present therein, were the main reason for this research. This is what makes this paper covering these issues significant. Many other professionals analyze the problem of photovoltaic systems in a sectional scope of view, adding to the knowledge but missing the overall image of this multidisciplinary issue. A relatively complex, however, incomplete, picture of these systems can be found in some larger publications, like "Building-Integrated Solar Technology: Architectural Design with Photovoltaics and Solar Thermal Energy" [5] or [6]. This deals with the historical aspects of PV systems and contains a series of study cases. There are also some other published papers related to the issue [7–12], to mention a few, but none are of full practical use for architects. The purpose of this work is to enhance the knowledge of the designers of architecture by issuing a research-based study, which would encourage them to approach their creative activity in a less intuitive way, in terms of solar electricity generation. This is important as the relations between the building components and installed PV panels must be analyzed at the first concept sketches for designed buildings. To do this in a competent way, an architect should possess an appropriate knowledge before he eventually analyzes the problem with specialists in the field, who, in turn, are less knowledgeable on spatial and esthetic issues. Contributing to improvements in architects' competence makes this study purposeful.

## 2. Materials and Methods

This research is by its nature, and the character of targeted professionals, a complex task. Its scope is closely linked to the consecutive stages of architectural design to be of practical use for designers. Therefore, the method and structure of the paper were determined, by the design procedures, as outcomes of every consecutive step; this philosophy has a very distinctive impact on the next stage and related analysis. The idea underlying the design procedure usually consists of the gradual passage from large-scale decisions to small-scale solutions. In order to deal properly and systematically with the matter of this research, which is PV panels, the first step was to carry out an analysis of a wide range of accessible PV components offered on the market. Among many solar electricity-generating systems, the technology using PV panels is crucial, as it is the most popular and frequently opted for among building investors. It also requires in-depth analyses of multiple aspects of their installation. This is the reason for which this study has been overwhelmingly focused on this technology. The study is mainly concentrated on PV panels installed on roofs, as this location is presently more exigent for them in some positions, i.e., mainly facades.

The purpose of this research is to define the conditions assuring a rational choice of devices, and a method of their use to achieve the optimum energy and esthetic efficiency, coupled with the best spatial results. Large-scale considerations, being the next stage of this procedure, are the multifaceted analyses of the location characteristics aiming at the formulation of proposals for the optimum energy generation-related layout of a given land plot. This initial task is not an easy problem because of different spatial and some other restrictions comprised within zoning plans for defined areas of cities or villages.

The determination of the mutual spatial configuration of PV panels mounted on buildings, and their position in relation to incident solar radiation assuring their efficiency, is the subsequent

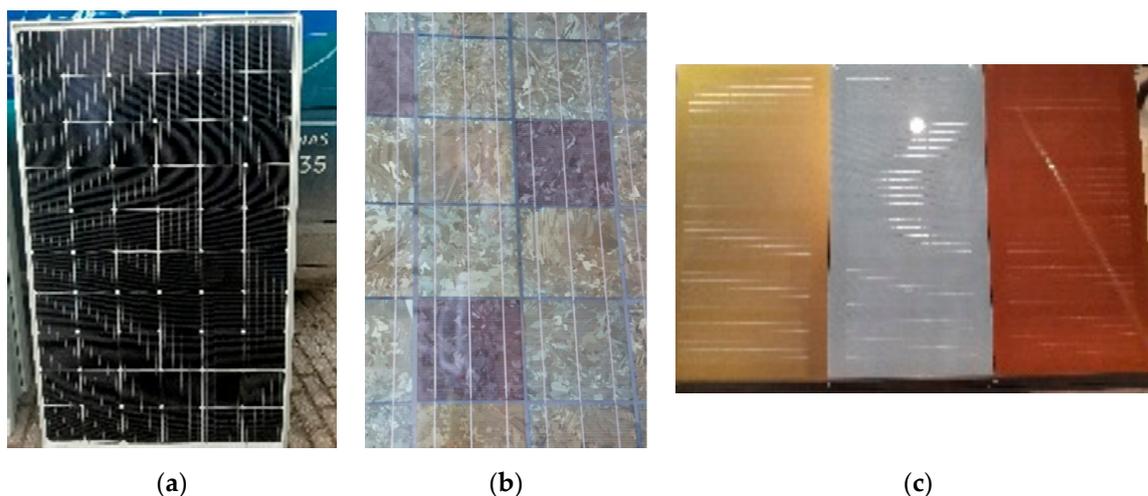
stage of this logical procedure. A method of deciding on the location of these devices on buildings and their parts is the next consideration. Esthetical issues are usually not considered a scientific domain. However, in the case of architectural discussions and analyses, it cannot be excluded from the relevant research. It also makes a significant consecutive part of this study. Finally, the research deals with some other functions that the PV panels used in architecture take on, and thus contribute to a better energy efficiency of contemporary buildings. A chart with the energy yield of an analyzed house was generated by sunnyportal.com. A simulation of the insolation and shading by PV panels was made with the use of Sketchup program and the application CuricSun.

The presented multifaceted and multistaged method permits the logically interrelate subsequent stages of research-based approaches to design buildings fitted with PV panels. The use of other PV technologies has been mentioned in these considerations, but they require a somewhat different approach.

### 3. Analyses of PV Technologies and Important Design Issues

#### 3.1. PV Panel Systems and Their Development

PV panels, the most popular system for providing renewable energy to buildings on the market, have developed rapidly, bringing down their prices. The low performance of PV panels has increased gradually up to a 17% energy effectiveness, on average. Some of the newest systems boast a 40% energy effectiveness. The development of these systems enhanced not only the higher energy efficiency of panels, but also made some breakthroughs in terms of basic materials. The systems are classified into three generations [13] (p. 24). The first one is the most popular monocrystalline silicon cells (SCPV, m-Si) which have the highest efficiency (13–26.1% [14]), and are durable and expensive, as well as polycrystalline silicon cells (PCPV, p-Si) which have a lower energy efficiency of 10–23.3%, typically 11–14%, and are less expensive, as evidenced by [14,15] (p. 291), and [1] (pp. 76–77). The second generation are the transparent thin-film cells, which offer flexible systems, are less durable, less expensive and have lower efficiencies (5–7%), as evidenced by [1] (pp. 77–78), due to other sources having a maximum of 14% for amorphous Si:H stabilized solar cells [14]. They can be installed on curved surfaces. An attractive option is the possibility of their integration with membrane flexible constructions. The third-generation systems are of very different technologies. One novel solution is a polymer-based system (DSSC—dye-sensitized solar cells) which has a 12.3% efficiency (as can be seen in [14] and [16] (pp. 1–11)). Perovskite/Si tandem (monolithic) cells achieve a 29.1% energy yield [14]. The modules of mass production have somewhat lower efficiencies. The available maximum energy efficiency of multijunction solar cells is about 47.1% [14]. The solar cells at more than 40% efficiencies are mostly of very small dimensions and are used mostly in concentrated solar modules and in rigid frames (not flexible), which require heliostats for installations and operations. It should be mentioned that some current top solar cells are not ready or appropriate for applications in buildings now. The focus of the innovative third-generation PV systems is on thin-film technologies that combine the high electrical efficiency of monocrystalline cells with the flexibility and lower costs of thin-film manufacturing [8] (p. 106). Monocrystalline panels are black or deep-blue, which is a serious drawback from an architect's viewpoint (Figure 1a). Polycrystalline panels offer a wider palette of accessible colors, which was welcomed by architects (Figure 1b). However, an even better and more attractive solution is a new generation of PV cells that come in a much more diversified scale of colors (Figure 1c). In this case, there is an interrelation between a given color and the efficiency of a panel. Generally, it has been proved that the most energy efficient panels are black PV panels, and lighter colors reduce the efficiency [17].



**Figure 1.** Photovoltaic panels: (a) monocrystalline, (b) polycrystalline, (c) dye-sensitized colored cell (photo by Celadyn, W.).

PV panels can be mounted on roofs, facades or be stand-alone frames on the ground. When they are in some way integrated with building components, they are termed building-integrated PV (BIPV) systems. Especially exciting are the building-integrated photovoltaic technologies integrating solar cells directly into building materials, such as semitransparent insulated glass windows, skylights, spandrel panels, flexible shingles, and raised-seam metal roofing [18] (p. 309), [19] (p. 3) and [20]. Well-integrated PV modules are suitable to contribute to the comfort of the building: they serve as weather protection, heat insulation, shading modulation, noise protection, thermal isolation and electromagnetic shielding, etc. [11] (p. 126). Holistically designed BIPV systems will reduce a building's energy demand from the electric utility grid while generating electricity on-site and performing as the weathering skin of the building [6] (p. 2). The first pioneering building with a BIPV installation was a multifamily residence designed by T. Herzog and B. Schilling and constructed in Munich in 1982 [21].

In future cities, solar cells and BIPV systems will evermore play an increasingly significant role in facade forming and electrical energy generation in the residential and other types of objects [8] (p. 104). The comparable prices between BIPV systems and conventional building materials confirm this assumption [20,22] (p. 9).

Retrofitting historical buildings, which aims at improving their energy-related parameters, can make use of photovoltaic systems. However, in this case the installation of these systems on facades or rooftops can be more difficult and controversial than in contemporary buildings as it can involve interventions in a building's valuable historic appearance. Therefore, instead of considering BIPV as a technical constraint for designers, a new approach based on the integration of BIPV solutions as a new "raw material" for architectural renewal projects is a good option avoiding conspicuous disfigurements of the building envelope [10] (pp. 1–2).

PV solar systems can store the produced energy, locally converted from a DC to AC current, in home batteries, or send it into the utility grid—the community's electrical wires—to be distributed to others [23] (p. 223). Panel installations can be fixed or track the sun, usually on one axis only.

Not everyone likes the appearance of typical solar electric systems, which are usually mounted on roofs. Therefore, solar manufacturers have begun to produce less conspicuous systems like thin-film solar electric materials using a noncrystalline sun-absorbing layer, which use a fraction of the semiconductor material of their predecessors. This amorphous silicon is, however, only 5% efficient. Despite its evident positive characteristics permitting its use in windows and skylights to produce electricity, it has some significant disadvantages [23] (p. 221).

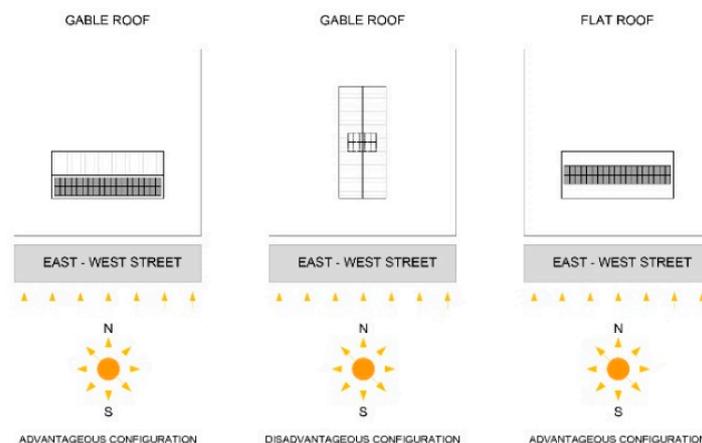
Meeting the sustainability paradigm requires building resiliency, which can be achieved using a diversity of energy sources. This option enhances the system's ability to function under a wide

variety of conditions and withstand many kinds of disturbances. Individual homeowners and businesses are encouraged to install small-scale wind turbines, photovoltaic panels, and other devices to produce renewable energy [24] (p. 158). PV panels are considered an indispensable, easy to install, and relatively inexpensive solution to such systems. Therefore, they play a significant role in increasing the sustainability of buildings of all kinds.

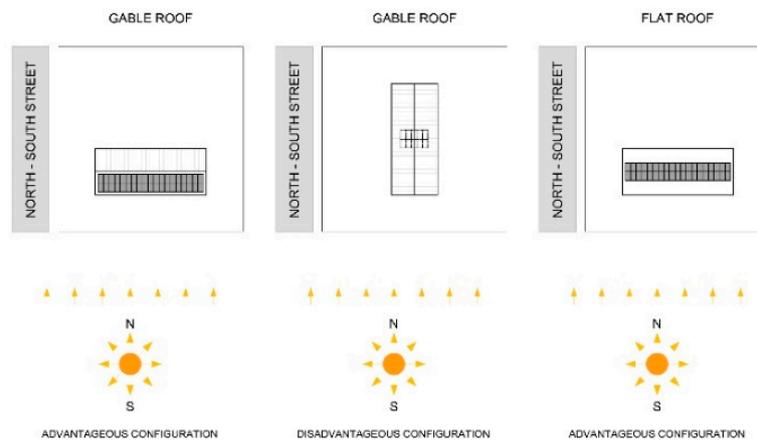
### 3.2. Impact of the Local Zoning Plans and Building Location on the Energy Efficiency of PV Panels

Decisions concerning the implementation of solar systems at the urban scale should be based on the local conditions of solar irradiation and these values defined in solar maps. Solar maps provide data about the position and system size of PV systems on roofs, the produced amount of electricity, the installation size, and the financial payback time. In this case, the output of the PV system is, besides the efficiency and additional losses, calculated by considering the air temperatures near urban rooftops [25] (p. 44). The appropriate configuration of PV panels with a building and its components is a basic requirement for the energy efficiency of PV systems. In many cases, it is the built or natural elements surrounding a building that may be crucial for solar harvesting on building facades and roofs. They can impair the solar radiation incident on the building and PV panels. Therefore, the building designers should carefully analyze the proposed site plan in terms of the potential obstacles to the undisturbed flow of radiation toward a building. There are two determining factors in this regard: (1) regulations in development (zoning) plans and (2) site planning solutions unrestricted by building regulations.

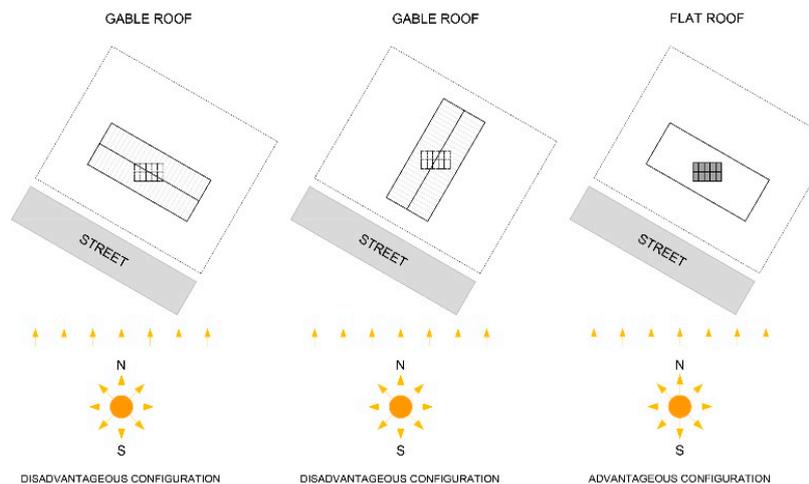
Zoning plans contain various regulations that must be respected by architects when designing buildings and implementing site plans. Especially important are stipulations regarding the orientation of buildings, their position on the lot, and their relation to the urban grid. They all impact the efficiency of PV panels installed on buildings. Even if respecting the local ordinance does not result in some impairments to solar systems, other elements of site plans, of which their location is unrestricted or undefined therein, may conflict with the efficiency of panels. The built structures located on the same or adjacent tract of land, as well as vegetation, can aggravate their yield or even thoroughly render them inefficient or useless if they are an obstacle intercepting the path of solar rays. There are some typical situations in zoning plans that could be indicated as conflicting with the rules for PV panel positioning to ensure an acceptable electricity yield in these installations. In the case of the pitched roofs of houses, the optimum location for the installation of panels is the south-inclined roof surface. A problem appears when the zoning plan determines the north–south axis of a building as compulsory for the building's orientation. The panels, for obvious reasons, must be exposed to the east or west, which are not optimal situations (Figure 2). Similar problems can occur in the case of a north–south street orientation (Figure 3). NW–SE orientations can also be disadvantageous for a similar reason (Figure 4).



**Figure 2.** Possible positions of photovoltaic (PV) panels as a function of a W–E street orientation (diagram by W. Celadyn, P. Filipek).

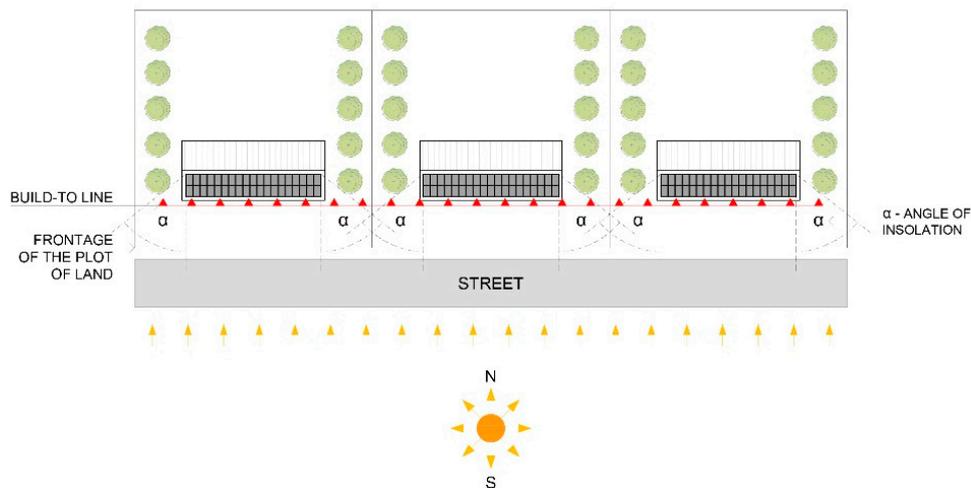


**Figure 3.** Possible positions of PV panels as function of an N–S street orientation (diagram by W. Celadyn, P. Filipek).

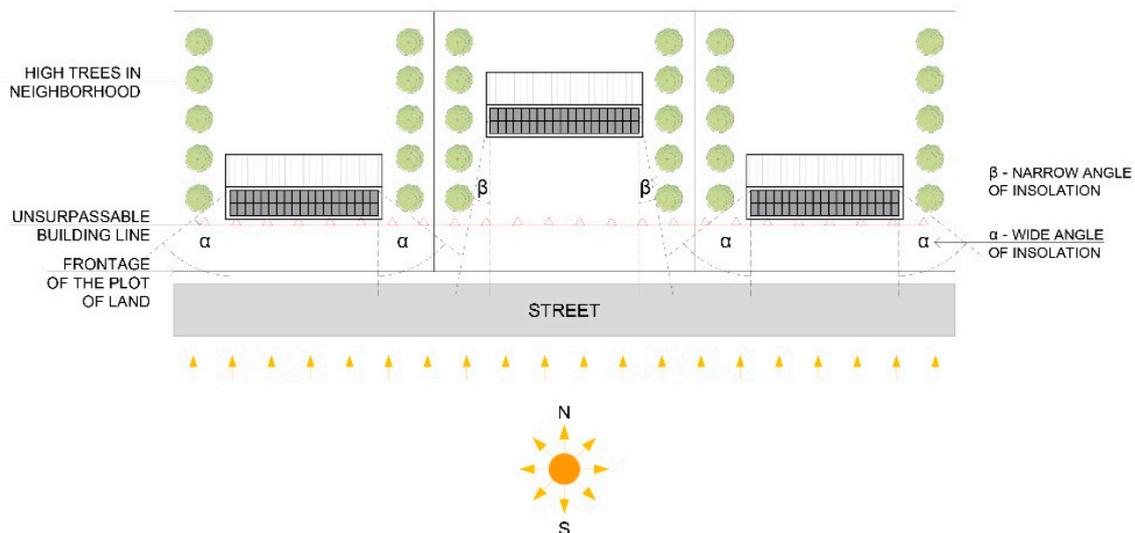


**Figure 4.** Possible positions of PV panels as function of an NW–SE street orientation (diagram by W. Celadyn, P. Filipek).

Another aspect of zoning plan regulations and their consequence on PV panels' efficiency is the obligation to respect the building lines comprised therein. There are usually two basic types of building lines that determine the location of constructions on building lots: the build-to line and unsurpassable building line. In the first case, a building should be located on a building lot so that its main facade is contiguous to the line. The compulsory character of a building's location permits the design of surrounding vegetation, if present, to ensure that the intensity of solar radiation incident on PV panels is not impaired (Figure 5). In the second variant, a building can be located to ensure the defined line is not surpassed. The first option ensures that the spatial situation is controllable, whereas, in the second, it is impossible to predict the final location, which is dependent on the architect's decision. This occurrence makes the issue of the reasonable configuration of adjacent buildings and the vegetation existing on-site prior to their construction unpredictable, as it does for the efficiency of the potential solar systems installed on buildings (Figure 6).



**Figure 5.** Predictable positions of buildings and PV panels because of a compulsory built-to line defined in the zoning plan (diagram by W. Celadyn, P. Filipek).



**Figure 6.** Probable positions of buildings and PV panels because of noncompulsory unsurpassable building line defined in the zoning plan (diagram by W. Celadyn, P. Filipek).

This analysis indicates that the zoning plan regulations have meaningful relationships with building solar systems. Their mutual dependence should be seriously considered and carefully analyzed by both urban planners and architects to ensure the systems work in terms of the potential electrical energy generation. Zoning plans generally do not envisage such analyses. This creates challenges for the installation of PV panels, rendering them frequently useless. This occurs with existing buildings and their surroundings. The property relations and adjacent parcels being built and arranged with high vegetation make the situation difficult to resolve. So far, the awareness of planning officers and urban planners in this regard appears insufficient, if not absent.

### 3.3. Spatial Position of PV Panels and Their Energy Efficiency

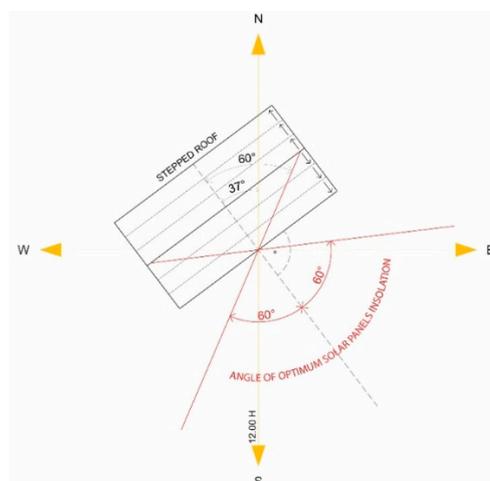
Whereas solar thermal systems have always been closely tied to the planning of buildings, developments in photovoltaic technology allowed photovoltaic elements to be integrated in the building envelope since the early 1980s [26] (p. 106). However, the yield from a vertical facade panel is much lower. Unlike with thermal collectors, even an incident energy  $<200 \text{ W/m}^2$  can still contribute to generating electricity [15] (p. 291). This is why photovoltaic systems are less dependent on the orientation

of building components. However, to be energy efficient, the mutual configuration of the panel surfaces and the angles of incidence of solar rays must be optimized. This is a factor that, in practice, determines the possibility of installing effective solar systems on buildings. Therefore, it is important for the configuration to avoid any disturbances in the accessibility of solar rays. In contrast to solar thermal applications, in photovoltaics, even relatively little shading of the solar cells can lead to a considerable reduction in the energy yield [26] (p. 106).

The highest transmission of solar radiation through glass occurs when the angle of incidence of the solar rays on the glass surface is perpendicular. Research indicated that within the range of 0–60°, the deviation from perpendicular gives a transmission loss of energy between 8 and 10% [27], or even more. This loss (technically an incident angle modifier) is due to the glass internal transmission (due to a longer light path length) and glass surface reflection, not attributed to the total irradiance on the panel and PV electricity generation. The solar radiation (the beam component) is reduced to 50% for an incident angle of 60°, and abruptly drops down to 0% by the direct radiation angle of incidence approaching 90°. Behind this range, the intensity of the transmitted solar energy abruptly drops down to 0% when the angle of incidence approaches 90°. This does not mean that below this range that the electricity is not generated. About 50% of the radiation occurs in the form of diffuse radiation [15] (p. 291), so it still can generate some amount of energy; this even occurs under an overcast sky. PV cells can be mounted on movable panels programmed to track the sun so that the cells are always perpendicular to the sun's rays for the maximum interception of solar radiation [4] (p. 64).

The issue of the relationship between the angle of incidence of solar rays and the plane of photovoltaic panels is less important in the case of photovoltaic cells mounted on the membrane that absorb all incident sun rays from any direction at any time of the year without the need for any manual or automatic override [28] (p. 34) (Figures 7 and 8).

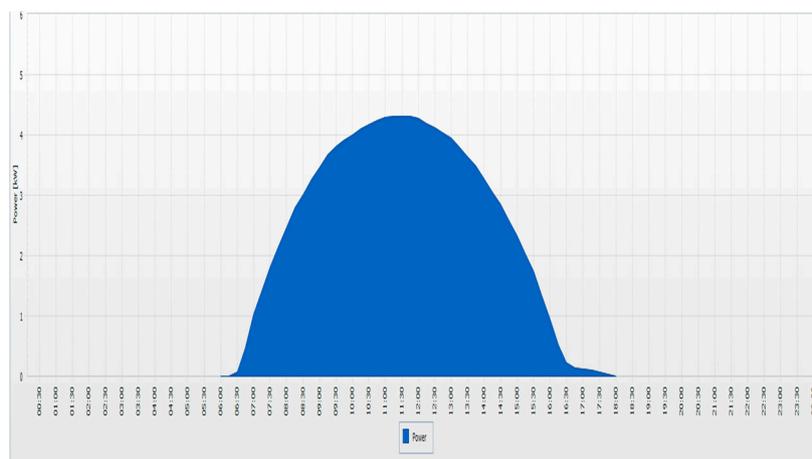
Solar radiation varies widely over the course of a day and a year and is strongly influenced by the prevailing weather conditions. Radiated energy can differ up to a factor of 10 on two consecutive days, being, at times, up to 50 times higher values on a clear summer day than on an overcast winter day [29] (p. 49). Some sources suggest that the highest annual radiation volume in Central Europe is available to south-facing fixed systems installed at an angle of 30 degrees or less to the horizontal [15] (p. 291). A south-west orientation by the same inclination reduces the yield to only 96% [29] (p. 54). The case of a house in Figures 7 and 8 proves that PV panels with an energy efficiency of 5.5 kWp installed on its roof and deviating by 37° from the north–south towards the south–east can still produce electricity in significant quantities (Figure 9). On the winter day of 15 March, the electricity generation reached its peak of 4.2 kW, and was registered as late at 6 pm.



**Figure 7.** A house oriented at an angle of 37° from the N–S direction with PV panels installed on a stepped roof (diagram by W. Celadyn, P. Filipek).



**Figure 8.** Stepped roof with PV monocrystalline photovoltaic panels installed at the recommended angle of  $15^\circ$ . Location:  $49^\circ 57'$  N,  $19^\circ 55'$  E (photo by W. Celadyn).



**Figure 9.** A chart indicating the solar efficiency of the above house on a sunny day (15 March 2020). Location:  $49^\circ 57'$  N,  $19^\circ 55'$  E (source: sunnyportal.com).

Computer tools are available for the calculation of the efficiency of photovoltaic systems; an example is PVSYST, used by, e.g., Fartaria [30] (pp. 93–101), to calculate the mutual shading of direct normal and diffuse radiation. Building envelopes can lend walls and roofs to photovoltaic installations, and substantial differences exist between their solar conditions. In the latter, pitched and flat roofs are also differentiated in this regard. Flat roofs are a particularly good place for the location of PV panels as their arrangement is independent of the roof pitch. However, the problem of self-shading occurs due to adjacent tilt panels on flat surfaces or due to them tilting away from low sloped roofs. As a rule of thumb, there must not be any shading on 21 December. The calculated minimal module spacing (in the Northern Hemisphere) is defined by the equation previously reported by [31] (p. 227). To accommodate as much PV power as possible, the optimum angle of attack,  $\beta$ , equal to  $15^\circ$  to the horizontal, is often changed to  $20^\circ$ , as the energy yield is then only reduced by 2% [31] (p. 227). This angle varies with the latitude of installation. The optimal tilt angle is within the latitude angle plus or minus  $10\text{--}15^\circ$ . The lower the angle of inclination of the module surface, the higher the usable incident radiation. When the modules are installed over the entire roof surface, almost horizontal, the overall

energy yield is maximized [26] (p. 107). The energy output of PV panels can be compromised by their low tilt as the cleaning of their surfaces by rainwater is less efficient.

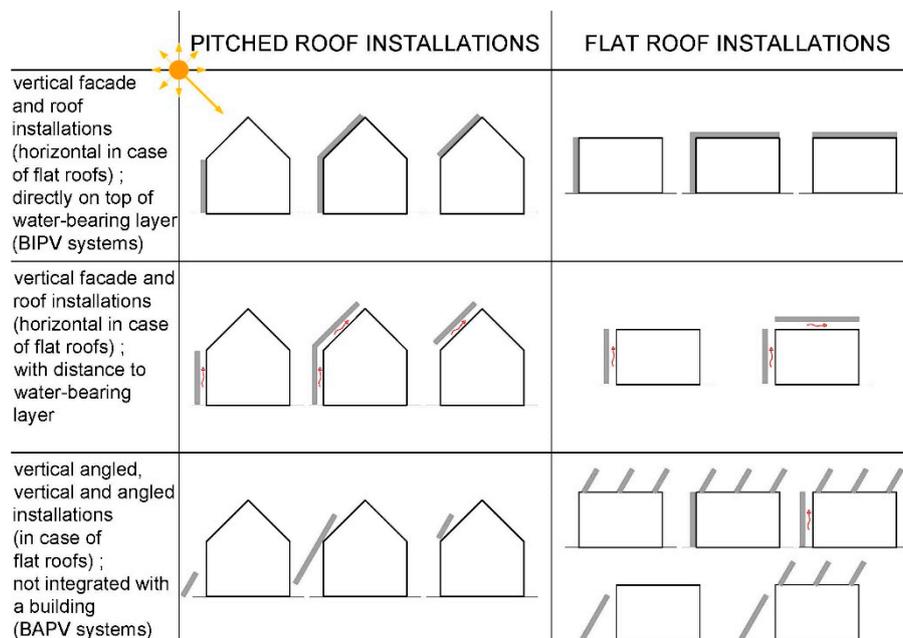
Most of the absorbed solar radiation becomes thermal energy that can heat up the PV panels. An increase in the temperature of the panels over 25 °C is disadvantageous as the PV panel will produce less than the rated generation efficiency. This efficiency loss due to an increased temperature depends on the types of solar cells involved. An effective ventilation of the back of panels or the use of generated thermal energy to heat the interiors or water can be helpful.

### 3.4. Spatial Relations of Buildings and PV Panels

Photovoltaic panels are installed on buildings in two basic configurations with respect to building components [29] (p. 59):

- (1) vertical, horizontal, or angled installations directly on top of water-bearing layers;
- (2) vertical, horizontal, or angled installations with a distance from water-bearing layers.

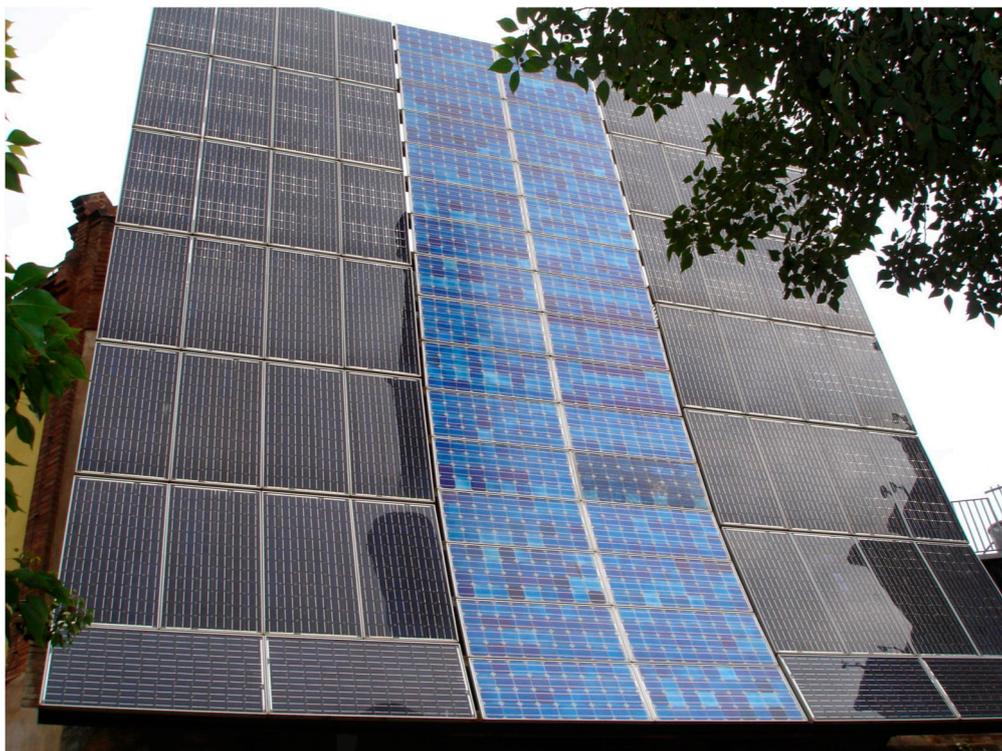
These relations between building components and photovoltaic array mounting systems can be also classified as BIPV and BAPV. BIPV is considered a functional part of the building structure as it is architecturally integrated into the building's design. This category includes designs that replace the conventional roofing materials, such as shingles, tiles, slate, and metal roofing. BAPV is considered an add-on to the building, not directly related to the structure's functional aspects (Figures 10–12). It relies on a superstructure that supports conventional framed modules. Standoff and rack-mounted arrays are the two subcategories of BAPV systems. Standoff arrays are mounted above the roof surface and are parallel to the slope of a pitched roof. Rack-mounted arrays are typically installed on flat or pitched roofs. In the second case, the tilt is either parallel to or different from the roof inclination to be more suitable to the angle of solar incidence. From the above definition, the main difference between BIPV and BAPV is the extent of tightness of the integration of photovoltaic systems and buildings [9] (p. 3593). The multitude of possible relations between these two components is illustrated in Figure 10.



**Figure 10.** Types of relations between the photovoltaic solar systems and building forms and components (diagram by W. Celadyn, P. Filipek).



**Figure 11.** Solar electricity generating thin-film system independent of the building (photo by W. Celadyn).



**Figure 12.** PV modules installed on a structure added to an office building (photo by W. Celadyn).

An analysis of a building demonstrated the direct link between the functional requirements and external appearance. The drastic changes in the energy sector have had a lasting impact on this traditional link. The relationship between local conditions and their impact on the built environment is mostly nullified [29] (p. 38). Contrary to collectors that are mounted onto the building skin, these systems allow for a full integration both in terms of construction and design [32] (p. 262).

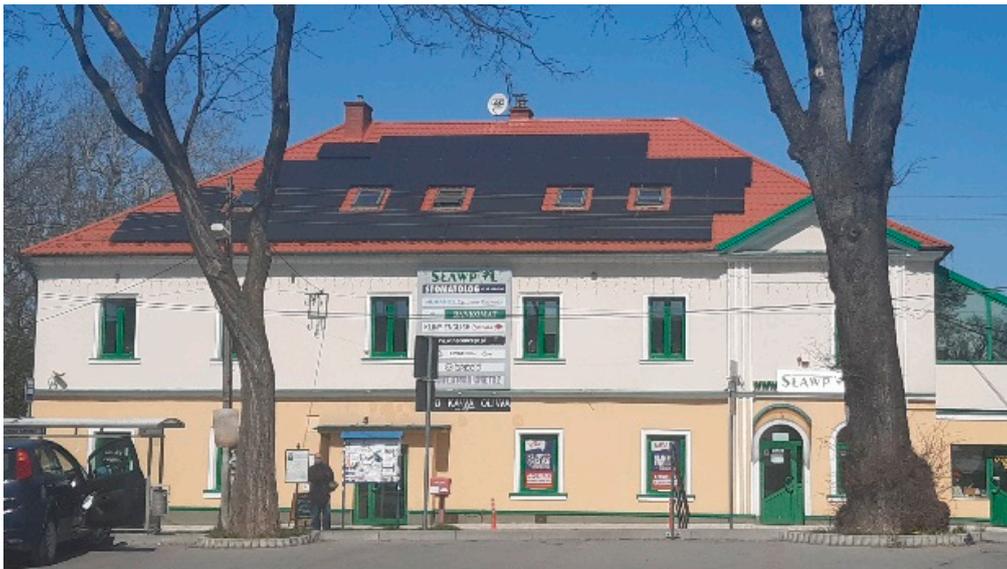
### 3.5. Photovoltaic Panels and Esthetical Issues in Buildings

The growing popularity of solar photovoltaic systems has created new problems regarding esthetic values. The unstoppable trend toward the installation of solar systems on building envelopes, especially the first-generation PV panels, evoked ambiguous opinions from architects. The esthetic effects of PV assemblies mounted on buildings were criticized. Two decades ago, the issue of esthetics concerning the “solar design” was raised. Then, some steps should have been undertaken to modify the appearance of PV panels so that they would not only generate electrical energy but also have visual appeal and blend in with their surroundings [33] (p. 1). At that time, voices stated that the esthetic qualities of the buildings continued to be a largely unsolved problem.

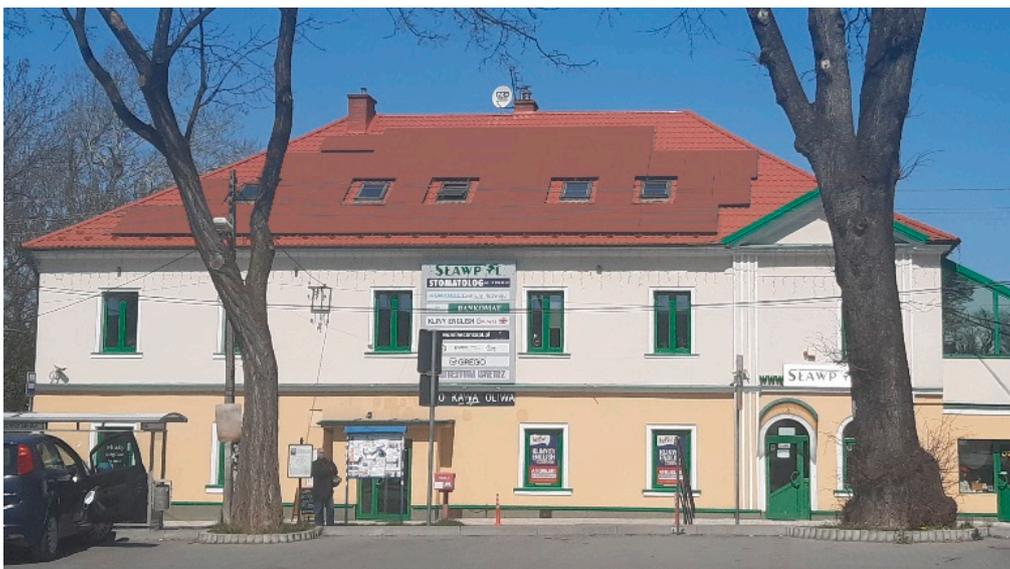
Typological studies of building skins are still lacking, which would be an important basis and evaluation tool for the visual integration of solar technical systems. They should be visually integrated into the overall architectural concept [29] (p. 60). Innovative PV systems of the second and third generations are much less controversial than conventional PV panels, as they can be easily integrated with building components, being available as roof tiles, window glass, or facade finish panels replacing other typical materials. This assortment has changed the attitude of designers toward solar systems because they can be hidden or visually blended in with the background. The esthetics issues in the case of solar buildings require a wider perspective to be discussed. A new kind of esthetic for the built environment has been suggested that explicitly teaches people about the potentially symbiotic relationship between culture, nature, and design. This is a powerful approach since new ideas are learned most rapidly when they can be expressed visually and experienced directly. This esthetic is called visual ecology and is opposed to the method of designing that hides natural processes and related technology out of the public view [34] (pp. 188–189).

Well-articulated ethics have not been developed for sustainable designs, neither has the environmental movement in general, with its various ethics on biodiversity, animal rights, stewardship, intergenerational ethics, and holism [35] (p. 83). A sustainable design gives people a beautiful experience of nature through highlighting the elegance of its processes. It may also forward the interaction of these processes with the patterns of space in the design, revealing the beauty of their connections [35] (p. 115). Something can be considered beautiful if it reveals how it changes over time, especially toward a greater integration, order, and complexity [35] (p. 119).

Solar systems fall into this philosophy. Many examples exist of buildings with conspicuous disharmoniously contrasting surfaces of installed PV modules and the covering materials of pitched roofs or facades. The rectangular or even irregular compositions of PV modules are negatively assessed against the backdrop of roof materials in colors significantly different from the black or deep-blue tones of typical monocrystalline panel materials (Figure 13). Such disharmonized color compositions usually appear on existing houses covered with ceramic tiles. Novel photovoltaic panel systems, as innovative organic cells and nanocrystals, offer interesting color effects for the panels [36]. They are available in a much richer palette of colors and tones and can offer a remedy to this problem as an appropriate color choice can reduce unwanted contrasts, but unfortunately, they are of a much lower energy efficiency (Figure 14). Darker colors of panels absorb solar radiation better and therefore are better in this regard. Multicolored glass–glass (MCGG) and crystalline silicon cell (c-Si) PV laminates are an approach to overcome some of these issues and achieve aesthetically pleasing, yet technically and economically viable, building-integrated PV systems [37] (p. 2).



**Figure 13.** Disharmonious color composition on the building's roof covered with red ceramic tiles and monocrystalline PV panels (photo by W. Celadyn).



**Figure 14.** Harmonized color composition on the building's roof with the application of a new generation of color PV panels (computer simulation by P. Filipek).

Some new methods are available for computationally matching the color of PV panels with roof covering materials. This procedure can achieve a perfect match [33] (p. 9). It is not only the issue of disharmonious colors; controversies exist over the excessive differences in the texture of shiny PV panels and matte roofing materials, which can substantially modify the originally well-matched colors.

Products are, by their very materiality, transient; their usefulness is unavoidably a function of time. They become obsolete for a variety of reasons, all of which help fix a product in a specific timeframe [38] (p. 139). PV panels are automatically associated with recent times and their installation on old-looking roof coverings or facades also creates a disharmonious and anachronic image. Photovoltaic panels are conspicuous technological components on building facades and roofs. This initiates an interaction between architecture and technology, which produces much controversy over the issue. Certain viewpoints state that they continually redefine each other. Depending on the type of applied solar systems and the way they are installed, they can define a high-tech or eco-tech aspect of a building,

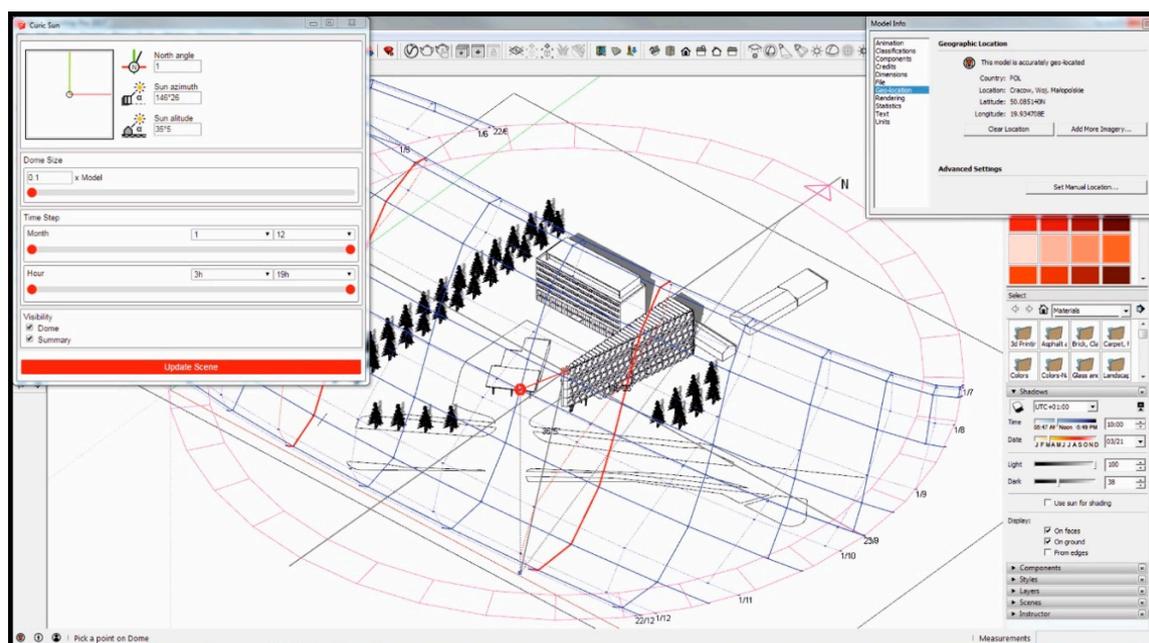
both considered opposite to each other [39] (p. 7). As the novel color PV modules offer many new unconventional esthetic opportunities, the possible integration of this technology and building envelope facilitates the approach of the built environment to the promoted eco-tech esthetics.

### 3.6. Other Functions of PV Panels for Buildings

In addition to the generation of electricity, PV modules are taking on more additional functions and are hence achieving numerous synergy effects—photovoltaic panels can provide protection from the weather, sun shading, and privacy functions, or, as insulating units, even constitute the thermal envelope. In addition, they can characterize the architecture [26] (p. 106). Some authors considered sun–shade systems, in addition to roof and facade systems, as one of the three basic photovoltaic systems [7] (p. 8). PV panels as sun protective devices, if they are strategically located, and due to adequate shading analyses, can effectively fulfill this role. There are many examples thereof. This strategy can lower the costs of construction through the dematerialization effect. Among such solutions, the shading role seems especially interesting due to the constantly increasing role of overheating in buildings. It relates mainly to office buildings, where this issue is important.

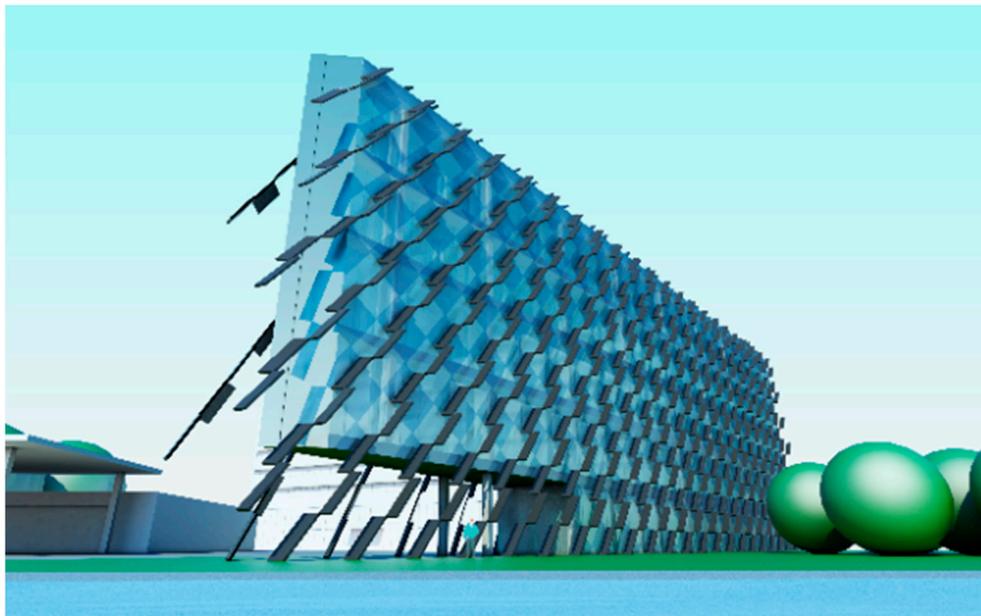
The southward-oriented building volume can be designed with a complementing facade module geometry. The overall irradiation of the building can be translated to a system of modules that allows external shading from solar radiation while permitting daylight entry and unimpeded views of the surrounding landscape from inside the building [40] (p. 3608). If the application of PV panels as shading systems on south-facing elevations is comprehensible, their use on other facades can be debatable, as is the case of conventional sun protective systems.

Sun shading on east or west facades is a difficult task. Solar radiation can be especially disturbing on office buildings with north–south orientations, with the longest facades exposed to low-angle of incident sunlight. The problem was illustrated with an example of an office building for which the incident solar beams and the shading pattern by PV modules were simulated (Figure 15). The set of diagrams presented below shows the path of solar rays and the resulting pattern of dark shadow patches on the elevation assigned to every hour between 7 a.m. and 12 p.m. (Figure 16). The simulation was carried out with the computer program Sketchup with a precisely defined geolocation and application CuricSun.



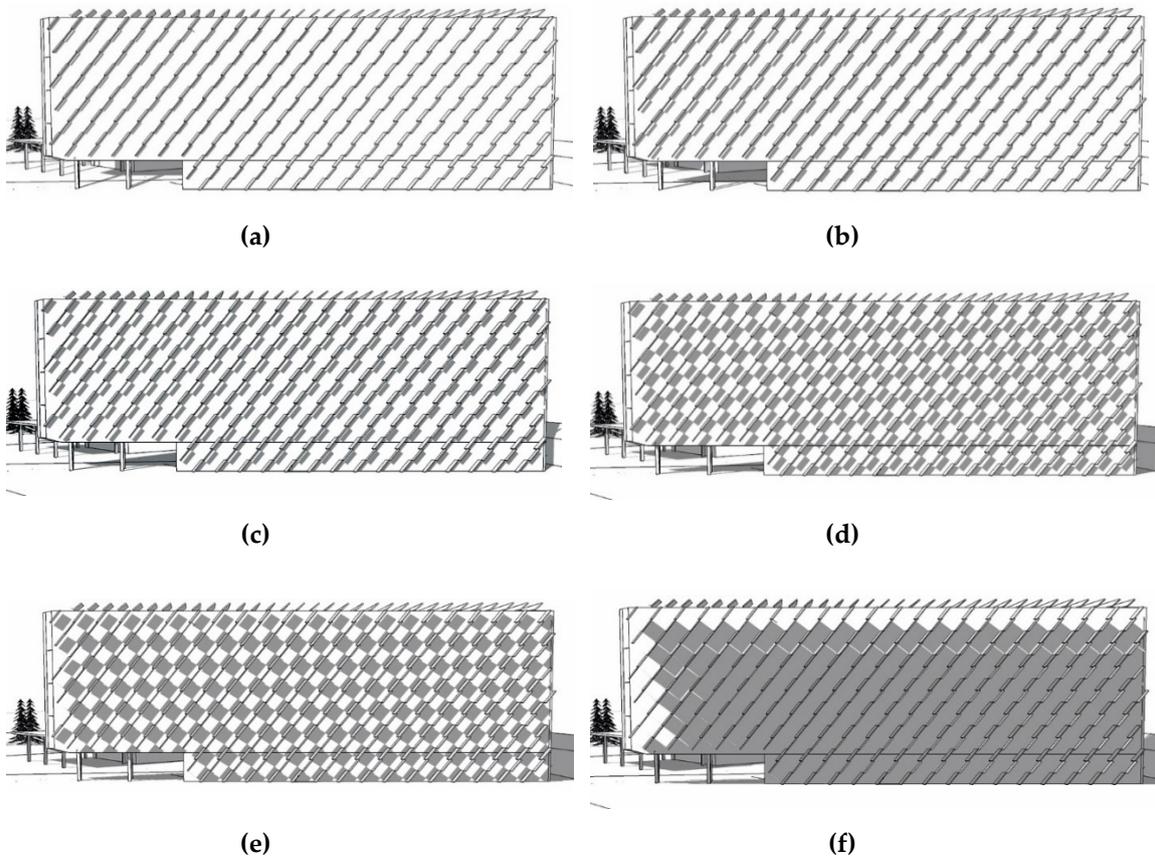
(a)

Figure 15. Cont.



(b)

**Figure 15.** Study of the sun shading of an office building fitted with PV panels located on geographical coordinates  $50^{\circ}5.118' N$  and  $19^{\circ}56.096' E$  (author: P. Filipek). (a) building's location, (b) building model and its shading pattern.



(a)

(b)

(c)

(d)

(e)

(f)

**Figure 16.** Hourly sequential shading of an office building fitted with PV panels on the east façade (a) At 7.00 a.m.; (b) At 8.00 a.m.; (c) At 9.00 a.m.; (d) At 10.00 a.m.; (e) At 11.00 a.m.; (f) At 12.00 a.m. (by P. Filipek).

Photovoltaic solar systems are applied on buildings in the form of panels that come in glossy and shiny finishes and are either opaque or semi-transparent. Reflections on this surface may make the modules highly visible at a distance and occasionally cause undesirable glare. There are some reports of blinding people in their vicinity [41] (p. 70), [23] (p. 221) and [33] (p. 1). Blinding by the reflective surfaces of PV panels can be reduced by the application of an antireflexive layer on top, and this increases the panels efficiency. This problem can be neglected in the presented analyzed office building. The location, layout, and orientation of the two main facades facing the west and east could potentially be reflective enough to blind the drivers approaching the building from the west or east along the street. However, the regular and all-over application of PV panels on these two facades and the rational arrangement at an angle resulting from the analysis of sun path diagram significantly reduce this problem. A possibility exists of blinding but only from the southern approach, which is impracticable for vehicles. There are methods of reducing the glare of glazed elevations. This effect can be achieved by a nonreflective film applied to panel surfaces [42] (p. 2). This method is practical for photovoltaic façade systems. Various designs were developed for prototypical applications to integrate PV systems into rooftop gardens, with a specific focus on retrofitting flat roofs. The concurrent integration of PVs and green roofs into the same surface area can be achieved with lightweight construction, which is particularly suitable for existing buildings. Such solutions for retrofitting existing roofs must be sought to transform the current building stock into energy generating green habitats [43] (pp. 1–2).

#### 4. Discussion

This research covered issues that are now rapidly changing due to new developments in the photovoltaic industry. Given the large discrepancies concerning the energy performance and material efficiency of these systems, systematic updates of designers' knowledge is required for choosing an appropriate option. Despite the novel third-generation systems offered by producers, conventional monocrystalline panels are still the most popular choice, especially for residential buildings. However, the second- and third-generation systems are becoming increasingly popular on the market, as they are more versatile in terms of their location on buildings or their components. They also offer more opportunities in terms of their variety—i.e., flexibility and colors. Along with their improved energy efficiency, they will be implemented more frequently. Their potential for retrofitting historic buildings seems especially promising. Although all the considered PV systems are on the market in a wide variety, they are undergoing constant improvements. This applies to increasing the economy and the options for architectural integration [44] (p. 68). The applied technology covers a wide range of problems pertaining to the technical durability of buildings. PV systems may conflict with other building systems in this regard. The potential problems of their longevity may appear in the case of BIPV. The materials or components can perform satisfactorily for a long time if they are autonomous within the structure, but coupled with other materials, they might form a new and less-stable system [45] (p. 21).

Zoning plans, as a rule, do not consider the prospective use of solar systems in buildings despite such applications not being new. Their impact on planning procedures has not yet been noted or recognized. Given the analyzed spatial configurations of buildings and access streets, as well as other elements of various arrangements, this problem should be raised and broader discussions among specialists and architecture authorities responsible for planning should be inspired. Some design-established procedures practiced among professionals in the field exhibiting a traditional and meaning-limited scope of analyzed aspects during their work on zoning plans should be modified and supplemented with energy-related issues. This means that the building location on the lot and a multitude of parameters related to buildings and their parts should be an indispensable part of plans, as well as other regulations related to energy. So far, this is not the case and no serious discussions are being conducted related to this subject. The reasons for this may be the complexity of the issue, the diversity of urban grids, difficulty in properly fitting the buildings, and the building orientation.

Another meaningful cause is property colliding with the optimum vegetation patterns. Harmonizing all these factors is hardly a feasible task. Discussions must be undertaken if a sustainable building and land use are to find logical solutions.

Conventional black photovoltaic panels installed on red, brown, or similar roofing materials are a frequently seen picture in landscapes. The replacement of red tiles or steel panels on existing buildings to harmonize them with the color of modules is rarely performed. New buildings offer opportunities to achieve satisfactory outcomes in this regard, as the option can be selected during the design stage. Matching the roof and panel, both in color and texture, is considered the most desirable solution from the esthetical point of view. However, when comparing the energy-related parameters of monochromatic black monocrystalline panels with the next-generation systems, which offer an increased esthetic potential, unavoidably a trade-off must be considered. As indicated earlier, monocrystalline panels are still the best option in terms of the ratio of electrical energy yield to costs. When a typical investor is faced with such a dilemma, they would, in most cases, opt for a less expensive and more efficient solution. This situation mainly refers to residential buildings. Only this segment of construction is responsible for the aforementioned controversies. The buildings of other functions are, in most cases, covered with flat roofs, which make photovoltaic roof installation invisible from the ground level. Small houses pose yet some other related problems. The more articulated the layout and roof form of a building, the less appropriate it is for the installation of PV panels, as fewer plane roof surfaces are offered, making the investment less rational. The color integration of panels and roof coverings can be considerably improved once more efficient and more affordable photovoltaic systems appear on the market and gain popularity. This could substantially contribute to an increased harmonization of the built landscape and improvement of its esthetic values.

Photovoltaic systems applied as sun protection modules, as analyzed earlier, are steadily appearing on more office buildings. They generate the most energy when exposed and inclined to the south. This occurs both on roofs and facades. East and west elevations are less efficient as their insolation is reduced merely to the half of the incident on the south-exposed walls. However, it does not make such applications useless. A reduction in the heat load due to the use of solar protective PV panels could at least partly compensate for the extra expenditure on the panels. This disadvantageous orientation of a building from the analyzed point of view, as an alternative installation of solar systems on flat roofs characteristic of office buildings, is not an encouraging solution. The reason for this is the longitudinal roof layout extended along the north–south axis, which is disadvantageous due to the limited amount of PV modules that would fit in the space given the necessary long distancing of adjacent panels in the space-consuming row arrangement mentioned earlier. A remaining question is the installation of PV panels on facades of multistory buildings. They are not yet economically feasible, as was calculated for a commercial building in the 10- to 20-story range (USA) [7] (p. 104).

The problem of blinding in the case of large glazed facades is potentially important when they are perpendicular to the direction of pedestrian or driver movements. Therefore, installed exterior sun protective systems can be an effective solution to reduce glare. A reasonable proportion of PV panels play that role, provided they are mounted on facades in the configuration depicted in Figure 15.

Findings from surveys on public educational barriers showed various reasons for a poor public understanding of the cost perceptions of BIPV systems and their financial benefits, and a lack of enough knowledge by clients and the public in general. Additionally reported was a high negative perception of the system price and costs associated with aesthetic BIPV options. The lack of knowledge on how to ensure the most efficient choice of BIPV design was also noted [46] (p. 5). All of this highlights the need for further relevant written contributions. The application of BIPV systems will progress in the near future, but some practical barriers remain, such as investment costs and the payback times of the solar energy technology, which are highly important for real estate developers.

## 5. Conclusions

Photovoltaic systems are an indispensable part of contemporary low-energy buildings. Their increasing popularity is linked to them being the cheapest and easiest method of making new and existing buildings at least partly sustainable due to using a renewable source of energy (solar energy), hence the financial support offered for their installation in special state programs in many countries. Their application requires specific knowledge from designers and building specialists. The systemic approach to the issue of suitable design decisions, which was presented in this study, entails the need for analyses of factors like: the spatial and technical parameters of a building, an in-depth study of site features including the orientation of building and its relation to the access street and other built structures on the building lot, as well as the position and type of vegetation. This broad view facilitates the choosing of the optimal solution to obtain the desired energy efficiency of the applied PV system.

Another problem of increasing significance is the esthetics concerning features such as building materials and their color and texture in terms of their harmony with PV panels, which are frequently considered inconsistent with buildings' traditional esthetic values. Building designers and investors have offered various systems that feature different characteristics covered in this research. This study was designed for architects to enhance their knowledge on this subject and to systematize the knowledge, providing a step-by-step process with the proposed procedure of suitably coupling designed buildings with photovoltaic systems. Notably, obstacles remain on this path, including an insufficient and obsolete knowledge of these systems, potential problems with their implementation, and mistrust of investors wary of potential excessive costs. However, some positive experiences with photovoltaics and imaginative thinking would help further the application of photovoltaic solutions in building developments and related industries. This promising vision should encourage further studies on the subject.

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