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Analysis of the properties and impact of the shape of a flexible photovoltaic roof tile on the effectiveness of its performance

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This paper concerns building integrated photovoltaics (BIPV), and in particular, potential advantages resulting from the use of this technology. The possibilities of integration of the BIPV elements in the building structure were presented, with particular consideration of photovoltaic roof covering. In order to demonstrate the legitimacy of using solutions of this type in real conditions, the subject of the analysis was the thin–film photovoltaic module, which constitutes an integral part of the photovoltaic roof tile. During the tests, particular attention was paid to changes in parameters of the tested object, depending on the way it is shaped in relation to the solar radiation, demonstrating in this way, the necessity to strive for the optimal exposure of the BIPV elements in relation to the sun.

KEYWORDS: photovoltaic roof tile, BIPV, amorphous cells, energy yield, current–voltage characteristics, photovoltaic module exposure

1. Introduction

Priority actions in the field of energy industry and environmental protection aimed at limitation of the exploitation of natural resources and minimisation of emission of harmful gases into the atmosphere, are conducive to searching alternative and innovative solutions applicable to renewable energy. Photovoltaics, as the field which deals with direct processing of the solar radiation energy into electric energy deserves particular attention here [4].

At present, one of the main applications of photovoltaics is the production of electricity in BAPV (Building Applied Photovoltaics) concept, i.e. the use of traditional photovoltaic modules installed on existing buildings. To make the most of this solution, it is required to ensure the availability of large space [1].

In response to this issue and in connection with the more and more frequent desire of architects and design engineers to create energy–saving buildings, while still maintaining their attractive and innovative form, the concept of integration of photovoltaics into the building structure appeared on the market.

The concept is defined as Building Integrated Photovoltaics (BIPV) and assumes the use of photovoltaic modules as optional elements in relation to the traditional building materials [1, 3]. Modules manufactured in the BIPV technology are distinguished by their greater functionality in comparison to the traditional solutions. Being integral components of a building, as well as producing electric energy, they can also fulfil such functions as: shading, thermal or sound insulation. One of advantages of the BIPV modules both with regards to the structural and material aspects is the possibility of their application on facades, roofs, windows, or in the form of sunshades [2]. Each of these solutions results in generation of different amounts of electricity.

At present, one of the most frequently used solutions is the integration of photovoltaics with the building by means of photovoltaic roof tiles [3]. The application of high quality components makes the installation look low–profile while at the same time maintaining all the waterproofing properties of ordinary roof tiles. Both solar roof coverings which preserve the shape of traditional ceramic tiles and those consisting of a series of serially connected several cells – bituminous roof tiles – are commercially available (Fig. 1).

Fig. 1. Example of use of a bituminous photovoltaic roof tile [7]

Due to the fact that a solar bituminous roof tile is characterised by high flexibility owing to the application of amorphous cells, and thus can be mounted in many more ways, it was decided to carry out the analysis of the impact of the shape of its surface on the electric energy efficiency [8]. Therefore, the roof tile was subjected to bending in a manner which enabled the achievement of different angles of inclination, and thus, a different distribution of intensity of radiation incident on its surface.

2. Research method

2.1. Subject of research

Based on the overview of companies offering flexible photovoltaic roof tiles, which are offered on the Polish market, including: Fotton, Tegola or Prefa, a decision was made to use the TEGOSOLAR PVL–68 bituminous roof tile manufactured by Tegola (Fig. 2). Its assembly does not require any additional load–bearing structures. It can be fixed directly to roofs covered with tar board or shingles and to roof laths by means of screws. A roof tile weighing about 4 kg is built of two elements: bituminous substrate and flexible Uni–Solar photovoltaic module. The module with the maximum power of 68 W consists of eleven serially–connected solar cells based on amorphous silicon. Each of the cells has a parallel–soldered bypass diode, which allows for the current flow, if any part of the module is shaded [8].

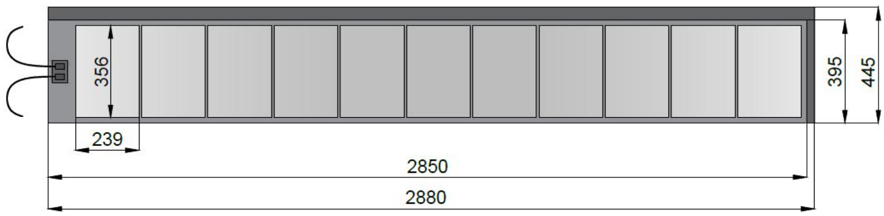

Fig. 2. TEGOSOLAR PVL–68 roof tile [8]

Although the cells based on amorphous silicon are characterised by a relatively low efficiency (6–10%), they are much cheaper to manufacture than the cells made of crystalline silicon and can be manufactured in almost any shapes and sizes [5]. The structure of the discussed photovoltaic roof tile, made on the basis of the construction with the triple junction, is presented in Figure 3. The structure that generates electric energy consists of stainless steel foil on which three layers of amorphous silicon as well as transparent electrode and mains socket are placed [6]. The structure is covered with a polymer coat, which contains the EVA polymer and, additionally on the upper surface, the ETFE polymer, both of which protect the module against water and prevent pollution from being deposited [8]. Due to the fact that the main cause of low efficiency of amorphous cells is poor absorption of the low–energy infrared radiation, the function of each of the three layers of amorphous silicon is to absorb solar radiation waves of different lengths.

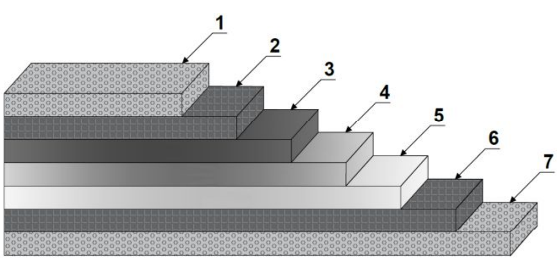

Fig. 3. UNI–SOLAR cell structure (1 – outer polymer layer, 2 – connecting mesh (+), 3 – silicon cell (a–Si), 4 – silicon cell (a–SiGe), 5 – silicon cell (a–SiGe), 6 – stainless steel foil (–), 7 – inner polymer layer) [6]

The most essential parameters of the tested photovoltaic roof tile were presented in Table 2.1. The technical data were determined in standard test conditions, i.e. for radiation intensity equal to 1000 W/m^2, module operating temperature – 25 °C and air mass – 1.5 [5].

Table 2.1. Parameters of the TEGOSOLAR PVL–68 roof tile [8]

Parameter	Value
Dimensions	(2849 x 394 x 2.5) mm
Active surface	0.936 m^2
Weight	3.9 kg
Nominal power	68 W
Power tolerance	5%
Open circuit voltage	23.1 V
Short–circuit current	5.1 A
Voltage at MPP	16.5 V
Current at MPP	4.13 A
Efficiency	7.26 %
Temperature coefficien of power	–0.21 %/°C
Operating temperature	10°C – 40 °C

2.2. Measuring station

Tests, whose scope covered the determination of the current–voltage characteristics of the module and the measurement of the atmospheric conditions were performed in November 2015, in local climatic conditions of the city of Poznan, on the premises of the Poznan University of Technology (52°23'N 16°55'E). The area in which the tests were carried out was deprived of elements, which could cause the shading of the module during the tests.

The following devices were used to measure the electric parameters of the module and the atmospheric conditions:

- the TEGOSOLAR PVL–68 photovoltaic roof tile,
- the CONTREX PRN3/322 3x10Ω slide rheostat,
- the CONTREX PRN3/322 3x1000Ω slide rheostat,
- the INSTEK GDM–394 digital voltmeter, (resolution – 0.01V, +/– 0.8%),
- the BRYMEN BM806 digital ammeter, (resolution – 0.001A, +/– 2.0%),
- the HT INSTRUMENTS HT204 luxmeter (resolution – 1W/m^2, +/– 5.0%),
- the KAINDL WINDMASTER 2 anemometer (resolution – 0.1 m/s, +/– 4.0%),
- the CEM DT–8865 pyrometer (resolution – 0.1°C, +/– 1.0%),
- the mercury thermometer,
- test leads.

During the tests, four cases of photovoltaic roof tile shape were taken into consideration. Each time, the structure was placed perpendicularly to the substrate, in the southerly direction, and then at the level of the fifth solar cell, bent at an angle of 90°, 60°, 45° and 30° in relation to the surface. The conducted measurements covered electric parameters of the module, i.e. open circuit voltage and short–circuit current, as well as the respective values of voltage and current, corresponding to the current–voltage characteristics. Furthermore, the tests were performed with regards to the surface temperature of the respective solar cells of the module and the intensity of solar radiation perpendicularly incident on its surface. The diagram of the measuring station built for the purposes of the tests is presented in Figure 4.

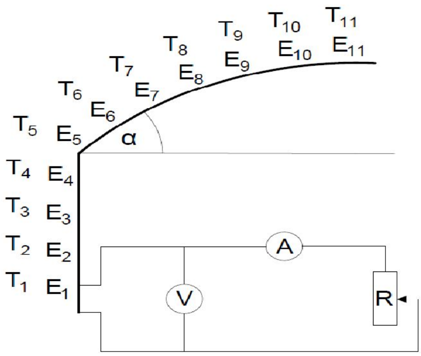

Fig. 4. Diagram of the measuring station: α – roof tile bending angle, V– voltmeter, A – ammeter, R – resistor, T_i – roof tile surface temperature measurement, E_i – solar radiation intensity measurement

3. Measurement results

The key parameters related to the level of power generated by the photovoltaic module include: the amount of the solar radiation which reaches the module and the temperature of its surface. Each of these parameters affects the shape of the obtained current–voltage characteristics, giving a picture of how favourable the conditions for production of electric energy are [5]. In the case of the tested building, an increase in the module temperature by 1°C above the level of 25°C caused a decrease in the generated power by 0.21% [8].

Table 3.1 presents the real distribution of intensity of solar radiation incident on the module surface. It can be noticed that as the angle of inclination of a roof tile increased, also the disproportion in the intensity of radiation which reached the respective module cells became greater. The biggest difference in the observed values of radiation intensity occurred when the roof tile was bent at an angle of 30° and amounted to almost 550 W/m^2.

Table 3.1. Distribution of the intensity of solar radiation on the surface of the photovoltaic module

Roof tile bending angle	Solar radiation intensity [W/m^2]										
	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}
90°	778	783	795	802	822	815	811	806	799	821	817
60°	750	767	780	796	754	741	620	586	453	431	410
45°	775	781	795	805	828	812	603	452	358	253	248
30°	776	785	792	791	821	833	536	415	363	290	229

Temperature distribution on the surface of the tested building was presented in Table 3.2. It can be easily seen that its value depends strictly on the amount of the absorbed radiation. During the performance of the tests, under the influence of the natural wind cooling, the temperature of photovoltaic cells was subject to a significant decrease [5]. Unfortunately in the conditions of the real application of the photovoltaic roof tile, the possibility of ensuring adequate ventilation and free exchange of heat with the surrounding environment is very limited. This follows form the structural assumption of the BIPV elements, which, by replacing the building components, become an integral part of the building.

Table 3.2. Temperature distribution on the surface of the photovoltaic module

Roof tile bending angle	module surface temperature [°C]										
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}
90°	27.9	27.2	27.6	27.7	29.3	29.0	28.1	27.9	26.8	27.2	27.1
60°	25.0	25.5	26.0	26.2	25.1	23.2	16.6	14.8	11.9	10.4	9.7
45°	24.5	24.5	25.8	25.9	26.0	23.6	20.0	15.1	14.4	14.2	13.0
30°	23.2	23.5	23.1	22.7	23.5	23.6	22.0	20.8	14.5	13.9	13.8

The vertical placement of the roof tile (90°) caused the tested module to be deprived of any bends or protuberances, and its surface was illuminated evenly. Based on the obtained current–voltage characteristics and power curve (Fig. 5), whose appearance is close to the theoretical ones, it can be claimed that the operation of module during the tests was smooth. The maximum power obtained during its performance, at the average solar radiation power density equal to 804.45 W/m^2 and average cell temperature at 27.8°C, amounted to 47.61 W, which constitutes 70% of the nominal value.

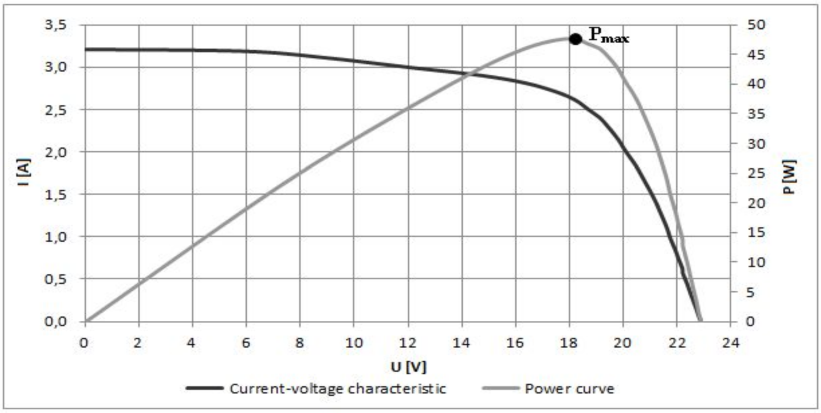

Fig. 5. Current–voltage characteristic and power curve of the module bent at an angle of 90°

The bending of the roof tile at an angle of 60° resulted in the uneven distribution of the intensity of radiation incident on its surface. 40% less solar radiation energy reached the bent part of the roof tile.

The effects of this phenomenon are reflected in the current–voltage characteristics of the module, shown in figure 6. Its shape was subject to visible deterioration. Low current value at the maximum power point and a reduction in short–circuit current below 3 A was observed; this, as a consequence, contributed to a decrease in power to the level of 55% of the nominal value, e.g. 38.16 W.

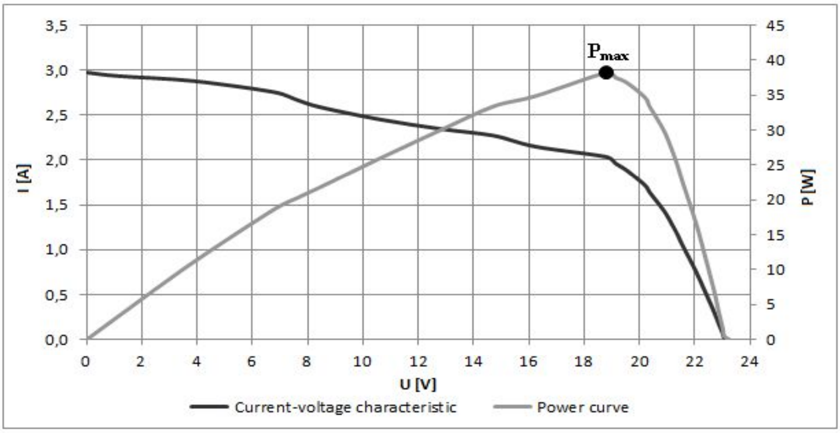

Fig. 6. Current–voltage characteristic and power curve of the module bent at an angle of 60°

The bending of the roof tile at an angle of 45°, just like in the previous case, caused the solar radiation intensity level to be uneven on its entire surface. As a consequence of this, the operation of the photovoltaic module was similar to the situation in which its surface becomes locally shaded. The presence of bypass diodes caused the disconnection of cells which were reached by the least amount of sunlight, thus allowing for the flow of current from the solar cells whose operation was proper. This enabled the protection of the module against the reduction in power to the value generated by the poorest cell [4]. The effects of differences in the radiation intensity and the effects of operation of bypass diodes are visible both on the power curve and the current–voltage characteristics in the form of ”steps” (Fig. 7).

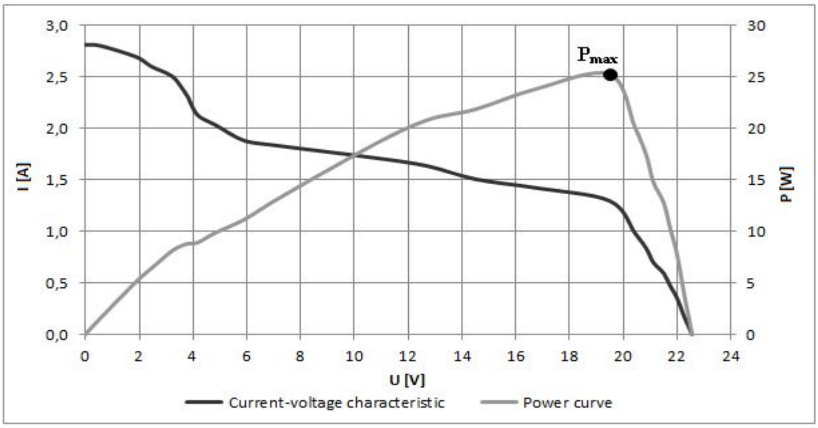

Fig. 7. Current–voltage characteristic and power curve of the module bent at an angle of 45°

The last stage of the tests, which assumed the bending of the roof tile against the substrate at an angle of 30°, caused the greatest disproportions in the cases tested so far with regards to the distribution of the intensity of radiation incident on the module's surface. Just like in the case of bending of the roof tile at an angle of 45°, the current–voltage characteristics (Fig. 8) obtained on the basis of the measurements has the features of the partly shaded module curve. A reduction in the value of current at the maximum power point, the effect of which is the generation of hardly 36% of the module's nominal power is visible. Furthermore, because of the smallest quantity of radiation reaching the module, the lowest of all measured values of short–circuit current, equal to 2.73 A, was observed.

In order to summarize the conducted tests, Figure 9 presents the current–voltage characteristics of all the tested variants. Their comparison allowed for demonstration of the existence of the impact of way a roof tile is shaped on the energy yield. The bending of the photovoltaic roof tile, causing differences in the intensity of the radiation reaching each of the module cells contributed to the significant reduction in its performance and the necessity of operation of the bypass diodes. Despite the fact that the obtained value of short–circuit current was at the level of 3A in each of the cases, current reduction at the maximum power point at the moment of the largest bending of the roof tile resulted in the reduction of the level of generated power by about 50%.

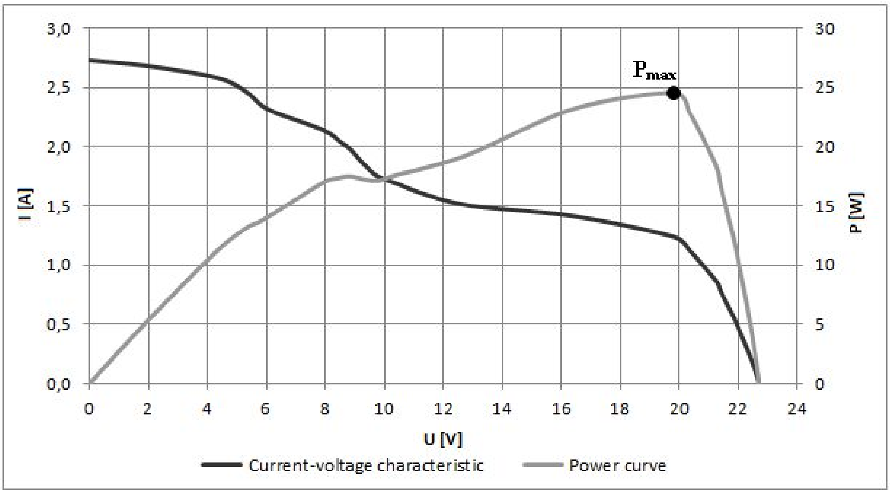

Fig. 8. Current–voltage characteristic and power curve of the module bent at an angle of 30°

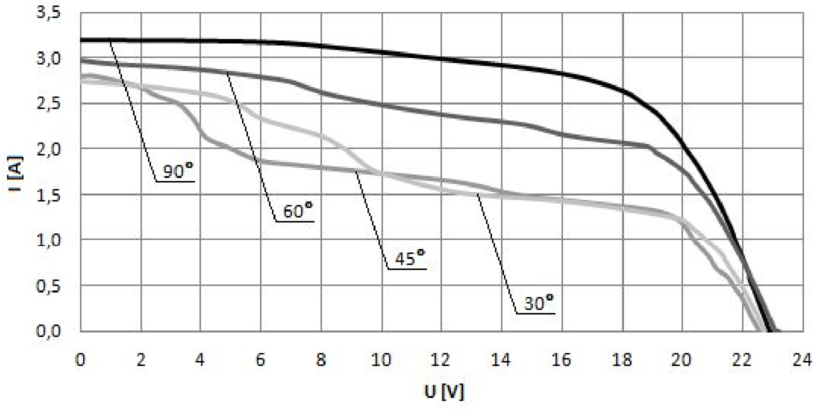

Fig. 9. Comparison of current–voltage characteristics

Information about basic parameters of the tested photovoltaic roof tile obtained on the basis of the tests are compiled in Table 3.2 together with the data provided in the manufacturer's data sheet. On their basis, it is possible to confirm the existence of a relation between the change in the basic parameters of the module's performance and the way it is placed in relation to the source of solar radiation.

The biggest energy yield was observed in the case of the vertical placement of the roof tile, i.e. when even solar radiation at the level of 800 W/m^2 reached each module cell.

Table 3.3. Comparison of test results

Parameter	Manufacturer's data	Roof tile bending angle			
		90°	60°	45°	30°
Open circuit voltage U_{oc} [V]	23.10	22.91	22.68	22.57	22.68
Short–circuit current I_{sc} [A]	5.10	3.20	2.97	2.81	2.73
Voltage at maximum power point U_{mpp} [V]	16.50	18.24	18.80	19.51	19.83
Current at maximum power point I_{mpp} [A]	4.13	2.61	2.03	1.29	1.24
Maximum power P_{max} [W]	68.00	47.61	38.16	25.23	24.51
Fill factor FF [–]	0.58	0.65	0.57	0.40	0.40
Efficiency η [%]	7.26	6.33	6.33	4.42	4.34
Module surface temperature T_{module} [°C]	25	27.8	19.5	20.6	20.4
Radiation intensity E [W/m^2]	1000	804	644	610	603

Most frequently, the module surface temperature in the presented cases was lower than the temperature assumed in the standard test conditions, that is, 25°C, thus, it did not have an adverse effect on the value of the obtained power [4]. However, in real operating conditions of the photovoltaic installation, during a sunny and hot day, the temperature of the modules may be much higher and reach even 75°C. For this reason, if a photovoltaic roof tile is to be applied, particular attention must be paid to the material from which the roof substrate is made. Its thermal properties may be of key significance for the efficient operation of the installation.

The lowest effectiveness of solar radiation conversion into electric energy is observed, if the roof tile is placed at an angle of 45° and 30°. The significant disproportion in the amount of the absorbed solar radiation caused the efficiency to be hardly at the level of 4.5%, which constituted a much lower value than that assumed for cells made of amorphous silicon.

4. Summary

The concept of the building integrated photovoltaics is in line with the trend of searching for innovative solutions for energy–efficient buildings and pursuit of the maximum reduction in energy consumption by already existing buildings. The application of the BIPV elements may have many benefits, starting from the electricity production, through fulfilment of the function of traditional building materials and ending with the enrichment of the aesthetics of designed or upgraded buildings.

The production of building–integrated components using thin–film cells made of amorphous silicon allows the creation of structures with almost unlimited shapes and sizes. The cells are characterised by high flexibility and, in the form of a photovoltaic roof tile, are perfectly fit for covering roof surfaces with non–standard, also rounded shapes.

Analysis of the energy efficiency, depending on the way a given photovoltaic roof tile is shaped, in relation to the source of solar radiation, demonstrated that despite benefits resulting from the possibility of bending the roof tile, and thus, easier integration into the building's architecture, not every method of its installation has a positive effect on the process of electricity generation. While integrating the BIPV elements into the building's structure, as well as taking into consideration the aesthetic factors, it is necessary to strive for ensuring their optimal exposure to the sun. Tests demonstrated that in the case of occurrence of great disproportions in the intensity of radiation reaching the respective cells, the operation of the module is comparable to the occurrence of a local shading of the installation, generating much less electricity.

While designing the roof construction which is to include the BIPV elements discussed above, it is necessary to take care of the selection of structural materials for the roof substrate characterised by the best possible thermal parameters. Otherwise, the heating of the photovoltaic module as a consequence of the lack of back ventilation of its surface will be an important problem in obtaining high effectiveness of the cell performance.

To sum up, in order to make the application of the BIPV technology in the form of the roof covering effective and justified, the cooperation between specialists from many fields is required. At the design stage, it is necessary to take into account the factors which influence the effectiveness of the installations such as photovoltaic technology, construction and aesthetics of the building, costs of the installation and location as only their appropriate balancing will allow the expected effects to be obtained.

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