ECONTECHMOD. AN INTERNATIONAL QUARTERLY JOURNAL – 2018, Vol. 07, No. 1, 79–85

Mechanical aspects of designing of supporting structures for photovoltaic generators

Mariusz Sarniak

Warsaw University of Technology
Faculty of Civil Engineering, Mechanics and Petrochemistry
Łukasiewicza 17, 09-400 Płock, Polska, e-mail: mariusz.sarniak@pw.edu.pl

Received: March 29, 2018; Accepted: April 12, 2018

Abstract. The paper is an analysis of typical supporting structures of photovoltaic generators that are the most exposed to the effects of external factors such as snow or heavy winds. Various construction solutions used to minimize the destructive effects of environmental factors were presented. The installation recommendations, including the strength properties of construction materials, were also presented. The method of distribution of photovoltaic modules in the generator has been analyzed, depending on the geographical location of the installation and the type of modules used. The theoretical analyzes will allow for the optimal design of the strength of the supporting structures, taking into account also the cost criterion, which is important due to materials used for this purpose, most often aluminum and stainless steel.

Key words: photovoltaic, supporting structures, mechanical aspects, strength, corrosion.

INTRODUCTION

The most important element of all types of photovoltaic systems (PV - is a widely accepted abbreviation of the term photovoltaic), is a generator in which the phenomenon of direct conversion of solar energy to electricity occurs. A single PV cell generates a very small amount of electricity and therefore PV generators are built from modules consisting of serially connected cells. At present most often we find PV modules made of 60 cells arranged in four rows, but there are also larger constructions, such as modules with 72 PV cells [7, 10, 11].

If we consider the most common type of PV system - the so-called on-grid, that is, connected to the power grid, the largest reserves of potential improvement of the overall PV system can be found in the PV generator [10]. And here comes a paradox: very often it is emphasized that the greatest advantage of photovoltaics is that in such systems there are no wearable mechanical components. The paradox is that even using the most efficient PV modules does not guarantee optimum energy yields if the support structure is improperly designed and constructed. This construction is important because it must be designed for the life time planned for the PV generator, which is currently estimated even for about 30 years.

The supporting structure must take into account the following functional aspects of the entire PV system:

1. Weight of PV generator.
2. Stresses due to large temperature range during operation.
3. Endurance for extreme wind gusts.
4. Endurance for snow and possible snow removal.
5. Optimal circuit layout for DC cabling.
6. Planning effective grounding of the structure.
7. Layout of optimal spacing between rows of PV generator.
8. Optimal arrangement of modules in the PV generator depending on their type.
9. Optimal selection of construction materials (long-term corrosion resistance).

All of these issues are mechanical aspects to consider when designing and implementing PV installations. A typical example of neglect in this regard is the PV farm in Wierzchosławice, launched with great media hype in 2011 [10].

THE DESTRUCTIVE EFFECTS OF SHADING OF PART OF THE PV GENERATOR

Currently manufactured PV modules made from monocrystalline or polycarbonate silicon cells are made up of 60 or 72 PV cells connected in series (6 rows of 10 or 12 pieces of cells) and single cells are 156x156mm in size. Each of the two adjacent rows of PV cells are protected by bypass diodes that reduce the destructive effects of partial shading of the PV module (Fig. 1).

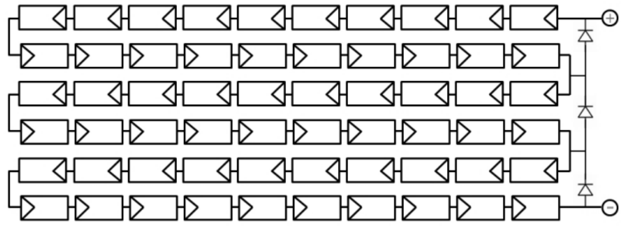

Fig. 1. Internal wiring diagram of typical silicon PV module with three bypass diodes, built of 60 cells [10]

The bypass diodes are mounted in the PV junction box and are connected in parallel to the adjacent PV chains, and their polarity is reverse – blocking [3]. Under normal operating conditions, the PV cells are polarized in the conduction direction, while the bypass diodes are polarized in the bar direction. In case of shading of the PV cell, a reverse current that polarizes the bypass diode in the conduction direction is polarized and becomes a bypass for a current that cannot normally flow through the shaded cell. If there was no bypass diode, the cell would have heated up and could have been destroyed. The cells with invisible micro-degradation are especially vulnerable, which in this case quickly become, so-called "Hot spots" in the PV module. If there is a difference of up to 20% of the incident radiation on the plane of the PV module, then the current is flowing by the diode. The effect of the bypass diode is that when we cover one section (two rows of PV cells), the other two, i.e. 2/3 of the module, functions normally (Fig. 2).

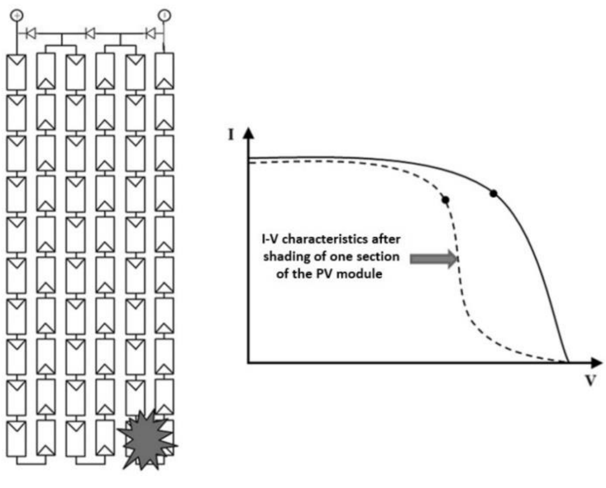

Fig. 2. Effect of partial shading of typical PV module on characteristic curve I-V [10]

Differently, this is the case for thin-layer modules, which are usually made of thin elongated PV cells (usually 154 pieces). Such modules usually only have one bypass diode, but there are also the ones that do not have this protection. Transverse shades to the cells lower the current proportionally to the shade (Fig. 3), and shading along the cells that cover the entire cells causes a large decrease in the generated current. The PV system in the thin-film module may be different from the vertical one, and if the cells are transverse, then the shading effect would be reversed.

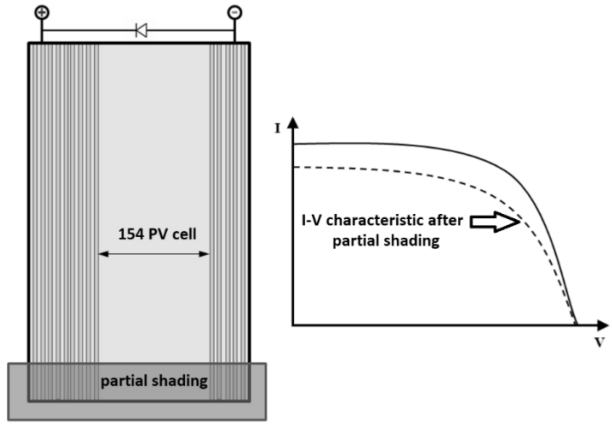

Fig. 3. Effect of partial shading of a typical thin-film module on the course of I-V characteristic [10]

For classical modules (crystalline silicon) and thin films, set vertically as shown in Fig. 4, when about 20% of their surface area is shortened along the shorter edge of the modules, we see a significant decrease in power for classical modules (approx. 100%), and in this case, the power drop will be proportional to the degree of shading (i.e. approx. 20%).

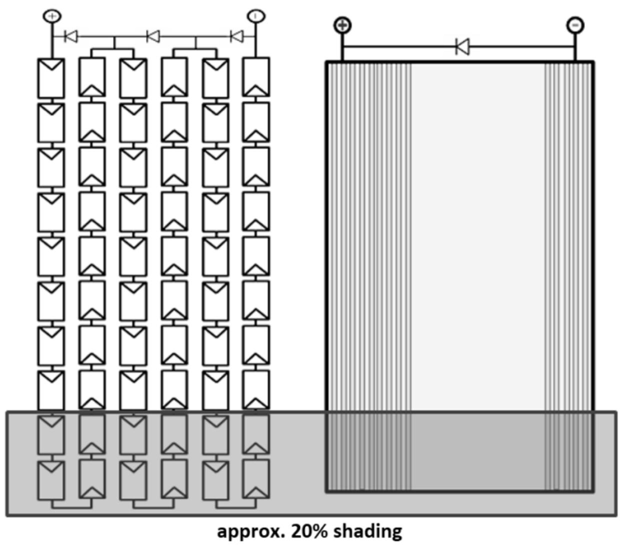

Fig. 4. The method of shading of classic and thin layer vertically oriented modules [10]

Situation will be different in the case of horizontal arrangement of the modules, as shown in Fig. 5, there will be a significant decrease in the power of the thin-layer modules (up to 100%) as all the adjacent cells are covered. In the case of classical modules, the power drop will only be slightly higher than the shade degree (approx. 33%).

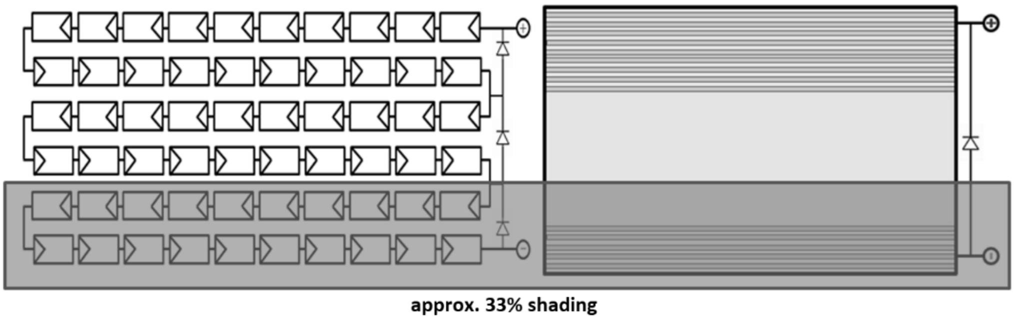

Fig. 5. The method of shading of classic and thin layer horizontally oriented modules [10]

METHOD OF ARRANGEMENT OF PV MODULES IN MULTI-ROW GENERATOR

By observing the plane with installed PV modules, it can be seen that in different installations they are mounted along shorter or longer edges [1]. If there are no other operational considerations, install them as shown in Figure 6 (horizontal arrangement of modules), as most of the PV modules currently manufactured have three bypass diodes installed that secure two PV rows along the long edge of the rectangular PV module. This reduces the losses due to the fact that the part of the PV module obstructs the sliding snow from the plane of the module. Conversely, in the case of thin-layer modules made of e.g. amorphous silicon, where the vertical arrangement of the modules is preferable. When planning a PV farm, one must take into account the so-called shade zone occurring in winter. When designing a load bearing structure for PV modules, it is necessary to provide solar radiation in the winter noon, a compromise is to allow partial coverage of subsequent rows in winter mornings and afternoons when radiation is low. The angle α shown in Fig. 6 is calculated from the formula [10]:

$$\alpha = 90^0 - \phi - 23^0 27' , \qquad (1)$$

where:
ϕ - is the geographic latitude.

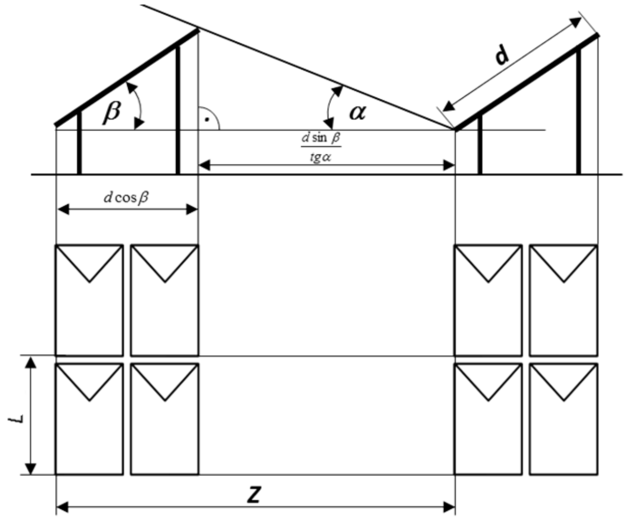

Fig. 6. Scheme of optimum arrangement of PV modules in multi-row generator

Other parameters that influence the size of the "shading zone" are the β angle and length d, presented on Fig. 6. Taking into account the geometric relationships, we can determine the distance Z based on the formula [13]:

$$Z = d \cdot \frac{\sin(\alpha+\beta)}{\sin\alpha} . \qquad (2)$$

When determining the length of the sections marked in Fig. 6 as d and L, one should take into consideration the allowances for mounting brackets (approx. 2 cm). Calculations are complicated when there are significant differences in levels on the plot for the PV farm.

SNOW LOAD AND WIND LOAD OF SUPPORTING STRUCTURES OF PV GENERATORS

An important factor to consider when designing a PV system is the weight of not only the PV modules themselves (having a mass of approx.10÷15kg·m^{-2}, so the pressure force of 100÷150N·m^{-2}) and construction elements, but also occasional snowfalls, forming layers that lie on snow PV modules [3]. For stand-alone PV systems, the supporting structure will have to withstand the mechanical pressure of the entire weight of its components and possible snow. For installations integrated with the building, this additional weight is taken over by the roof structure, which must be appropriately selected at the design stage of the building itself.

The basic reference value used to determine the snow load of roofs was the development of meteorological surveys and observations of snow loads on the lands. Based on long-term measurements conducted according to the same measurement methods and techniques, the area of Poland was divided into 5 zones of snow load, which were depicted in Fig. 7, according to the PN-EN 1991-1-3:2005 standard [8].

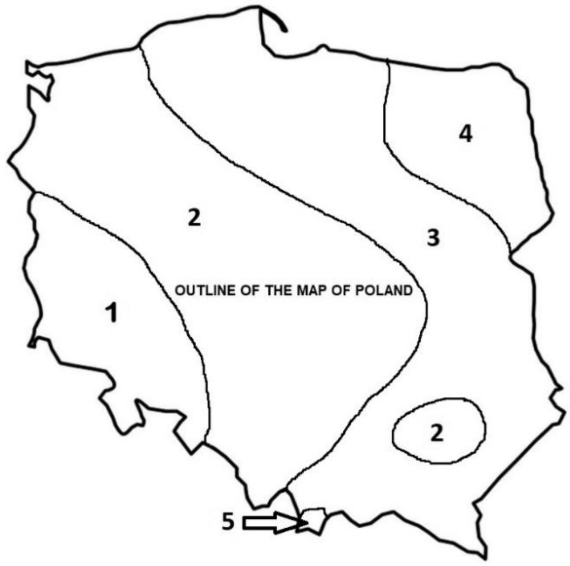

Fig. 7. Approximate division of Poland into zones of snow load according to PN-EN 1991-1-3:2005 standard [13]

Each zone is characterized by a different snow load, which depends on the amount and frequency of occurrence of snowfall. The number of snow days in Poland varies between 20 and 80, depending on the zone. The values of characteristic snow load in Poland are summarized in the Tab. 1.

Tabel 1. The approximate values of snow load on the ground in Poland [5]

The zone number according to Fig. 7	1	2	3	4	5
q_s [kN·m^{-2}]	≥ 0.7	0.9	≥ 1.2	1.6	≥ 2

Loads for individual zones apply to vertical pressure on the horizontal surface, i.e. the force is directed horizontally to the surface. PV panels are usually mounted at an angle α to the ground. Then the snow load has a lower value than that of the horizontal surface. Hence, the value of snow pressure acting on the sloping surface of the PV generator is calculated from the formula [4]:

$$q_{sPV} = q_s \cdot \cos\alpha\ , \qquad (3)$$

where:
q_{sPV} - snow load pressure on sloping surface [N·m^{-2}];
q_s - snow load pressure on horizontal surface [N·m^{-2}];
α - angle of inclination of surface to the level [deg].

In case of PV installation inclined to a horizontal plane, snow quickly melts and slides out of it. In case of heavy snowfall, for terrestrial installations installed on relatively low supporting structures, it may happen that the snow will no longer have a place where it can slip off, filling the entire free space between the ground and the frame. The slipping snow laying on the bottom parts of the PV module results in uneven pressure on their surface and supporting structure. If the coefficient of friction is less than the tangent of the slope of the installation, then the spontaneous slipping of the snow may occur. For PV modules installed on roofs of buildings, especially for laminates, the coefficient of friction is lower than for sloping roofs covered with tiles. The optimum inclination of panels, due to the energy yield of about 40° in Poland, will decrease by a few percent the value of the snow force on the surface of the PV module, and for angles of more than 60° it can be safely assumed that the snow slides spontaneously and the snow load can to be omitted during the selection of components of the supporting structures of the PV generators.

Wind load is an important issue and should be considered when designing stand-alone PV systems or those installed on the roofs. The strength of the wind, which rises with the square of its velocity, depends on the type, size and arrangement of the nearby objects, and the direction of its flow. Depending on the type and angle of the installation and thus the roof, the windward side of the installation is exposed to wind pressure while the leeward side is equally exposed to wind suction. In Poland, the average annual wind speed ranges from 2.8 to 3.5 m/s. Lower values occur in summer, while higher in winter. According to PN-EN 1991-1-4:2008 [8], depending on the wind speed, the Polish area was also divided into 5 wind load zones, which are shown in Fig. 8.

Fig. 8. Approximate division of Poland into zones of wind load according to PN-EN 1991-1-4:2008 [13]

Tab. 2 presents the characteristic values of pressure for particular wind load zones in Poland according to PN-EN 1991-1-4: 2008, depending on the wind speed.

Table 2. Speed and pressure values for individual wind load zones [5]

The zone number according to Fig. 8	1	2	2a	2b	3
v_w [m·s^{-1}]	20	24	27	30	24÷47
q_w [kN·m^{-2}]	0.25	0.35	0.45	0.55	≥0.35

According to Bernoulli's law, you can determine the dynamic pressure q_w [Pa] for a specific wind speed [13]:

$$q_w = \frac{1}{2} \cdot \rho_p \cdot v_w, \quad (4)$$

where:

ρ_p - air density in [kg·m^{-3}] (under normal conditions, i.e. at 0°C and at a pressure of 1013.25[hPa], dry air has a density of 1.293 kg·m^{-3});

v_w - wind speed in [m·s^{-1}].

The force (in [N]) of the wind pressure on the exemplary structure of the autonomous PV system is shown in Fig. 9, and its pattern is defined as follows:[3]

$$\mathrm{F_x} = \mathrm{c_x} \cdot \mathrm{q_w} \cdot \mathrm{S_{wx}} = \mathrm{c_x} \cdot \frac{\rho_p \cdot v_w^2}{2} \cdot \mathrm{S_{wx}}, \quad (5)$$

where:

c_x - coefficient of air resistance, determined in the axis x;

S_{wx} - the surface of the body tossed in the direction of the wind in [m^2].

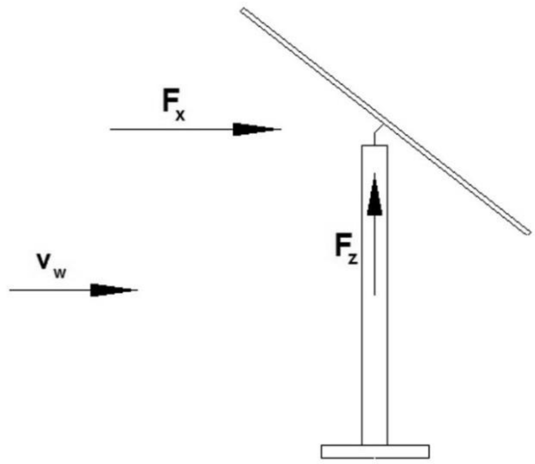

Fig. 9. The directions of exemplary force acting on the construction of an autonomous PV system under the influence of wind in a certain direction

Depending on wind direction, PV panel size and shape of surrounding structures, air resistance coefficients assume values in the range of 0.4 to 1.6. The calculation for the PV panel measuring 6240x1322 mm and the assumed wind speed performed according to this methodology v_w=30 m/s led to the following results:

1. For panel inclination angle 90° force F_x=5646 [N].
2. For 32° inclination angle the forces amount to: F_x=2507 [N], F_z=3478 [N].

It is clear from the calculations that these forces are not small enough to be skipped when calculating the support structure for the PV panel. In practice, East-West compromise systems are often used to eliminate the formation of dangerous components of force F_z from the wind [10].

RISK OF CORROSSION OF SUPPORTING STRUCTURES

Galvanic corrosion occurs when three basic conditions are met:

1. There will be contact of metals with different electrochemical potential.
2. There will be a conductive connection between the metals.
3. Both metals are connected by conductive electrolyte.

If this corrosion occurs, the less minded metal (with lower potential) becomes an anode and corrodes, and the more minded metal that is a cathode does not corrode. In such connection, the electrons flow from the anode to the cathode. Contrary to popular belief, potential difference is not the only criterion for corrosion. The decisive factor is the actual potential difference in operating conditions. The most important factors that determine the actual operating potential difference are:

1. Total corrosion current.
2. Electrolyte resistance.
3. Wetting time and environment.
4. Cathode to anode ratio.

Raw aluminum has a very high corrosion resistance, it automatically covers itself with a very thin oxide protective layer, which prevents further oxidation. Unlike the oxide layer formed on many other metals, alumina tightly and closely adheres to the substrate. In case of mechanical damage, the alumina layer is quickly repaired. Oxide coating is the main factor that aluminum owes its good anticorrosion properties. It is stable for pH values in the range of 4 to 9. Under strong acidic or alkaline conditions, aluminum usually corrodes quickly. The risk of electrochemical corrosion of aluminum occurs only in the case of metallic contact with high-minded metals, with the simultaneous presence between metals of an electrolyte of good conductivity.

The contact of two different metals with different electrochemical potential, as in the case of stainless steel and aluminum, can lead to galvanic (contact) corrosion. In this arrangement, the more high-minded material – corrosion-resistant - is stainless steel, and the material exposed to accelerated corrosion is aluminum. This type of corrosion can occur when connecting large stainless steel components with aluminum screws. In this case, aluminum fasteners will be subjected to accelerated corrosion. The situation is different in case of large aluminum surfaces connected by stainless steel screws. In this case "strength" of more high-minded material - stainless steel is insufficient to cause corrosion of aluminum. It should be borne in mind that corrosive phenomena occur in the area of the electrolyte and affect the area moistened by this electrolyte. This may lead to local oxidation of aluminum and corrosion at the connection point - in the vicinity of the screws heads. For the prevention of galvanic corrosion, suitable techniques are used to isolate materials of different electrochemical potential by means of plastic washers, painting the elements with protective coatings, and applying insulating pastes.

Analyzing whether the use of stainless fasteners is justified, whether it would be sufficient to use galvanized steel fasteners. Connections made several years ago using galvanized steel fasteners have corrosion marks on the fasteners themselves and the material around them. The difference in potentials of aluminum alloys and a layer of zinc steel or steel is so big that it leads to the development of electrochemical corrosion. The zinc layer is often damaged during the connection, resulting in an aluminum/steel connection that is subject to rapid corrosion damage.

If we analyze the difference in potential of aluminum and stainless steel alloys, then we find that theoretically it is large enough to cause electrochemical corrosion. But that does not happen. And it is this passive layer that is formed on the surface that is responsible for the lack of reaction of stainless steel and aluminum, because they have a similar electrical potential. Contacting these layers at the connection does not cause electrochemical corrosion. The passive layers damaged during installation are regenerated in a short time, providing adequate protection. The only disadvantage of this solution is about four times the cost of stainless steel fasteners compared to the counterparts made of galvanized steel [4].

Galvanic corrosion (contact) between stainless steel and zinc can occur, but in this pair of materials the stainless steel is more high-marked (it is a cathode that does not corrode, and causes accelerated corrosion of the anode material), while the zinc in the pair acts as an anode and undergoes accelerated corrosion.

Summing up, it can be stated that if the cathode surface area (the more high-minded metal in the galvanic cell) is very small compared to the anodic surface area (less high-minded metal), no corrosion is observed. A typical example is the use of stainless steel fasteners for joining aluminum or galvanized carbon steel. Corrosion phenomena are also the reason for the need to make additional grounding wires for the PV modules, which, despite clear recommendations from manufacturers, are often overlooked (it is mistakenly assumed that the grounding of the support structure is sufficient). In the case of joining of materials, the fasteners should always be made of a more high-minded material, then the cathode surface will be smaller.

CONCLUSIONS

The conducted analysis showed that mechanical aspects are very important both at the design stage and in the execution of photovoltaic installations. The paper has not exhausted the subject, as many other important factors affecting the longevity of PV systems can be analyzed. It is possible to carry out analyzes of the thermal expansion of the components and related, for example, screw tightening torques. For aluminum mounting clamps, where M8 screws are used, the optimum tightening torque should be 8.5 Nm [6]. In this situation, it seems reasonable to make a decision to establish special professional qualifications of the installer of PV systems. This authority is issued by the Office of Technical Supervision for specially prepared installers. The specificity of these types of PV systems is that they require people dealing with them with broad interdisciplinary skills.

The Association for Assurance of Quality and Safety of Work of Photovoltaic Installations (QSPV), which brings together experts and auditors evaluating PV installations, presents its expertise in various conferences and industry training sessions. QSPV experts point out the most common mistakes made in the evaluated PV systems, and many of them concern the mechanical aspects of the PV installations.

In Poland, optimal solutions in the discussed range of production of supporting structures for PV generators are offered by several companies, among others CORAB Ltd.[10], ENERGY5 Ltd. [2] and an authorized distributor of offers of other manufacturers – KENO Ltd.[3].

REFERENCES

1. Dokumentacja oferty produkcyjnej firmy **Corab Sp. z o.o.** z Olsztyna (Polska, woj. warmińsko-mazurskie) http://fotowoltaika.corab.eu/oferta/elementy-mocowan-pv
2. Dokumentacja oferty produkcyjnej firmy **Energy5 Sp. z o.o.** z Gostynina (Polska, woj. mazowieckie) http://www.energy5.pl/10_dokumenty
3. Dokumentacja oferty handlowej firmy **KENO Sp. z o.o.** z Gliwic (Polska, woj. śląskie) http://www.keno-energy.com/index.php?go=konstrukcje-montazowe
4. EUROINOX. 2011. Kontakt stali nierdzewnej z innymi materiałami metalowymi. Seria Materiały i zastosowania, zeszyt 10.
5. **Głuchy D., Kurz D., Trzmiel G. 2013:** Wpływ wiatru i śniegu na instalacje fotowoltaiczne w Polsce. Electrical Engineering. Nr 74, strony 253-260.
6. Instrukcja montażu dla instalatorów i użytkowników. 2015. Producent firma: Corab Sp. z o.o. http://www.fotowoltaika.corab.eu
7. **Kapica J., Ścibisz M. 2013**: Employing empirical model decomposition to determine solar radiation intensity curve. TEKA. COMMISSION OF MOTORIZATION AND ENERGETICS IN AGRICULTURE. Vol.13, No. 1, 65-70. Lublin-Rzeszów.
8. PN-EN 1991-1-3:2005 - wersja polska - Oddziaływania na konstrukcje - Część 1-3: Oddziaływania ogólne - Obciążenie śniegiem.
9. PN-EN 1991-1-4:2008 - wersja polska - Oddziaływania na konstrukcje - Część 1-4: Oddziaływania ogólne - Oddziaływania wiatru.
10. **Sarniak M. 2015:** Budowa i eksploatacja systemów fotowoltaicznych. Zeszyty dla elektryków nr 13. Warszawa: Grupa MEDIUM.
11. **Siedliska K. 2014:** Photovoltaics – The Present and the Future. TEKA. COMMISSION OF MOTORIZATION AND ENERGETICS IN AGRICULTURE. Vol.14, No. 3, 103-110. Lublin-Rzeszów.
12. **Szymański B. 2015:** Farma w Wierzchosławicach obnaża jakość inwestycji samorządowych w PV. http://solaris18.blogspot.com
13. TECHNIK SHRACK 2015: System ogniw fotowoltaicznych SHRACK. http://image.schrack.com/produktkataloge/w_p-phovol10_pl.pdf