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Research Article

EFFECTIVE USE OF PHOTOVOLTAIC SYSTEMS IN POLISH CONDITIONS

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ABSTRACT
Photovoltaic (PV) systems form two groups: grid-connected ones and stand-alone ones. The first group can be divided into: centralised systems with large power (PV farms), and decentralised systems with low-power (especially prosumer ones). The second group includes systems with electric buffer sources (especially with electrochemical batteries), and those without electric buffer sources (possibly with non-electric buffer sources). Due to significant decline in price of PV modules, both of these groups are becoming increasingly common in Poland, especially grid-connected ones. Additional factor for prosumer systems is economic and legal support in a form of exemption from fees for connection to grid, lack of additional required licenses for such connection, and possible support in a form of guaranteed sale prices to grid (feed-in tariffs) of electrical energy generated in system. However, in case of systems not covered by economic benefits, increasing, or even ensuring, their cost-effectiveness, requires the number of ventures regarding areas of proper installation and operation rules of PV generator from installer/user/owner of system, as well as selection of suitable tariff and rational restructuring of energy demands. Detailed analysis and conclusions of these ventures, especially for prosumer systems, is discussed in paper.

Keywords: photovoltaics, grid-connected systems, prosumer systems

INTRODUCTION

Photovoltaic systems are the systems in which a PV generator, also popularly known as solar battery, is the basic source of the electrical energy produced. This generator directly converts the solar irradiation energy into DC current electrical energy, with significantly time-varying output parameters, such as achievable power, current and voltage. The elementary classification of PV systems distinguishes: systems co-operating with public electro-energetic grid (on-grid, or grid-connected systems), and not-connected to the grid (off-grid, or stand-alone systems).

Depending on the nominal power of the PV generator and the destination of the energy produced, the following on-grid systems may be distinguished (Borut et al. 2016, Mandelli et al. 2016, Mohamed et al. 2016):

1) Centralized systems, also known as PV power plants, or PV farms. These are the systems with medium or great nominal power of PV generator, for orientation over hundreds of kW. They are dedicated to selling energy to the grid, characterised by very low self-consumption, i.e. consumption for own needs.
2) Decentralised systems, with PV generator nominal power clearly below hundreds of kW. Fundamentally, they are dedicated for self-consumption of generated energy. Among these systems, there is a special group of micro-installations called: prosumer PV systems. They are mainly used by consumers not engaged in professional economic activity, but who wish to sell the surplus of generated energy to the grid.

In turn, the off-grid systems may be classified as (Treado 2015):

1) The systems with electrochemical batteries as electric buffer sources (energy storage devices), optionally with additional backup generators (electrical machine generators driven by diesel motors or wind turbines).

2) The systems with batteries of supercapacitors, or electrolytic capacitors, as electric buffer sources. So far, they are not widely used because of relatively small energy capacity of capacitors, compared with the same volume or weight of electrochemical batteries.
3) The systems without electric buffer sources, which however can be equipped with so-called non-electric buffer sources (Niechaj 2014). The examples are: the system with water pump and water tank as a non-electric buffer source, the system of farmland irrigation with the natural storage of water in irrigated ground, a system with air conditioner using the heat capacity of the room for cold storage, a system without any buffer source with a fan for drying grain, hay or herbs.

In the last few years, there was a significant decrease in nominal prices of PV modules. Currently their unit cost is at the level of (3÷5) PLN/W (03.2016, http://www.sklep.soltechenergy.pl), while in 1998 it equalled about 16 PLN/W. Taking into account the Polish inflation in the years 1998–2016 (about 80%), this means almost a 10-fold decrease in the real prices of PV modules.

The result of significant decline in the price only of PV modules, is the change of investment costs structure in the whole system. For example, previously the PV generator was the most expensive unit in off-grid systems with electrochemical batteries, and currently the electrochemical battery pack is the most expensive element of the system. In addition, due to the shorter lifetime of electrochemical battery than a PV generator, the investment in rechargeable batteries is a recurring expense in such system. The afore-mentioned factors resulted in a significant decrease in the importance of stand-alone systems with electrochemical batteries. For this reason, such systems with the power of PV generator above a few hundred W, are presently not recommended in Poland from an economic point of view.

In turn, the off-grid systems without electrochemical batteries were never popular in Poland due to the potential niche applications and extended structure of public electro-energetic grid.

As for PV power plants (PV farms), the sale of energy generated by them to the grid is still based on a system of green certificates. Also, there are mostly subsidies to the cost of installation of such plants. Although the new Act of Renewable Energy Sources (RES) from 2015 provided for the use of auction scheme instead of green certificates subsidies, the currently proposed amendments to this law will perhaps restore the support in the form of green certificates. Investments in PV farms are currently profitable. Thereby, new PV power plants are constantly being created in Poland. The payback period of such investments is in the range of 6÷11 years, primarily depending on the level of investment co-financing.

However, the most promising solution for development in Poland includes the decentralised on-grid systems, especially the prosumer ones. Therefore, the rest of this article is devoted to these systems.

The above-presented aspects are also of interest to many research centers in the world (Kacejko et al. 2014, Karki et al. 2001, Mikulik et al. 2015, Reza et al. 2016).

ANALYSIS OF EFFECTIVE PHOTOVOLTAIC PROSUMER SYSTEMS USE

A typical structure of prosumer PV system is shown in Figure 1. The functions of an inverter are:
1) Converting the DC current electrical energy into AC current electrical energy fulfilling the requirements of electro-energetic grid owner

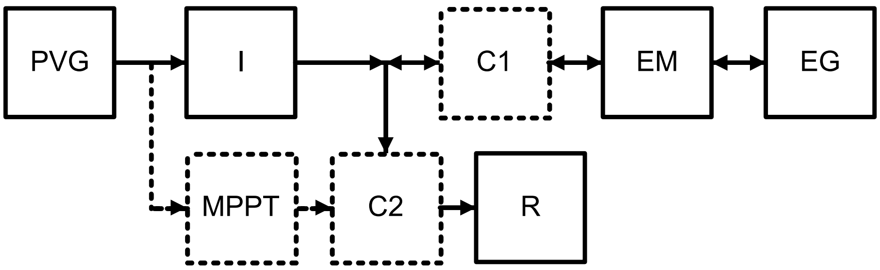

Figure 1. General block diagram of prosumer PV on-grid system: PVG – photovoltaic generator; I – inverter; R – receivers of the prosumer; EM – bi-directional energy meter; EG – electro-energetic grid; C1, C2 – optional contactors; MPPT – optional unit for maximum power point tracking.

(energy distributor), for parameters of this energy such as: rate of THD (Total Harmonic Distortion), the maximum rate of changes in the output parameters (mainly output power), adequate response to voltage dips in the grid.
2) Maximization of output power of PV generator (so-called MPPT function), in order to maximize the operation efficiency of a PV generator.
3) Disconnecting the PV generator from electroenergetic grid in the case of grid failure, in order to ensure the security of grid support staff while fixing this failure.

The latter of the above-mentioned functions adversely affects the reliability of supply of prosumer receivers, and the full possibilities of PV generator energy use, because the grid failure does not allow for supplying any prosumer receivers, even when PV generator is able to produce energy. Therefore, when a given prosumer is often affected by electrical energy outages, it is recommended to apply an optional solution in a form of C1 contactor, disconnecting the inverter and all (or just some) of receivers from the grid. However, this requires the use of a special inverter, with software allowing for stand-alone operation of an inverter. Moreover, this solution can work only for such receivers that properly operate when supplied from the power source with variable parameters, which includes such source as a PV generator. Another solution is to use, instead of C1 contactor and a special inverter, the C2 contactor switching power supply of some of receivers from the grid to the PV generator through the optional MPPT unit. In such case, there need to be the receivers for which it is indifferent whether they are powered either by DC voltage with variable attainable power, or by AC voltage with constant parameters. Examples of such receivers include: units for charging electrochemical batteries; units for domestic water heating; some drive units for water pumping, ventilation or air conditioning, containing their own power converters which can immediately act as MPPT units (Kacejko et al. 2014, Mikulik et al. 2015, Niechaj 2013, Salpakari et al. 2016, Sangwongwanich et al. 2016).

For prosumer systems, a significant change for the status of photovoltaics in Poland is the legal change, and also another economic change (besides the afore-mentioned decline in prices of PV modules), associated with this legal change – the procedures of connecting the prosumer systems to the grid were streamlined, therefore, the connection of such a system is currently much cheaper, because the prosumer does not bear the cost of connecting it to the grid, including the cost of protection elements and a measuring-settlement meter. In addition, the connection of it is much easier, because when the installed nominal power of a PV generator is not greater than that specified in recipient connection conditions, it is only required to register the PV system for energy distributor. Moreover, some prosumer systems will probably be covered by the economical support in a form of guaranteed selling prices of energy transferred from PV generator to the grid (so-called feed-in tariffs).

A simplified economic analysis of prosumer system for the payback period t_z of the PV system costs of investment, can be performed using equation (1). The simplification involves, among others, the negligence of PV system operating costs, which are usually insignificant comparing to the installation costs.

$$t_z = \frac{K_i}{w_r \cdot k_e \cdot P_{PV}} = \frac{a + b \cdot P_{PV}}{w_r \cdot k_e \cdot P_{PV}} = \frac{1}{w_r \cdot k_e} \cdot \left(\frac{a}{P_{PV}} + b\right) \quad (1)$$

where: K_i – installation costs of PV system.

a – independent part of installation costs, regardless to the nominal power of the PV generator. This component has its share in all units of the PV system, but it is most noticeable in the purchase cost of inverter and protection elements.

$b \cdot P_{PV}$ – the part of installation costs approximately linearly dependent on P_{PV} (the nominal power of PV generator). This component has its share in all units of the PV system, but it is most noticeable in the purchase cost of PV modules forming PV generator, of the structure for mechanical mounting the modules, and of wires electrically connecting the modules (wiring of the whole PV generator). Presently, the independent costs a have a significant contribution, especially for the systems up to a few kW. It is the result of the afore-mentioned significant decline in prices only of PV modules, that consequently resulted in the change of relationship between the components a and $b \cdot P_{PV}$.

w_r – annual unit energy generation in PV system. For Lublin region, it can be assumed as a value about w_r=1100 kWh/kW·year for the systems with fixed tilt and azimuth angles of PV panels, and about w_r=1400 kWh/kW·year for the systems with frequently trailing of the Sun's position by PV panels (so-called two-axis trackers). However, due to the approximately 2-fold higher cost of installation of two-axis trackers in comparison with fixed angles ones, the energy yield does not compensate for their prices and other defects, such as shorter life span and additional maintenance costs.

k_e – the unit cost of electrical energy.

In prosumer system, k_e can take two values, when prosumer accounts with energy distributor with a single-zone tariff, or it can take three values, when prosumer is accounted for by dual-zone tariff. For example:

- k_{e1}=0.138 PLN/kWh (the average selling price of energy on the competitive market in 2015 was 0.17 PLN/kWh, according to the information of the President of Energy Regulatory Office No. 13/2016, and then after deducting the income tax 19%). It is a prosumer's income from the sale of the generated PV energy to the grid, when prosumer has a surplus of this produced energy that cannot be reasonably used for his own needs.
- k_{e2}=0.574 PLN/kWh (single-zone tariff G11 of PGE). This is a cost of purchasing energy from the grid, when the energy produced by the PV generator is currently used for the prosumer's own reasonable needs.

However, for the PV prosumer system, the dual-zone tariff G12n is more recommended than single-zone tariff G11. In G12n tariff, the energy at night and on Sundays is much cheaper than in G11:

- k_{e2}=0.631 PLN/kWh during the day and in the evening from Monday to Saturday;
- k_{e3}=0.298 PLN/kWh during each night (1:00÷5:00) and during the whole Sunday.

The essence of the PV system economic analysis, using index t_z, is the fact that for the first years of operation of system, that is before the time runs t_z, the owner of system (prosumer) bears the economic loss. In turn, at t_z moment, the cost of investment pays for itself (that is, the loss is reduced to zero), and after time t_z the investment becomes profitable. Unfortunately, this specificity of the PV system results in the prosumer's dependence, by the t_z time, on possible adverse decisions of legislators (e.g. changes in energy prices, changes in feed-in tariffs), although the degree of dependence is still lower than for PV farms owners, in which all energy is sold to the grid at the rate imposed by legislator.

Prosumer systems with PV generator nominal power of the order of a few kW, are characterised by the investment cost in the range of (4÷8) PLN/W (03.2016, http://www.sklep.soltechenergy.pl), mainly depending on the prices required by the providers of the system's components, and the degree of personal (i.e. cost-free) work effort of the system owner in the production of the structure for mechanical mounting of the PV modules, and in self-assembly of the system.

When energy production is not supported by green certificates and feed-in tariffs, the price offered by energy distributor for the energy sold by prosumer is very low (0.138 PLN/kWh). Accordingly, the owner of a prosumer PV system should not be set up to achieve profits from supplying (selling) electrical energy into the grid.

Estimated results of calculations by equation (1) for an exemplary prosumer system with a PV generator power of about (2÷6) kW show that t_z may range from a minimum t_{z1}≈8 years, assuming that all the generated energy will be self-consumed at the time when grid energy cost is equal to k_{e2}=0.631 PLN/kWh, to a maximum t_{z2}≈36 years, assuming that all the generated energy will be sold and transferred to the grid at a profit k_{e1}=0.138 PLN/kWh without any consumption for prosumer's own needs. These estimates are based on the assumption that no unforeseen costly failures, and no decline in grid energy prices, would take place in the future. Since the lifetime of the on-grid PV system without electrochemical batteries is estimated to be over 20 years, one can see that the prosumer system, even operating in economic and legal state that does not guarantee high rates of purchasing energy from the prosumer, can be cost effective, but under certain conditions.

The factors influencing the payback period t_z decreasing, and thus increasing cost-effectiveness of the system, directly resulting from equation (1), are as follows:

1) Minimizing the cost of installation K_i, possible e.g. with co-financing or with tax deductions. Such treatments help to lower installation costs up to 4-fold. Hence, a resourceful prosumer could reduce the payback period to only two years.
2) Maximizing of energy production w_r, mainly due to a good location of the PV generator (not

shaded places, especially not shaded from the southern side) and its respective maintenance (periodic cleaning of PV modules surfaces, especially in areas with significant dustiness, and in winters). It is also recommended to change the tilt angle of PV panels twice a year (in spring and in autumn) which means the use of a so-called one-axis tracker, which is much cheaper than two-axis one.

3) High rate k_{e1} for the energy sold to the grid, but system owner has no control at this value.
4) High rate k_{e2} for the energy bought from the grid, because the essence of earning with prosumer PV system relies on the savings resulting from not having to purchase the energy from the grid. Therefore, if the energy bought from the grid is more expensive, it will contribute to a faster return of the investment costs of the PV system.

An additional, and very important factor, is the rational planning of prosumer energy consumption. That is the prosumer's useful consumption for his own needs of the highest possible amount of cost-free energy generated in the PV system, instead of buying expensive energy from the grid at the rate of k_{e2}. This is why the said sample dual-zone tariff G12n is more favorable than single-zone (fixed) G11 tariff, but only for a conscious prosumer, willing to implement a rational approach to the management of his consumption of energy. This issue is discussed below in detail.

The values calculated earlier, i.e. t_{z1}≈8 years and t_{z2}≈36 years, are mostly unavailable in practice. The actual payback period is strongly dependent on the profile of energy demand by prosumer. Indicatively, the actual payback period would be included between 10 years with suitable profile of demand, and 20 years with inadequate profile. Therefore, the prosumer's attitude largely influences the possibility of minimizing this period. With nearly 5-fold disparity between the rates of k_{e1} and k_{e2} it can be inferred that a prosumer should take action to rationally use for his own needs as much energy generated in the PV system as possible, and only the remaining, possibly the smallest surplus, should be sold to the grid.

Graphically, this situation is illustrated in the Figure 2. A sample average daily power demand profile for the prosumer (line A) and the most favorable daily production profile of a PV generator (line B) are compared. It is true that the actual course of the production profile will almost always be located clearly below line B in the Figure 2. However, the analysis should take place just for the most favorable profile for two reasons. Firstly, the sunny days, not cloudy, affect to the greatest extent the value of w_r, i.e. indirectly to reduction of the payback period value. Secondly, on cloudy days the production profile, when set lower than in the most favorable one, will mean that the amount of energy sold to the grid at the low rate k_{e1} will be strongly reduced, so a lesser amount of generated energy will be used much

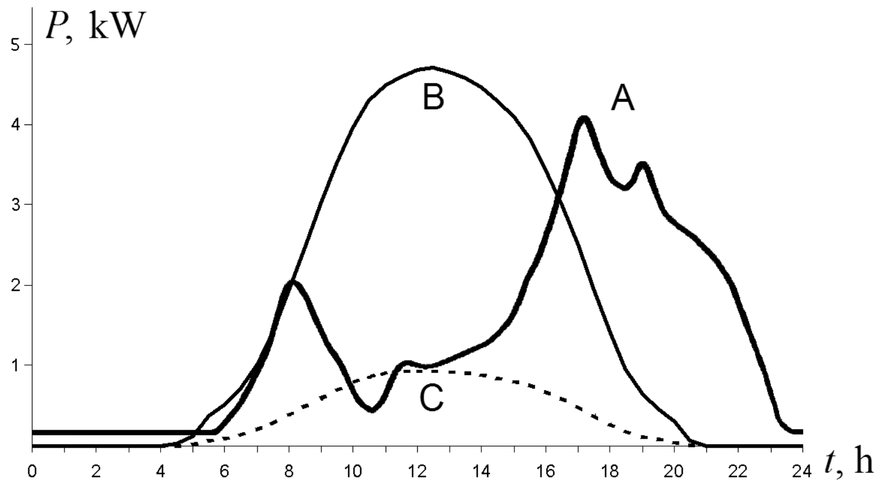

Figure 2. Comparison of a sample daily profile of prosumer power demand (line A) with the most favorable daily profile of PV generator production (a sunny day in June): – for a higher value of PV generator nominal power, e.g. P_{PV}=5 kW (line B); – for a lower value of PV generator nominal power, e.g. P_{PV}=1 kW (line C). The profiles B and C are based upon the results of author's measurements carried out in Lublin for over 17 years (since 1998)

better economically, as it will mainly be spent for self-consumption with high rate of k_{e2}.

When the region under line A (Fig. 2) is completely contained in the region under line B or C, then the energy produced by the generator, numerically represented by the surface of area under lines B or C, fully covers the self-consumption energy demands of the prosumer, numerically represented by the surface of area under the line A. However, this would not minimise the payback period t_z, because with significant mismatch of demand and production courses, a large part of generator energy (the part represented by the surface area above line A located at the same time under the line B) would not be consumed by the prosumer, and therefore it would not provide his profit by a high rate of k_{e2} (and rarely, on Sundays, by k_{e3}), but it would be sold to the grid at a profit by the low rate of k_{e1}.

In order to minimize the amount of energy sold to the grid (that is: to minimize the surface area above line A and at the same time under line B), a prosumer using the dual-zone tariff may primarily reorganize the operation time of his receivers, in terms of ensuring proper regime of their work that will shorten the payback period t_z.

This reorganization should take place according to the following guidelines:

1) As many receivers as possible should operate on sunny days, in order to use all the possible cost-free generated energy from a PV generator (that is produced at a rate of 0 PLN/kWh). Examples of receivers which can help to achieve this recommendation are as follows:
   - receivers the operation of which is needed mainly on sunny summer days: air conditioners, fans, pumps for filtering water in swimming pools and fountains, pumps for irrigation of greenhouses and farmlands, pumps for transfer of fluid medium in solar collector systems;
   - receivers in which the principle of operation is based on the storage of electrical energy, or the storage of processed electrical energy: charging electrochemical batteries in electric vehicles, water pumps filling tanks, heating water in boilers for domestic or agricultural use, storage heaters in the heating season, heat pumps;
   - receivers the operation of which is slightly dependent on the time of the day: washing machines, vacuum cleaners, irons, dishwashers, kitchen electric ovens, chargers for electronic equipment, production of boiled (decalcified) water, personal computers during their automatic operation that does not require human presence.
2) The operation of receivers that cannot be subjected to the regime according to the above item 1), should be, if possible, planned for nighttime (from 1:00 to 5:00 for G12n tariff), and for the whole Sunday. Although this means their operation with energy purchased from the grid, this purchase is at a not very high rate: k_{e3}=0.298 PLN/kWh.
3) All other receivers, the operation of which cannot be subjected to the regimes in 1) and 2), should be planned to work, as a necessary complement, when there is no surplus of PV energy and when there is no night (for example on cloudy winter days, or during evening hours) at the high rate of k_{e2}=0.631 PLN/kWh.

The control over the schedule operation of receivers, according to the above items, should be automated as much as possible, to make it less of a burden for the prosumer and other users, e.g. family or co-workers.

Another way to minimize the payback period t_z is the optimal choice of value of the nominal power of a PV generator: P_{PV}. Primarily, as shown in Figure 2, the reduction of nominal power of a PV generator (e.g. 5-fold, which means the transition from line B to line C) will cause, with constant demand profile (line A) that a much greater part of energy produced by a PV generator will be self-consumed by the prosumer, which is definitely economically beneficial. On the other hand, according to the final form of the transformed formula (1), P_{PV} parameter is found only in the denominator of this formula. This is why a too large a reduction of the PV generator's nominal power would increase t_z, although – to a certain value of P_{PV} – it indirectly increased k_e and thus reduced t_z. Summing up the impact of the P_{PV} value, it can be seen that for every case of prosumer system there is a specific value of nominal power of a PV generator, for which the payback period will be the shortest. This is the most recommended P_{PV} value for practical application, of course as long as the basic criterion for installation of the system is the economic criterion, in the form of minimizing the payback period, and not, for example, the management of all the available roof area. For determining the optimum value of P_{PV} it is necessary to know the shape of the demand profile (line A), which for each prosumer has a different course.

Another way to minimize t_z is the strategy opposite to the one described, consisting in "reducing" line B by reducing P_{PV}, with line A kept constant. The idea of this strategy is to "raise" line A with constant line B, which in practice means increasing the demand for energy. Of course, it is pointless to increase demand only to squander the energy, it comes only with a rational increase in demand. This can be done e.g. by sending the energy generated in a PV generator to other consumers, without the participation of the distributor's grid. An example would be the system with a PV generator installed on the roof of a multi-family residential building, where the internal electrical grid of the building is privately owned by its residents, not by distributor. In such a situation, the PV generator would supply with "free" energy not only one apartment, but all apartments in the building. The settlement with the distributor would be conducted on the basis of one energy meter disposed in the electrical connector of the building, not by many energy meters in the joints of each apartment. On the other hand, a fair sharing between residents of the costs of settlement with the distributor would be possible thanks to private energy meters installed in all apartments. This solution would have the additional advantage, because it would reduce total fixed charges paid to the energy distributor.

It is worth mentioning yet another method of minimizing t_z: installation of prosumer PV systems in places where natural energy demand occurs primarily at middays, especially in summer. The examples are: a large proportion of manufacturing companies, agencies and offices. Schools are less recommended, due to the low demand for energy during summer holidays, which is the period of the largest production of photovoltaic energy.

The so-called net-metering is another possibility of minimizing the payback period. This method is provided in the new law on renewable energy sources. Net-metering means balancing the production and consumption of the prosumer's energy, e.g. in half-yearly cycles: January-June and July-December. With such an arrangement, the prosumer has the ability to receive payment from the distributor (or to pay the distributor) only for the difference between the amount of energy supplied to the grid and from the grid, with possible weightings of correction the difference. Unfortunately, this is an unfavorable option for the electro-energetic system, as it does not encourage the prosumers to perform favorable, for uniforming load distribution in the grid, management of their energy demand profiles, as the prosumers would have no motivation to control the hours of energy consumption. Also, this is not a beneficial proposal to other consumers without prosumer renewable energy systems, as the result of its application a distributor would have to increase the variable fee for energy distribution for all energy consumers. This is due to the fact that energy accounted on the basis of the balance would disappear from the overall balance of energy sold by the distributor to all consumers (both prosumers and ordinary consumers), and because the cost of grid operation would not decrease, hence the variable fee for energy distribution would have to increase, in order to avoid additional financial loss suffered by the energy distributor.

CONCLUSIONS

Legislative actions (adoption and amendments of the so-called new Act of Renewable Energy Sources), on the one hand can make prosumer photovoltaic systems even more profitable for their owners. In addition, a significant increase in the amount of energy generated in distributed PV systems would reduce the risk of so-called black-outs, as it would help to reduce the amount of energy transmitted during hot summer days with the grid of energy distributor, despite the considerable energy consumption by air conditioners in such days.

Unfortunately, this Act in the currently proposed form (high feed-in tariffs, net-metering) adversely affects the electro-energetic system, as it does not encourage prosumers to rationally plan their energy consumption schedule. In addition, a substantial increase in the power installed in renewable energy sources, converted by pulse operating power electronic devices (mainly by inverters), increases the problems caused by the deformation of sine wave voltages and currents in electro-energetic grids. Moreover, the effects of the implementation of this Act adversely affect other energy consumers, who do not have a RES, indirectly forcing them to partially subsidise the owners of prosumer systems. These shortcomings are one of the major reasons why the well-intentioned assumption of the RES Act (ordering the legal situation), is still controversial and still awaits the final settlement, thus causing the disappointment of people who invested in PV installations because they wanted to become prosumers not for ideas, but for profits.

Despite the uncertain legal status and uncertain support by the state (and thus, by all taxpayers) in the form of feed-in tariffs and net-metering, the application of the recommendations mentioned in this article could help to increase the profitability of prosumer systems, even in the absence of the implementation of such legal/economic support.

REFERENCES

1. Borut Del Fabbro, Aljoša Valentinčič & Andrej F. Gubina, 2016. An adequate required rate of return for grid-connected PV systems. Solar Energy, Vol. 132, 73–83.
2. Kacejko P., Pijarski P. & Gałązka K. 2014. Odnawialne źródła energii, prosument, mikrogeneracja, fotowoltaika, systemy wsparcia. Rynek Energii 5(114), 2014.
3. Karki R. & Billinton R. 2001. Reliability/cost implications of PV and wind energy utilization in small isolated power systems. IEEE Transactions on Energy Conversion, 2001, 16(4), 368–373.
4. Mikulik J. & Jurasz J. 2015. Determination of photovoltaic installation nominal power based on electrical energy consumption profile in the context of prosumer policy. Przegląd Elektrotechniczny, No. 1.
5. Mandelli S., Barbieri J., Mereu R. & Colombo E. 2016. Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review. Renewable and Sustainable Energy Reviews, Vol. 58, 1621–1646.
6. Mohamed A. Elsaharty, Hamdy A. Ashour, Elyas Rakhshani, Edris Pouresmaeil, Joao P.S. Catalao 2016. A Novel DC-Bus Sensor-less MPPT Technique for Single-Stage PV Grid-Connected Inverters. Energies, 9(4), 248.
7. Niechaj M. 2014. Modeling of photovoltaic generator operating in stand-alone system without electric buffer source. Przegląd Elektrotechniczny, 90(3), 215–218.
8. Niechaj M. 2013. Autonomiczny fotowoltaiczny system napędowy bez elektrycznego źródła buforowego z silnikiem indukcyjnym jednofazowym. Napędy i Sterowanie, No. 9, 148–153.
9. Reza Bakhshi & Javad Sadeh 2016. A comprehensive economic analysis method for selecting the PV array structure in grid–connected photovoltaic systems. Renewable Energy, Vol. 94, 524–536.
10. Salpakari J. & Lund P. 2016. Optimal and rule-based control strategies for energy flexibility in buildings with PV. Applied Energy, Vol. 161, 425–436.
11. Sangwongwanich Ariya, Yongheng Yang & Frede Blaabjerg, 2016. High-Performance Constant Power Generation in Grid-Connected PV Systems. IEEE Transactions on Power Electronics, 31(3), 1822–1825.
12. Treado S. 2015. The Effect of Electric Load Profiles on the Performance of Off-Grid Residential Hybrid Renewable Energy Systems. Energies, 8(10), 11120–11138.