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CASE STUDY – BASED EXPERIENCE CONCERNING TECHNICAL AND ECONOMICAL EFFECTIVENESS RESULTING FROM THE OPERATION OF PHOTOVOLTAIC INSTALLATIONS

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Abstract: The article presents some experience concerning technical and economical effectiveness arising from operation of an example of real photovoltaic micro installation. The main goal is to draw attention not only to its benefits, but also to the existing problems, that generate additional costs.

Keywords: photovoltaic microinstallation, operational problems, exploitation, failure, technical and economical effectiveness.

1. INTRODUCTION

The Renewable Energy Sources Act introduced in July 2016 and the introduced photovoltaic microinstallation support system caused significant interest in such systems among the potential investors. At the same time, the experience from the operation of the existing facilities should contribute to informed decision-making. Only the complete and properly conducted analysis of PV project profitability enables making a conscious and suitable decision on the implementation or abandonment of a planned project. For this reason, the decision was made to examine photovoltaic microinstallations with installed capacities of up to 10 kWp. These installations, pursuant to the regulations, are defined as renewable energy source systems up to 50 kWp, connected to the power grid with a rated voltage lower than 110 kV (previously, the capacity limit was 40 kWp) [Prawo budowlane 2020]. The construction of these installations on the roof or on the soil requires no permit. In this situation, the generation and potential input of the electricity to the grid is not considered as a business activity within the meaning of the Freedom of Business Activity Act. Neither is it regarded as the provision or sale of services within the meaning of the Goods and Services Tax Act of 11 March 2004 (i.e. Journal of Laws of 2016, item 710, as amended) [Prawo budowlane 2020]. For this reason, photovoltaic microinstallations have become very popular.

Both the literature and the available media present a series of studies on the selection of a specific installation type, operation type, and expected profitability resulting from the assumed maximum capacity at the assumed sunlight exposure level and the specified operation duration [Lewandowski 2006]. It is worth noting that the amount of information on the evaluation of the existing installations that have been in operation for some time and subject to reliable operational tests, is limited.

The purpose of the following analysis is to present specific experience from the operation of the photovoltaic microsystem installed on the roof of the single-family house of the author. While appreciating the necessity and purpose of implementation of pro-environmental electricity solutions, it is worth noting some operational problems that generate additional costs and that are often not mentioned in the commercial promotion of the construction of photovoltaic microinstallations.

A significant piece of the problem in question is the analysis of technical and economic data in the specified period of operation of PV microinstallations. In addition, an important problem addressed in this analysis is the project payback period, which depends on various technical and economic parameters (with and without external support), the role of technological progress in the PV technology and the drop of system efficiency resulting from the installation wear and tear characteristics and the occurrence of additional variables that have an impact on the operation of the installation (sunlight exposure level different from the assumed, panel operating temperature, etc.). A significant problem, often neglected in photovoltaic installation solutions, is installation disposal after the operating time. The cells are considered to be dangerous waste, which generates significant additional costs.

The photovoltaic installations that are part of the eco-friendly energy generation system in the era of promotion of pro-environmental activities are aligned with the entire package of solutions referred to as renewable energy sources. This set of solutions includes: nuclear energy generation, use of water, wind, sun energy, and other sources, such as biomass and biogas. In the foreword or introduction, most publications on these subjects stress the eco-friendly aspect and environmental protection. This issue, however, should be considered from multiple perspectives, because the industrial energy generation solutions transformed into lower capacity systems do not always show adequate energy and environmental effectiveness. Any investor selecting a specific energy system should be aware of the advantages and disadvantages of the given solution and make their decisions based on actual and adequate analyses.

Perhaps this article will be an inspiration for reliable pre-investment studies that enable making conscious decisions to construct a specific PV installation. The presented results are based on the experience resulting from several years of operation of the presented photovoltaic installation. The first section presents basic information on the placement and operation of the examined photovoltaic installation. The second section is dedicated to the components of the system, the third to the expected and actual energy yield. The fourth and fifth sections are dedicated the technical verification of operation of the installation for the obtained energy, efficiency, return on investment, and failure rate. The article ends with the conclusion and references.

2. SUBJECT OF THE STUDY

The examined photovoltaic microinstallation was constructed on a single-family building in the town of Reda in 2014. Due to the ineffectiveness of the beneficial Act on PV microinstallations at the time and problems related to the connection of the two-way measuring system, it was designed and implemented as an autonomous system using 100% of the generated electricity for conversion into thermal energy (off grid). Originally, the installed system consisted of eight polycrystalline PV panels with a maximum single panel capacity of 250 Wp. The final installation powered the electric heaters installed in the heat exchanger with a capacity of 120 litres. In 2019, due to the unsatisfactory operating results (insufficient power for efficient heating of water in the given time), the system was expanded by four polycrystalline panels with a unit capacity of 270 Wp. Thus, the total installed capacity of the system increased from 2000 Wp to 3080 Wp.

At present, the microinstallation (Fig. 1) consists of 12 photovoltaic panels connected in six parallel sections, two panels in serial connection, the wired connection system, the PV panel controller designed to control the total capacity of the assembly of heaters, and the integrated 1400 W heater. The mains power supply system enables additional heating of the boiler with a heater connected to the 2000 W/230 V power grid. The microinstallation includes a measuring system built into the MPPT controller (optimum voltage-based adjustment of the capacity to the current sunlight exposure of the panels), an independent microprocessor measuring system and an analogue-digital system for measuring the actual voltage and current generated by the panels. The installation is earthed and protected by gPV 20 A fuses (Fig. 2).

The panels on the operating plane were placed on two separate sections of the roof, in south-east and south orientations, on a 50% to 50% installed capacity basis. The panels are placed on a traditional support frame, fitted to the roof with fixtures in the form of bolts screwed into the rafters (Fig. 2). Due to the voltage-based adjustment (MPPT 52 V voltage), the PV panels in the initial phase of operation were combined into four sections, and in 2019 the system was extended by two sections. Six panels operate under optimum solar adjustment conditions from sunrise to noon and six from noon to sunset. The actual effective operating time of the microinstallation with good sun exposure is approx. 12 hours in June (from 5 AM to 5 PM) and 6 hours in January (from 9 AM to 3 PM). The operating time is limited to the above hours due to shadowing from the nearby forest in the evening.

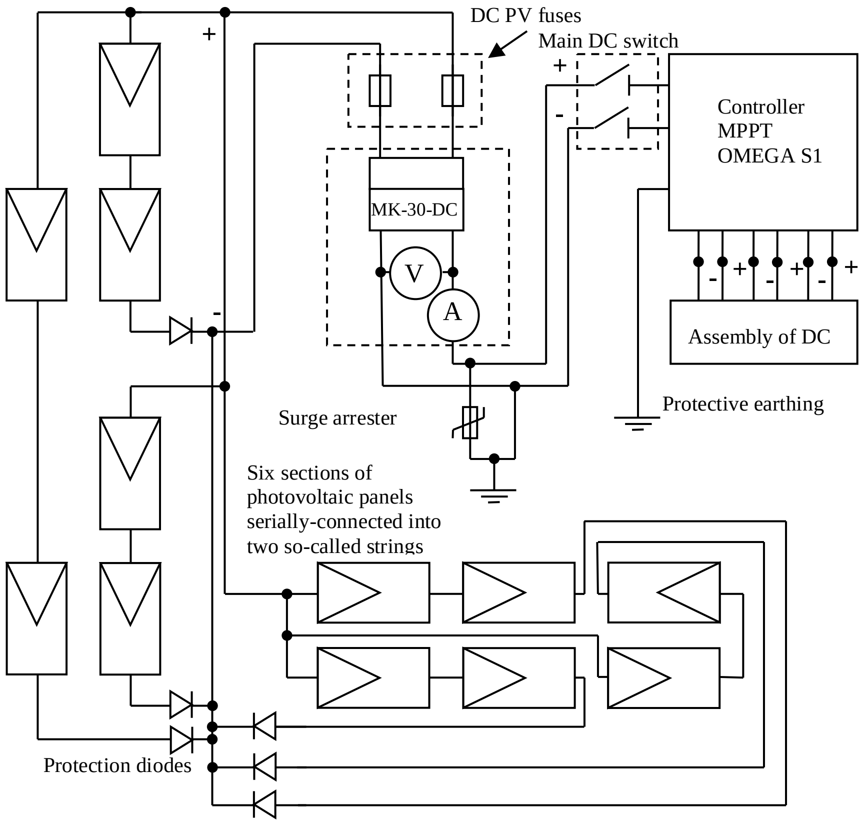

Fig. 1. Diagram of the examined PV photovoltaic installation

Source: own study.

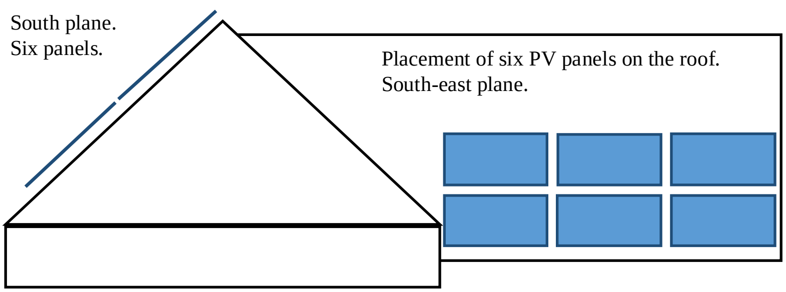

Fig. 2. Diagram of placement of photovoltaic panels on the roof of the residential building

Source: own study.

3. TECHNICAL CHARACTERISTICS OF THE COMPONENTS OF THE EXAMINED PV INSTALLATION

The evaluated photovoltaic installation is based on standard MaySun polycrystalline solar panels with dimensions of 1640 mm x 992 mm x 40 mm. They are panel type MS250P-60 (8 pieces) and MS270P-60 (4 pieces) with the following technical parameters (the parameters of the higher unit capacity panels are presented): Maximum capacity 270 ±3 Wp, rated voltage 31 V, rated current 8.71 A, short-circuit current 9.12 A, module efficiency 17.1%, rated operating temperature 47 ±2°C. The parameters of the panel were determined at a reference temperature of 25°C, a standard radiation intensity of 1000 W/m^2 and an optimum air mass of AM = 1.5. The temperature factors of the cells are: -0.30%/°C of the no-load voltage, 0.04%/°C of the maximum current, -0.40%/°C of the maximum capacity. Based on the temperature parameters, it was theoretically possible to obtain 280 W from a 250 W panel in January (0°C) and 220 W in June (45°C).

In the installation, six back-feed protection diodes were used in the parallel connections of the photovoltaic panel sections. The diodes are placed in an IP 68 sealed enclosure and connection-compatible with MC4 serial connectors. The basic electrical parameters of the diodes are: rated current 15 A, allowable voltage range 1000 V DC / UL 600 V DC and allowable operating temperature range -40°C to +85°C. The individual panels are connected with one another and the controller using copper solar cables in insulation and halogen-free coating in red (+) and black (-) with a section of 6 mm^2, terminated with MC4 connectors.

To protect the installation from the impact of short-circuit, it was equipped with DC 20 A PV fuses, installed in the distribution board in the positive and negative circuit, and fitted with the 100 A main FR switch.

Independent of the measuring system of the controller, a system was installed to measure and record the electrical parameters of the installation. It consisted of a traditional electronic voltmeter, ammeter with shunt (display with ranges selected for the appropriate parameters, that is, voltage up to 80 V, current up to 30 A, accuracy class 1). The distribution board with measuring gear was equipped with a universal Circutor MK-30-DC unit with the following technical parameters: voltage measurement up to 125 V DC ±0.5% FS ±1% digit, current measurement up to 30 A DC ±0.5% FS ±1% digit, power measurement up to 4.5 kW DC ±1% FS ±1% digit.

To optimise the operating point of the installation, an Omega S1 microprocessor controller was installed. It adjusts the water temperature in the DHW system by controlling the sections of the assembly of DC heaters using the MPPT algorithm and an additional heater powered with 230 V AC voltage. The controller features a clock module with time programmer that enables zone control of the mains-powered heater activation and deactivation. The settings of the technical parameters of the MPPT controller were adjusted to the number of installed photovoltaic panels.

Thus, the capacity range was set to 3 kW, the adjustment point to 52 V, the upper hysteresis adjustment range to 3 V, the lower hysteresis adjustment range to 22 V and the lower limit voltage of controller activation to 30 V. The photovoltaic installation loading system consists of three resistance heaters with rated voltages of 48 V, installed in a water heat exchanger. The heater power was selected as follows: H1 – 200 W, H2 – 400 W, H3 – 800 W.

4. ANALYSIS OF ELECTRICITY GENERATED BY THE EXAMINED PHOTOVOLTAIC MICROINSTALLATION

The annual average sunlight exposure in Poland is approx. 1000 kWh/m^2, while the annual average total sunlight exposure is 1600 hours [https://pdgr.urk.edu.pl...]. The solar radiation distribution is uneven in the annual cycle. Approx. 80% of the annual sunlight exposure occurs in the spring-summer period (April-September). In addition, in every region periodical sunlight exposure variations occur, caused by climate phenomena, clouding, and air pollution.

In accordance with the data available in the literature, based on the installed capacity (3 kW), the examined photovoltaic installation, under the rated conditions and the average solar radiation of 1000 W/m^2, should generate approx. 3000 kWh of electricity per year.

Based on the data in [https://finanse-w-energetyce.cire.pl...; https://pdgr.urk.edu.pl...] and the following calculations, the theoretical amount of electricity generated by the installation in a year should be 3560 kWh. (12 panels with dimensions of 1640 mm x 992 mm produce 1.63 m$^2 \cdot 12$ = 19.52 m^2 of active area of the installation. 19.52 m$^2 \cdot$1000 kWh/m^2 = 19,520 kWh. The estimated amount of generated electricity results from the following calculation sequence. 1 year is 8760 h. The effective operating time of the installation is 1600 h. Therefore, the corrective coefficient is 8760 h/1600 h = 5.475. Thus, 19,520 kWh/5.475 = 3560 kWh).

An installation with an installed capacity of 2 kW, based on an analogical analysis, should generate 2377 kWh of electricity per year.

The analysed photovoltaic microinstallation was installed in October 2014. From the start until today, automatic recording of electric parameters has been conducted. The following parameters are covered: current voltage, current, power, and the generated electricity is counted. In addition, the operating parameters of the DHW exchanger are displayed. In the analysed period, satisfactory domestic hot water parameters from the heat exchanger were not obtained, resulting in the decision to expand the system in 2019.

Table 1 presents the annual balance of the electricity generated before the installed capacity increase.

Table 2 presents the results obtained after the 30% increase of the installed capacity.

Table 1. Annual electricity generated by the 2 kW photovoltaic installation in Reda

No.	Annual measurement date	Generated energy [kWh]	Cumulative generated energy [kWh]	Comment
1	13/12/2014	4	4	Two months of operation. Very adverse sunlight exposure conditions
2	15/12/2015	1420	1424	Typical varied weather
3	17/12/2016	1160	2584	Hot and sunny summer
4	16/12/2017	1301	3915	Typical varied weather
5	17/12/2018	1193	5108	Typical varied weather

Source: own study.

Table 2. Annual electricity generated by the 3.1 kW photovoltaic installation in Reda

No.	Annual measurement date	Generated energy [kWh]	Cumulative generated energy [kWh]	Comment
1	15/12/2019	1646	6754	Typical varied weather
2	15/12/2020	1775	8529	Typical varied weather

Source: own study.

Based on the analysis of the results presented in the above tables, it may be concluded that the average energy generated by the 2 kW system in a year was 1277 kWh, which was 1100 kWh lower than the calculated assumed theoretical energy that the installation should achieve. In reality, 54% of the estimated energy was obtained. For the 3 kW installation, the difference was 1914 kWh, that is, 47% of the estimated energy value.

In this situation, it is natural to ask: why are the disparities between the estimated and the actually generated energy so wide? It seems that the result may be influenced by the placement of microinstallation panel sections on two planes with different geographic orientations (implemented to increase the energy yield in the morning hours). This orientation extends the operating time, while reducing the actual installed capacity. For the purposes of this analysis, the actual installed capacity was reduced by 25%, that is, to 1.5 kW and 2.25 kW for a capacity of 2 kWp and 3 kWp, respectively. Then, the annual estimated generated energy should be 1786 kWh and 2679 kWh, respectively. In this case, 72% and 62% of the estimated energy value was actually obtained, respectively. The results for the system with a capacity of 3 kWp differ from the percentage results for the system with a capacity of 2 kWp. This may result from the overlap of a series of additional reasons. However, it is difficult to identify them clearly due to the insufficient testing time of the operation of the photovoltaic microinstallation with the increased installed capacity. It seems, however, that they included: lower sunlight exposure in the previous year, suboptimal seating angle of the panels relative to the solar disc, contamination, suboptimal operating temperature of the system, etc.

5. OPERATIONAL PROBLEMS OF THE PHOTOVOLTAIC INSTALLATION

It may seem that once constructed and commissioned, a photovoltaic installation operates without maintenance and generates electricity. This is possible, but essentially not recommended for many reasons. Operation without maintenance significantly decreases system efficiency, which to a large extent depends on the cell cleanliness. The cleanliness of the panels is directly influenced by dust, smoke, tar fatty deposits, and contaminants of avian origin.

To maintain reasonable (unrelated to ageing losses) efficiency of the system, the panels should be cleaned at specific time intervals, in particular at the beginning of the season. This activity generates additional costs depending on the access to the installation. If installed in a field or on a flat roof, it does not generate additional costs (the owner of the installation can perform the maintenance activities). On the other hand, installations on the roofs with high slopes require using special equipment or contracting a third party for the service.

Maintenance interventions related to inspections should not be omitted. PV installations generate different voltages and currents (depending on the configuration). If a particularly high current is generated, attention should be paid to all electrical connections. In the considered installation, a failure occurred related to the melting of the power supply wire connection to the controller and measuring panel due to the loosening of a screw connection and a consequent electrical arc. The failure forced a repair of the controller and replacement of the measuring system. The costs of this operation exceeded PLN 1000 and the failure constituted a real fire hazard.

Another problem that occurs during the operation of the installation is the contamination of the roof under the photovoltaic panels. This phenomenon is very detrimental, because it significantly accelerates the wear and tear of the roof surface, in particular by growing micro-organisms, moss and the omnipresent moisture. These places are most often hard to reach and effective cleaning and drying is practically impossible. This results in problems with roof tightness after several years of operation. In this case, a comprehensive renovation undermines the economic rationale of the operation of such an installation.

The first problems with roof tightness in the case of the considered installation emerged after five years of operation, despite the removal of the contaminants and moss found with a pressure washer. The reason for the leakage, determined based on a visual inspection of the installation, was the wear and hardening of the rubber seals used at the fixing bolts on the support frame of the panels on the roof.

In addition, the operation of the considered system requires periodical replacement of the built-in battery (1.2 Ah, 12 V) powering the MPPT controller (control of the 230 V mains-powered heater) when there is a lack of sunlight and at night. Despite being recharged by the recharging system integrated into the controller, the insufficient sunlight in the autumn-winter period results in quick depletion of the battery, resulting in the malfunction of the entire system. During the six years of operation, four batteries were replaced in the system.

During the modernisation works (increase of the installed capacity), a series of defects was identified and eliminated. They were most often related to the destruction of the plastic components supporting the connection wires, loosening of the fixing bolts, loosening of wire connectors, cracking of the enclosures of protection diodes, etc.

The literature on the presented research subject also listed other possible causes of deterioration of the general operating efficiency of such installations, including for example [Solińska and Soliński 2003] system maintenance, area leasing and maintenance, installation insurance, security, taxation, and others.

When analysing a photovoltaic installation over a long operating period, it is also worth noting the costs related to the potential replacement or repair of its specific components (the so-called replacement and modernisation expenditure).

Unfortunately, photovoltaic modules are characterised by a gradual decrease of performance, resulting for example from the deteriorating optical properties of the modules, module delamination, rear protective film cracking, air and humidity penetration into the modules, metallic contact corrosion, etc. The average decrease of performance of the PV modules available on the market is approx. 0.7% per year, however the best modules achieve a result of less than 0.2% per year, but some technologies are characterised by a decrease of performance of even more than 1.5% per year [Wielewska 2017]. In the examined microinstallation in the presented period, the above-mentioned damage was not found. The additional costs of security, leasing and insurance were omitted in the analyses.

In addition, another problem in the photovoltaic systems operating in the prosumer system (energy collection in the electricity system using the electricity company's resources) is the voltage increase in the operating area of inverters in the power input mode. In the case of collection of a significant amount of electricity from an installation at a specific point in the network (high unit capacity or installation quantity in a specific space), the generated voltage may exceed the permissible mains voltage standard. This fact results in the deactivation of the inverter and no energy generation. Thus, the efficiency of the system is technically limited. At the same time, long-term operation of the equipment at increased voltage is a cause of accelerated wear-and-tear. The problem of the rated voltage being exceeded in the case of significant electricity generation is being addressed much more often in Internet-based sources of operational reports on different photovoltaic installations. In the case of a large number of prosumer installations, the connection networks should be specially designed.

6. ECONOMIC ANALYSIS OF OPERATION OF THE EXAMINED PHOTOVOLTAIC INSTALLATION

In the analysis of the factors constituting the basis for the installation of the photovoltaic installation, the economic issue was considered to be of secondary importance.

The basic criterion for the construction of this installation was the need to supply the household with hot water in the summer period. An additional reason was the opportunity to use the installation for research purposes.

Considering the promotion of dispersed energy generation using renewable energy sources in the European Union, the economic matters related to the implementation of such enterprises cannot be omitted.

Simple and complex economic analyses were conducted, based on the obtained data. The comparison of simple efficiency was based on the direct return method, also referred to as the simple rate of return method.

This method determines the ratio of the annual profit to the capital expenditure in the given project. A disadvantage of this method is that it is based on single-year values and does not include changes in the value of money over time.

The simple rate of return on own capital expenditure is determined by the relationship [Solińska and Soliński 2003]:

$$RW = \frac{ZN}{KW} \tag{1}$$

where:

RW – rate of return on capital expenditure,
ZN – annual net profit [PLN],
KW – capital expenditure value.

Knowing the capital expenditure involved and using the relationship for the simple rate of return, without including the subsidy, the interest on the potential loan, using the simplified formula for the capital expenditure payback period, the year in which the expenditure will be equal to the profits can be calculated. This is the payback period.

The basic formula determining the payback period can be presented in the following form [Solińska and Soliński 2003]:

$$J - D = \sum_{i=1}^{tz} Z_i + A_i + O_i \tag{2}$$

where:

- J – capital expenditure [PLN],
- D – project subsidy [PLN],
- Z_i – net profit in the i-th year of operation [PLN],
- A_i – depreciation rate in the i-th year of operation, counting from the actual project value J [PLN],
- O_i – interest on the loan in the i-th year of operation [PLN],
- t_z – the year in which J-D will be equal to the sum of $Z_i+A_i+O_i$ constitutes the capital expenditure payback period.

However, the simplified formula takes the following form [Solińska and Soliński 2003]:

$$J = \sum_{i=1}^{tz} Z_i \tag{3}$$

Economically, the examined microinstallation was compared using the simple and complex method, based on the NPV method.

The NPV decision-making method, or the net present value method, enables evaluating relatively complex cash flows related to the project (they require comparing the current value of future revenue with the present capital expenditure) [Solińska and Soliński 2003].

$$NPV = \sum_{i=1}^{n} \frac{CF_i}{(1+r)^n} - J_0 \tag{4}$$

where:

- I_0 – expenditure,
- CF – cash flow,
- n – number of periods considered,
- r – rate of return.

6.1. Simple analysis of the return on investment without subsidies and tax exemptions

During the meetings and conversations with the owners using photovoltaic installations, the most frequently used argument for the decision to construct the installation was the significant reduction of energy bills and relatively quick depreciation of capital expenditure. In an era of current and future increases of electricity prices resulting from CO_2 emission fees paid by the Polish electricity companies, this argument seems valid. It is worth confronting the quoted argumentation with the analysis of the costs resulting from the presented case study.

In the case of the examined installation, an “off grid” system was used, directly connected through the controller to the resistance load heating the heat exchanger. This situation enables using the one-to-one economic conversion rate for the energy yield at the purchase prices of electricity from electricity companies.

Based on the stated assumptions, the examined microinstallation with the original installed capacity of 2 kWp was completed in 2014. It was designed and constructed by a currently non-existent private company from Gdynia.

At the time, the total cost of construction, without subsidy, was PLN 12,000 gross.

In 2019, the increase of the installation capacity to 3 kWp cost an additional PLN 3,000 (without labour). Thus, the total cost of the currently operated microinstallation amounted to PLN 15,000.

Based on the electricity bill for 2014 (360164167/00001/0034/1F), the total gross cost of 1 kWh (including all fixed and variable fees) under the G11 rate applicable to the considered household in which the photovoltaic system operates was PLN 0.655. After minor increases (corrections), resulting from the addition of RES, cogeneration and energy quality components in the invoice, the energy price in 2019 increased to 0.75 PLN per kWh (for calculations, the average price of 0.7 PLN per kWh was assumed).

Therefore, considering the data included in Tab. 1 and Tab. 2, using the relationship (1), (3), the actual return on investment in the given time can be calculated (Tab. 3).

The results obtained were: PLN 2.8 in 2014, PLN 996.8 in 2015, PLN 812 in 2016, PLN 910.7 in 2017, PLN 835.1 in 2018, and PLN 1,152 in 2019. The total financial yield in the considered period was PLN 4,709.6. On this basis, it may be concluded that, theoretically, the return on investment will be obtained in 10 years. Excluding the subsidies and additional costs, considering the current increase of electricity prices to approx. PLN 1 per 1 kWh and the assumed annual energy yield at 1750 kWh, such an installation operated in the described manner should provide return on investment after approx. 11–12 years of operation since the construction.

Considering the additional operating costs at the level of 3% of the capital expenditure for the construction of the installation within a year, the payback period extends to 12–14 years.

6.2. Simple analysis of the return on investment including 25% subsidy and tax exemption

If systemic support is received for the construction of the photovoltaic installation, the direct investment cost of the examined installation would be approx. PLN 11,250. Considering the income tax refund, the cost would be reduced to approx. PLN 9,000.

On this basis, it may be concluded that if no additional costs are incurred, the simple return on investment would occur within approx. 6 years (with the current total energy price level of approx. 1 PLN per kWh). Considering the additional operating costs at the level of 3% of the capital expenditure for the construction of the installation within a year, the payback period extends to 7–8 years.

6.3. Economic analysis of the return on investment using the NPV method without subsidies, tax exemptions and additional costs

Table 3. Return on investment calculated using the NPV method with the return rate at 2.85%

Years of operation n	**Cash flow CF_i [PLN]**	**NPV [PLN]**	**Payback 12,000 Plus 3,000 after the 4th year of operation [PLN]**	**NPV including the 10% electricity price increase after the 5th year of operation [PLN]**	**Payback [PLN]**
1	996.8	969.18	-11,030.82		
2	812	767.62	-10,263.2		
3	910.7	837.12	-9426.08		
4	835.1	746.3	-8679.78		
5	1152	1120.07	-10,559.78		-10,559.78
5	1200	1134.41	-9425.38	1646	-8913.78
6	1250	1148	-8276.44	1556.04	-7357.74
7	1250	1117.1	-7159.34	1512.93	-5844.81
8	1250	1086.15	-6073.2	1470.99	-4373.81
9	1250	1056.05	-5017.15	1430.24	-2943.52
10	1250	1026.79	-3990.36	1390.61	-1552.91
11	1250	998.33	-2992.03	1352.07	-200.83
12	1250	970.67	-2021.36	1314.6	**<u>1113.77</u>**
13	1250	943.77	-1077.59		
14	1250	917.62	-159.98		
15	1250	892.2	**<u>732.21</u>**		

Source: own study. For calculation purposes, the average discount rate for the considered projects was assumed.

Based on the data in Table 3, the examined installation will begin generating profits (excluding costs) after 15 years of operation in the pessimistic scenario and after 12 years of operation in the optimistic scenario. If the cash flow reduction resulting from the installation wear and maintenance costs is considered, the payback period is significantly extended. However, the expected increases of electricity prices compensate for these costs. Therefore, the presented analysis of the capital expenditure payback time period based on the measurements seems reasonable. In the literature and in particular in electronic media, a series of information on the operation of different PV microsystems is found [Wielewska 2017; Szyja 2020; Tytko 2021].

Most claims included therein (not including the optimistic slogans advertised by different content owners of PV installations, not supported by reliable analyses) end with the following conclusion: using this type of installation without subsidies is not profitable. Only the subsidy makes the installation interesting for an investor, by reducing the average payback period to approx. 9 years.

7. CONCLUSIONS

The results of energy and economic effectiveness analyses clearly confirm that the estimated (model) data may significantly differ from the actual data on the electrical energy generation value of the installation, therefore the profitability of such an investment must be based not only on the directly measured parameters.

The above-presented analysis of the results of the operated installation confirms these conclusions. At the same time, the operation of the installation showed that operating costs are inevitable and increase over time, which lowers the assumed economic effectiveness. The construction of such installation is supported by the actual and planned increase of electricity prices. However, in investment planning, the following should be considered, in particular:

- proper direction of installation adjustment for optimum sunlight exposure and relatively averaged solar panel setting angle;
- access for inspections and repairs of any damage to the installation (sometimes very expensive);
- access for periodical washing of photovoltaic panels;
- additional hazards in the forms of moisture, microbial and moss growth in the areas shaded by the panels, in particular roofing;
- significant impact of the thermal performance of the panels on the operating efficiency of the installation;
- reduction of the operating efficiency of PV panels over time;
- necessity of replacement of the components of the installation due to technological advancement, for example the inverter, controller, etc.

The examined photovoltaic installation operates below the assumed performance parameters guaranteed by the installation company. The obtained energy yield during the year is at the level of 75% of the assumed values. However, this poor result, not confirmed by other authors that describe PV microinstallations, may result from the assumption of the division of this installation into two sunlight exposure adjustment directions. As a consequence, the installation operates nominally longer, but effectively shorter at maximum power. An additional stimulus that makes the contemporary installations more investor-friendly are the increasing power densities from the active panel surfaces. At present, the panels have a minimum rated capacity of 350 W. This is on average 30% more power than in earlier solutions and these components are still in development. This development determines the relatively proportionally better return on investment time than presented in the article. However, the disadvantages of a long-term photovoltaic installation are also inevitable in new systems.

The presented long-term experience from the operation of the photovoltaic system should not discourage potential investors, but become an additional criterion to be considered in the planning, design and construction of new photovoltaic installations or during the modernisation of existing facilities.

The direct conclusions are: the best photovoltaic installation is one made of high quality, state-of-the-art materials, with high power density, immune to the technological ageing process, and to which access is relatively easy to enable care (panel washing) and inspections. It seems that such criteria can be met by installations on inclined frames in squares and fields, and on properties and roofs of service buildings, or flat roofs of residential houses.

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