sciendo

PRODUCTION ENGINEERING ARCHIVES 2021, 27(2), 90-99

PRODUCTION ENGINEERING ARCHIVES

ISSN 2353-5156 (print)
ISSN 2353-7779 (online)

Exist since 4th quarter 2013
Available online at https://pea-journal.eu

Economy and energy analysis in the operation of renewable energy installations – a case study

Adam Idzikowski[1] **Tomasz Cierlicki**[2]

[1] Czestochowa University of Technology, Armi Krajowej 19B str., 42-201 Częstochowa, Poland
[2] University of Science and Technology in Bydgoszcz, prof. S. Kaliskiego 7 str., 85-796 Bydgoszcz, Poland
Corresponding author e-mail: tomcie001@utp.edu.pl

Article history
Received 12.02.2021
Accepted 18.05.2021
Available online 14.06.2021

Keywords
solar panel
renewable sources of energy
inverter

Abstract
In the paper an economic, ecological and energy analysis of a home photovoltaic on grid installation was presented. The increase in ecological awareness of the Polish society contributes to the continuous growth of interest in green energy. However, many people haven't been aware of the ecological, economic and energy benefits of photovoltaic installations yet, so the following analysis is made. The analysis concerns a photovoltaic installation with a capacity of 3.96 kWp located in Ościęciny near Włocławek. The photovoltaic installation consists of 11 monocrystalline panels with a power of 360 Wp, a 4 KTLM Sofar Solar inverter and other necessary components. The first part presents basic issues related to photovoltaic installations. Parameters related to the proper functioning of the photovoltaic installation were replaced. The analysis of the literature will help to understand the essence of the proper functioning of the photovoltaic installation. In the practical part, an analysis of a selected home photovoltaic installation was carried out. Based on the available data, it has been calculated that the installation will have a payback period of over 9 years. The photovoltaic installation will produce approximately 3 582.61 kWh of electricity and will contribute to the reduction of 70 tons of carbon dioxide during the entire operation.

DOI: 10.30657/pea.2021.27.11

JEL: P30, M11

1. Introduction

In households, electricity consumption is steadily increasing, electricity prices are also rising, and the government in Poland has committed to shutting down some coal-fired power plants by 2030 in order to meet climate goals. It may cause that in the future we will have a problem with the deficit in electricity.

However, Poland's environmental awareness is growing year by year, and more and more people are aware of the consequences of producing energy from non-renewable fuels (Ulewicz et al. 2021; Tutak et al. 2020). Therefore, for environmental and economic reasons, more and more people are investing in home photovoltaic installations and thus becoming producers of electricity for their own needs, i.e. prosumers (Figure 1).

At the end of December 2020, the installed capacity for photovoltaics in Poland was 39.670 MW. This means an increase of over 200% compared to December 2019. The installed capacity for all renewable energy sources in December amounted to 51.86 GW, which means that the share of renewable energy sources (RES) in the energy sector is 12.5%. In the RES sector, photovoltaics ranks second (after wind farms) in the production of electricity in Poland. In 2020, the highest monthly production was in April, and the daily production was on August 12, that day, photovoltaic installations produced 12.3 GWh of electricity (PSE data).

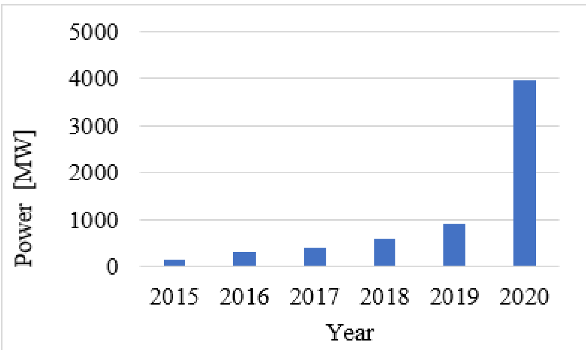

Fig. 1. Photovoltaic market in Poland (The data taken from the Institute of Renewable Energy)

The helioelectric method is based on the direct conversion of solar radiation energy into electricity, using photoelectric cells. The material used to build photovoltaic cells are crystalline or amorphous semiconductors, usually silicon (Si). In order to produce the photovoltaic effect, phosphorus or boron are added to the silicon crystal. By adding phosphorus to silicon, n-type silicon is obtained, and by doping silicon with boron, p-type silicon is obtained. Plates p and n pushed together form a p-n junction. When the light radiation absorbed in the area of the joint and in the material adjacent to the area on both sides of the joint has an energy greater than the band gap, electron-hole pairs are formed which are separated by the electric field of the joint. The separated minority carriers on one side of the junction become majority carriers with an infinite lifetime on the other side, generating potential differences. After the circuit is closed, a current flows in it (Mroziński and Flizikowski, 2016; Mroziński and Piasecka, 2016).

Nevertheless photovoltaic cells have both advantages and disadvantages. The main advantages include their long-term and failure-free operation, which allows to significantly reduce the emission of harmful compounds, causing dangerous respiratory diseases. The disadvantages of PV cells mainly concern their production, as it is energy-consuming, which in turn entails the emission of harmful combustion products. The last phase of the life of photovoltaic modules may also be a problem due to the presence of heavy metals in PV panels. The advantage of this branch of energy is the inexhaustibility and unlimited availability of solar radiation. The disadvantage is the uneven intensity of solar radiation depending on latitude, time of day or year, and the still high cost of the devices used (Piasecka et al., 2021).

The results of the presented analysis may be useful in designing intelligent buildings in terms of their thermal comfort (Majewski et al., 2020), as well as in methodological issues related to the assessment of repeatability (Szczotok et al., 2017).

The main aim of the work is analyzing the principle of operation of a selected home photovoltaic installation. On the basis of the main goal, authors tried to assess the economic, environmental and energy benefits of the selected photovoltaic installation. At the very beginning, the literature was analyzed. During the analysis of the literature, the aim was to evaluate the necessary components affecting the correct operation of the photovoltaic installation.

2. Literature review

The principle of operation of the photovoltaic installation is as follows. The intensity of solar radiation sends photons towards the PV panels, which are absorbed by the photovoltaic cells. The generated DC current through the wires is directed towards the inverter, where the DC current is converted into AC current. Then, the alternating current supplies the receivers or is fed into the power grid or charges the batteries. The installation consisting of batteries must have a battery charging and discharging controller that will control over-charging and discharging of the batteries. Currently, the technology of photovoltaic installations with batteries is not popular in Poland due to the high price of batteries. Below a literature review of the most important components of photovoltaic installations was presented.

The most important element of photovoltaic installation are photovoltaic cells that converts directly the energy of solar radiation into electricity of direct current. These cells are connected in series and placed in the housing to form a photovoltaic module. According to the general classification, cells are divided into three generations (Mroziński and Flizikowski, 2016; Szymański, 2020):

- I generation cells, which are produced on the basis of crystalline silicon wafers (currently they have the largest share in the sales market), the advantage of these cells is the prevalence of silicon, good adaptation to photovoltaic conversion and efficiency up to 22%.
- II generation cells are thin-film cells that are cheaper to produce and can be made of amorphous silicon, polycrystalline cadmium telluride. The efficiency of this type of cells is about 10-15%. The main disadvantage of the second generation cells is the LID effect (light induced degradation), i.e. fast but short-term degradation under the influence of solar radiation. The decrease for this type of cells reaches several dozen percent of the nominal power, usually 10-30%, therefore the power given by the manufacturers applies to the state after degradation.
- III generation cells are cells consisting of two or more materials with different energy gaps, each of which absorbs this part radiation, which it can most effectively convert into electricity. The advantage of these cells is low cost and simplicity of production. The main disadvantage is low efficiency and short service life.

As mentioned, the most popular are the first generation cells made of crystalline silicon cells. Generating electricity thanks to silicon photovoltaic cells is possible by creating a p-n type semiconductor junction in a silicon wafer. Under the influence of solar radiation, incident photons with an energy greater than the width of the semiconductor gap create an electric current. In this way, the wave and corpuscular properties of light become visible. The wave properties dominate the interactions related to reflection, refraction, diffraction, scattering, polarization, and the particle properties dominate in absorption, emission and luminescence (Corcelli et al., 2017).

Most PV cells are based on P-type silicon, which means that boron is added making the material a P-junction. The N junction is formed by sputtering phosphorus on the wafer surface. It is believed that N-type cells will be more popular in the future, as they eliminate the LID phenomenon and are less sensitive to pollution (Wrzesiński, 2017).

The I generation PV cells and modules are divided according to the degree of silicon crystallization into monocrystalline and polycrystalline. Monocrystalline cells are made of a single crystal of silicon and have a higher efficiency than polycrystalline panels by about 5%. Crystalline silicon does not occur in nature. It is produced by various methods, the most popular method is the method developed by the Polish scientist Jan Czochralski. It consists in removing a single crystal from liquid silicon with the addition of boron, formed in the form of a cylinder, and then cutting it into plates (type P), with a radius of several centimeters. Monocrystalline cells are dark blue to black in color, often with rounded corners. The photovoltaic module with polycrystalline cells is made of polycrystalline silicon. starting material is a block of silicon weighing approximately 100 kg, formed in a furnace by a melting and directed crystallization process. The block is divided into solids and then cut into square tiles. Polycrystalline cells are light blue in color with visible crystal edges (Mroziński and Flizikowski, 2016; Tytko and Góralczyk, 2013).

The PV cells in the module are connected by means of a thin metal strip, whose task is to conduct electricity. The silicon PV cells on the front and back sides have a prepared area for soldering these tapes, called the busbar. Initially, two busbars were used, but it has been noticed that more busbars increase the efficiency of the modules. Modules with more busbars have less stresses developed during the soldering of the strip. Which increases safety against the appearance of microcracks and slower degradation of the module. Another advantage of more busbars is that the distance the electrons have to travel is reduced, resulting in less losses (Goe and Gaustad, 2014).

After the PV cells are connected, they are laminated to protect them from damage. In the lamination process, connected links are placed between the encapsulating material and the pane. To increase the power of a photovoltaic generator, several modules are connected in parallel, in series or in series-parallel, thanks to this connection it is possible to obtain generator power up to several megawatts (Tytko, 2020).

The power of photovoltaic modules depends on the electrical parameters and environmental conditions. The most important is the intensity of solar radiation and the operating temperature of the module. All parameters of the modules are included in the catalog card, determined for specific test conditions, the so-called STC conditions. The STC conditions indicate under which conditions the efficiency of the modules was tested, these conditions are based on the PN-EN 61853-1: 2011 standard. The STC conditions say that the module has a maximum power at an intensity of 1000 W/m^2, a temperature of 25°C and for a radiation spectrum for an atmosphere thickness of 1.5. Usually, modules do not work in such conditions, therefore most manufacturers provide cell operating conditions in nominal NOCT conditions. The tests determine the temperature at 20°C, radiation intensity 800 W/m^2, solar radiation spectrum for the atmosphere thickness of 1.5 and wind speed 1 m/s.

In the Figure 2 there can be seen change the current depend on the solar radiation (E) in constant temperature (T = 25°C). The low solar radiation is cause of descend the maximum power point (MPP), which results in a reduction of electricity production.

Another important parameters of PV modules are the short circuit current (I_{sc}), the current at the maximum power point (I_{mpp}), the open circuit voltage (V_{oc}) and the voltage at the maximum power point (V_{mpp}). By multiplying the current at the maximum power point (I_{mpp}) and the voltage at the maximum power point (V_{mpp}), the maximum power of the module (P_{max}) under given environmental conditions will be obtained. These parameters strongly depend on the intensity of solar radiation. As the solar radiation intensity level decreases, the I_{mpp} and I_{sc} currents decrease. In turn, solar conditions will have a small effect on the voltage of the module. Changing the current value will consequently change the power of the PV module.

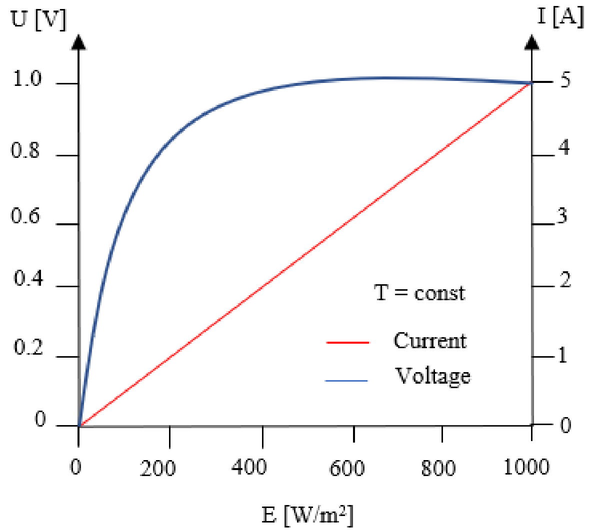

Fig. 2. Influence of solar radiation intensity on the power of a photovoltaic panel (developed on the basis of Mroziński and Flizikowski, 2016)

The factor that affects the power of photovoltaic modules is temperature. Temperature affects the vibrations of the atoms of the crystal lattice that builds the photovoltaic cell. The vibrations of the network hinder the flow of current, which reduces the electromotive force. As the temperature rises, the power of PV modules will decrease. Therefore, it can be seen that PV modules have the highest production in the spring season than the summer season. The indicator informing about the decrease in power with increasing temperature is provided by the temperature indicator of power. The lower the temperature power index, the lower the power loss with increasing temperature. There are differences between the types of modules in the value of the maximum power temperature index. As a rule, thin-film modules lose half slower power with increasing temperature than mono or polycrystalline modules. The cell temperature depends on the radiation intensity, wind speed, air temperature and installation assembly. In the summer, the temperature on the surface of the modules can be up to 70°C, therefore, incorrect installation of the module on the roof without the possibility of free air flow may cause significant drops in the installation power (Szymański, 2020; Wrzesiński, 2017).

The quality of the module is indicated by the fill factor (FF), which is the ratio of real power to apparent power. Solar cells are sold in three main quality classes:

- grade A cells without flaws,
- grade B cells with few flaws,
- grade C cells with numerous flaws

The fill factor is calculated using the formula placed in Figure 3. The higher the cell class, the higher its power and quality. A perfect PV cell has a shunt resistance R_b that goes to infinity and a series resistance that goes to 0. If the shunt resistance drops, it is due to a failure of the photovoltaic cell. Grade A photovoltaic modules should have a fill factor above 0.75, grade B cells within 0.7-0.72, grade C cells with a fill factor between 0.6 and 0.7 (Mroziński and Piasecka, 2016).

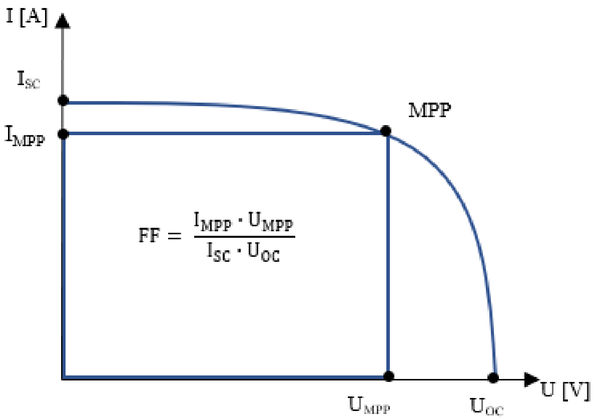

Fig. 3. Current-voltage characteristics of a photovoltaic module (developed on the basis of Mroziński and Piasecka, 2016)

What current or voltage will flow from the modules to the inverter depends on how the PV modules are connected and the weather conditions. When connecting modules in parallel, it should be remembered that it causes an increase in the intensity of the flowing current, in turn the voltage is equal to the nominal voltage of one PV module (Figure 4). Serial connection of PV modules increases the voltage, while the current remains equal to the nominal current of one PV module (Figure 5). In installations, avoid combining photovoltaic modules with different electrical parameters or different manufacturers.

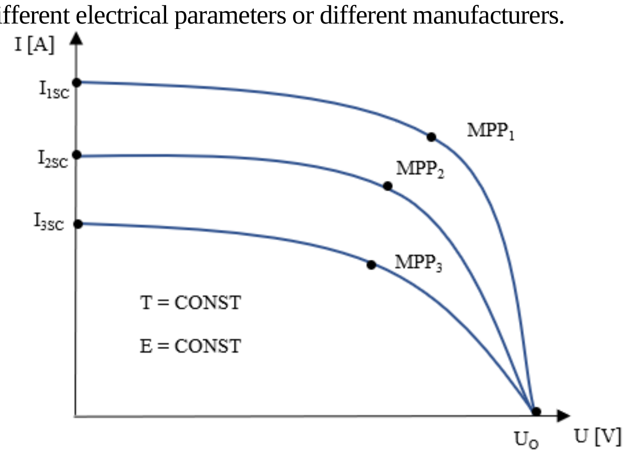

Fig. 4. Parallel connection of photovoltaic panels (developed on the basis of Mroziński and Flizikowski, 2016)

Another important element of a photovoltaic installation is an inverter, whose task is to convert electricity from photovoltaic modules that produce direct current into alternating current, with parameters compliant with the public grid (230/240 V, 50 Hz). In addition to the current conversion, the inverter performs control, safety and installation monitoring functions. These devices can be divided into transformer and transformerless. Transformer inverters have a transformer that separates the DC side from the AC side. The inverters can be divided depending on the cooperation with the network or off gird inverters are devices that do not cooperate with the power grid and do not introduce electricity into it. The surplus energy is stored in batteries. On grid inverters are devices that synchronize with the public grid, thus feeding energy into the grid.

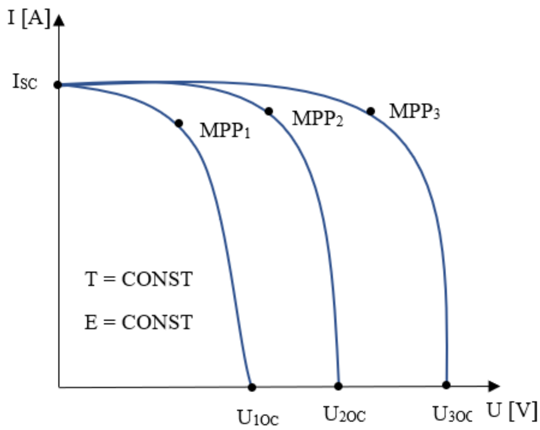

Fig. 5. Series connection of PV modules (developed on the basis of Mroziński and Flizikowski, 2016)

The efficiency of the inverter depends on the degree of load and voltage level. Therefore, manufacturers of inverters provide the efficiency characteristics of inverters as a function of load and voltage level on the DC side. The inverter works optimally when it is loaded in the range of 20-80% of nominal power, while lowering the power below 20% causes a rapid decrease in efficiency. This device can operate within the specified DC voltage range. The starting voltage V_{start} is above the minimum operating voltage V_{min} but below the voltage $V_{mppt\text{-}min}$. Means that when the voltage on the DC side exceeds V_{start}, the inverter will switch on and start looking for the maximum power point. As long as the voltage does not exceed $V_{mppt\text{-}min}$, the inverter will not be able to run at its nominal power.

Modern inverters allow to measure a wide range of their work. They allow to read the amount of electricity produced, it is possible to read DC input, AC output, inverter operating status and errors. The computerized monitoring system allows to see the inverter operation alarms, which are sent to the user by e-mail or text message about problems with the installation. These devices most often communicate using the Modbus RTU interface, some communicate using Modcus TCP, and the new trend is the use of power line communication (PLC). As part of wireless communication, it is possible to communicate using Bluetooth or Wi-Fi (Tytko, 2020).

The cables in a photovoltaic installation are often overlooked when optimizing an installation. Cabling is low cost in relation to the value of the installation. It is worth noting that there should not been savings on this component, because any damage may result in the need to disassemble and reassemble the entire cabling, which is associated with high costs. For this reason, the best quality cables with a high safety factor, high resistance to UV radiation, humidity, low and high temperature should be used. It is worth to route the cables and protect them with a special cover. The conductors on the DC side are different to the conductors on the AC side. The cable on the DC side has a larger outer diameter due to thicker insulation. The cable should have a silver core, which proves that the copper wires are tinned (Lelek et al., 2016).

The photovoltaic installation should also be properly secured so as not to cause dangerous situations that threaten the lives of residents who use it, or damage to the system element. The installation should be overcurrent protected on the DC side with fuses, whose task is to break the circuit in the event of too high current flow. It is not recommended to use AC fuses as they may not fulfill their function. Fuses for PV installations are characterized by a very short circuit break time when a certain current level is exceeded. These devices should have gPV characteristics. The PN-HD 60364-7-712:2016 standard makes it possible to bypass overcurrent protection on the DC side when the installation consists of one or two strings of PV panels connected in parallel. On the AC side, it is important to use an overcurrent breaker in the event of a short-circuit current on the mains side. For this purpose, type B overcurrent circuit breakers are used. They are fire protection elements, so it is important that their operation time is quick. The maximum tripping time cannot be longer than 0.2 s. The installations also use the residua current device. Provides protection against electric shock. Type B RCDs should be used that detect leakage current, sinusoidal, direct, pulse. The standards stipulate that RCDs are not to be used when the inverter has an AC-DC separation transformer. The individual elements of the photovoltaic installation should be protected against lightning. It is important to use appropriate insulation gaps, i.e. the free space between the elements of the lightning protection system and the elements of the photovoltaic installation. The assembly of the lightning protection system is combined with the use of appropriate surge protection (Tytko, 2020; Szymański, 2020).

3. Experimental

The analyzed photovoltaic installation is a home on grid installation located on the roof of a single-family building, inhabited by two adults in Osięciny. The installation uses 11 monocrystalline the Longi Solar modules with a power of 3.96 kWp and an efficiency of 19.3%. They were attached at an angle of 30° to the horizontal and azimuth of 130°. Longi Solar modules are made of cells cut in half (called half cut). As a result, there are no 60 cells in the module, only 120, this slight change allows you to get about 5-10 Wp more power from the PV module. Another noteworthy effect is the reduction of the power loss on the PV cell-PV module line, which results in an increase in efficiency in periods of high insolation, i.e. an increase in the fill factor and higher module efficiency. These modules are based on PERC type cells, which can be translated as cells with bottom emitter passivation. The backward passivation of the emitter reduces the attraction of electrons to the aluminum electrode and causes sunlight to be reflected back into the cell. In the Table 1 the basic parameters of 360 Wp photovoltaic panels by Longi Solar was shown. The manufacturer both presented the electrical parameters for the STC and NOCT conditions. It is clear that these parameters differ from each other. It is worth noting that the power for real conditions is 93.3 W lower than for laboratory conditions.

Table 1. Parameters of panel Longi Solar 360 Wp

Electrical and Mechanical Characteristic		
	STC	NOCT
Maximum Power (P_{max}, W_P)	360.00	266.70
Open Circuit Voltage (V_{oc}, V)	40.90	38.20
Short Circuit Current (I_{sc}, A)	11.20	9.03
Voltage at Maximum Power (V_{mpp}, V)	33.70	31.10
Current at Maximum Power (I_{mpp}, A)	10.69	8.57
Module Efficiency (%)	19.30	
Operational Temperature	40°C- 85°C	
Nominal Operating Cell Temperature	45°C ± 2°C	
Front Side Maximum Static Loading (Pa)	5400	
Rear Side Maximum Static Loading (Pa)	2400	
Temperature Coefficient of P_{max}	+0.057%/C	
Temperature Coefficient of V_{oc}	+0.286%/C	
Temperature Coefficient of I_{sc}	+0.370%/C	
Hailstone test	25 mm Hailstone at the speed of 23 m/s	

The quality of the module is indicated by the fill factor (FF), which is the ratio of real power to apparent power The fill factor (FF) for the STC and NOCT conditions is:

$$FF_{NOCT} = \frac{I_{mpp} \cdot V_{mpp}}{V_{oc} \cdot I_{sc}} = 0.77 \quad (1)$$

I_{sc}- the short circuit current, I_{mpp} - the current at the maximum power point, V_{oc} - the open circuit voltage, V_{mpp} -the voltage at the maximum power point

$$FF_{STC} = \frac{I_{mpp} \cdot V_{mpp}}{V_{oc} \cdot I_{sc}} = 0.79 \quad (2)$$

It can be seen that the fill factor for the STC and NOCT conditions is different. However, in both conditions it is more than 0.75 (Formula 1 and 2), which means that the cells were made of high quality materials.

The manufacturer assures that the power of the modules will drop 0.37%/C. The panel will withstand a static strength on the front side of 5400 Pa, a static strength on the rear window 2400 Pa. They are resistant to hailstones with a diameter of 25 mm and speeds of 23 m/s.

The installation uses the Sofar Solar 4KTLM one-phase inverter. This type of inverter converts the direct current generated by the photovoltaic modules into alternating current. The generated electricity goes to the home network to supply the receiver and the excess electricity goes to the power grid, which becomes a virtual electricity storage. This energy can be retrieved from the grid on days with low insolation or at night when the installation has low efficiency. It is worth emphasizing that in Poland there is a discount system in the ratio of 1: 0.8, so investors can receive energy with a 20% loss on storage.

The installation includes protections in the form of overvoltage limiters, overcurrent switches, DC and AC switchgear and earthing rod.

An application was used as a research method. The application allows to monitor the photovoltaic installation via the website home.solarman.cn (after logging in). You must first create an account, then after entering the data related to the photovoltaic installation, i.e. position, azimuth, angle of inclination and power, you can start monitoring the installation. Based on the monitoring of the installation, you can plot a graph of electricity production in individual months, during the day and year of operation of the installation. After entering the data, the installation allows to calculate the amount of CO_2 emission reduction and the economic benefits. Thanks to the monitoring of the installation, it was possible to conduct an economic, ecological and energy analysis of a home photovoltaic installation.

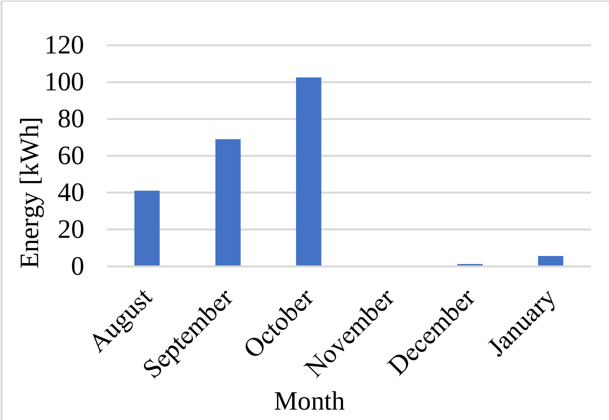

Fig. 6. Electricity production in individual months

The diagram of electricity production on individual days is presented the Figure 7. From the data taken from the chart, it can be stated that the production in this month was 102.54 kWh.

4. Results and discussion of exploitation

One of the phases of the existence of a technical object is operation. Exploitation is a process that includes two phases - the use of an object and its operation. Most module manufacturers on the market ensure that their modules have a service life of approximately 25 years. This does not change the fact that the use of a photovoltaic installation is associated with its operation in order to ensure its proper suitability. The most important task during the operation of a photovoltaic installation is to satisfy the user with electricity. In the next part, the operational analysis of the home photovoltaic installation was performed.

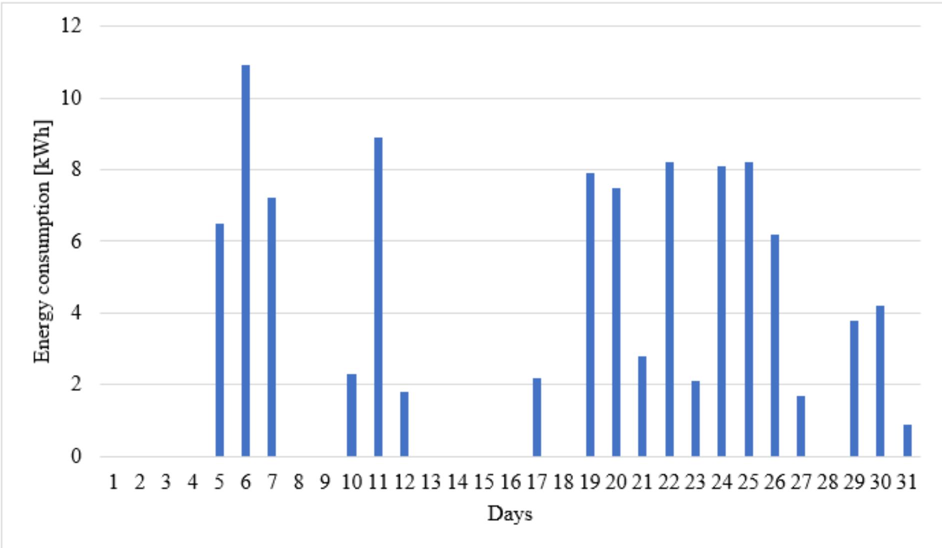

Fig. 7. Energy production on individual days of October

4.1. Energy benefits of operating a photovoltaic installation

If the photovoltaic generator is correctly selected, it should ensure the full energy demand of a residential building. Taking into account that in Poland, on average, one person uses 1200 kWh, the daily value is approximately 3.3 kWh. The analyzed installation was installed in August 2020, the diagram on the Figure 6 shows electricity production in the months from August 2020 to January 2021. According to the data presented in the diagram, it can be seen that the installation in 2020 produced 213.77 kWh and in 2021 5.6 kWh, i.e. a total of 219.37 kWh. In the Figure 6 it was shown that the highest production was in October, therefore the analysis of the efficiency of the photovoltaic installation for this month was analyzed.

Assuming that the average insolation in October is 1.54 kWh / m^2 and using the Formula 3, it is possible to calculate the amount of energy that can be, obtained with a photovoltaic installation. The formula takes into account the inefficiency in absorbing solar radiation, therefore it was multiplied by the factor 0.75.

$$E = P_m \cdot 0.75 \cdot J \cdot S \cdot n \quad (3)$$

E - energy obtained from the photovoltaic installation, P_m - power of photovoltaic modules, J - solar radiation flux density, S - surface of photovoltaic modules, n - number of photovoltaic modules.

Using the Formula 3, it can be calculated that for the power of 3.96 kWp of photovoltaic panels and the insolation of 1.54 kWh / m^2 and for modules with an area of 1.87 m^2 (1.776 x 1.052 m) and the average value of insolation is:

$$E = 3.84 \cdot 0.75 \cdot 1.54 \cdot 1.87 \cdot 1 = 91.33 \text{ kWh} \quad (4)$$

This result shows that the photovoltaic modules produced about 12% more electricity. Based on the assumption that a person consumes 3.3 kWh per day, it can be concluded that for about 15 days the installation provides the building's total electrical demand.

Using Formula 5, it is possible to calculate the amount of energy produced by the installation for different modules.

$$E_{rz} = \frac{J \cdot P_m \cdot WW}{I_c} \quad (5)$$

E_{rz} - real energy of the installation [kWh], J – insolation [kWh/m^2], P_m - power of photovoltaic modules [kW], WW – performance ratio, I_c - radiation intensity STC [1 kW/m^2]

In order to calculate the real energy, a performance ratio, an insolation, a power of photovoltaic modules must be established. The study assumes an average insolation of 1000 kWh /m^2, an installation power of 3.96 kW, the performance ratio is still unknown. It is possible to estimate it by determining all losses of the installation. There are losses in the installation (Szymański, 2020):

- cabel losses approx. 1%,
- inverter losses approx. 3-7%,
- panel losses due to temperaturę approx. 4-8%,
- losses due to work at low intensity of solar radiation, approx. 1-3%,
- losses due to shading, dirt approx.1-5%,
- losses due to current mismatch in PV panels approx.1%,
- losses on bypass diodes approx. 0.5%.

The performance ratio for the analyzed installation is 83%, for installations optimized in every detail it can be even 88%, in the case of weak components this ratio can be at the level of 75%. On the basis of the established the performance ratio, it is possible to determine the real energy for the discussed installation and for the most and the least effective.

Real energy for the discussed installation:

$$E_{rz} = \frac{1000 \cdot 1.09 \cdot 3.96 \cdot 0.83}{1} = 3\,582.61 \text{ kW}h \quad (6)$$

Real energy for the best optimized installation:

$$E_{rz} = \frac{1000 \cdot 1.15 \cdot 3.96 \cdot 0.88}{1} = 4007.52 \text{ kWh} \quad (7)$$

Real energy for an installation with weak components:

$$E_{rz} = \frac{1000 \cdot 1.09 \cdot 3.96 \cdot 0.75}{1} = 3\,237.30 \text{ kWh} \quad (8)$$

The insolation was multiplied by the correction factor, for the analyzed installation it is 1.09, and for the installation oriented towards the south it is 1.15. Based on the results, it can be determined that the installation will produce approximately 3582.16 kWh of electricity (Formula 6), approximately 424.91 kWh less electricity than the most efficiently optimized installation (Formula 7), and 345.31 kWh more electricity than the installation with weak components (Formula 8).

4.2. Ecological benefits of operating a photovoltaic installation

Assuming that 1 kWh emits 700 g of CO_2 (the emission index for 2020), in October the analyzed installation reduced carbon dioxide (CO_2) emissions by 71.78 kg. The life cycle of a photovoltaic installation is assumed to be around 25 years. In the Table 2 an estimate of the carbon dioxide reduction over the entire life cycle of the PV plant was presented. The table includes a 0.5% decrease in the production of solar panels each year. In 2020, the installation reduced 149.64 kg carbon dioxide due to the fact that it did not start up until August. In the following years, taking into account the decrease in the installation capacity, a total of 70 tons of carbon dioxide will be reduced.

Tab. 2. Reduction of carbon dioxide in individual years of operation (own research)

Reduction of CO_2			
Year	Reduction [kg]	Year	Reduction [kg]
2020	149.64	2033	2605.68
2021	2772.00	2034	2591.82
2022	2758.14	2035	2577.96
2023	2744.28	2036	2564.10
2024	2730.42	2037	2550.24
2025	2716.56	2038	2536.38
2026	2702.70	2039	2522.52
2027	2688.84	2040	2508.66
2028	2674.98	2041	2494.80
2029	2661.12	2042	2480.94
2030	2647.26	2043	2467.08
2031	2633.40	2044	2453.22
2032	2619.54	2045	2439.36

Nevertheless, it is worth emphasizing that photovoltaic installations in the operation phase do not affect harmful to the environment. The environmental analysis should also include the phase of production and waste menagement of the photovoltaic installation. The authors of the article entitled *Eco-Energetical Life Cycle Assessment of Materials and Components of Photovoltaic Power Plant, Energies* present the impact of a photovoltaic installation in various phases of its existence. The authors emphasize that the production phasa and waste management in the form of landfill storage had the greatest impact on the environment. Recycling of photovoltaic waste would reduce the impact in this phase of the life cycle. The production of photovoltaic modules causes emissions to the environment of hazardous compounds for humans, including sulfur dioxide and oxide, nitrogen oxide and solid particles of less than 10 µm.

4.3. Economic benefits of operating a photovoltaic installation

Investing in renewable energy sources is associated with certain costs. In Poland, there are several forms of co-financing in renewable energy sources, including: my electricity program, thermo-modernization relief, clean air program or preferential loans for the purchase of a renewable energy source. In the discussed case, the purchase of a photovoltaic installation with a capacity of 3.96 kWp was associated with costs of PLN 23 549.49 (€5 153.10). Investors took advantage of *the My current* program PLN 5 000 (€1 094.10) and PIT thermo-modernization relief PLN 3 152.00 (€689.71). The Table 3 shows the costs and income from the photovoltaic installation in the various years of operation of the photovoltaic installation. The revenue column takes into account the savings caused by electricity production, they differ, as the installation loses about 0.5% of its efficiency each year. In the first year, the income amounted to PLN 8 295.23 (€1815.1) because subsidies and no need to purchase 213.17 kWh electricity were included. The costs' column includes the annual service of the photovoltaic installation, about PLN 250.00 (€54.70) per year, fees related to connection to the grid, about PLN 19.60 (€4.29) per month (these are fixed fee, power fee, transition fee and subscription fee) and replacement of the inverter after about 15 years of its use.

Tab. 3. Costs and income from the photovoltaic installation (own research)

Year	Income [PLN]	Costs [PLN]	Operational profit [PLN]
2020	8295.23	23582.68	-15287.50
2021	2122.56	485.20	1637.36
2022	2111.95	485.20	1626.75
2023	2101.33	485.20	1616.13
2024	2082.76	485.20	1597.56
2025	2069.50	485.20	1584.30
2026	2056.23	485.20	1571.03
2027	2042.96	485.20	1557.76
2028	2029.70	485.20	1544.50
2029	2016.43	485.20	1531.23
2030	2003.16	485.20	1517.96
2031	1989.90	485.20	1504.70
2032	1976.63	485.20	1491.43
2033	1963.37	485.20	1478.17
2034	1950.10	485.20	1464.90
2035	1936.84	5735.20	-3798.36
2036	1923.57	485.20	1438.37
2037	1910.30	485.20	1425.10
2038	1897.04	485.20	1411.84
2039	1883.77	485.20	1398.57
2040	1870.51	485.20	1385.31
2041	1857.24	485.20	1372.04
2042	1843.97	485.20	1358.77
2043	1830.71	485.20	1345.51
2044	1817.44	485.20	1332.24
2045	1804.18	485.20	1318.98

Net Present Value (NPV) can be calculated from the table data, thanks to this, it is possible to assess whether the investment in photovoltaics is profitable. The Formula 9 allow to calculate NPV:

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} - I_o \qquad (9)$$

NPV- net present value, CF_t – cash flow (net) for the period t, r – discount rate, I_o – initial outlay, t- subsequent periods (usually years) of exploitation of the investment.

Using the excel spreadsheet, it was calculated that NPV is PLN 16 320.67 (€3 571.26). This means that NPV > 0, the investment is profitable.

Based on Formula 10, it can be calculated the payback period for the investment in a photovoltaic plant:

$$T = t + \frac{N_o}{P_t} \qquad (10)$$

T - payback period, t - the last year at the end of which the expenditure is not reimbursed, N_o - outlays not reimbursed at the end of the year t, P_t- net revenues in the next year.

Using Formula, it has been calculated that the payback period is around 9 years (Formula 11):

$$T = t + \frac{N_o}{P_t} = 9 + \frac{462.88}{1517.96} = 9.3 \text{ years} \qquad (11)$$

5. Summary and conclusion

The research goal was achieved through the analysis of the home photovoltaic installation. The research allowed to analyze the ecological, economic and energy aspects of a home photovoltaic on grid installation.

At the beginning of the work, literature analyzes related to the photovolataic installation were carried out. It can be concluded that in Poland the interest in photovoltaic installations is increasing year by year. Poles deepen their environmental awareness and invest in renewable energy sources. This can be stated on the basis of the data published by the Polish Power System (PSE). The data indicate that in 2020 the installed capacity of photovoltaic installations was 39.670 MW. Which means that photovoltaics ranks second in the production of electricity, taking into account all renewable energy sources. This may be due to the fact that in 2020 we had various support measures for this type of investment in Poland. Poland, as well as other member states of the European Union, invests billions of zlotys every year to develop renewable energy sources. By 2030, it has adopted the goal that renewable energy sources will produce energy at the level of 27%. I cannot fill it, it is a high-level goal, because now renewable energy sources produce about 12.5% of energy. Poland still has a long way to go to reduce energy production from non-renewable energy sources. It would be worth creating new support programs for investors, in particular for people who consume electricity the most, i.e. farmers and companies.

The main advantages include their long-term and failure-free operation, which allows to significantly reduce the emission of harmful compounds, causing dangerous respiratory diseases.

The biggest disadvantage of photovoltaic modules is their energy-intensive production, which in turn causes the emission of harmful combustion products. The last stage of the life of PV modules can also be a problem due to the presence of heavy metals in PV panels. Another disadvantage of photovoltaic panels is their low efficiency in converting radiation energy into electricity. All over the world, research is being carried out to increase the efficiency of converting energy radiated into electricity.

The analysis of the literature showed that photovoltaic installations seem to be simple systems, but in fact they are not. Improper selection of a component may contribute to problems with the operation, production or exploitation of photovoltaic installations. Efforts were made to replace all the necessary elements of the photovoltaic installation to show what it should look like. Each of the above-mentioned elements is important because their mismatch may reduce the efficiency of the installation, and thus the production of electricity. Nevertheless, the panels and an inverter play an essential role in the overall design. Not only functional but also economical. There are many producers of photovoltaic panels and inverters in Poland and around the world. Many people have a problem with choosing the right PV array. Attempts were made to show what parameters to look at in order to choose the right type and model of the panel. Before buying, the investor should look at the parameters of the solar panel, such as: short circuit current (I_{sc}), the current at the maximum power point (I_{mpp}), the open circuit voltage (V_{oc}) and the voltage at the maximum power point (V_{mpp}), the temperature indicator of power and fill factor, which indicates the quality of the photovoltaic cell.

The attention should be paid to the safety of the installation so that it has all the necessary security measures and that they comply with the standards. Improper protection of the installation may cause damage to some element of the installation or fire. Therefore, it is worth paying attention to safety that the installations should be installed by specialists in this field.

In the practical part, the operation of a home photovoltaic installation was analyzed. The analysis used applications monitoring the photovoltaic installation, thanks to which the analysis was possible. As mentioned in the literature, it was possible thanks to the inverter, which has the function of connecting to the Internet. This installation was mounted on a gable roof facing east. During the analysis, the parameters of the Longi Solar monocrystalline panel, being a component of the tested installation, were examined. It can be concluded that it is a high-quality photovoltaic cell, because the fill factor was at the level of FF_{NOCT} = 0.77 and FF_{STC} = 0.79, also the cells used in these panels have a low power temperature index (0.37% / C), which makes it more resistant to high air temperatures. These panels were also manufactured in the hut cut and PERC technology, which contribute to increasing the efficiency of the cells and greater resistance to shading. The panel will withstand a static strenght on the front side of 5400 Pa, a static strenght on the rear window 2400 Pa. They are resistant to hailstones with a diameter of 25 mm and speeds of 23 m / s. Thanks to this strength, the panels are protected against extreme weather conditions.

The results show that having a photovoltaic installation undoubtedly affects the ecological, economic and energy benefits. The data on energy production in October was used during the analysis. October is not the most favorable month for high efficiency photovoltaic installations in Poland. Despite this, the installation produced 12% more electricity than the average data show and satisfied the electricity for 15 days of residents. Based on the available formulas, it was calculated that the photovoltaic installation will generate 3582.61 kWh electricity annually. Another benefit is the reduction of CO_2, thanks to the installation it was possible to reduce about 71.78 kg of carbon dioxide in October. About 70 tons of carbon dioxide can be reduced over the life cycle. The constant increase in electricity prices brings the economic benefits of having a photovoltaic installation. In October, the installation allowed to save PLN 142.82 (€31.25) assuming the electricity price of PLN 0.67 (€0.15) per kWh. During the economic analysis, calculations related to the profitability of the photovoltaic installation were made. The net present value (NPV) calculation shows that the investment is profitable because NPV = PLN 16 320.67 (€3 571.26), i.e. NPV > 0. The payback period is approximately 9 years.

The installation was compared in terms of electricity production with an installation with an efficiency of 88% and an installation with an efficiency of 75%. On this basis, it was found that the tested installation produces approximately 424.91 kWh less electricity than the most efficiently optimized installation (Formula 7), and 345.31 kWh more electricity than the installation with weak components (Formula 8). It was not possible to compare the tested installation with another installation, because it is difficult to find installations with the same power and different components.

The analysis of the home photovoltaic installation has shown that despite the financial, ecological and energy-related, during operation, attention should be paid to its proper operation. Photovoltaic installation, like any device / machine, needs appropriate service in order to maintain its viability. During the entire period of operation, proper installation service should be ensured, which is to maintain the cleanliness of the module surface, the safety of module connections and faster detection of any damage.

It is also worth emphasizing that the photovoltaic installation in the operation phase do not affect harmful the environment, but in the production and waste menagement their impact is significant. During production, they emit dangerous compounds for people and the environment and in waste menagement. Therefore, it is necessary to carry out activities aimed at reducing the energy consumption of the photovoltaic module manufacturing process and its impact on the environment by recycling photovoltaic panels and constructing more environmentally friendly materials.

Reference

Corcelli, F., Ripa, M., Ulgiati, S., 2017. End of life treatment of crystalline silicon photovoltaic panels, An emergy - based case study, J. Clean. Prod., 9, 1129-1142, DOI:10.1016/j.jclepro.2017.05.031

Dincer, I., Midilli, A., Kucuk, H., 2014. Progressin Sustainable Energy Technologies: Generating Renewable Energy, Springer, Cham, Switzerland.

Goe, M., Gaustad, G., 2014. Strengthening the case for recycling photovoltaics: An energy payback analysis, Appl. Energy, 5, 41-48, DOI:10.1016/j.apenergy.2014.01.036

Hossain, J., Mahmud, A., 2014. Renewable Energy Integration: Challenges and Solutions, Springer, Singapore, 69–95, DOI: 10.1007/978-981-4585-27-9

Twidell, J., Weir, T., 2015. Renewable Energy Resources, Routledge, London, United Kingdom.

Kasner, R., Bałdowska-Witos, P., Flizikowski, J., Kruszelinicka, W., Tomporowski, A., 2020. Sustainable Wind Power Plant Modernization, Energies, 13(6), 1461, DOI:10.3390/en13061461

Lelek, Ł., Kulczycka, J., Lewandowska, A., Zarębska, J., 2016. Life cycle assessment of energy generation in Poland, Int. J .Life Cycle Assess, 21, 1-14, DOI:10.1007/s11367-015-0979-3

Majewski, G., Orman, Ł.J., Telejko, M., Radek, N., Pietraszek, J., Dudek, A., 2020. Assessment of thermal comfort in the intelligent buildings in view of providing high quality indoor environment, Energies, 13(8), 1973, DOI: 10.3390/en13081973

Merkisz, J., Rymaniak, Ł., 2017. The assessment of vehicle exhaust emissions referred to CO_2 based on the investigations of city buses under actual conditions of operation, Eksploat. Niezawodn., 19, 522-529, DOI: 10.17531/ein.2017.4.5

Mroziński, A., Flizikowski, J., 2016. Engineering of photovoltaic installations, Grafpol Agnieszka Blicharz-Kurpińska, Bydgoszcz, Poland, (in Polish).

Mroziński, A., Piaecka, I., 2016. Computer support. Computer design of selected RES installations, Wydawnictwo Grafpol Agnieszka Blicharz-Krupińska, Bydgoszcz, Poland, (in Polish).

Piasecka, I., Tomporowski, A., Flizikowski, J., Kruszelnicka, W., Kasner, R., Mroziński,A., 2019. Life Cycle Analysiso of Ecological impacts of an offshore anda Land-Based Wind Power Plant, Appl. Sci., 9, 231–246, DOI: 10.3390/app9020231

Piasecka, I., Bałdowska-Witos, P., Kasner, R., Piotrowska, K., Kruszelinicka W., Tomporowski, A., 2020. Identification of the most important areas of impact on the environment in the life cycle of car tires, Przemysł chemiczny, 99/11, 1593-1599, DOI:10.15199/62.2020.11, (in Polish).

Piasecka, I., Bałdowska-Witos, P., Piotrowska, K., Tomporowski, A., 2020. Eco-Energetical Life Cycle Assessment of Materials and Components of Photovoltaic Power Plant, Energies, 13, 1-24, DOI:10.3390/en13061385

Piasecka, I., Bałdowska-Witos, P., Flizikowski, J., Piotrowska, K., Kruszelinicka, W., Tomporowski, A., 2021. Ecological life cycle assessment of the 1 MW photovoltaic power plant under Polish environmental conditions, Przemysł chemiczny, 100/1, 40-46, DOI: 10.15199/62.2021.1.2, (in Polish).

Piasecka, I., Bałdowska-Witos, P., Flizikowski, J., Piotrowska, K., Tomporowski, A., 2020. Control the System and Environment of Post-Production Wind Turbine Blade Waste Using Life Cycle Models. Part 1. Environmental Transformation Models, Polymers, 12, 1-30, DOI:10.3390/polym12081828

Joint publication, 2017. Green technologies and environmental sustainability (red. Singh, R., Kumar S.), Springer International Publishing, DOI: 10.1007/978-3-319-50654-8

Joint publication, 2018. Renewable energies (red. F.P.G. Márquez, A. Karyotakis, M. Papaelias), Springer International Publishing AG, DOI: 10.1007/978-3-319-45364-4

Joint publication, 2017. Energy efficiency and the future of real estate (red. Coulson, N.E., Wang, Y., Lipscomb, C.A.), Palgrave Macmillan US, DOI: 10.1057/978-1-137-57446-6

Szczotok, A., Pietraszek, J., Radek, N., 2017. Metallographic Study and Repeatability Analysis of γ' Phase Precipitates in Cored, Thin-Walled Castings Made from IN713C Superalloy, Archives of Metallurgy and Materials, 62(2), 595-601. DOI: 10.1515/amm-2017-0088

Szymański, B., 2020. Photovoltaic installations, Globenergia Sp. zo. o., Kraków, Poland, (in Polish).

Toke, D., 2011. Ecological Modernization and Renewable Energy; Palgrave Macmillan, NewYork, US, 167–179, DOI: 10.1057/9780230302167.

Tutak, M.; Brodny, J.; Siwiec, D.; Ulewicz, R.; Bindzár, P., 2020, Studying the Level of Sustainable Energy Development of the European Union Countries and Their Similarity Based on the Economic and Demographic Potential, Energies 13, 6643, DOI: 10.3390/en13246643

Tytko, R., 2020. Photovoltaics, Wydawnictwo i Drukarnia Towrarzystwa Słowiaków w Polsce, Kraków, Poland, (in Polish).

Tytko, R., Góralczyk I., 2013. Rational energy management, Wydawnictwo i Drukarnia Towarzystwa Słowaków w Polsce, Kraków, Poland, (in Polish).

Ulewicz, R.; Siwiec, D.; Pacana, A.; Tutak, M.; Brodny, J., 2021. Multi-Criteria Method for the Selection of Renewable Energy Sources in the Polish Industrial Sector. Energies, 14, 2386. DOI: 10.3390/en14092386

Wrzesiński, Z., 2017. Thermodynamics of renewable energy sources, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa, Poland, (in Polish).

可再生能源装置运行中的经济和能源分析-案例研究

關鍵詞
太阳能板
可再生能源
逆变器

摘要

本文提出了对家庭光伏并网安装的经济，生态和能源分析。波兰社会对生态意识的增强，促使人们对绿色能源的兴趣不断增长。但是，许多人尚未意识到光伏装置的生态，经济和能源优势，因此进行了以下分析。分析涉及位于 Włocławek 附近的 Ościęciny 的容量为 3.96 kWp 的光伏装置。光伏装置包括 11 块单晶面板，360 Wp 功率，4 个 KTLM Sofar 太阳能逆变器和其他必要组件。第一部分介绍了与光伏装置有关的基本问题。更换了与光电装置正常运行有关的参数。对文献的分析将有助于了解光伏设备正常运行的本质。在实际部分中，对选定的家用光伏装置进行了分析。根据可用数据，已计算出该安装的投资回收期将超过 9 年。光伏装置将产生大约 3 582.61 kWh 的电能，并将在整个操作过程中减少 70 吨的二氧化碳。