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SELECTED ASPECTS OF A PHOTOVOLTAIC INSTALLATION ANALYSIS FOR A SINGLE-FAMILY DETACHED BUILDING

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Purpose: Increased awareness of the society in the field of environmental protection and support programs addressed to prosumers encourage investment in renewable energy sources. This paper presents selected aspects of the operational, utility and economic analysis of a photovoltaic installation, based on the example of a selected single-family building located in a rural area of Mazowieckie Prowince.
Design/methodology/approach: The basis of the research was an analysis carried out in two variants of technical solutions, data obtained from the Photovoltaic Geographical Information System program and data from energy meter readings.
Findings: Photovoltaics covered 100% of the energy demand in the analyzed case and the actual energy production from photovoltaic panels (6,069 kWh) exceeded the theoretical yield (5,431 kWh). The analysis of energy collected from the power grid and that returned to the grid enabled making a balance, which, combined with the energy produced by the photovoltaic installation, was used to calculate the energy consumed by residents. It was therefore possible to present the relationship between the energy consumed and the energy supplied by the PV (photovoltaic) system in individual months.
Research limitations/implications: As part of the technical analysis for the case study, there were limitations in the selection of both a specific model of photovoltaic panels and the number of pieces thereof. This was due to the prosumer's participation in a program that supports the development of photovoltaics in a given area (the "Clean Air" Program implemented in 2018-2030).

Keywords: photovoltaics, renewable energy, return on investment, operation.

Category of the paper: research paper.

1. Introduction

The dynamic economic and technological development as well as the ever-growing population generate an increased demand for energy (Ahmad, Satrovic, 2023). The increase in fossil fuel prices which results from the cumbersome processes of extraction, storage and transport as well as the issues of negative impact on the environment are the basis for the development of renewable energy sources (RES) (Wielewska, 2020; Xiong, Dai, 2023). These natural energy resources originate mainly from the earth, sun, water, wind, aside from being stored in biomass (Mackay, Probert, 2023). Their use is of great importance to reach the climate goal of the European Union (EU), which intends to achieve climate neutrality by 2050. In 2030, the share of energy from RES in the EU is to be 42.5 percent (Indeo, 2019).

The amount of electrical power installed in Poland for all types of energy sources (conventional and renewable) in May 2023 amounted to 62,574.522 MW, of which almost 40 per cent of electricity was produced from renewable energy sources (24,951.277 MW).

In the case of households, the most popular source of energy from the RES group is the solar radiation (Goraj et al., 2023). This is mainly due to the fact that the installation does not require large financial outlays, as is the case with energy from underground (heat pumps), hydropower (water power plants) or wind energy (wind turbines). The installed capacity of photovoltaics in May 2023 in Poland was 13,925.8 MW.

A photovoltaic installation is a set of properly selected devices and cables which make it possible to convert solar energy into electricity (photoelectric conversion) and transport it to a designated place (Kijo-Kleczkowska et al., 2022). The electricity generated in solar panels is transformed from direct current to alternating current through an inverter (Javeed et al., 2023). The main elements of the installation – the panels are made of modules, which in turn consist of individual cells. Photovoltaic panels fall into three basic generation categories, in which cells are made of different materials and characterized by a distinct structure (Ye et al., 2023).

Photovoltaic installations can be divided into two groups, depending on the method of connection: connected to the grid (on grid) and off-grid installations (Keiner et al., 2023).

In the on-grid installation, energy is used for the needs of electrical appliances in the household (Albatayneh et al., 2022). The unused energy excess electricity is sent to the power grid (prosumer) (Sabadini et al., 2021). The disadvantage of this system is that, in case of a power grid failure, the inverter disconnects the photovoltaic panels from the installation, which results in a complete power cut in the residential building (Guidara et al., 2020). The size of the on-grid installation depends, among others, on the area that is intended for the installation of panels, the selected type of solar batteries and the financial capabilities of the owner (Bahou, 2023). The percentage share of on-grid installations among all photovoltaic installations in Poland is about 70% (Dzikuć, et al., 2022).

In installations not connected to the power grid, the electricity generated by the photovoltaic panels is converted into alternating current by an inverter, and then used to power household appliances (Hassan, 2021). The excess energy is used to replenish the electricity in batteries (Ariztia, 2020). The stored energy can be used during a power outage (Navarro-Gonzalez et al., 2021). There is a regulator that is responsible for the appropriate level of battery charge (it also stops the charging when fully charged) as well as disconnection of all electrical devices as part of protecting the battery against complete discharge (Li et al., 2023). The main advantage of an off-grid system is the energy independence of the household. Off-grid installations are usually installed in places where there are large distances from power grids or grids are not even intended to be constructed (Jamroen et al., 2023). The only downside is an off-grid installation is much more expensive than an on-grid one. The size of the off-grid installation depends on the demand for energy and the hourly demand distribution.

2. Research methodology

The object of the research was a detached home with a photovoltaic (on-grid) installation, which was used to conduct an operational and economic analysis. The building was located in a rural area of Mazowieckie Province. The household does not use a heat pump, air conditioning, electric water heaters or accumulation stoves. Also, no additional devices such as heat buffers, swimming pools, etc. were installed, which would increase own consumption.

For an analysis of a photovoltaic installation, natural factors are of great importance – especially sun exposure. The average annual sunshine for the town where the building is located is 1000 kWh/m^2.

2.1. Technical Assessment

The correct choice of installation devices and the estimation of yields that the installation is able to achieve in a specific latitude will be verified by calculations. They will also suggest the appropriate installation variant for a specific single-family building. The calculations were carried out for two variants of technical solutions of the installation.

In Variant I, the photovoltaic power plant is fitted on a single-family building and consists of 15 panels, 400 W each, which gives a total of 6,000 W of rated power. The choice of a specific model of photovoltaic panels as well as that of the number of pieces was conditioned by a program that supports the development of photovoltaics in a given area (the "Clean Air" Program, implemented in 2018-2030). The technical specification of the photovoltaic panel is included in the table below (Tab. 1). The area of the photovoltaic panels amounted to 31.5 m^2. A transformerless inverter with a rated power of 5kW was selected for the installation. Its main parameters are presented in Table 2. In the analyzed case, the voltage difference is about 0.1463V with every change of the temperature of the photovoltaic panel by 1° C. This means that the voltage changes by this amount, both when the temperature decreases and increases by 1°C. The maximum short-circuit current is 20.62 A. The voltage at high temperature is 268.3 V, and the voltage at low temperature is 448.52 V. The calculated low and high temperature voltages are in line with the design requirements of the fitted PV installation.

In Variant II, the photovoltaic installation consists of 18 panels with the power of 310 W each, which in total gives 5,580 W of the rated power of the installation. These panels were selected because they are monocrystalline cells, while the number of pieces was limited by the roof area of the selected building. The technical specification of the selected panel is presented in Table 1.

The area of the photovoltaic panels was 31.5 m^2. A 5 kW-rated power inverter was selected for the installation. Its main parameters are presented in Table 2. The voltage difference in variant II is about 0.1114 V with every change of the temperature of the photovoltaic panel by 1°C. The maximum short-circuit current is 19.78 A. The voltage at high temperature is 248.5 V, and the voltage at low temperature is 417.51 V.

Table 1.
Technical specification of the photovoltaic panel

	Variant I	**Variant II**
Electrical parameter STC		
Rated power [Wp]	400	310
Short-circuit current [A]	10.31	9.89
Open-circuit voltage [V]	48.75	40.82
Maximum current [A]	9.81	9.35
Maximum voltage [V]	40.86	33.18
Yield [%]	20.02	18.9
Electrical parameter NOCT		
Rated power [Wp]	295.8	226.1
Short-circuit current [A]	9.46	7.75
Open-circuit voltage [V]	39.05	36.29
Maximum current [A]	9.04	7.38
Maximum voltage [V]	32.71	30.64
Temperature parameters		
NOCT (800W/m2, 1m/s, AM 1,5, 20° C)	42±2° C	44±2° C
Temperature current coefficient	0. 027%/C	0.037%/C
Temperature voltage coefficient	-0.30%/C	-0.273%/C
Temperature power coefficient	-0.36%/C	-0.375%/C
Construction		
Front glass hardened	hardened 3,2 mm	hardened, anti-reflective 3.2 mm
Encapsulant	EVA foil	EVA foil
Rear layer	Multi-layer polyester	Multi-layer polyester
Frame	Anodized aluminium	Anodized aluminium
Cell type	BB N-TYPE Monocrystalline	Monocrystalline silicon
Cell dimensions	158.75x158.75	157x157
Number of cells [pcs.]	72 (6x12)	60 (6x10)
Socket resistance class	IP67, 3 By-pass diodes	IP67, 3 By-pass diodes
Wiring	1,100 mm, 4 mm^2	1,000 mm, 4 mm^2
Connectors	MC4 compatible	MC4 compatible
Mechanical parameters		
Length [mm[	1,990	1,650
Width [mm]	1,005	992
Thickness [mm]	40	35
Weight [kg]	22	18.5

Cont. table 1.

Application parameters		
Power tolerance	0/+4.99 Wp	0/+5 Wp
Application class	A	A
Safety class	II	II
Maximum system voltage	1,000/1,500 VDC	1,000VDC
Working temperature	-40/ +85°C	-40/ +85°C
Initial current protection	20A	15A
Certificates		
Maximum load	8,000 Pa (815 kg/m^2)	5,400 Pa (54 kg/m^2)
Maximum wind lift	5,400 Pa (550 kg/m^2)	5,400 Pa (240 kg/m^2)
Salt resistance	IEC 61701	IEC 61701
Ammonia resistance	IEC 62716	IEC 62716
Hailstone	Fi= 55mm, V= 33.9m/s	Fi= 55mm, V= 33.9m/s
PID effect resistance	IEC EN 60804	IEC EN 60804

Source: Own study based on JBG Product catalog.

Table 2.

Technical specifications of the inverter

		Variant I	Variant II
Catalog parameter	**Unit**	**Value**	**Value**
Input Data			
Number of MPP trackers	[pcs.]	2	2
Maximum input current	$I_{dc\ max}$[A]	16/16	12/12
Maximum short-circuit current	I_{max}[A]	24/24	18/18
DC input voltage range	$U_{dc\ min}$- $U_{dc\ max}$ [V]	150-1000V	80-1000
Rated voltage	U_{dc} start [V]	200	80
Rated input voltage	$U_{dc,\ r}$ [V]	595	710
MPP voltage range	$U_{mpp\ min}$- $U_{mpp\ max}$ [V]	163- 800	240- 800
Usable MPP voltage range	[V]	150- 800	80- 800
Number of DC connections	[pcs.]	2+2	2+2
Maximum PV generator power	$P_{dc\ max}$ [kWp]	10	7.5
Output data			
Rated power	AC ($P_{ac,\ r}$) [W]	5,000	5,000
Maximum Rated power	$P_{ac\ max}$ [VA]	5,000	5,000
Output current	AC ($I_{ac\ nom}$) [A]	7.2	21.7
Mains connection	$U_{ac,\ r}$ [V]	3~ NPE 380/220	1~ NPE 380/220
Voltage range	AC (U_{min}- U_{max}) [V]	150- 280	180- 270
Frequency	F_r	50/60 Hz	50/60 Hz
Frequency range	(f_{min}- f_{max})	45-65 Hz	45-65 Hz
Power factor	-	0.85-1	0.85-1

Source: Own study based on JBG Product catalog.

With the use of the Photovoltaic Geographical Information System for checking yields from photovoltaics, it was estimated that the selected installation with the power of 6 kW should produce 5,431 kWh per year (Variant I). These forecasts include geographical location, installation parameters, roof (panel) inclination angle and azimuth angle (deviation of panels in the horizontal plane). In the case of variant II, the selected installation with a capacity of 5.58 kW should produce nearly 5,051 kWh per year. Predicted monthly yields from installations in Variants I and II are presented in Table 3.

Table 3.
Predicted monthly yields from PV installations

Month	Predicted yield [kWh]	
	Variant I	Variant II
January	141.6	131.7
February	209.4	194.8
March	436.7	406.2
April	626.7	582.8
May	700.5	651.5
June	725.3	674.5
July	737.1	685.5
August	676.7	629
September	544	506
October	376	349.7
November	149.9	139.4
December	107	99.5

Source: Own study based on Photovoltaic Geographical Information System (PVGIS).

The values of energy production from a given installation in individual months presented in Table 3 were generated by the Photovoltaic Geographical Information System program. The database of this program consists of analyses of insolation yields from previous years. It should be emphasized that these are projected values, as the value of the sun exposure largely depends on the weather on a given day or in a given month. In addition, it is not known from which year the regional insolation values come from and when they were last updated.

The calculation results presented above indicate that the best solution in terms of the amount of energy produced are multicrystalline panels described in Variant I. For the location in question, their projected yields from the program simulation will amount to 5,431 kWh of energy. After the technical assessment of a given installation, it may be concluded that its basic elements have been selected correctly. The size of the inverter perfectly harmonizes with the power of the system. The results obtained from the calculations are within the ranges of values provided by the manufacturer, both for the inverter and the panels themselves. In addition, the yield simulation system shows that the fitted installation will work at a very good level, while generating significant amounts of electricity.

2.2. Settlement of energy collected and returned by the photovoltaic installation

Courtesy of the owner of the building being the subject of the research and the materials made available, it was possible to settle the electricity collected from the grid and returned to the grid, which came from surplus production (Fig. 1). This made it possible to analyze the amount of energy produced by the photovoltaic installation, and then compare the theoretical and actual yields.

After fitting the photovoltaic installation, the distribution system operator (electricity provider) is obliged to replace the traditional electric meter with a bidirectional meter. This way, the user of the installation can observe how much energy is drawn from the grid and how much is returned to the power grid as part of the production from the photovoltaic installation. This also allows the owner to make payments for the electricity consumed. It is important to remember about the method of drawing energy from the grid with functioning photovoltaics. The PV installation (in the on-grid system) supplies the produced energy for the primary needs of the residents. Should these needs not be met, the energy is collected from the network and it is this energy that constitutes the value of the energy consumed on the meter. If, on the other hand, the energy produced by the PV system is not fully used to meet the energy needs, then it is returned to the grid, which is also recorded by the meter (returned energy).

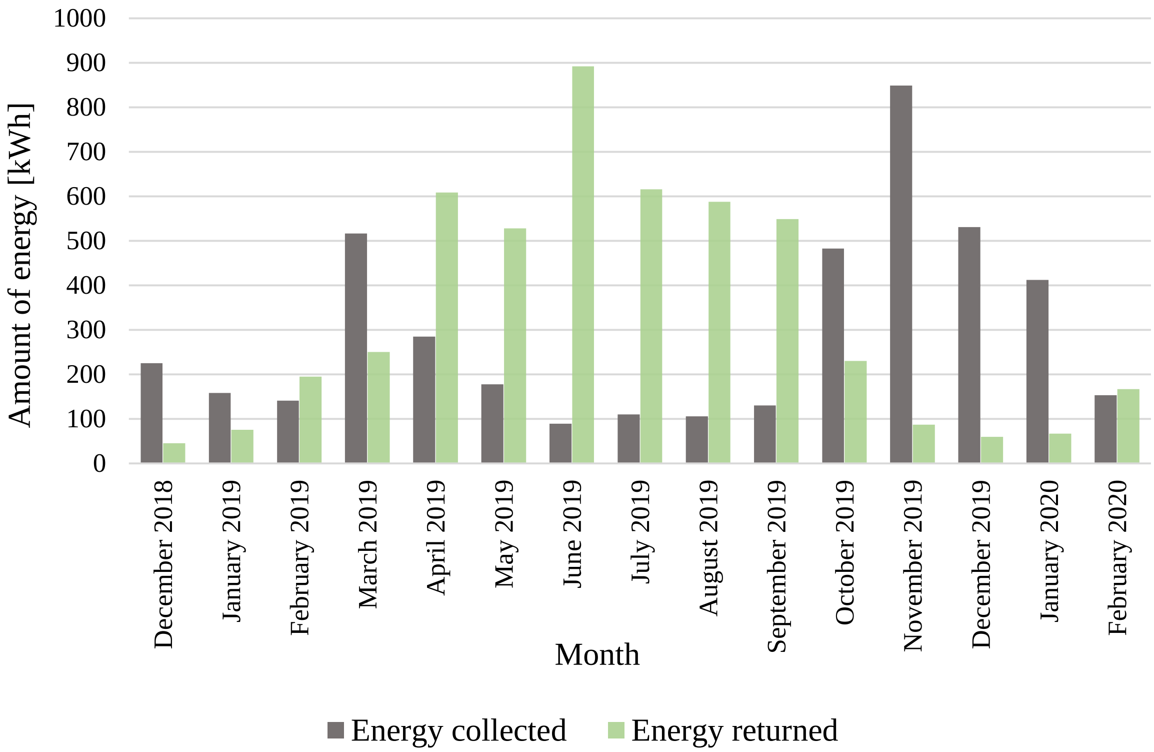

Figure 1. Comparison of the amount of energy consumed in relation to the energy returned.
Source: Own study.

2.3. Production of energy from photovoltaic panels

The fitting of a photovoltaic installation with all accessories makes it possible to track the energy produced from the sun. The yields for a given household after fitting the photovoltaic installation system for individual months (during its use) are presented in table 4.

Table 4.
Energy production for individual months

Month	Energy production [kWh]
October 2018	457
November 2018	172
December 2018	57
January 2019	107
February 2019	249
March 2019	475

Cont. table 4.

April 2019	819
May 2019	679
June 2019	996
July 2019	733
August 2019	730
September 2019	637
October 2019	391
November 2019	126
December 2019	127
January 2020	126
February 2020	220
March 2020	62

Source: Own study.

The highest yields of energy from photovoltaic panels in a given calendar year (2019) were recorded in June, which is typical for a specific latitude. The smallest production occurred in January, which is conditioned by weather conditions. The total energy produced during the year is 6,069 kWh, while the monthly average is 398 kWh. The energy production in individual months is shown in Figure 2.

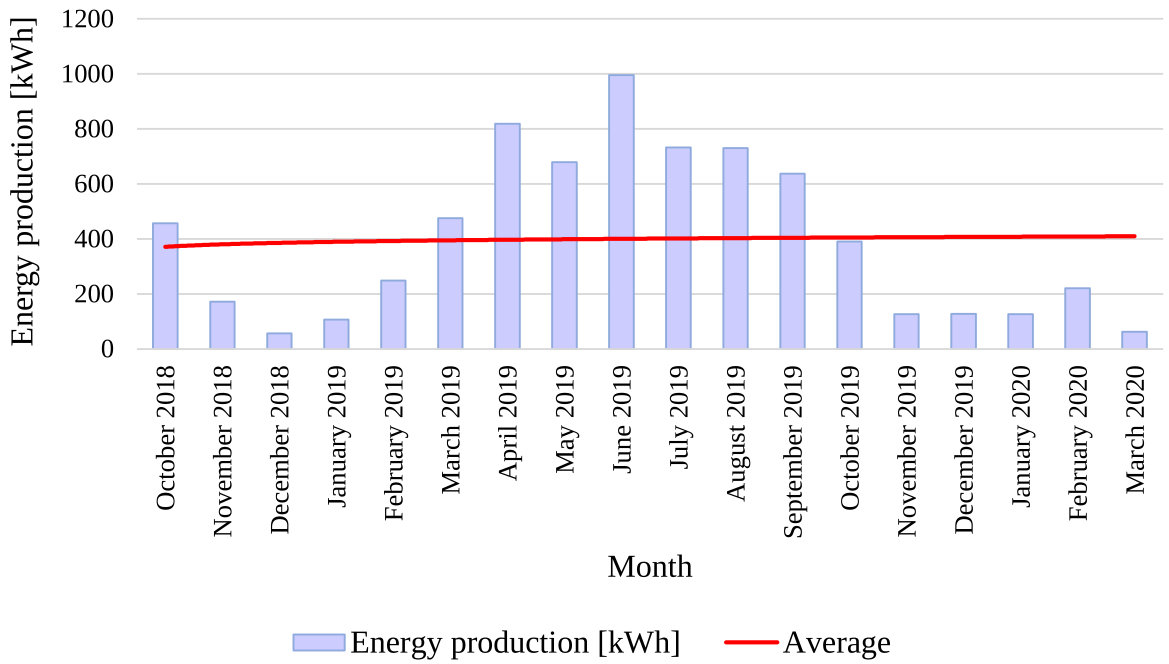

Figure 2. Energy production for individual months.

Source: Own study.

2.4. Comparison of theoretical and actual yields

The projected annual yields from a given photovoltaic installation were at the level of 5,431 kWh, while the actual production amounted to 6,069 kWh. This much better result certainly brought a lot of satisfaction to the prosumer. The comparison of the projected monthly yields from the photovoltaic installation with the actual yields is shown in Figure 3 (one full calendar year was selected).

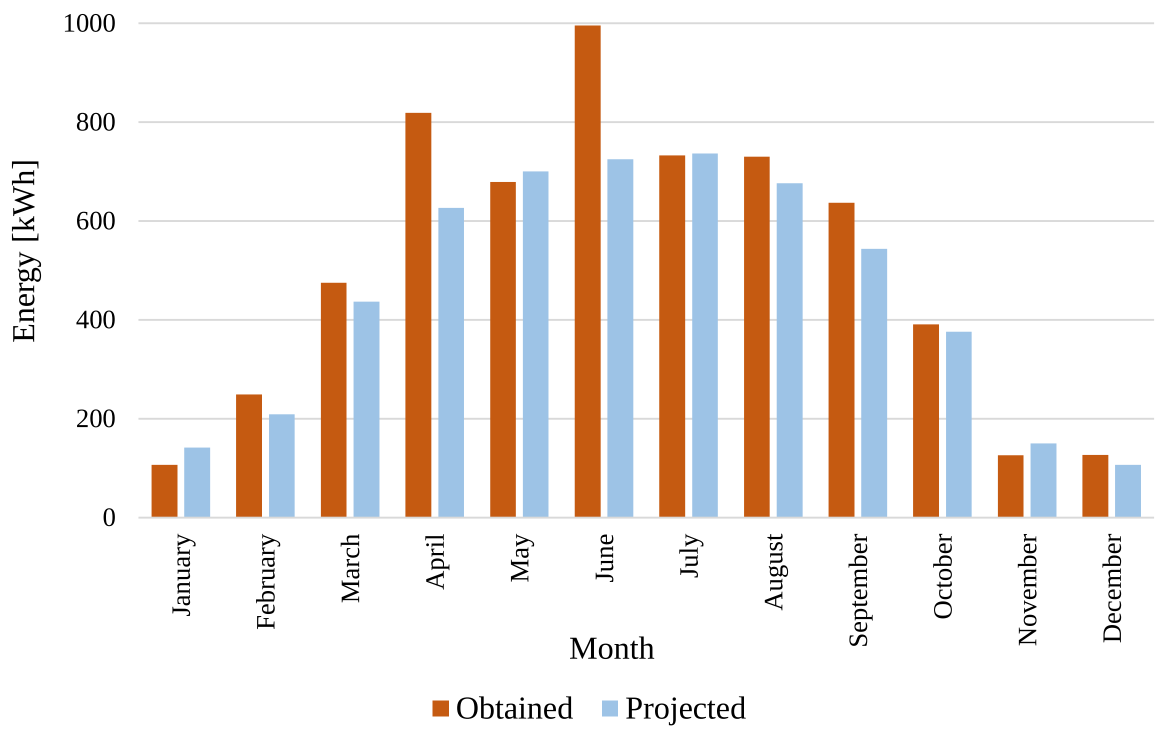

Figure 3. Projected vs actual yields.

Source: Own study.

2.5. Energy consumption by the users of the installation

With data on the energy fed into the grid, taken from the grid and produced by photovoltaic panels, the monthly electricity consumption in a household can be calculated. For this purpose, the following formula was used:

Energy consumption by users = energy collected from the grid + energy produced by PV panels – energy returned to the grid

Monthly electricity consumption values are presented in Table 5.

Table 5.
Monthly electricity consumption

Month	Monthly difference between energy collected and returned [kWh]	Monthly yield from the PV installation [kWh]	Monthly energy consumption (column 1 + column 2) [kWh]
December 2018	179.9	57	236.9
January 2019	82.8	107	189.8
February 2019	-53.4	249	195.6
March 2019	256.5	475	731.5
April 2019	-324.1	819	494.9
May 2019	-350	679	329
June 2019	-803	996	193
July 2019	-506	733	227
August 2019	-482	730	248
September 2019	-419	637	218
October 2019	253	391	644

Cont. table 5.

November 2019	812	126	938
December 2019	471	127	598
January 2020	345	126	471
February 2020	-14	220	206

Source: Own study.

The annual energy consumption (in the calendar year 2019) amounted to 5,007 kWh. The electricity consumption values in the table above are sometimes very diverse. This is due to the very careful management of energy by the owner of the household. The host conscientiously keeps a spreadsheet, calculates the balance of energy produced, while taking into account the appropriate coefficient (0.8) for energy storage by the operator. It is therefore known how much energy can be taken back from the grid yearly, so that the photovoltaic installation works only for the needs of a given building. The surplus energy collected back from the grid is usually used in transition periods for electric home heating. Hence, in March and November, the highest energy consumption can be observed, so that in the annual settlement the balance of energy produced from PV to electricity consumption stays at the lowest possible level.

The summary of the values from Table 5 made it possible to present a graph of the relationship between the energy consumed and the energy produced in individual months. It can therefore be seen when there was overproduction and when there was a shortage of energy (Fig. 4).

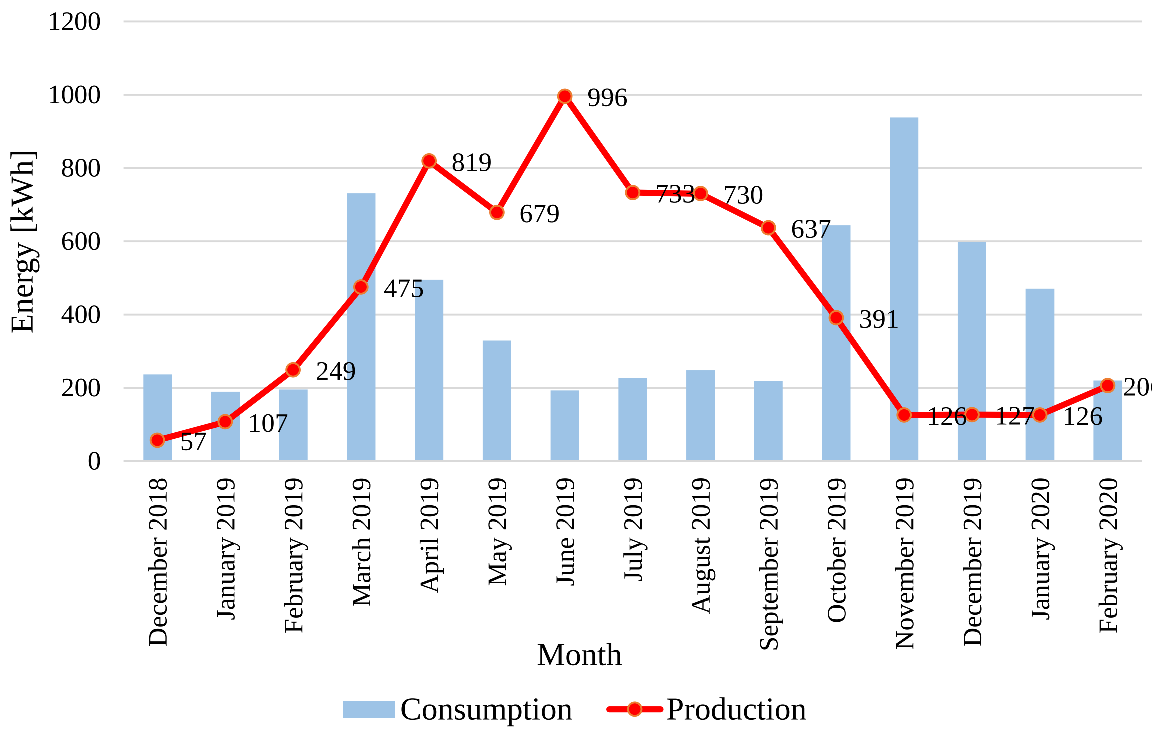

Figure 4. Relationship between energy production and consumption.

Source: Own study.

2.6. Savings resulting from the photovoltaic installation

The annual energy consumption for 2019 was 5,007 kWh, while the photovoltaic installation operating in this period produced 6,069 kWh. It can therefore be concluded that the installation covered 100% of the energy demand for the building.

6,069 kWh/5,007 kWh = 1.21 = 121%

The surplus energy that was produced by the PV system was distributed in such a way that it covered the demand for energy in a different period of time. This is also evidenced by electricity bills (PLN 77 for the period from January to June and PLN 81 for the period from July to December). Therefore, the owner of the installation paid only fixed fees. The household uses the G11 tariff (basic tariff for individual customers).

The savings resulting from the installed photovoltaics can therefore be calculated by subtracting the electricity bills in a given year.

5,007 kWh * PLN 0.60/kWh = PLN 3,004/year

The calculations assume the rate of PLN 0.60 per 1 kWh of energy used. For the sake of transparency of the settlements, it was assumed that the installation is not degraded in the considered period. Service costs are therefore PLN 0. Energy prices are stable. The total installation cost of the analyzed installation is PLN 32,200. The owner of the building benefited from funding from the "Clean Air" Program, under which natural persons can obtain co-financing of the investment from 40 to 100% of the cost, depending on their income.

3. Summary and discussion

The subject of the analysis was the operational evaluation of the photovoltaic installation on the example of a selected single-family building located in a rural area of Mazowieckie Province.

The selected photovoltaic installation consisted of: 15 multicrystalline photovoltaic panels with the power of 400 W each (total power of 6,000 W), a transformerless inverter with the rated power of 5 kW, wiring and security devices inside the building. The criterion for the choice of these photovoltaic panels was the projected yields for a specific latitude and the roof area which limited the number of pieces. Exactly such a solution was used in the building in question.

The installation was commissioned in 2018. The fitted installation covered 100% of the household electricity consumption, and the costs incurred were only certain fixed fees imposed by the network operator. Thanks to this, the owner of the household is able to save over PLN 3,000 on electricity bills per year.

The efficiency assessment was made on the basis of the adopted assumptions, both those resulting from weather conditions, as well as the basic parameters of the functioning installation. In the analysis, own calculations were made and a simulation program of the production of energy from photovoltaic panels was used. With data on the balance of energy supplied to and collected from the grid, the annual production from PV, energy consumption, and the calculated value of photovoltaic savings, it was possible to carry out a detailed analysis of the operation in a specific building.

After doing so, it can be concluded that the working photovoltaic installation has been selected with due accuracy. All its calculation parameters comply with the required values and are within the ranges provided by the manufacturer of the panels and the inverter. In addition, the size of the installation is ideally suited to the electricity consumption profile of the residents, and the surplus production is used at a later time.

The results of the analysis:

- Annual electricity consumption: 5,007 kWh;
- Theoretical yield from photovoltaic panels: 5,431 kWh;
- Actual energy production from photovoltaic panels: 6,069 kWh;
- Difference between projections and actual yields: 638 kWh;
- Coverage of energy demand by photovoltaics: 100%;
- Energy collected from the grid: 3,577.5 kWh;
- Energy transferred to the grid: 4,639.7 kWh;

Final conclusions:

1. Thanks to the operational analysis conducted, it can be concluded that that the production of energy from photovoltaic panels is higher by 638 kWh per year than the estimated production from the program, which is as much as 10.5%.
2. The economic analysis conducted proves that the savings resulting from the installation of photovoltaic panels on a given building generate savings of around PLN 3,000 within a calendar year.
3. Before purchasing selected photovoltaic panels, an operational analysis should be carried out in order to determine which variant will work best for a given facility, electricity consumption and at a specific latitude.
4. Multicrystalline panels are the most favourable for the weather conditions of Poland due to the very good ratio of yields to the purchase price.
5. The fitted installation is certainly able to produce more electricity if it faced directly southward (currently it is south-west).

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