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The effect of photovoltaic system operating parameters on exergy efficiency

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Abstract Solar energy is a unique source of renewable energy due to its availability and the unlimited quantity. It has long attracted the attention of scientists who are conducting theoretical and experimental research into its use. Solar energy plays an increasingly important role in the context of energy conservation. With the rising cost of conventional energy sources and limited access to natural resources, interest in the use of renewable energy sources is increasing. In this context, environmental protection is another factor favoring the development of technologies based on renewable energy sources. With economic development, the significance of new environmentally friendly technologies is increasing. One of the most popular ways for the average household to utilize renewable energy sources is by installing photovoltaic panels. Such an installation allows the use of solar energy to generate electricity, which contributes to reducing energy costs and protecting the environment. The article presents the results of an analysis of the exergy efficiency of prosumer photovoltaic systems found in the area of northern Poland. The analysis presented was based on actual operating parameters over a certain time interval. A key aspect is the analysis of exergy, which is not distributed in renewable energy sources (RES) systems.

Keywords: Renewable energy sources; Photovoltaic; Exergy; Electric power

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Nomenclature

$\dot{b}_r$	–	radiation exergy flux, W
F	–	surface area of photovoltaic modules, m^2
$\dot{I}_\beta$	–	radiation energy flux, W
P_{el}	–	electric power, W
PV	–	photovoltaic
RES	–	renewable energy sources
T	–	surface temperature emitting radiation, K
T_0	–	ambient temperature, K
$\eta_{B,\mathrm{PV}}$	–	exergy efficiency, %
$\eta_{E,\mathrm{PV}}$	–	energy efficiency, %

1 Introduction

The development of renewable energy sources as a substitute for fossil fuels has been taken into account in the last few years of the decade. Solar energy as an accessible, low-cost, ecological and friendly alternative source has been and continues to be the subject of much theoretical and experimental research. Energy from the sun plays an important role in the aspect of energy conservation. The use of solar energy in the desalination process is an opportunity to provide potable water from salt water. Exergy analysis evaluates the effective use of solar energy [1].

Non-conventional energy sources have become a popular alternative to conventional energy. Energy derived from solar radiation, wind or water ripples and tides is free, requires no transportation, is not counted, and most importantly, has no negative impact on the environment. Solar radiation energy and its utilization allows to perform exergy analysis studies. An important indicator of the quality of photovoltaic installations is exergy efficiency. It is defined as the ratio of the amount of electricity produced by the installation to the amount of energy required to produce, install and maintain the installation. It thus seeks to ensure that the installation generates more electricity than it consumes for its maintenance [2].

Climate change and environmental degradation are among the greatest challenges facing humanity today. With the rising cost of traditional energy sources, such as coal and gas, and increasing access to renewable energy technologies, such as solar, wind and geothermal, many countries around the world are seeking to increase their energy production from renewable sources. At the same time, the negative effects of atmospheric emissions, such as smog and climate change, are becoming increasingly apparent, with negative impacts on human health, economic development and ecosystems. Therefore, more and more people and institutions are paying attention to the need to protect the environment by reducing harmful emissions and increasing the use of energy from renewable sources [3, 4].

The primary reason behind the popularity of photovoltaic systems is the clean and limitless nature of this energy source. In contrast to fossil fuels, which become increasingly challenging to access as reserves deplete, solar radiation offers a constant and readily available energy supply, ensuring power generation round the clock. Furthermore, photovoltaic systems produce no environmentally harmful emissions nor generate noise, thus making them a more eco-friendly choice. Figure 1 shows a generalized schematic of a photovoltaic system.

A number of studies confirm that photovoltaic systems will make a significant contribution in the future, and their development will accelerate due to technological innovations, improvements in the efficiency of photovoltaic panels, and support programs from the government and the private sector [5].

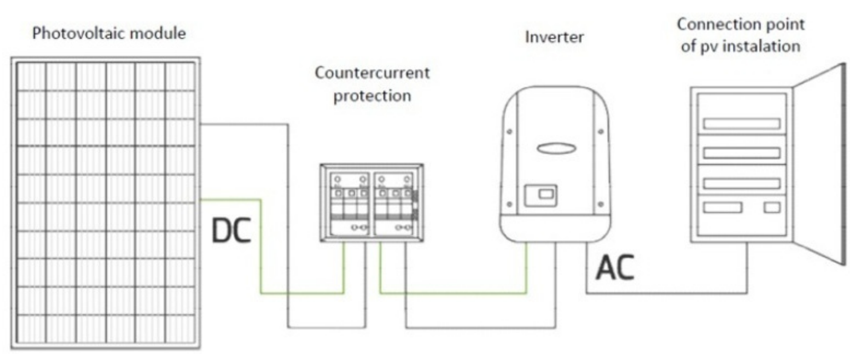

Figure 1: Schematic diagram of the photovoltaic system: DC – direct current, AC – alternating current [6].

1.1 Sustainable development and renewable energy sources

An important aspect is the pursuit of a balance between economic and social progress, and environmental protection. This is why the construction and operation of machinery, equipment, installations and systems for renewable energy sources is so important for our future. They allow to use energy in a sustainable and environmentally safe way. The implementation of modern RES (renewable energy sources) technologies and systems contributes to improving the quality of life of the population by providing clean energy and generating new jobs. At the same time, we reduce emissions of greenhouse gases and air pollutants, thus balancing development and environmental protection. That is why it is so important to develop and use renewable technologies, such as solar panels, wind turbines and heat pumps, and to support the development of electric transportation. In the context of long-term sustainable development, it is crucial to develop and use technologies that strike a balance between economic progress, social progress and environmental protection. In this way, a future can be created that is safe for us and for future generations.

Energy supply is a key element for the socio-economic development of the European Union. Recently, the European Union has placed increasing emphasis on improving energy efficiency and increasing the share of renewable energy sources in total energy production. This is key to creating a secure, clean and competitive energy market that will contribute to stable economic development while minimizing environmental impact [7].

The European Union's energy policy is based on the Europe 2020 Strategy, which sets goals related to improving energy efficiency and increasing the share of renewable energy in total energy production. This way, the European Union aims to reduce emissions of greenhouse gases and other air pollutants. This is crucial for future generations, as by providing a clean and safe environment, we create the conditions for stable economic development.

Improving energy efficiency and increasing the share of renewable energy in total energy production also has a positive impact on the competitiveness of the European Union. Investment in renewable technologies and improved energy efficiency stimulate the development of innovative economic sectors and industries, which contributes to employment and economic growth.

Economic development requires an ever-increasing demand for electricity to ensure the comfort of human life. The exploitation of fossil fuels has a negative impact on the environment, hence the need for a healthy and sustainable energy transition such as harnessing the potential of renewable energy [8].

In summary, the development of energy efficiency and the utilization of renewable energy sources are crucial for creating a stable, clean, and competitive energy market in the European Union. This enables the achievement of goals such as reducing greenhouse gas emissions, protecting the environment, and enhancing economic stability. The Europe 2020 strategy is a significant tool of the European Union's energy policy and should be consistently implemented to achieve the intended outcomes.

In addition, renewable energy also has beneficial effects on human health. Compared to traditional energy sources such as coal and gas, renewable energy does not generate toxic dusts that negatively affect human health, such as PM2.5 or PM10 particulate matter. Reducing emissions of these particulates can help reduce respiratory and cardiovascular diseases, which can improve people's health and quality of life.

Except environmental and human health benefits, renewable energy also has economic benefits. Renewable energy production generates new jobs in sectors related to the design, manufacture, installation and maintenance of RES-related facilities. At the same time, renewable energy generation can help reduce dependence on fossil fuel imports and reduce their prices, which can contribute to competitiveness and economic stability.

Renewable energy has a positive impact on the environment, human health and the economy. Therefore, more and more countries and institutions are introducing programs and initiatives to increase the share of renewable energy sources in total energy production, which can contribute to long-term sustainable development [9, 10].

1.2 Exergy efficiency

As a result of the application of a sustainable and emission-free way of generating electricity from solar radiation, quality indicators are sought, which are used to evaluate the efficiency and performance of photovoltaic installations. With this in mind, a key indicator is the exergy of the equipment used in these installations.

Kinetic energy, potential energy and energies associated with the motion of molecules are considered types of mechanical energy that are readily convertible to other forms of energy, such as electricity or heat. On the other hand, the internal energy of substances and the energy of chemical bonds are forms of internal energy that are more difficult to convert into other types of energy. Internal energy is also responsible for thermodynamic processes, such as thermal conduction and heat flow, which are crucial in many technological processes. Depending on the context, different types of energy can have different significance and uses [11–13].

The term exergy refers to the concept of qualitative energy analysis, which takes into account the ability to convert energy into mechanical work or other desired effect. Exergy is also referred to as 'real energy' because it takes into account energy losses due to thermodynamic imbalances and process imperfections [14].

In the context of photovoltaic installations, exergy is used to assess the efficiency of converting solar radiation energy into electricity. Exergy analysis makes it possible to determine the maximum amount of electricity that can be produced by a given installation under ideal conditions, which is important information for designers and users of photovoltaic systems [15]. An important feature of exergy is that it can be used as a tool to compare different technologies and processes from the point of view of their energy efficiency. Thus, it can help select the most economical and environmentally friendly technological solutions [16].

2 Analysis of operating parameters of photovoltaic installations

Three photovoltaic installations located in the northern Poland, in the West Pomeranian Voivodeship of Koszalin County, were analyzed. The installations in question belong to prosumer RES systems. They were designed and installed on household buildings, according to the electricity needs of the household members living there. In order to juxtapose and compare them, the photovoltaic installations differ in the direction of the location of the photovoltaic modules in relation to the south, i.e., they are installations mounted in the following directions: south-west, south, south-east. The power value of the photovoltaic installation is the same in each case and is 4.94 kWp. At the design stage, a simulation was carried out to determine the amount of electricity generated by each system. Table 1 summarizes of the two most important values: the projected amount of electricity generated and the amount of energy generated from 1 kWp, the so-called characteristic annual yield.

Table 1: Summary of the results obtained in the program for PVsol.

	Installation facing south	Installation facing south-west	Installation facing south-east
Forecasted amount of electricity generated (kWh/year)	4 667.6	4 317.0	4 740.2
Characteristic annual yield (kWh/kWp)	940.0	869.0	956.6

The designed photovoltaic system constitutes a current-generating unit classified as a micro source of renewable energy utilizing solar power. The primary objective of this system is to generate electricity for the facility's own needs. By being connected in parallel with the internal grid, it enables the excess energy generated to be fed back into the power grid of the operator of the distribution system (OSD) in case the facility's consumption is insufficient. This sustainable energy system not only allows for the utilization of clean solar energy to power the facility but also contributes to the overall energy balance by supplying surplus energy to the distribution grid. With such a solution, the facility can benefit from eco-friendly energy, minimizing its environmental impact while also leveraging the opportunity for energy exchange with the distribution grid.

Each photovoltaic (PV) installation has the ability to remotely read the hourly, daily, monthly and annual amount of electricity generated. With the help of monitoring the operation of the installed equipment, the annual amount of electricity generated is recorded in Table 2. Table 3 shows the actual annual yield values, in order to identify how much each plant will generate electricity from 1 kWp to compare them with each other.

Table 2: Reading the results from the Fronius SolarWeb photovoltaic monitoring application [17].

Actual amount of electricity produced (kWh/year)			
Year	Installation facing south	Installation facing south-west	Installation facing south-east
2018	5 357.45	5 380.06	4 518.07
2019	4 814.38	4 815.30	3 917.59
2020	4 730.73	5 053.60	3 758.20

The monitoring system for PV installations on the FroniusWeb platform allows users to track the performance and operation of their installation. With this tool, users can monitor the performance of photovoltaic panels in real-time and analyze historical data on energy production. The FroniusWeb platform also provides access to various system parameters such as voltage, current, power, and temperature, allowing for a thorough evaluation of the installation's operation. Additionally, users can receive notifications of any malfunctions or irregularities in the system operation, enabling quick response and issue resolution. Overall, the monitoring system for PV installations on the FroniusWeb platform offers a comprehensive tool for monitoring and optimizing the operation of a photovoltaic system.

Table 3: Actual annual yield.

Characteristic annual yield (kWh/kWp)			
Year	Installation facing south	Installation facing south-west	Installation facing south-east
2018	1 084.50	1 089.08	916.44
2019	974.57	982.04	794.64
2020	957.64	1 023.00	762.31

The explanation for the differences in the magnitude predicted by the program and the actual state is the fact of cyclical weather anomalies. It can be observed that the climate is warming from year to year. The year 2018 was abundant in the number of sunny days as can be seen in Table 4. It can also be seen that the average sunshine from 1998 to 2005 differs from 2018 by about 653.30 hours.

Table 4: Number of hours of sunshine on an annual basis and for individual months [18].

Month	Year		
	2018	2019	2020
January	32.5	47.8	37.7
February	102.0	72.8	68.6
March	149.4	92.2	184.0
April	248.7	298.2	286.2
May	373.2	224.4	258.3
June	307.7	354.1	260.9
July	292.3	267.8	223.0
August	259.3	266.1	286.5
September	205.4	145.7	208.5
October	176.9	94.2	91.0
November	88.9	45.5	38.1
December	6.5	41.1	37.6

Both the forecasted amount of electricity generated and the characteristic annual yield deviate from the actual state. This is because the program in which the simulation of the operation of photovoltaic installations was carried out works on the basis of analyses of the number of hours of sunshine from 1986–2005, and for the selected location takes its average value. Table 4 shows the actual number of solar hours on an annual basis for each month, for those years for which the three selected photovoltaic installations are analyzed.

Figure 2 shows a diagram of the dependence of the sum of hours of sunshine from 1998 to 2020. The characteristics do not show a clear regularity. The parameter of sunshine is a variable quantity, but with each year there is a trend of its increase compared to previous years.

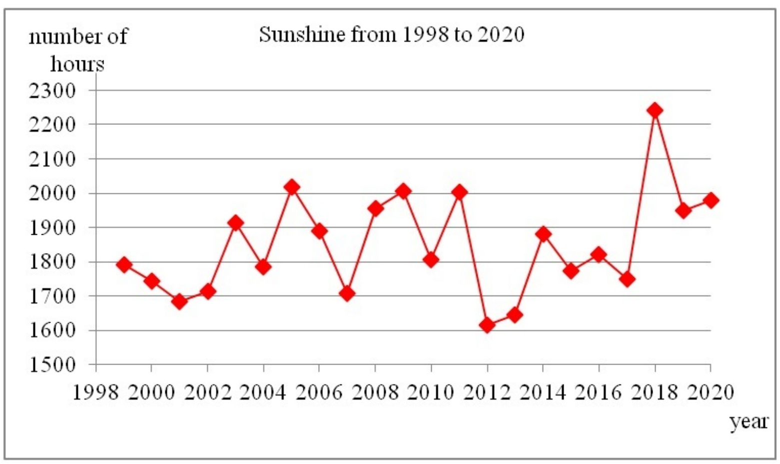

Figure 2: Diagram of sunshine hour totals by year from 1998 to 2020.

Another, deviating from the so-called pure theory, is the fact that an installation facing south has slightly worse performance than an installation facing south-west, while it should be just the opposite. An installation facing south should generate the best electricity production. This is due to the location of these installations. Koszalin is a city located in the northwestern part of Poland. In the summer, a long time of sunset can be observed. The area of northwestern Poland is better insolated than the rest of the country, as shown in Fig. 3.

The characteristics shown in Figs. 4–6 illustrate the amount of electricity generated by a photovoltaic system. In each of them, three main stages of

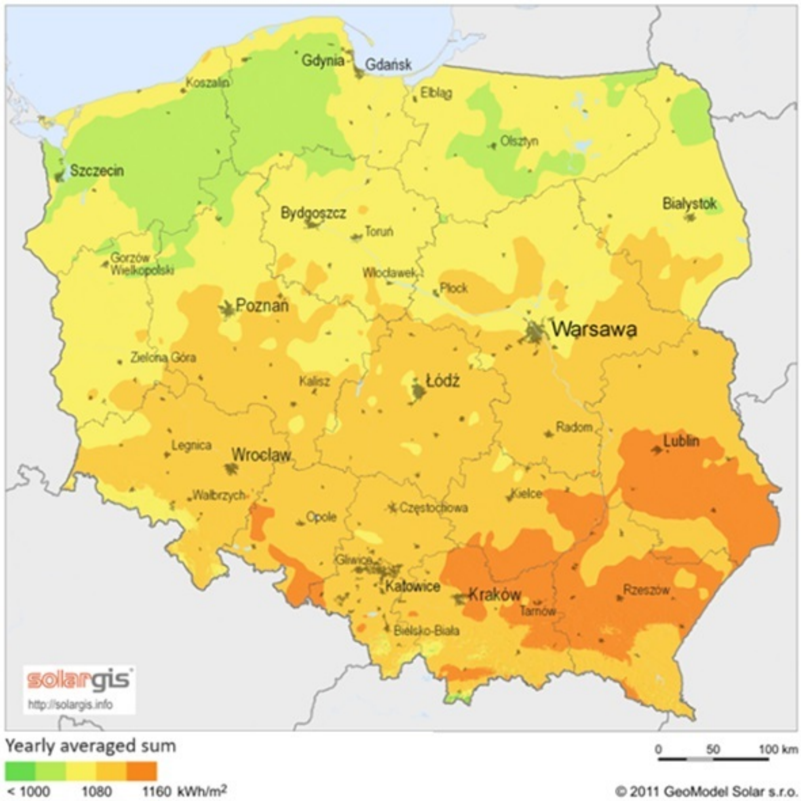

Figure 3: Map of insolation of Poland [19].

operation can be distinguished: start of operation, maximum energy generation and end of operation. The start of operation as well as its endare characterized by a flattening of the graph. At the time of the peak in energy generation, the curve resembles a parabola in its shape. The graphs that show shaky operation of the system (Fig. 5) reflect disturbances caused by weather changes. Table 5 makes a summary of the values for the highest daily energy generation read from the graphs showing the operation of each plant.

Based on the data in Table 5, the regularity of photovoltaic system operation is preserved. Despite the differences in terms of directionality of the location of the installations, each of them begins and ends operation and generates electricity at a similar hour. Small deviations are due to climatic changes (occurrence of cloudy, rainy days) and sunshine.

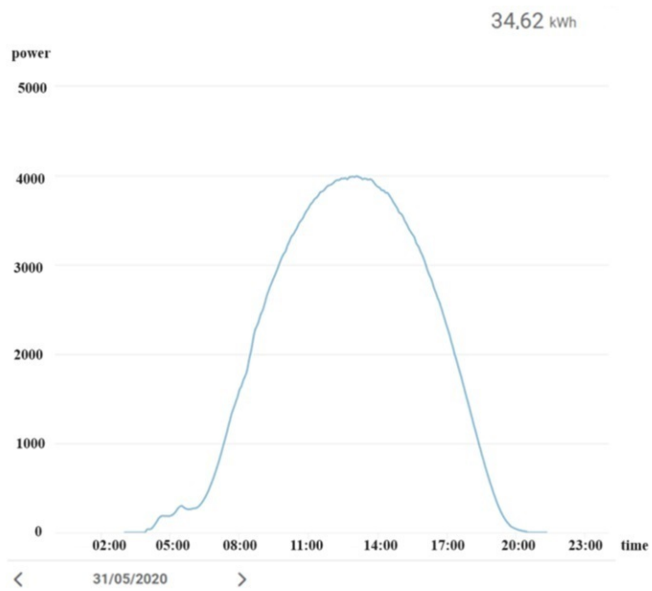

Figure 4: Largest daily electricity generation of installation facing south in 2020 [17].

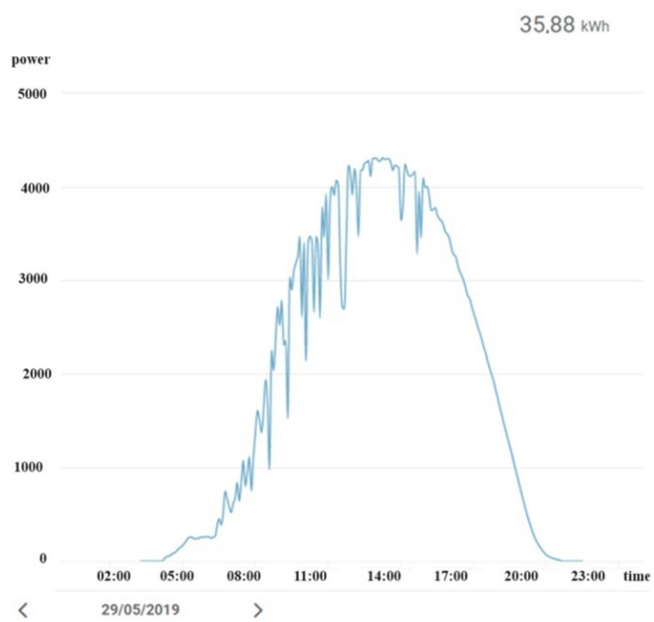

Figure 5: Largest daily electricity generation of installation facing south in 2019 [17].

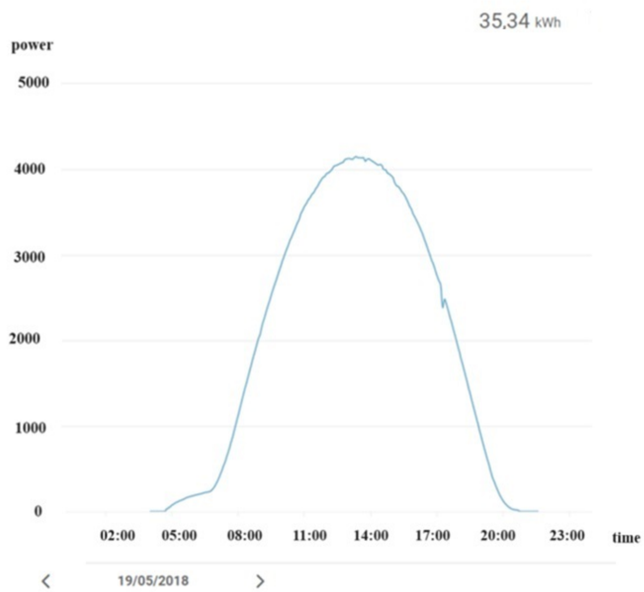

Figure 6: Largest daily electricity generation of installation facing south in 2018 [17].

Table 5: Summary of the various stages of operation of photovoltaic installations.

		Year 2018	Year 2019	Year 2020
Installation facing south	start of operation	4:50 (40 W)	4:20 (20 W)	4:00 (3 W)
	maximum generation of electricity	13:20 (4 148 W)	13:00 (4 303 W)	13:00 (3 995 W)
	end of operation	20:45 (1 W)	20:35 (6 W)	20:24 (14 W)
Installation facing south-west	start of operation	5:25 (18 W)	4:50 (36 W)	4:45 (50 W)
	maximum generation of electricity	14:30–15:50 (4 302 W)	13:50–14:25 (4 305 W)	14:30–15:30 (4 302 W)
	end of operation	21:05 (14 W)	21:45 (9 W)	21:00 (25 W)
Installation facing south-east	start of operation	4:50 (14 W)	4:30 (30 W)	5:10 (1 W)
	maximum generation of electricity	10:10 (4 274 W)	10:45 (4 214 W)	11:15 (4 206 W)
	end of operation	19:45 (6 W)	19:40 (1 W)	20:30 (1 W)

3 Exergy efficiency in photovoltaic installations

The technology of electricity generation through photovoltaic installations is characterized by lower efficiency compared to systems powered by non-renewable energy sources. However, it is worth noting that energy efficiency is not the only criterion for selecting an energy source. In addition, renewable energy sources allow energy independence and reduce the costs associated with purchasing electricity from traditional suppliers [20].

The following methods can be used to determine solar exergy and direct exergy efficiency for solar-powered systems: balance, thermodynamic and empirical. In each method, it is necessary to take into account the characteristics of photovoltaic modules (such as efficiency, operating temperature, lighting conditions), the design characteristics of the system (e.g., orientation of modules with respect to the sun, geometry of the system), and the efficiency of conversion of solar energy to electricity [21].

The following equation was used to determine the value of exergy efficiency [21]:

$$\eta_{B,PV} = \frac{P_{el}}{F\dot{b}_r} = \eta_{E,PV}\frac{\dot{I}_\beta}{\dot{b}_r}. \tag{1}$$

The present values were calculated based on energy efficiency, determining the exergy flux of solar radiation according to the formula

$$\frac{\dot{b}_r}{\dot{I}_\beta} = 1 - \frac{4T_0}{3T} + \frac{1}{3}\left(\frac{T_0}{T}\right)^4. \tag{2}$$

The exergy efficiency for an installation facing south-west is 13.95%, for the south-east it is 15%, for the south it is 13.95%.

4 Summary and conclusions

The purpose of this paper was to analyze the exergy efficiency of three photovoltaic installations mounted on household facilities operating in northern Poland in the West Pomeranian Voivodeship, Koszalin County. Each installation faces a different direction of the world: south, south-east and south-west. The analysis was based on collected operating parameters in a monitoring system that archives readings with hourly accuracy over 3 years (from 2018 to 2020). Conducting this analysis led to the following conclusions:

1. Both the projected amount of electricity generated and the characteristic annual yield deviate from reality. This is because the design program works on the basis of analysis of the number of hours of sunlight from 1986 to 2005, and for the selected location takes its average value.

2. The designed photovoltaic system is a current-generating unit classified as a micro source using renewable (solar) energy. Its primary purpose is to generate electricity by the system for the facility's own needs. Making it in a system of parallel connection with the internal grid allows giving back the excess of generated energy in case of consumption at this facility – to the power grid of the operator of the distribution system.

3. Analysis of the exergy efficiency of the installations facing south and south-west shows the same value (i.e., 13.95%) while the installation facing south-east shows a value 1.05% higher. This is due to the fact that the installation with the lower exergy efficiency is made of polycrystalline modules, while the installation facing south-east consists of monocrystalline modules. The exergy efficiency of a monocrystalline module is higher than that of polycrystalline modules.

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