

STATISTICAL EVALUATION OF PERFORMANCE INDICATORS OF PHOTOVOLTAIC PLANTS AS A SOURCE OF ENERGY FOR WATER DESALINATION IN THE AZOV-BLACK SEA REGION OF UKRAINE

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The application of statistical methods for the analysis of random processes to obtain quantitative estimates for the performance indicators of photovoltaic plants as a stochastic energy source is considered. The power generation process is represented by a set of daily random functions with their respective trends and stochastic components. One hour was taken as the minimum stationarity interval of trend's statistical characteristics. A time period of 16 years was studied to obtain statistically stable estimates. The meteorological database SARA2 was used as a source of hourly data on the density of solar irradiance, ambient temperature and wind speed in the middle part of the Azov-Black Sea region of Ukraine. For mathematical modelling of power generation and electricity production processes, specialized software PVGIS version 5.2 of the European Commission was used. Hourly quantitative estimates of expected daily power generation trends for each month of the year, as well as their correlation functions, were computed. Algorithms were developed and levels of probabilistic assurance for hourly generated power were evaluated. Statistical estimates of the expected daily, monthly, and annual volumes of electricity production by photovoltaic power plants were studied, taking into account the meteorological conditions in the said region.

Bibl. 48, Tables 2, Fig. 8.

Key words: random function, electricity, probability, power, solar irradiance, statistics, photovoltaic plant.

СТАТИСТИЧНА ОЦІНКА ПОКАЗНИКІВ ФУНКЦІОНУВАННЯ ФОТОЕЛЕКТРИЧНИХ СТАНЦІЙ ЯК ДЖЕРЕЛА ЕНЕРГІЇ ДЛЯ ОПРІСНЕННЯ ВОДИ В АЗОВО-ЧОРНОМОРСЬКОМУ РЕГІОНІ УКРАЇНИ

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Розглянуто застосування статистичних методів аналізу випадкових процесів для отримання кількісних оцінок показників функціонування фотоелектричних станцій як стохастичного джерела енергії. Процес генерування електроенергії представлено сукупністю щоденних випадкових функцій зі своїм трендом та стохастичною складовою. За мінімальний інтервал стаціонарності статистичних характеристик тренду приймалась одна година. Досліджувався період часу тривалістю 16 років для отримання статистично стійких оцінок. Використовувалась метеорологічна база даних SARA2 з погодинною інформацією про щільність сонячного випромінювання, температуру навколишнього середовища та швидкість вітру в середній частині Азово-Чорноморського регіону України. Для

математичного моделювання процесів генерування потужності та виробництва електроенергії застосовувалось спеціалізоване програмне забезпечення PVGIS версії 5.2 Європейської Комісії. Отримано очікувані погодинні кількісні оцінки параметрів щоденних трендів генерування потужності для кожного місяця року та їх кореляційні функції. Розроблено алгоритми та визначено ймовірнісні рівні забезпеченості щогодинної генерованої потужності. Досліджено статистичні оцінки очікуваних денних, місячних та річних обсягів виробництва електроенергії фотоелектростанціями з урахуванням метеорологічних умов регіону. Бібл. 48, табл. 2, рис. 8.

Ключові слова: випадкова функція, електроенергія, імовірність, потужність, сонячне випромінювання, статистика, фотоелектрична станція.

Introduction. The importance of the problem of water desalination on the industrial scale in the Azov-Black Sea region of Ukraine is caused, first of all, by the need to prepare fresh water for the electrolytic production of “green” hydrogen, in accordance with Ukraine’s participation in the implementation of the European program “2x40 GW Green Hydrogen Initiative” [1, 2]. The program envisages the construction of 10 GW capacity of electrolyzers on the territory of Ukraine for the production of low-emission hydrogen in the amount of 1.65 million tons per year. That, in turn, will stipulate the demand for prepared fresh water of at least 24 million m³/year [3]. It’s important to note that the needs for fresh water in Azov-Black Sea region of the country are not limited only to the implementation of the “green” hydrogen production program. The use of water desalination technologies is relevant both in industry and the private sector for the preparation of drinking water, for agriculture and desalination of mine waters [4 – 8]. The choice of an acceptable desalination technology depends on the composition and content of salts in the feed water and also the requirements to desalinated water’s properties [9 – 12]. Each technology is characterized by the corresponding costs and amounts of energy consumed to produce a unit of fresh water (kW·h/m³, kJ/kg, etc). Energy supply for technological processes can be based on either fossil fuels or renewable sources [13 – 15]. The southern territories of the

country have the highest potential of wind energy and solar irradiance. A number of powerful wind power plants (WPP) and photovoltaic power plants (PVP) have already been constructed and commissioned there [16]. The use of energy from WPPs and PVPs has no alternative for the production of “green” hydrogen, taking into account the stage of desalinated water preparation for the operation of electrolyzers. The general view of a high-output PVP on the territory of Ukraine is shown in Fig. 1 [17].

This paper aims at investigating indicators of the PVP’s stochastic power generation process to achieve the maximum integration of its energy into the technological schemes of water desalination in the climatic conditions of the Azov-Black Sea region of Ukraine. The stochastic changes of the generated power are caused by the influence of cloudiness, air temperature, and wind speed at the PVP’s location [18]. However, the energy equipment of desalination facilities operates under a stable power supply, thus requiring coordination in time of the power consumption and generation processes [19 – 21]. The search for acceptable compromise solutions regarding the implementation of rational modes of energy generation and consumption requires the determination of equipment load diagrams of the desalination technological scheme and statistical estimations of the stochastic process of electrical energy generation at the PVP.



Fig. 1. General view of a high-output PVP [17]

The measurements of the PVP's generated power during several individual days, which are shown in Fig. 2, indicate that it is appropriate to use the principles of random processes theory [22 – 24] to analyse the variability of the PVP's operation indicators (power and volume of electricity production). Therefore, the stochastic process of PVP's power generation during long time intervals can be represented by a set of daily random functions; statistical methods for the analysis of such processes are covered in [25 – 28].

Problem statement. The main task of this study is to determine the quantitative statistical estimates of the parameters of power generation stochastic processes and the PVP's electricity production in the climatic conditions of the Azov-Black Sea region of Ukraine. The set of daily random functions of PVP power generation, that is necessary for achieving statistically stable results, will be formed using mathematical modelling of the photo-voltaic modules' operation modes and information about the changes in meteorological factors at the plant's location over a long time [18, 29, 30].

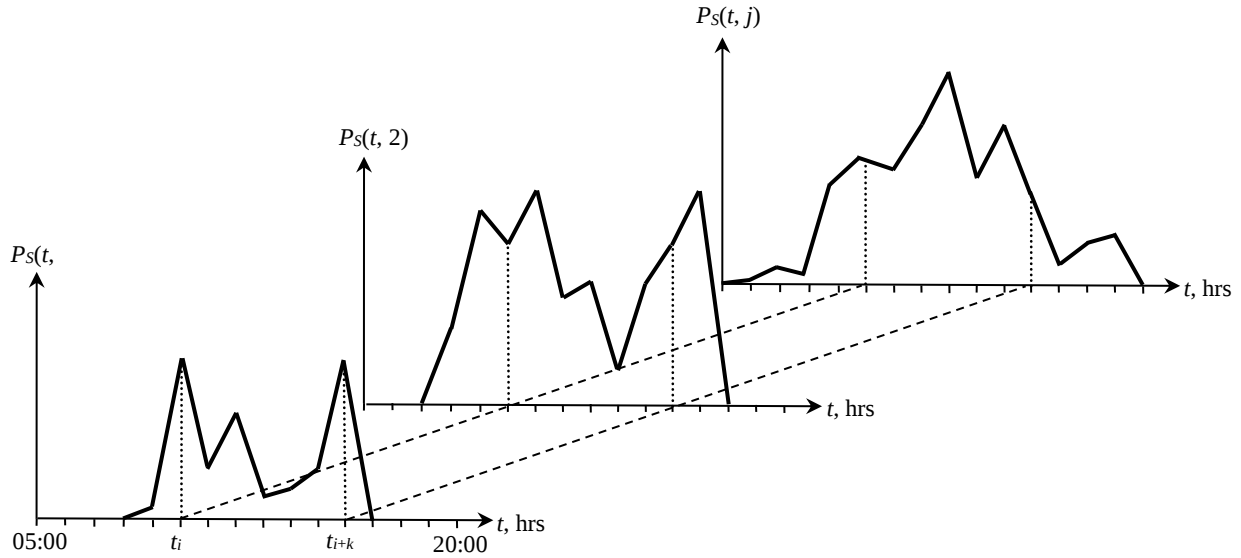


Fig. 2. Set of daily random functions of PVP's power generation

Mathematical modelling of power generation processes and outputs of the PVP and processing of the results.

The main components of the high-output PVP's electrical circuit include photovoltaic modules (PVM), photovoltaic batteries, inverters, internal power transmission lines, internal transformer substations, a diagnostic and monitoring system, a control system, output transformer substations and power transmission lines for connection to the industrial power system or power consumer [31, 32]. PVM is the smallest component that can be connected to the electric circuit of the PVP. The nominal power of modern industrial PVMs is usually less than 600 W, therefore PVPs have a distributed structure with a large number of components. So, in particular, a typical electrical scheme of a 50 MW PVP includes approx. 200,000 PVMs, 2,200 inverters, and 40 internal transformer substations (0.4/10 kV).

During operation, some part of the components fails and needs to be replaced, losses of electrical energy in the equipment and transmission lines exist, and there is a degradation of photovoltaic properties of PVMs. All this together decreases the power efficiency of the PVP. Degradation of PVM's photovoltaic properties is caused by temperature changes cyclicity, the influence of the ultraviolet spectrum of solar radiation and hot spots on photocells, the cracks appearing on the module surfaces and sealing failures [33, 34]. PVM manufacturers provide warranties regarding yearly degradation level, that depends on the type of modules and can change in the range of (0.25...0.8)% per operation year [35].

Considering the above and theoretical principles of photo-voltaic energy [18, 29, 30, 32], let's write down the initial expressions for determining the generated power of the PVP at an arbitrary moment in time (t) as follows:

$$P_s(t) = N \cdot P_n(t) \cdot k_g(N, t) \cdot k_d(t) \cdot k_e(N, P_n(t)), \quad (1)$$

$$P_n(t) = I_r(t, \zeta, \gamma) \cdot f_1(\varphi, \alpha) \cdot k_n(t), \quad (2)$$

$$k_n(t) = f_2(P_n(t), Q(t), v(t)), \quad (3)$$

where $P_s(t)$ – power of the PVP; N – number of PVMs in the PVP; $P_n(t)$ – power of the PVM; k_g – equipment availability factor of the PVP; k_d – degradation factor of the PVM; k_e – factor of electrical power losses in the components of power plant (internal electrical joins, invertors, transformer substations, tie lines); I_r – solar energy flow density; ζ, γ – geographical coordinates at the PVP location; φ – tilt-angle between the PVM surface and the horizontal plane; α – azimuth of the PVM surface normal relative to the South; k_n – PVM efficiency ratio; Q, v – air temperature and wind speed at the PVP's location.

Set of equations (1) – (3) allows for mathematical modelling of PVP power depending on the climatic conditions at the construction site, spatial arrangement and electrical performance of the PVM, and the power plant design.

Climatic conditions are characterized by the solar energy flow density on a clear day, the presence of cloudiness, air

temperature and wind speed. Density values I_r depend on geographic coordinates, meteorological factors, and time of day. Daily trend of the I_r value changes is uniquely determined by the trajectory of the solar irradiance flow relative to the PVM surface [36], and the stochastic component – by the rate of change in cloud cover, ambient temperature, and wind speed. In order to obtain statistically stable estimates of values $I_r(t, \zeta, \gamma)$, it is required to possess the results of meteorological observations at long time intervals [37]. The necessary information for the territory of the Azov-Black Sea region of Ukraine can be found in the international databases of NASA SSE (NASA Surface meteorology and Solar Energy) and PVGIS (Photovoltaic Geographical Information System) of the European Commission. Further research will use the PVGIS database [38 – 40], which provides weather information on solar irradiance, air temperature, and wind speed at a height of 10 meters above the Earth's surface for 16 years: from 2005 to 2020, inclusive. In accordance with methodological recommendations on the applied analysis of hydro-meteorological factors [41], the use of a period of 16 consecutive years is sufficient to determine trend fluctuations and random features of the process. PVGIS software version 5.2 [42] implements hourly calculations of PVM power with arbitrary orientation of its surface, taking into account ambient temperature and wind cooling. Therefore, application of the mentioned software allows for obtaining quantitative values of expressions (1) – (3), which, after data systematization, can be represented by a set of daily random functions of the generated power $P_s(t, i)$, as it is shown in Fig 2, and random sequence of values (time series) of the power at fixed moments of day time t_j for the set of random functions:

$$P_s(t_j, i), \quad t_j = 1, 2, \dots, 24, \quad i = 1, 2, \dots, Y, \quad (4)$$

$$\sigma_{pm}^2(t_j) = \frac{1}{D_m Y_m - 1} \sum_{k=1}^{Y_m} \sum_{i=1}^{D_m} (P_{sm}(t_j, i) - \bar{P}_{sm}(t_j))^2, \quad t_j = 1, 2, \dots, 24, \quad (6)$$

The strength of interdependency of the random sequence members $P_{sm}(t_j, i)$ is determined by normalized

$$r_m(t_j, \tau) = R_m(t_j, \tau) / \sigma_{pm}^2(t_j),$$

$$R_m(t_j, \tau) = \frac{1}{D_m Y_m - \tau - 1} \sum_i^{D_m Y_m - \tau} (P_{sm}(t_j, i) - \bar{P}_{sm}(t_j)) \cdot (P_{sm}(t_j, i + \tau) - \bar{P}_{sm}(t_j)), \quad (7)$$

$$t_j = 1, 2, \dots, 24, \quad \tau = 1, 2, 3, 4, \dots$$

The measure of correlation relationship is the correlation interval d , that characterizes an average number of days between intersections j and $(j + d)$ of the random sequence, beyond which the values of the generated power can be considered as practically independent random variables. For the considered task, the value of correlation interval can be understood as the expected duration of continuous total cloudiness. Quantitatively, the value of correlation coefficient $d_m(t_j)$ at fixed day time moments t_j for month m will be determined from the following condition:

$$r_m(t_j, \tau) \leq 0.02 \quad \text{for} \quad \tau \geq d_m(t_j). \quad (8)$$

where Y – number of observations of the daily random functions of the PVP's generated power.

Sequential values of the time series, in contrast to simple statistical samplings, can be mutually dependent for the closely located observations. The strength of the mutual dependency is determined by physical properties of the process and by discretization step of the sample time moments.

We will perform the statistical processing of the defined above random process of the PVP power generation, according to the periodical changes of the meteorological factors [37, 41] and the capabilities of the specified software, for the hourly, daily, and monthly time intervals during the 16-year period of consecutive years using the mathematical principles from [24, 25, 43].

We will determine the daily trend $\bar{P}_{sm}(t_j)$ of the random function of power generation for a particular month of the year (m) by computing the set of its average values at fixed time moments t_j during the entire period of observation:

$$\bar{P}_{sm}(t_j) = \frac{1}{D_m Y_m} \sum_{i=1}^{D_m Y_m} P_{sm}(t_j, i), \quad t_j = 1, 2, \dots, 24, \quad (5)$$

where m – sequential number of the month in the year, Y_m – number of the same months m within the observation period, D_m – number of days in the month m , $P_{sm}(t_j, i)$ – random sequence of the values of power at the fixed day time moments t_j for month m .

The average values $\bar{P}_{sm}(t_j)$ characterize a center of variation of the random process of power generation at the fixed time moments of the specified month of the year. The variation of the random power generation value around the center is characterized by standard deviation σ_{pm} :

correlation function $r_m(t_j, \tau)$:

Probability distribution of the random sequence is an important statistical property of the considered quantity. However, for the task of integration of electrical energy from renewable sources into technological schemes of water desalination, it is more important to know the duration of power generation [44]. Therefore, in further analysis, we will use the statistical characteristic of the probabilistic assurance of the achievable levels of the generated power $z_{pm}(t_j, P)$. We will understand the mathematical essence of variable z as the probability for the random value of power to be greater than some given value P . Calculation of the probabilistic assurance will be performed with the

use of random sequence $P_{sm}(t_j, i)$. Let's divide the range of P_{sm} variation into G intervals of the same width, moreover, let $\bar{P}_{sm}(t_j, g)$ be a middle of interval g , where $g = 1, 2, \dots, G$. Based on the sequence $P_{sm}(t_j, i)$, let's build

$$z_{pm}(t_j, P) = 1 - \frac{1}{Y_m D_m} \sum_{g \in [1, G] \cap \bar{P}_{sm}(t_j, g) < P} n_{pm}(t_j, g), \quad [\text{p.u.}], \quad z[\text{days}] = z[\text{p.u.}] \cdot D_m. \quad (9)$$

Estimation of the expected amount of PVP electrical energy production is computed for monthly and yearly time intervals based on the daily trend of the random function of power generation for a particular month of year (5):

$$\bar{E}_{sm} = \frac{1}{D_m Y_m} \sum_{i=1}^{D_m Y_m} \sum_{j \in T_m} P_{sm}(t_j, i), \quad (10)$$

$$\sigma_{em}^2 = \frac{1}{D_m Y_m - 1} \sum_{i=1}^{D_m Y_m} (E_{sm}(i) - \bar{E}_{sm})^2, \quad E_{sm}(i) = \sum_{j \in T_m} P_{sm}(t_j, i). \quad (12)$$

Calculation of the probabilistic assurance of the daily electrical energy production amount during a month will be

$$z_{em}(E) = 1 - \frac{1}{Y_m D_m} \sum_{g \in [1, G] \cap \bar{E}_{sm}(g) < E} n_{em}(g), \quad [\text{p.u.}], \quad z[\text{days}] = z[\text{p.u.}] \cdot D_m, \quad (13)$$

where $\bar{E}_{sm}(g)$ – middle of interval g built for the random sequence $E_{sm}(i)$, $n_{em}(g)$ – number of samples that fall in the interval g .

Numerical experiment and analysis of results. Computations were performed for a hypothetical PVP with installed capacity of 1 kW, located in the central part of the Azov-Black Sea region of Ukraine. For this value of the installed capacity, all obtained quantitative results will be equivalent to the indicators of a plant with arbitrary power represented in p.u., and therefore can be easily scaled for a designed PVP with desired capacity. The following provisions and assumptions were used to conduct the numerical experiment:

- computations are performed for the first operation year of the PVP, without consideration of the degradation of electrical properties of the photovoltaic modules;
- total power losses in the PVP, including the reliability of the components, are equal to 14%;
- crystalline silicon photovoltaic panels are used;
- lower limit for the sensitivity of the modules to luminosity is estimated around 150 W/m²;
- the panels mounting is fixed-tilt, with tilt angle corresponding to the geographical latitude of the central part of the region 47° (longitude 35°), azimuth – 0°;
- database of solar irradiance – PVGIS-SARAH2 with hourly data for the time period of 2005-2020.

The obtained functional dependencies of the daily trend, as well as its standard deviation, for all months of the year, are shown in Fig. 3. They have a convex shape, which is a direct consequence of the daily cycle of solar activity. According to the obtained results, the process of annual power generation can be represented by three typical periods with corresponding quantitative indicators: “winter” period from November to February, “spring-summer” period from

ordered list of its values and then count a number $n_{pm}(t_j, g)$ of samples that fall in every interval. Dependency $z_{pm}(t_j, P)$ is computed as follows:

$$\bar{E}_s = \sum_{m=1}^{12} \bar{E}_{sm}, \quad (11)$$

where $\bar{E}_{sm}$, $\bar{E}_s$ – expected monthly and yearly amount of PVP electrical energy production; T_m – interval of energy generation in month m .

Dispersion of monthly amount of electrical power production (σ_{em}) around the corresponding average values is determined as:

performed according to the described algorithm for the generated power:

April to September, and “transient period” including March and October. In the “winter” period, it is possible to generate power for (7-8) hours a day. The power trend values are low compared to the installed capacity of the PVP, and significant variability of the generation process is observed. These peculiarities are caused by significant cloudiness variability, which is typical for this period of the year. For the “spring-summer” period, the daily duration of generation is expected to be within (11-12) hours with significant power and low variability. In the most advantageous hours, the maximum value of the power trend reaches the level of (0.60-0.64) kW, which is comparable to the nominal value of the generated power of 0.86 kW (according to the conditions of the numerical experiment, described above). The obtained power ratios indicate a low probability of cloudiness at noon in the specified months.

Estimates of the normalized correlation function were computed for each working hour of each month. The amount of obtained information is too large for a detailed presentation in this publication, therefore we will only present the results for the middle of the daylight hours in the typical months of the above-mentioned periods of the year (Fig. 4). According to the calculated dependencies, the interruption of PVP power generation is expected in August, due to continuous cloudiness, for at least 3 consecutive days. For other months, the interruption of generation can be observed for more than a week.

Probabilistic assurance of achievable levels of generated power was calculated for each working hour of each month, too. As an example, the obtained functional dependencies for two different hours of the day of typical months are presented in Fig. 5, where the selected points on the curves correspond to the average values of the daily trend in the PVP power output for the corresponding month at the indicated hours.

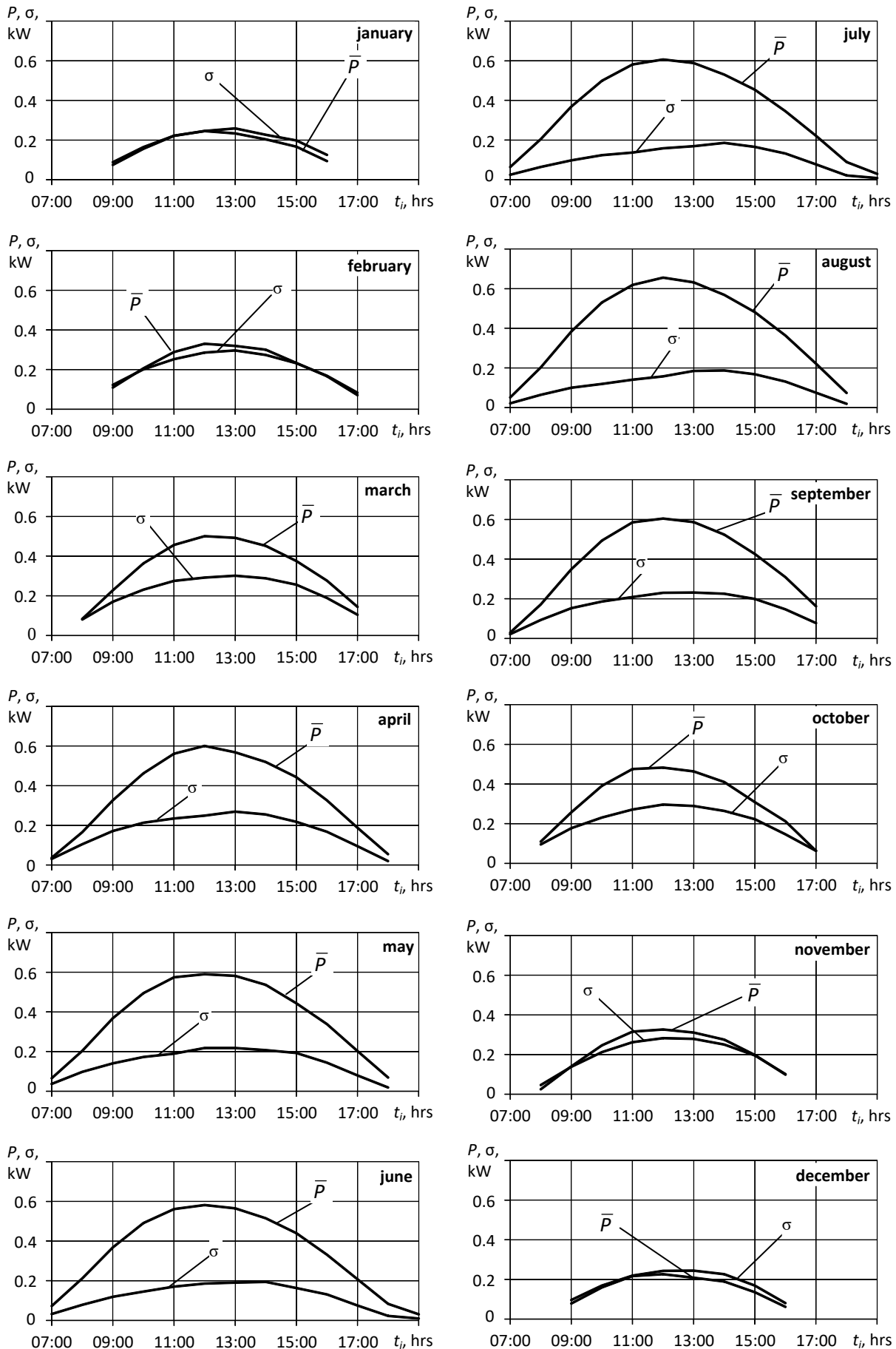


Fig. 3. Daily trend and standard deviation of the random power generation function

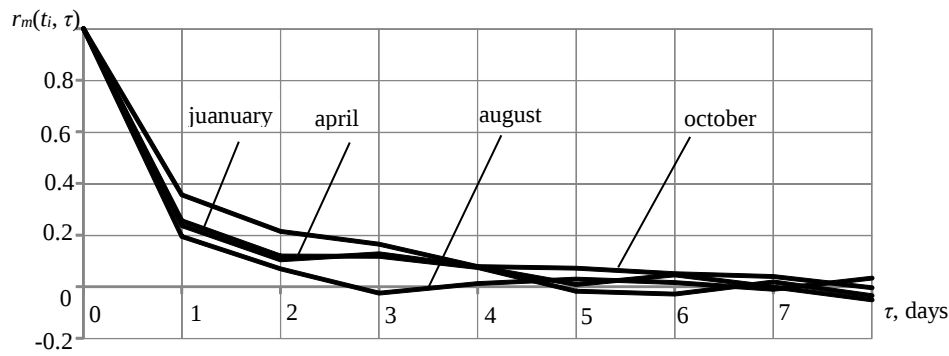


Fig. 4. Dependencies of the normalized correlation function for typical months at 12 o'clock

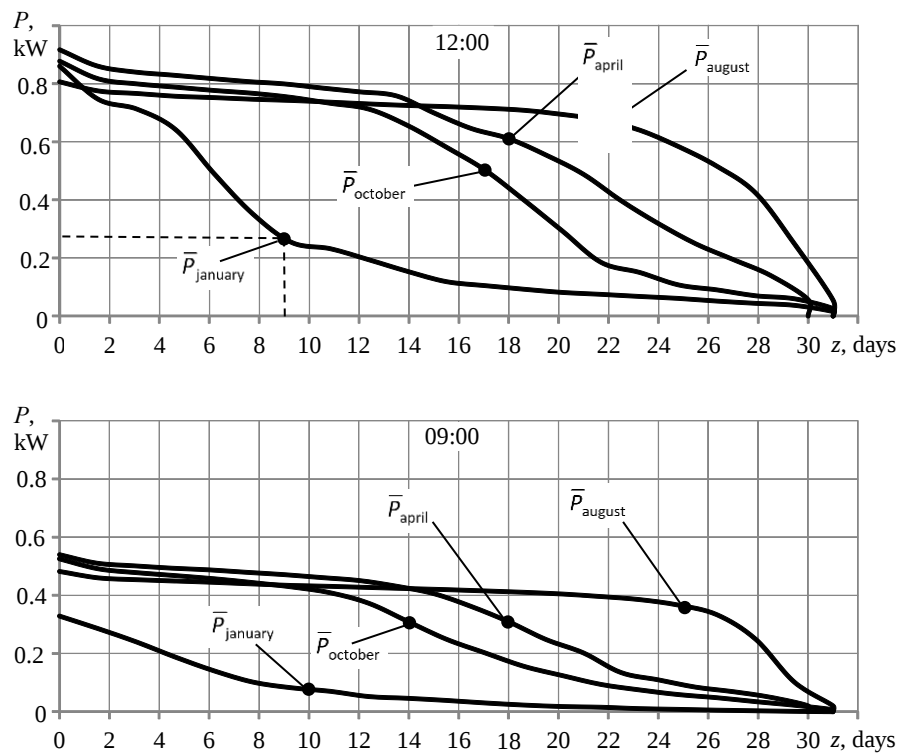


Fig. 5. Curves of probabilistic assurance of PVP power for 9:00 a.m. and 12:00 a.m. of some months

The results of power generation around (12:00 a.m. – 1:00 p.m.) of the day characterize the area of maximum values of the monthly trends in the plant's energy efficiency (Fig. 3). Therefore, the levels of probabilistic assurance of generated power, determined for this moment in time, will represent achievable values for each month during the year. The information shown in Fig. 5 makes it possible to determine achievable quantitative values of indicators for typical months of the above-mentioned periods of the year. For example, in August at 12:00 a.m., the generation will exceed the monthly daily average value for 23 days, in April – 18 days, in October – 17 days, in January – 8 days. Similarly, the probabilistic assurance of other generation outputs can be determined. In particular, power generation of more than 0.5 kW will be observed for 6 days in January, 17 days in October, 21 days in April, and 27 days in August. For the 9:00 a.m., power generation of more than 0.3 kW will

be observed for 1 day in January, 15 days in October, 18 days in April, and 27 days in August.

According to the obtained results (Fig. 5), the maximum power value is observed in April and reaches 0.92 kW, whereas the maximum value in August is 0.82 kW. This situation is caused by the influence of the ambient temperature and cooling of the photovoltaic panels by wind on the efficiency of the solar irradiance photoelectric conversion process.

The amount of electricity production is determined by the parameters of the daily power trend and the duration of generation in the specified time intervals. In this work, we analyzed daily, monthly and annual volumes of production. Indicators of the PVP's daily electricity production for different months of the year are given in Table 1 and partially visualized in Fig. 6 in the form of annual trends of the average value and standard deviation. In the winter period, the process of electricity

production is characterized by significant variability, when the value of standard deviation reaches the level of the average value, which is due to the presence of cloudiness in this period of time. The electricity output in the winter season is almost three times smaller than in the summer months. In particular,

the average value of the daily electricity production in August is about 4.8 kW·h/day, while in January it is only 1.4 kW·h/day. The total duration of electricity generation in August is 372 hours, in April – 360 hours, in October – 300 hours, in January – 248 hours.

Table 1. Indicators of daily electricity production of PVP by months of the year

Indicators	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$E_{\max}$, kW·h/day	5.200	5.998	6.559	6.748	6.525	5.993	5.887	6.079	6.140	5.834	5.189	4.688
$\bar{E}$, kW·h/day	1.407	2.059	3.443	4.251	4.506	4.488	4.604	4.793	4.257	3.171	1.928	1.275
σ , kW·h/day	1.36	1.754	1.876	1.745	1.329	1.13	0.979	1.063	1.472	1.783	1.554	1.255
T_m , hours	248	254	310	360	372	390	403	372	330	300	269	248

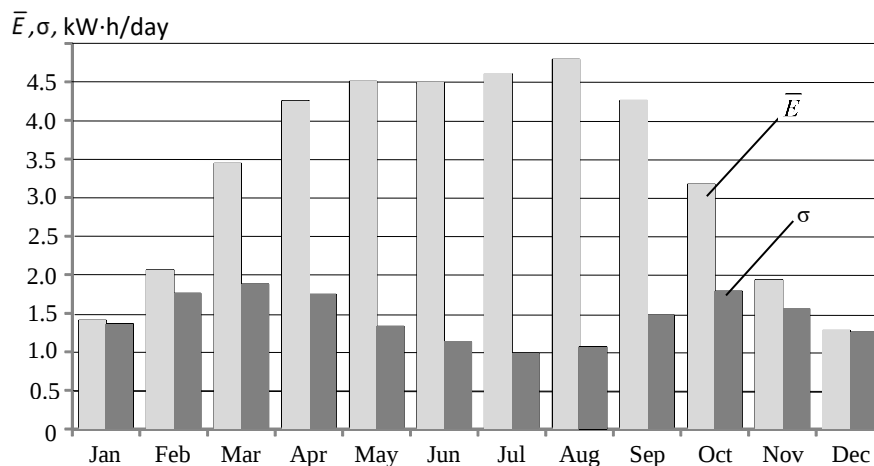


Fig. 6. Trends in the PVP's daily electricity outputs by months of the year

The obtained functional dependencies of the probability of the daily volume of electric energy production at a monthly time interval are presented in Fig. 7 for the most representative months of the respective seasons. The maximum possible value of the daily production is observed in the month of April, the same as in the case of power generation. The total duration of generation on the level of average daily production or above is expected in August for 20 days, in April – 17 days, in October – 16 days, in January – 10 days. For example, a daily volume of electric energy production of more than 4 kW·h/day will be observed in August for 25 days, in April – 18 days, in October – 12 days, in January – 2 days. Exceeding the daily production volume of 5 kW·h/day will be observed in August for 18 days, in April – 13 days, in October – 6 days, in

January – for less than one day. Probabilistic assurance of other values of the daily amount of electricity production for any month of the year can be determined in a similar way based on the data in Table 2.

The results of calculation studies with respect to the annual electricity production are presented in Fig. 8.

The highest electricity production within the investigated time interval was observed in 2020 – nearly 1,300 kW·h/year, and the lowest in 2006 – 1,120 kW·h/year. Consequently, the value of the capacity factor of this PVP changes in the range (0.128 - 0.148) p.u. There are signs of climatic cyclicity in the amount of electricity production with a duration of (3-5) years.

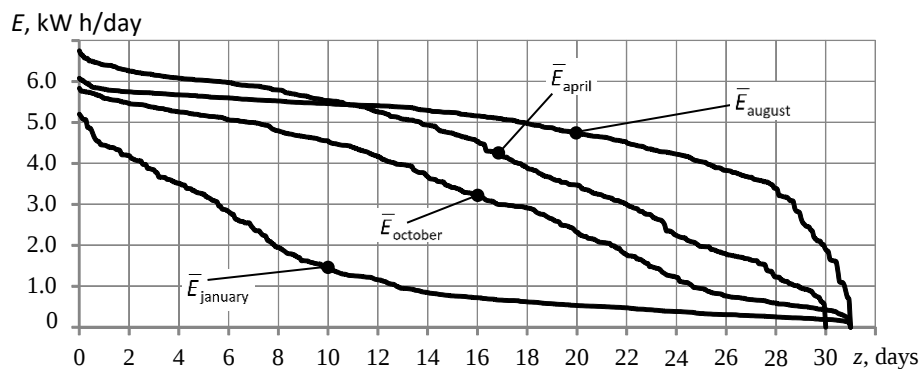
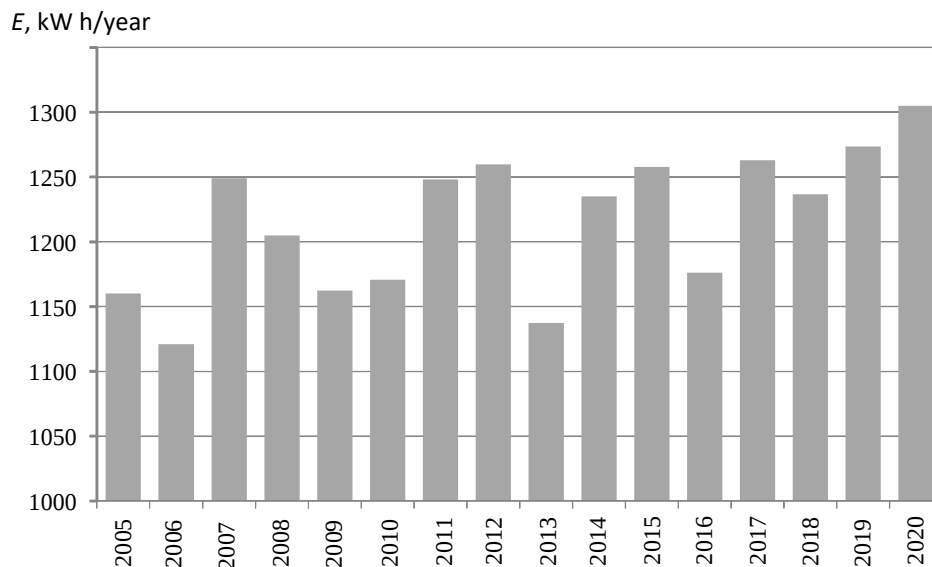


Fig. 7. Probabilistic assurance of the daily volumes of electrical energy production for monthly time interval

Table 2. Probabilistic assurance of the PVP's daily volumes of electrical energy by months, days

z, days	E, kW·h/day											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	5.200	5.998	6.559	6.748	6.525	5.993	5.887	6.079	6.140	5.834	5.189	4.688
2	4.182	5.296	6.160	6.254	5.981	5.684	5.605	5.748	5.779	5.468	4.447	3.934
4	3.512	4.769	5.872	6.082	5.851	5.576	5.520	5.674	5.613	5.258	4.119	3.189
6	2.822	3.763	5.578	5.973	5.742	5.477	5.438	5.601	5.521	5.062	3.817	2.399
8	1.939	2.893	5.177	5.791	5.616	5.358	5.341	5.525	5.399	4.793	3.248	1.869
10	1.421	2.199	4.576	5.533	5.460	5.214	5.237	5.460	5.295	4.550	2.659	1.389
12	1.157	1.752	4.127	5.257	5.237	5.045	5.131	5.409	5.143	4.159	2.011	1.039
14	0.843	1.371	3.748	4.934	4.975	4.882	5.009	5.291	4.942	3.677	1.551	0.767
16	0.718	1.033	3.294	4.536	4.748	4.720	4.836	5.159	4.623	3.235	1.138	0.650
18	0.615	0.825	2.813	3.878	4.477	4.539	4.668	4.967	4.300	2.913	0.795	0.518
20	0.529	0.654	2.447	3.468	4.243	4.256	4.425	4.728	3.954	2.323	0.687	0.418
22	0.472	0.547	1.984	2.997	3.865	3.899	4.258	4.492	3.429	1.788	0.548	0.372
24	0.382	0.442	1.580	2.250	3.573	3.590	4.008	4.224	2.858	1.218	0.457	0.317
26	0.305	0.360	1.152	1.770	3.163	3.045	3.647	3.828	2.201	0.767	0.357	0.269
28	0.251	0.205	0.871	1.225	2.478	2.237	3.198	3.366	1.392	0.592	0.267	0.225
30	0.186	-	0.636	0	1.354	0	2.246	1.869	0	0.430	0	0.162

*Fig. 8. Annual volumes of electricity production of the PVP within the studied time interval*

Discussion. The statistically estimated energy indicators for the PVP's power generation process are given for a plant with the fixed-tilt mounting of PVMs and their orientation to the South. The tilt angle was equivalent to the geographical latitude at the installation location (φ). That slope was justified by estimation of the annual volume of electrical energy production with variable angle in the range from $(\varphi - 20)$ to $(\varphi + 20)$. Increasing the tilt angle leads to a decrease in production volume, therefore this range of angle change was not studied. When the slope decreases, an increase in volumes is observed. However, at the edge of the specified range the increase is as small as approx. 5%, due to weaker cooling of the structure by wind and consequent increase in the PVM's temperature. As a result, the output of electrical energy decreases in autumn-winter period, which causes significant variability in the production amount throughout the year. The stochastic component of the generated output remain virtually unchanged within

the specified range of changes in the tilt angle. An increase in the PVM's temperature contributes to faster degradation of their energy properties. It is worth noting that a specific value of PVM tilt angle for a particular plant will also depend on conditions for cleaning the surface of the modules from dust, which improve when the angle increases. These conditions vary depending on the location of the station and its power. Therefore, the quantitative results presented in the publication can be used in feasibility studies for PVP construction projects in the Azov-Black Sea region, and then refined at the stage of operational design by applying specific input data and using specialized commercial software.

The calculation of quantitative statistical estimates of the PVP's energy indicators was based on the determination of the daily trend in power generation and its random component for each month of the year separately using an

observation interval of 16 years. The duration of the stationarity interval was equal to one hour according to the used database of historical data. Therefore, the obtained characteristics of the probabilistic assurance of power levels and correlation functions at monthly time intervals are characterized by significant reliability and allow quantitative assessment of the electrical energy production process. For example, the duration of interruption in PVP power generation, due to continuous cloudiness, is expected in August for at least three consecutive days (fig. 4). In January, this interval is at least eight days in a row. Since the maximum value of daily electricity production in August is almost three times greater than in January (fig. 5), it can be assumed that the minimum capacity of the PVP electricity storage must exceed, at least three times, the largest daily generation volume in the annual time interval. It is possible to use pumped hydro energy storage on land [45], sea [46], or underground [47] to store the energy of a large PVP. However, it is worth noting that determining the amount of energy storage in each specific project requires comprehensive consideration of water storage, monitoring and control systems, operating modes, and equipment costs to achieve competitive technical and economic performance indicators of the facility [48].

Conclusions

1. The process of energy generation by a photovoltaic plant is represented by a set of daily random functions. Algorithms have been developed for calculating expected trends and their stochastic components, normalized correlation functions, probabilistic assurance of different levels of power and volumes of electrical energy production. Calculation studies were performed for a hypothetical power plant with installed capacity of photovoltaic modules of 1 kW that allows further scaling of the results to arbitrary power. To obtain statistically stable estimates, a 16-year time interval from 2005 to 2020 was studied. As the source of information, meteorological database SARAH2 was used, containing hourly information on the density of solar irradiance, ambient temperature, and wind speed in the middle part of the Azov-Black Sea region of Ukraine. The obtained quantitative results can be used for feasibility studies of the integration of PVP energy into the technological schemes of water desalination in this region. The results can be further specified at the stage of operational design by applying specific input data and using specialized commercial software.

2. In the most advantageous hours of the summer period, the maximum value of the power trend reaches the level of (0.60-0.64) kW, and the corresponding average daily power value is 0.4 kW. Algorithms have been developed for calculating the probability of exceeding the various required levels of the power and volumes of electricity production by the PVP in each month and each hour. In particular, at noon (12:00 a.m.), power generation of more than 0.4 kW will be observed: in August – 28 days, in April – 22 days, in October – 18 days, in January – 7 days. In the morning, at 9:00 a.m., the duration of generation of the average daily power value

of more than 0.4 kW can be expected: in August – 18 days, in April – 15 days, in October – 11 days, in January – 0 days. In August, the interruption of PVP's power generation, caused by continuous cloudiness, is expected for at least 3 consecutive days. For the months of the autumn-winter period, the interruption of generation, due to continuous cloudiness, can be observed for more than a week.

3. Statistical estimates of the PVP's expected daily, monthly and annual volumes of electricity production were obtained taking into account the meteorological conditions of the region. The achievable annual value of the capacity factor of the PVP, provided that the generated energy is fully integrated into the technological schemes of water desalination, can be expected in the range of (0.128 – 0.148) p.u. In the winter period, the process of electricity generation demonstrates significant variability. The value of standard deviation reaches the level of the average value, which is caused by the presence of cloudiness in this period of time. The volume of electricity production in the winter months is almost three times smaller than in the summer months. In particular, the average value of the daily amount of electricity produced by the hypothetical PVP in August is about 4.8 kW·h/day, and in January – only 1.4 kW·h/day.

It is determined that the minimal capacity of the PVP storage system, required for the stable and uninterruptible power supply of the desalination facility, must be at least three times as big as the maximum daily volume of energy production of the plant evaluated in the yearly time interval.

The signs of climatic cyclicity in the amount of electricity production with a duration of (3-5) years were detected.

4. Successful integration of PVP electricity into technological schemes of water desalination requires detailed technical and economic optimization of the entire technological complex composed of the desalination facility, power plant, energy and water storages, monitoring and control system, as well as the cost of equipment, to achieve competitive technical and economic performance indicators.

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