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PROBABILISTIC CHARACTERISTICS OF WIND POWER PLANT OUTPUT FLUCTUATIONS IN THE CLIMATIC CONDITIONS OF THE AZOV-BLACK SEA REGION OF UKRAINE

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Abstract. *Scaling up hydrogen energy is a strategic priority of the energy policies of Ukraine and the European Union. Using renewable energy sources (RES) to power autonomous technological complexes for green hydrogen production and seawater desalination as a feedstock requires finding effective technical solutions to align the stochastic nature of power generation with the stable energy demand of such facilities. To address this challenge, this study performs a statistical evaluation of parameters characterizing the dynamics of electricity production based on retrospective data from a wind power plant (WPP) located in the Azov-Black Sea region of Ukraine. The research primarily focuses on analyzing the duration of power deficit and surplus intervals caused by the inherent variability of WPP operation. Numerical estimates were obtained for the maximum and average duration of such intervals, their standard deviation, as well as the parameters of exponential and Weibull probability distributions used for their modelling. The results of this study are essential for designing continuous energy supply systems for large-scale autonomous RES-based green hydrogen production and seawater desalination facilities.*
Ref. 36, Tab. 2, Fig. 8

Key words: *wind power plant, random processes, energy supply, green hydrogen, desalination, power, statistics, fluctuations.*

ІМОВІРНІСНІ ХАРАКТЕРИСТИКИ ФЛУКТУАЦІЙ ПОТУЖНОСТІ ВІТРОЕЛЕКТРИЧНОЇ СТАНЦІЇ В КЛІМАТИЧНИХ УМОВАХ АЗОВО-ЧОРНОМОРСЬКОГО РЕГІОНУ УКРАЇНИ

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Анотація. *Розвиток водневої енергетики є одним із стратегічних пріоритетних напрямів енергетичної політики України та Європейського Союзу. Використання відновлюваних джерел енергії (ВДЕ) для електроживлення автономних технологічних комплексів з виробництва зеленого водню та опріснення морської води як вихідної сировини потребує пошуку ефективних технічних рішень для узгодження стохастичного характеру генерування потужності та стабільної потреби в енергії таких об’єктів. З метою розв’язання цієї проблеми у межах даного дослідження на основі ретроспективних даних функціонування вітроелектричної станції (ВЕС), розташованої в Азово-Чорноморському регіоні України, проведено статистичне оцінювання параметрів, що характеризують динаміку виробництва електроенергії. Основну увагу зосереджено на аналізі тривалості інтервалів дефіциту та надлишку потужності, зумовлених варіабельністю роботи ВЕС. Отримано чисельні оцінки максимальної та середньої тривалості таких інтервалів, їх середньоквадратичного відхилення, а також параметрів експоненціального та вейбуллівського розподілів імовірностей для їх моделювання. Результати дослідження є важливими* *для проєктування систем безперервного енергозабезпечення потужних автономних комплексів з виробництва водню та опріснення морської води на основі ВДЕ. Бібл.36, табл.2, рис.8.*

Ключові слова: *вітроелектрична станція, випадкові процеси, енергозабезпечення, зелений водень, опріснення, потужність, статистика, флуктуації.*

Introduction. The territory of the Azov-Black Sea region of Ukraine is characterized by significant wind energy resources [1]. According to World Bank estimates, the achievable capacity of offshore wind power plants (WPPs) stands at 251 GW [2], while onshore plants reach 100 GW [3]. Expected annual capacity factor values, assuming full utilization of the generated electricity, reach 35% for coastal WPPs and up to 40% for offshore WPPs [4]. Calculation-based studies of wind energy potential are performed using averaged wind speed values over specific time intervals. Experimental power output curves of wind turbines, as a function of wind speed, are also determined through averaging [5]. Wind speed in the surface layer of the atmosphere varies chaotically in time and space, causing corresponding changes in the instantaneous power of the WPP, while the averaging of quantitative data obscures this variability, which is critical for integrating wind energy into centralized and local power systems, as well as autonomous power supply systems. WPP power fluctuations propagate through the electrical grid and, at certain levels, cause unacceptable voltage and frequency deviations from standardized ranges [6]. In such cases, to ensure stable grid operation, wind power curtailment may be applied, leading to subsequent financial consequences [7,8,9].

The variability of WPP power has an extremely important impact on autonomous power supply systems for energy-intensive technologies, particularly for the electrolytic production of green hydrogen and water desalination using the reverse osmosis method. Scaling up hydrogen energy is one of the strategic priorities of the energy policy of Ukraine and the European Union for the coming decades [10,11]. Ukraine is participating in the implementation of the European program "2×40 GW Green Hydrogen Initiative" [12], which emphasizes the construction of 10 GW of electrolyser capacity for green hydrogen production using wind energy in the Azov-Black Sea region. The program envisions an annual hydrogen production in Ukraine of 1.65 million tons, requiring approximately 24 million m^3/year of treated freshwater [13]. Achieving these production volumes requires the installation of about 40 GW of renewable energy capacity [14,15]. This capacity is too large for parallel operation with the national power grid, which requires identifying ways to integrate the stochastic supply of wind power into the technological schemes of hydrogen production and seawater desalination. Utilizing WPPs to power these complexes demands the development of effective technical solutions to ensure their continuous operation, taking into consideration the stochastic nature of power generation and the stable energy demand of electrolysers and membranes.

In the context of Ukraine, green hydrogen production is technically feasible in southern regions close to the coastline, where sufficient seawater resources and the necessary potential for wind power generation are available. Seawater requires preliminary desalination. For reverse osmosis technology, the stability of the power supply is critical, as frequent start-stop cycles significantly reduce the service life of desalination membranes, and hydraulic shocks caused by sudden voltage spikes can lead to total equipment failure [16]. The presence of WPP power fluctuations nearly halves the productivity of alkaline electrolysers [17]. The combination of these factors complicates the integration of wind power into hydrogen production and seawater desalination technologies. One way to address this challenge is the use of energy storage systems (ESS) [18–21] within an autonomous power supply system. ESS must have a short response time, sufficient power and capacity, and provide the capability for long-term (several days) energy storage with minimal losses. Justifying the required ESS parameters requires a study of wind power generation dynamics, as these systems have a significant impact on the overall technical and economic performance of the facility.

Preliminary observations. The presence of wind speed turbulence in the surface layer of the atmosphere causes fluctuations in the generated power of wind turbines and wind power plants [22]. Real-time wind speed variations are characterized by continuous disturbances that lead to changes in the torque on the wind turbine shaft and, consequently, in the parameters of the generated electricity. Fig. 1 shows a fragment of an oscillogram of analogue signals representing the load operating mode parameters of an experimental autonomous wind turbine with a nominal power of 20 kW and a moment of inertia of 9,000 kg·m^2 [23]. The oscillogram was recorded using a multi-channel analogue oscillograph at a constant value of electrical load resistance. The following notations are used in the graph: v – the horizontal component of the air flow velocity at the hub height; φ – the pitch angle of the wind turbine blades; U, I – the voltage and current of the valve generator; t – current time. The variable nature of wind speed and the nonlinear aeromechanical properties of the wind turbine are the causes of fluctuations in the parameters of the generated electricity.

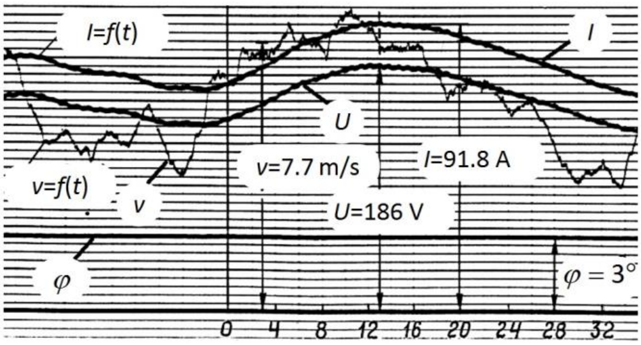

Fig. 1. Wind speed disturbances and output electrical parameters fluctuations of an autonomous wind turbine (oscillogram fragment)

Fluctuations in generated electricity are also inherent to wind turbines during parallel operation with the electrical grid. Fig. 2 shows a fragment of an oscillogram illustrating power variations of an industrial wind turbine with an induction generator operating within a power system [24].

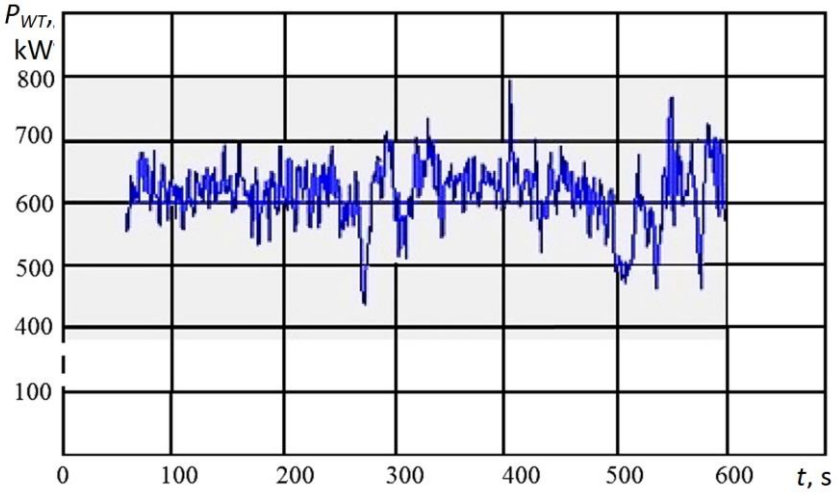

Fig. 2. Power output fluctuations of wind turbine operating within a power system (oscillogram fragment)

It is worth noting that the presented oscillograms were recorded over short time intervals; therefore, these results should not be taken as a benchmark, much less as a standard. Since the occurrence of wind gusts is probabilistic in nature, the oscillograms merely demonstrate their presence and the corresponding response of the wind turbine. To obtain statistically robust results regarding wind power fluctuations, long-term experimental studies are required [25].

Problem statement and research methods. The study of the random process of WPP power generation over long time intervals involves measuring and recording ordinate values at specific moments in time with a predefined sampling frequency [26,27]. For the analysis of wind energy processes, an acceptable sampling step is one hour, which aligns with the commonly used value for power supply systems [28]. In this case, the observation results represent a random function of time, where the argument takes only specific numerical values. Random functions of time obtained in this manner are referred to by the term "random sequence." As an example, Fig. 3 shows a random sequence of the power generation process for a modern WPP (with a wind turbine hub height of approximately 100 meters above the ground surface) over a monthly interval with a 1-hour sampling step in the climatic conditions of the Azov-Black Sea region of Ukraine. The generation process is characterized by significant power variability, the values of which are given in per-unit (p.u.) relative to the installed capacity of the wind turbines within the plant [4].

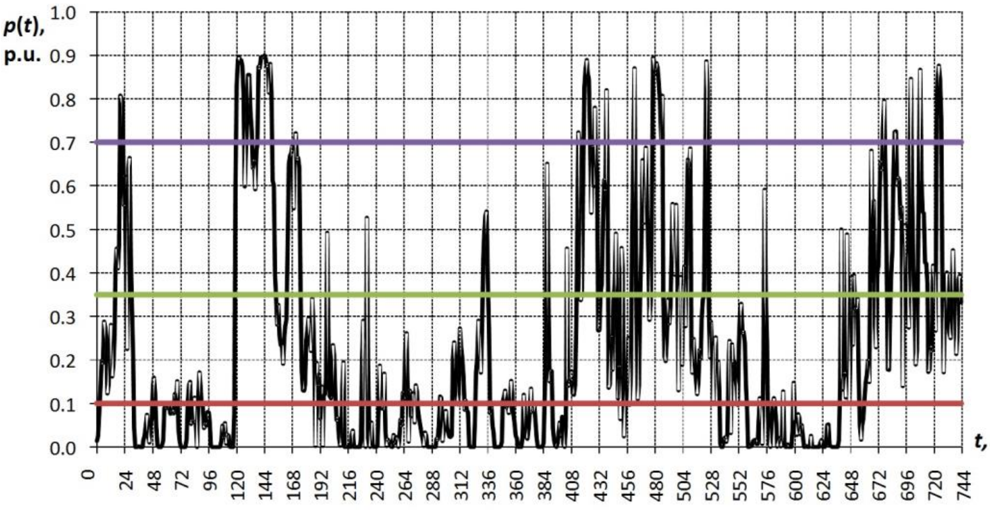

Fig. 3. WPP power fluctuations over a monthly time interval

Typically, the analysis of random sequence fluctuations involves the statistical estimation of the number of extreme trajectory values, the height of local maxima, the number of predefined level crossings, the duration of trajectory excursions above a given level, the relative time the trajectory spends within a specified range, and other indicators.

The aim of this study is to perform a statistical evaluation of the probability distributions of the duration of wind power trajectory excursions above specific characteristic levels, as well as the probability distribution of the duration of "zero-generation" periods for a WPP in the climatic conditions of the Azov-Black Sea region of Ukraine, based on the theoretical foundations of random processes and sequences [29,30].

Methodology for the determination of probabilistic characteristics. The input array of retrospective data consists of power generation measurements from a coastal WPP in the Azov-Black Sea region of Ukraine over a 1-year period, recorded with a 1-hour step. A fragment of this random sequence of the WPP power generation process $p(t)$ over a monthly interval is shown in Fig. 3. Power values are expressed in per-unit (p.u.) to standardise the results.

Consider a generalised representation of a possible trajectory of the power generation random process $p(t)$ (Fig.4). Let us define two power levels: minimum $L = p_{\text{mn}}$ and maximum $H = p_{\text{mx}}$. We assume that when $p(t) \le p_{\text{mn}}$, there is a power deficit; therefore, previously stored energy is used to power the equipment. When $p(t) > p_{\text{mx}}$, there is a power surplus, meaning the generated energy is sufficient not only to provide power to the equipment but also to charge the ESS. Fig. 4 illustrates the periods of power deficit and surplus, each corresponding to a specific start time t_i and a specific duration τ_i. In this case, periods 1, 2, and 4 represent a deficit, while period 3 represents a surplus. Since the process $p(t)$ is random, both t_i and τ_i are random variables. It is evident that over a sufficiently long observation interval T, a large number of τ_i values can be obtained. The objective of the study is to evaluate the probabilistic parameters of the $\xi_{\text{mn}} = \{\tau_1, \tau_2, \tau_4, \ldots\}$ and $\xi_{\text{mx}} = \{\tau_3, \ldots\}$ random sequences.

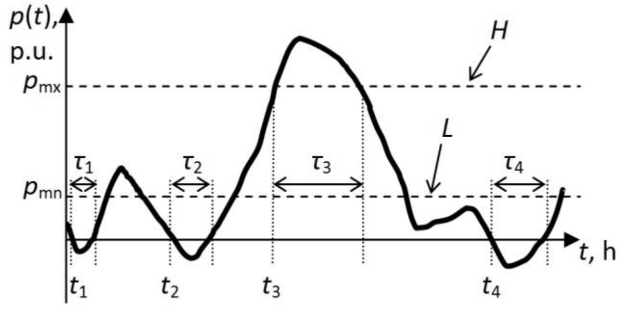

Fig. 4. Periods of power deficit and surplus

In several studies, for example [31], similar issues are examined in the most general formulation, where a continuous differentiable random process is considered, and the dynamics of its trajectory is investigated. An event in which the process trajectory crosses a fixed level H from bottom to top is called a positive excursion (up-crossing), whereas if the trajectory crosses a level L from top to bottom, it is called a negative excursion (down-crossing). It has been shown that obtaining an analytical expression for the probability distribution of the random process trajectory excursion duration is mathematically complex and remains not fully resolved in the general case. Therefore, in this study, the determination of this distribution is implemented using statistical methods.

According to the results in [31], for large values of τ, it can be assumed that the probability decreases exponentially as τ increases. The exponential distribution is widely applied in the theory of queuing, as well as in reliability theory, to describe the probability of failure-free operating time during sudden failures [32,33]. The probability density function of a random variable ξ_{exp} with an exponential distribution depends on a single parameter and is described by the formula:

$$f(\tau;b) = \frac{1}{b} e^{-\frac{\tau}{b}}, \ \tau \ge 0, \ b > 0, \tag{1}$$

and the cumulative distribution function has the form:

$$F(\tau;b) = 1 - e^{-\frac{\tau}{b}}, \ \tau \ge 0, \ b > 0. \tag{2}$$

Since the mathematical expectation of an exponentially distributed random variable ξ_{exp} is estimated as:

$$\mathbf{M}\{\xi_{\text{exp}}\} = b,$$

then to find an estimate of the parameter b of the distribution in form (1), it is sufficient to determine the average value for the available sample, which significantly simplifies the application of this type of distribution. In addition, the advantage of this distribution is the simplicity of its expression. Despite this, the exponential distribution, as a model for the duration of excursions of the WPP generation process $p(t)$, has the following significant disadvantages: 1) at small values τ, the exponential distribution can significantly deviate from the actual distribution of the duration of excursions of the process $p(t)$; 2) the exponential distribution exists on an infinite interval $\tau \in [0, \infty)$, whereas the actual durations are limited; 3) the use of the exponential distribution has been theoretically confirmed for describing the intervals between independent rare events [32,33], while the values of the studied process $p(t)$ at close moments in time can be correlated, which reduces the accuracy of such a distribution model.

Another distribution often used in reliability theory to describe the time to failure is the two-parameter Weibull distribution [32,33], the density of which is described by the expression [33,34]:

$$f(\tau;\alpha,\beta) = \frac{\beta}{\alpha}\left(\frac{\tau}{\alpha}\right)^{\beta-1} e^{-\left(\frac{\tau}{\alpha}\right)^{\beta}}, \ \tau \ge 0, \ \alpha, \beta > 0, \tag{3}$$

where α – scale factor, β – shape parameter.

The cumulative distribution function has the form:

$$F(\tau;\alpha,\beta)=1-e^{-\left(\frac{\tau}{\alpha}\right)^{\beta}},\ \tau\ge 0,\ \alpha,\beta>0. \qquad (4)$$

Owing to the fact that the Weibull distribution is characterised by two parameters, it can describe the empirical distribution more accurately. For $\beta=1$, it simplifies to an exponential distribution with the parameter α.

To find the estimates $\hat{\alpha}$ and $\hat{\beta}$ for the Weibull distribution parameters α and β respectively, based on the sampled data τ_i, $i=\overline{1,n}$, the relations obtained by the maximum likelihood method were used [34,35]:

$$\hat{\alpha}=\left(\frac{1}{n}\sum_{i=1}^{n}\tau_i^{\hat{\beta}}\right)^{\frac{1}{\hat{\beta}}}, \qquad (5)$$

$$\hat{\beta}=\left(\frac{s_3}{s_1}-\frac{s_2}{n}+\beta_0\frac{s_3^2-s_1s_4}{s_1^2}\left(\left(\frac{s_3}{s_1}-\frac{s_2}{n}\right)\beta_0-1\right)\right)^{-1}, \qquad (6)$$

where

$$\beta_0=v^{-1.075};\ \bar{\tau}=\frac{1}{n}\sum_{i=1}^{n}\tau_i;\ v=\frac{s}{\bar{\tau}};$$

$$s=\left(\frac{1}{n}\sum_{i=1}^{n}\left(\tau_i-\bar{\tau}\right)^2\right)^{\frac{1}{2}};\ s_1=\sum_{i=1}^{n}\tau_i^{\beta_0};\ s_2=\sum_{i=1}^{n}\ln\tau_i; \qquad (7)$$

$$s_3=\sum_{i=1}^{n}\tau_i^{\beta_0}\ln\tau_i;\ s_4=\sum_{i=1}^{n}\tau_i^{\beta_0}\left(\ln\tau_i\right)^2.$$

Research Results. Statistics for the duration of WPP power generation trajectory $p(t)$ excursions throughout the year, with 1-hour sampling step, are presented on a monthly basis in Table 1. It should be noted that the selection of specific values for the levels p_{mn} and p_{mx} depends on the ratio between the nominal power consumption of the equipment and the installed capacity of the WPP, that have not been defined at this stage. Therefore, within the framework of this study, the full range of power variation is represented by several level values: 0.1 p.u., 0.35 p.u., 0.7 p.u., and 0.9 p.u.

Table 1. Statistics of the WPP output power excursions above and below the fixed levels

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Power level	**Indicator**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Entire year**
p≥0.90	Mean	4.2	2.56	2.44	1.5	1	-	2.5	1	-	4	6.5	2.36	3.39
	Std. dev.	3.56	1.74	1.67	1.0	-	-	3.0	0.0	-	2.38	8.12	2.50	4.237
	Number	5	9	9	4	1	0	4	2	0	7	12	11	64
	Max	10	6	6	3	1	-	7	1	-	7	29	9	29
p>0.70	Mean	4.6	9.2	6.5	6.4	3.5	4.0	5.9	3.4	4.1	6.7	10.4	6.4	6.0
	Std. dev.	5.56	15.14	7.52	8.99	3.32	5.73	7.86	2.59	3.31	8.67	13.84	7.83	8.51
	Number	40	23	25	21	17	25	26	18	32	34	29	35	325
	Max	26	55	27	40	12	26	36	10	14	43	57	32	57
p>0.35	Mean	10.0	15.5	10.7	8.4	5.2	6.7	7.6	5.5	7.0	9.8	11.9	14.0	9.1
	Std. dev.	10.14	22.30	10.86	14.59	6.25	9.64	9.48	5.07	6.59	11.21	15.61	18.89	12.28
	Number	47	23	27	33	38	33	40	42	39	39	36	30	423
	Max	36	83	42	78	36	52	44	20	23	46	63	91	91
p>0.10	Mean	36.0	22.7	12.4	15.5	9.9	9.4	12.0	10.6	13.2	22.9	32.1	26.7	16.0
	Std. dev.	30.52	37.78	16.66	24.82	19.80	14.28	13.91	14.15	24.49	22.08	24.85	29.34	23.15
	Number	17	22	38	32	44	51	46	44	35	25	18	21	387
	Max	124	139	64	94	84	81	56	63	133	69	79	108	146
p≤0.10	Mean	8.3	8.9	7.2	7.0	7.0	4.8	4.2	6.2	7.1	7.1	8.4	9.2	6.7
	Std. dev.	6.06	11.71	7.87	7.23	7.91	4.57	4.79	6.73	9.36	6.68	6.28	9.27	7.55
	Number	16	22	38	32	44	50	46	45	36	24	17	20	386
	Max	22	42	37	26	39	17	23	35	38	24	26	32	42

The minimum level value *p*=0.1 p.u. characterises the initial power required for the effective integration of wind energy into consumer technological schemes, while the value *p*=0.9 p.u. represents the maximum achievable power of a multi-unit wind farm, accounting for all types of losses. The level *p*=0.35 p.u. aligns with the capacity factor of wind power plants in the southern regions of Ukraine [36], and the level *p*=0.7 p.u. corresponds to one of the possible load operating modes. For each of the investigated levels, the respective rows of Table 1 provide quantitative estimates of the mean value, standard deviation, as well as the number of elements in the corresponding sequence and its maximum element. This information is presented for each month of the year separately (columns 3 to 14) and for the entire year as a whole (column 15).

Based on the data in Table 1, preliminary assumptions regarding the required ESS parameters can be made. In particular, the mean annual duration of continuous generation at nominal power can be expected to be 3.39 hours, with the maximum duration reaching 29 consecutive hours. These values characterise the power and the maximum quantity of energy that the ESS can accumulate during a single charging cycle. The longest "zero generation" period was observed for 42 consecutive hours, which can serve as baseline information for determining the minimum required ESS capacity for a given load power. The results of the heuristic analysis of monthly random sequences regarding the duration of "zero generation" at the level of the WPP capacity factor indicated the necessity for continuous ESS operation for 10–12 consecutive days.

To mathematically model the probability distributions of power generation trajectory excursions beyond the investigated threshold levels, statistical estimates of their parameters were obtained according to (1,3) and (5,6), as presented in Table 2.

Table 2. Parameters of exponential and Weibull probability distributions
for modelling WPP power excursion durations

Power level	Distribution parameters		
	Exponential	Weibull (two-parameter)	
	$\hat{b}$	$\hat{\alpha}$	$\hat{\beta}$
p≥0.9	3.39	3.3251	0.9585
p>0.7	6.00	5.3178	0.8103
p>0.35	9.10	8.0127	0.8016
p>0.1	16.00	12.5908	0.7073
p≤0.1	6.70	6.5202	0.9360

Frequency polygons and their analytical approximation by continuous distributions for each power level are shown in Fig. 5. The results demonstrate that for large values of the variable τ both approximations align sufficiently well with the empirical distributions for each investigated level. However, for small values of τ the approximation error is significant, particularly for the levels $p > 0.7$; $p > 0.35$; $p > 0.1$. The value of the Weibull distribution density at $\tau = 0$ is infinitely large, as $\hat{\beta} < 1$. For the exponential distribution, the density value at $\tau = 0$ equals $1/\hat{b}$ and is finite. However, in all considered cases, it is substantially lower than the height of the first bin of the empirical density, indicating insufficient approximation accuracy for the investigated distributions at small values of τ.

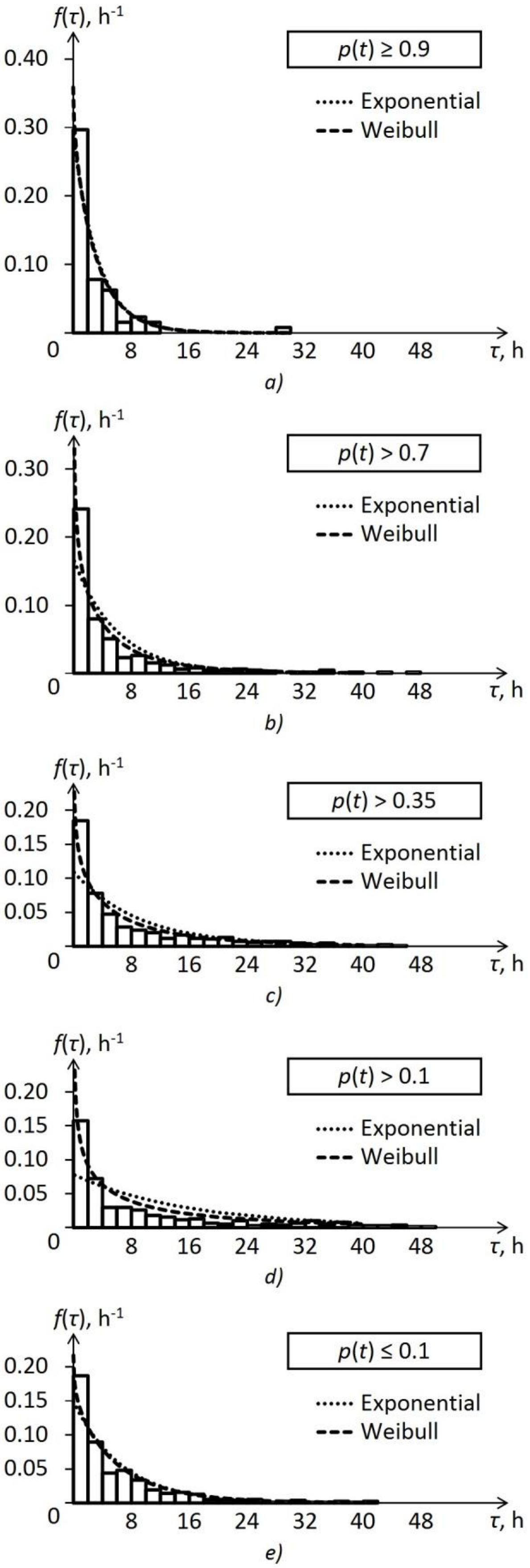

Fig. 5. Empirical and analytical probability distributions of WPP power generation trajectory excursion durations over an annual interval for various levels:
a) p≥0.9; b) p>0.7; c) p>0.35; d) p>0.1; e) p≤0.1

In subsequent analysis, the Weibull distribution will be used, as its analytical description is more flexible for application due to the presence of two parameters. Fig. 6 shows the plots of the Weibull probability density function and cumulative distribution function for the parameters given in Table 2. For visual clarity, only the left part of the plots is shown, where they have sufficiently large values. The right part of the density plots rapidly approaches zero, while the distribution functions approach unity, making them less informative. As can be seen, the slope of the distribution functions depends on the level value and varies synchronously with it. An interesting fact is that the Weibull density and distribution curves for levels $p > 0.35$ and $p > 0.7$ are located fairly to each other, which characterises the presence of comparable random sequences throughout the year within this range of generated power.

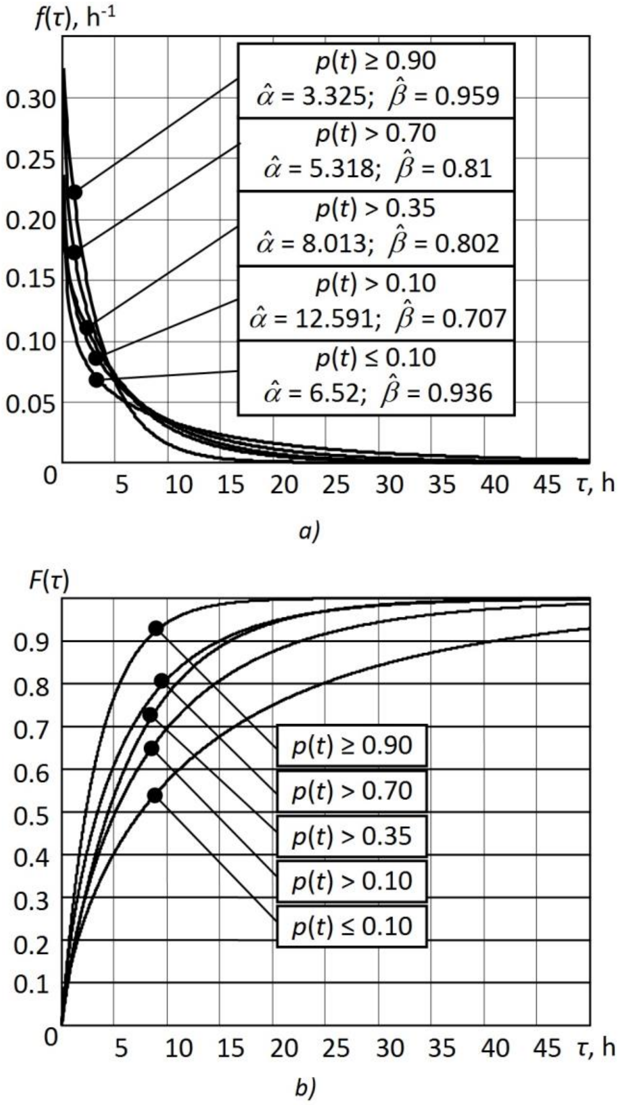

Fig. 6. Plots of Weibull probability density functions (a) and cumulative distribution functions (b) for WPP power generation excursion durations throughout the year for various levels

There is also practical interest in determining the statistical parameters of WPP power generation fluctuations for fixed hours of the day throughout a calendar month. Knowledge of these statistics is important when creating hybrid power systems based on WPPs and photovoltaic plants. In particular, Fig. 7 illustrates the maximum number of consecutive days when WPP generation was absent for a specific hour of the day. In the first half of the day, ranging from 00:00 to 12:00, the maximum duration of zero WPP generation is observed in March, lasting from five to ten consecutive days, and in May, from five to eight days. In the time interval from 12:00 to 24:00, the longest absence of WPP power generation is observed in September, ranging from four to eight consecutive days. A similar analysis can be performed for any interval of the day.

The cumulative characteristic of the total duration of low WPP generation across calendar months is shown in Fig. 8. The longest “zero generation” periods are expected in March, May, August, and September. Accordingly, the total duration of WPP generation with power exceeding 0.1 p.u. in March, May, August, and September is expected to be at a level of 450–500 hours per month. For the remaining months, the generation duration will range between 500 and 600 hours per month.

Conclusions

1. This publication initiates research aimed at creating autonomous power supply systems based on WPPs for large-scale green hydrogen production technologies and seawater desalination as a feedstock in the climatic conditions of the Azov-Black Sea region of Ukraine. The study validates the application of the principles of random process theory and random sequences to analyse the variability of power generation in modern WPPs with wind turbine hub heights of 100 metres and above. The durations of power generation trajectory excursions beyond specified threshold levels were investigated within the range of 0.1 ≤ P ≤ 0.9 per unit relative to the total installed capacity of the wind turbines within the plant.
2. The duration of WPP operation at nominal power over an annual interval is estimated at approximately 217 hours, while on monthly intervals it ranges from 0 to 78 hours. The lowest duration values are expected in May, June, August, and September, while the highest are expected in November. For the remaining months, the total duration of generation at nominal power ranges between 20 and 28 hours. The mean annual duration of continuous generation at nominal power can be expected to be 3.39 hours, with the maximum duration reaching 29 consecutive hours in November.

3. The total duration of WPP generation with power exceeding 0.1 p.u. in March, May, August, and September is expected to be at a level of 450–500 hours per month. For the remaining months, the generation duration will range between 500 and 600 hours per month.

4. The longest “zero generation” period over an annual time interval is expected to last for 42 consecutive hours, which can serve as baseline information for determining the minimum required capacity of the energy storage system for a given load. The results of the analysis of monthly

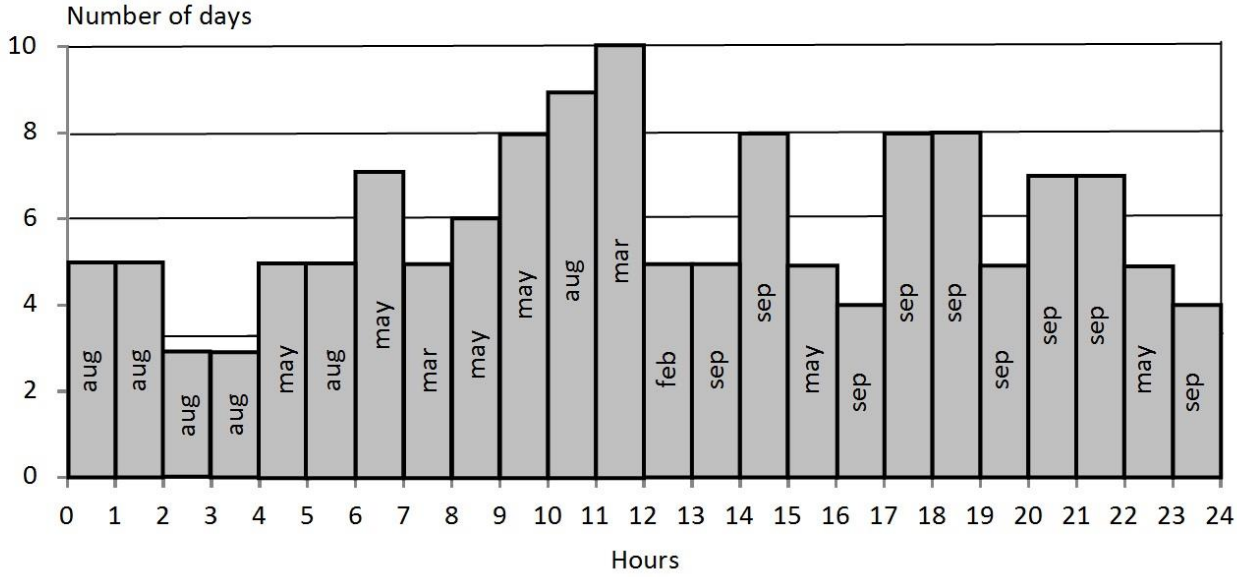

Fig. 7. Maximum number of consecutive days with low WPP generation for a specific hour of the day

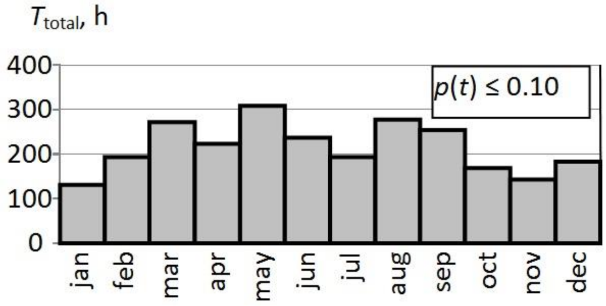

Fig. 8. Total monthly number of hours T_{total} of WPP "zero generation"

random sequences regarding the duration of "zero generation" at the level of the WPP capacity factor indicated the necessity for the continuous operation of the energy storage system for 10–12 consecutive days.

5. The use of the two-parameter Weibull probability distribution for the mathematical modelling of WPP power generation fluctuation durations has been justified.

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