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Assessment of the applicability of small wind power generation in the Kyiv region

***Abstract**. The article deals with the wind characteristics in the suburbs of Kyiv and identifies the location that is most promising for the development of small wind power generation. For the selected location, a statistical analysis of wind characteristics was carried out and the choice of the main technical parameters of the wind generator was substantiated. A mathematical model of wind speed repeatability was developed using a two-parameter Weibull distribution based on archival wind speed data from open sources. For the given location, the average productivity of a conditional wind turbine was estimated for different time intervals (year, month) according to the Weibull distribution. The results of the calculation obtained by the Weibull distribution and the actual wind speed values were compared.*

.***Streszczenie.** W artykule omówiono charakterystykę wiatru na przedmieściach Kijowa oraz wskazano najbardziej obiecującą lokalizację dla rozwoju małej energetyki wiatrowej. Dla wybranej lokalizacji przeprowadzono analizę statystyczną charakterystyki wiatru i uzasadniono wybór głównych parametrów technicznych generatora wiatrowego. Matematyczny model powtarzalności prędkości wiatru został opracowany przy użyciu dwuparametrowego rozkładu Weibulla na podstawie archiwalnych danych dotyczących prędkości wiatru z otwartych źródeł. Dla danej lokalizacji oszacowano średnią produktywność warunkowej turbiny wiatrowej dla różnych przedziałów czasowych (rok, miesiąc) zgodnie z rozkładem Weibulla. Porównano wyniki obliczeń otrzymane rozkładem Weibulla z rzeczywistymi wartościami prędkości wiatru. (**Ocena przydatności małej energetyki wiatrowej w obwodzie kijowskim**).*

Keywords: Wind turbine**;** Weibull Parameter; Statistical analysis; Frequency distribution; Wind power characteristics.
Słowa kluczowe: Turbina wiatrowa; Parametr Weibulla; Analiza statystyczna; Dystrybucja częstotliwości; Charakterystyka energetyki wiatrowej.

Introduction

The dynamic development of renewable energy sources (RES) is a sustainable trend of our time. This is due to several global factors, including climate change and the replacement of fossil (carbon) energy resources to reduce their negative impact on the environment [1]. For Ukraine, the issues of further development of green energy in the current environment are primarily related to overcoming the consequences of armed aggression (restoration of RES plants after damage due to hostilities) and post-war reconstruction of the industry. The Renewable Energy Research Center REN21 and the United Nations Economic Commission for Europe have recognized that due to Russia's full-scale invasion, 30% of solar generation power has been destroyed, and 90% of wind generation capacity in the southern regions of the country has been decommissioned. In general, solar and wind power generation in 2022 decreased by more than half compared to its pre-war level. Thus, if at the end of 2021, electricity generation at solar power plants (SPPs) amounted to 7,670 million kWh and at wind power plants (WPPs) – 3,886 million kWh, then at the end of 2022, electricity generation at SPPs is estimated at 2,007 million kWh and WPPs – 1,300 million kWh, respectively [2].

The significant electricity shortage and disruption of electricity supply to consumers observed as a result of massive rocket attacks in many regions of Ukraine, including Kyiv and the suburbs, is largely due to the shortcomings and inertia of centralized power supply systems [3]. Therefore, one of the priority areas for the development of the energy sector should be the introduction of more flexible systems of distributed generation and small-scale generation facilities based on RES (e.g., wind and solar power plants) to ensure energy independence and meet the energy needs of locally connected consumers. In these conditions, the issues of studying the potential of RES, in particular wind energy potential, in certain areas of the country and assessment of wind turbines productivity become particularly relevant.

Literature review and problem statement

Wind energy resource assessment is usually conducted to identify areas that are promising in terms of wind power development. In Ukraine, preference has recently been given to the development of large WPP with a power of 0.5 MW or more, primarily in the southern regions. Insufficient attention has been paid to the improvement of small and medium-sized wind generation systems, which include wind turbines with a power of up to 20 kW and a power of 20 to 500 kW, respectively. As the experience of foreign countries shows, small wind turbines should be used in cities with significant electricity consumption [4, 5]; in isolated areas remote from power sources as autonomous and auxiliary energy systems [6], where wind energy can be an adequate alternative to diversify electricity supply. In Ukraine, small- and medium-sized wind turbines (WTs) have already been used at such local facilities as hotels, energy cooperatives, farms, and military facilities, for mobile communication stations power supply, etc. The approach of WT using as an auxiliary source of lower power is proposed in [8, 9] for combined wind-solar power systems of local facilities, where the main role is played by photovoltaic generation, which provides power to the facility even in the absence of wind. At the same time, the WT operates around the clock, ensuring the required minimum level of generation. In these conditions, it is possible to reduce the installed power of photovoltaic modules with more complete use of it.

Important characteristics of the wind potential of an arbitrary territory are the average wind speed over a certain period and the repeatability of different gradations of wind speed. The research of wind characteristics is necessary to determine the expected level of electricity generation at the location of a WT. Some results of determining the wind characteristics are described in works [10-13] for different locations in Ukraine, in particular: for a separate city neighbourhood located close to a residential area [10]; for the needs of small agricultural enterprises [11]; for local areas with different combinations of physical and geographical conditions [12, 13]. Some publications are devoted to the study of wind characteristics in the metropolitan region, including the city of Kyiv [14, 15].

The wind potential was estimated by calculating coefficients for statistical distributions: Weibull, Rayleigh, Rice, Nakagami, inverse Gaussian, normal, lognormal, and gamma distributions – in [10]; Weibull distribution – in [11, 13, 15]. Data on wind conditions were determined by measuring in the points of potential placement of WT, in particular, based on data collection systems using wind sensors [10, 11]; data from weather stations [15]; data from geographic information systems (GIS) that provide collection, storage, processing, access, display, and distribution of geospatial data [12]. In [8, 9], the PVGIS database [16] was used for a preliminary assessment of both the generation of photovoltaic modules and wind power characteristics. In [9], the wind characteristics of the east of Ukraine were assessed based on PVGIS data. The PVGIS database is publicly available and contains an archive of wind speeds up to 2020 at a height of 10 m with a 1-hour resolution for a typical meteorological year (TMY) and provides information based on modeling daily long-term satellite data.

Thus, the analysis of publications made it possible to identify certain regularities that should be taken into account when selecting and placing WTs, including the following:

- wind speed in the center of an urbanized environment is lower than on the outskirts. For example, in Kyiv, the wind speed in all seasons during the day in most areas is 0.6-0.7 times lower than outside the city (Boryspil), and in almost all districts of the city it is 1.5-2.5 times higher than in the center [14];
- the Weibull distribution provides the best accuracy in assessing wind potential for most wind speed measurement zones [10, 11, 13, 15];
- wind power characteristics are usually assessed based on various approaches, including direct measurements of wind speed [10, 11, 13], geospatial and geographic data [12], as well as archived data from geographic information systems [8, 9].

At the same time, taking into account the extreme conditions of Ukraine's energy infrastructure during the war and the need for its post-war reconstruction, and climate change, there is a need for further study of wind energy resources in local areas of Ukraine, in particular in the suburbs of Kyiv. Under these conditions, it should be kept in mind that direct measurements of wind speed are not always possible and require considerable time and resources. The network of weather stations, although the main, is not the only source of information on wind characteristics. Therefore, for preliminary estimations and calculations that do not require high accuracy, it is advisable to use archived wind speed data from open sources.

The purpose of the article is to assess the potential and prospects for the development of small wind power generation in the suburbs of Kyiv to ensure the energy security of the region based on the use of archival data on wind speed from open sources.

The main tasks are defined:

- to determine the average wind characteristics for the Kyiv suburbs and assess the prospects for the development of small wind power generation in a given locations;
- to justify the choice of the main technical parameters (rated and cut-in speed) of the WT for use in the location selected for the research;
- to develop a mathematical model of wind speed repeatability and estimate the average productivity of WT at different time intervals on the example of the location selected for the research.

Research Results

Preliminary information on wind resources in the local area can be obtained based on the average wind speed V_{AV} indicator $V_{AV} = \sum_i V_i / n$, where V_i – wind speed on *i* interval of the observation period, n – number of intervals. Wind speed data from the PVGIS database for the period 2012-2016 at a height of 10 m (standard measurement height at weather stations) with an interval of 1 hour were used as the initial data for the calculation [16]. Average wind speed V_{AV} was calculated for the Kyiv suburbs listed in Table 1 (geographical coordinates were determined at dateandtime.info/uk/citycoordinates.php). Wind direction was not taken into account in the calculations.

As can be seen from Table 1, the highest average wind speeds are characteristic of the suburbs located to the northwest and north of Kyiv (Bucha, Hostomel, Vyshhorod). The average annual wind speed for these suburbs exceeds 3 m/s and is, respectively, 3.36 – for Bucha, 3.05 – for Hostomel, and 3.066 – for Vyshhorod.

In [17], a classification of the perspective wind speeds for wind energy purposes was proposed based on the average wind speed V_{AV}: V_{AV}<2 m/s – not perspective for any types of WPPs; 2≤V_{AV}<3 m/s – not perspective for small WPPs; 3≤V_{AV}<4 m/s – perspective for small WPP; 4≤V_{AV}<5,5 m/s – perspective for WPPs of small and medium power; V_{AV}>5,5 m/s – perspective for any type of WPPs. Wind speeds are considered as the perspective at which the power of the WT reaches 50% of the rated one [17]. Based on this classification, it is possible to determine the specific wind load P_{WS} by the average V_{AV} wind speed (Table 1):

$$P_{WS} = 0,5 \rho V_{AV}^3 , \quad (1)$$

where ρ – air density, the standard value is accepted at 1,225 kg/m^3.

Table 1. Average wind speed in the suburbs of Kyiv

Suburb	Geographic coordinates (Latitude / Longitude)	Altitude [m]	Average wind speed V_{AV} [m/s]	Maximal wind speed [m/s]	Specific wind load P_{WS} [W/m^2]
Brovary	50°31′05″ N, 30°48′24″ E	130	2,876	9,17	14,57
Bucha	50°32′36″ N, 30°12′43″ E	135	3,36	12,17	23,23
Irpin	50°31′18″ N, 30°15′01″ E	129	3,05	9,59	17,38
Boryspil	50°21′09″ N, 30°57′18″ E	113	2,761	8,69	12,9
Vyshneve	50°23′20″ N, 30°22′13″E	176	2,862	8,97	14,36
Vyshgorod	50°34'56″ N, 30°28'58″ E	108	3,066	9,52	17,65
Gostomel	50°34′06″ N, 30°15′54″ E	109	3,05	9,59	17,38

According to [17], the locations where the following condition is met 20≤P_{WS}<40 W/m^2 are considered the perspective for the development of small wind energy generation. Because of this, the north-western area of Kyiv region can be considered as promising for the development of small wind energy generation. Therefore, further statistical analysis will be carried out for the city of Bucha as the most promising location for small wind power generation development. The distribution of the average wind speed in Bucha by years of observations (2012-2016) is, respectively: 2012 – 3.25, 2013 – 3.22, 2014 – 3.12, 2015 – 3.36, and 2016 – 3.86 m/s. The average annual wind speed for all years of observations exceeds 3 m/s.`

The highest average monthly wind speed, as shown in Fig. 1, occurs in December (3.88 m/s). Quite high wind speeds, exceeding 3.6 m/s, are observed in the period from November to March. The lowest wind speeds are in summer, with wind speeds decreasing to their lowest values between May (2.98 m/s) and September (3.2 m/s). The difference between the winter maximum (December, 3.88 m/s) and the summer minimum (August, 2.86 m/s) in 2012-2016 is on average 1.02 m/s.

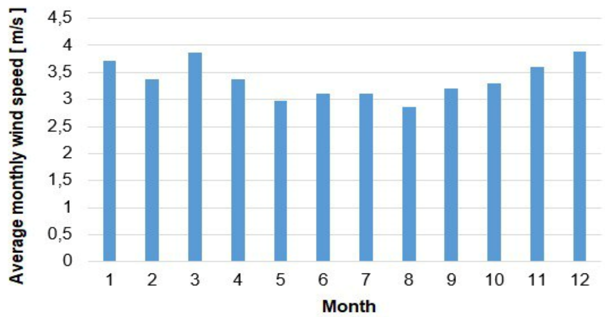

Fig.1. Average monthly wind speed in Bucha

The daily distribution of wind speed for the city of Bucha, shown in Fig. 2, confirms the known pattern of increasing the average daily wind speed in the daytime [6]. While in the summer month (July) there is a significant increase in wind speed due to daytime surface heating, in the winter month (January) the wind speed is more uniform throughout the day with a slight increase in the daytime hours.

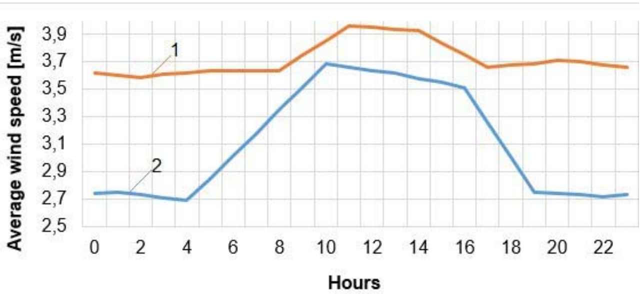

Fig.2. Average daily wind speed in Bucha (1 – January, 2 – July)

In wind power generation there are rated (calculated) speed, operating (cut-in) speed, and the maximum operating (cut-out) speed of WT [9]. At the rated wind speed, the WT operates at the rated power. As a rule, the rated wind speed does not exceed more than 2 times the average annual wind speed. The estimated wind speed V_R must satisfy the condition V_R≤(1,8…2)V_{AV} [9, 18]. Therefore, the wind speed corresponding to the rated power of the WT for the Bucha location is V_R≤ (6,05…6,72) m/s.

Thus, it can be concluded that a particular location is characterized by seasonal and daily variations in wind speed. Taking into account the average annual, seasonal, and daily wind speed characteristics is a priority when choosing the installation location and type of WT.

Sustainable generation of electricity by WTs begins at the operating (cut-in) wind speed, to justify which, the repeatability of a certain wind speed is determined by constructing a histogram of the distribution of wind speeds based on experimental (archival) data. The range of possible speeds is divided into *i* number of intervals (*i*=1, 2, 3 …), for each of which the probability p_i is calculated to get the speed into the appropriate interval:

(2) $$p_i = n_i / N,$$

where: n_i – the number of wind speed hits to *i* interval; N – total number of speed values in the sample.

Fig. 3 shows the histogram of wind speed distribution for Bucha with the grouping of wind speed intervals of 0.5 m/s (25 intervals). The wind speed range of 2.0...2.5 m/s is the longest in duration: it lasts 8250 hours with a probability of p_i=0,157. Therefore, it can be assumed that the cut-in wind speed for stable operation of the WT in the accepted location should be in the range of 2.0...2.5 m/s.

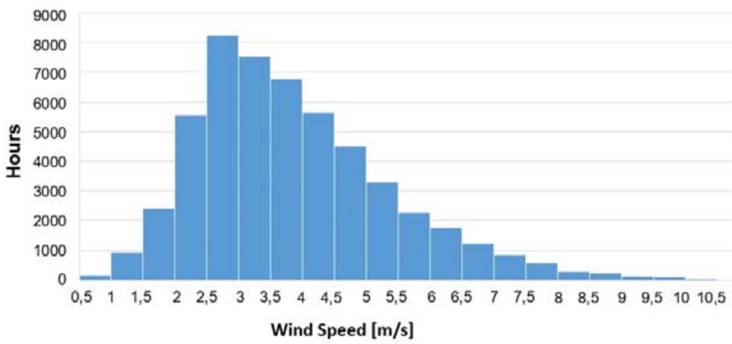

Fig.3. Histogram of wind speed distribution

In wind power generation, as justified above, statistical data on wind speed $V(t)$ are quite accurately approximated by a two-parameter standard Weibull cumulative distribution function (CDF) [6, 19, 20], which has the form:

(3) $$F(V) = 1 - \exp\left(-(V/c)^k\right),$$

and the Weibull probability density function (PDF):

(4) $$f(V) = \frac{dF(v)}{dV} = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} \cdot \exp\left(-(V/c)^k\right),$$

where c – a scale parameter proportional to the average wind speed; k – form parameter (usually it's located in the interval 1,5≤k≤2,5); $F(V)$ – the function of integral repeatability, which characterizes the part of the time (probability) when the wind speed is lower or equal to V.

The parameters of the Weibull distribution were determined by the mean standard deviation method [20] using the following expressions:

(5) $$k = \left(\frac{\sigma}{V_{AV}}\right)^{-1.086}, \quad c = \frac{V_{AV}}{\Gamma(1+\frac{1}{k})},$$

where σ – standard deviation of wind speed; $\Gamma(1+\frac{1}{k})$ – gamma function.

The repeatability (cyclicity) of wind speed is an important characteristic of the wind energy potential of a territory. Using the distribution function, it is possible to estimate the prospective productivity of WTs quite quickly (based on average wind speed values). WT prospective productivity is the average amount of energy that will be produced by a conditional WT of a given power over a certain interval of time [21]. It is also necessary to know data on the average performance of WT at different time intervals when calculating the parameters of combined (wind-solar) power systems using MATLAB modeling [22, 23].

Using expressions (5), we estimated the parameters k and c of the Weibull distribution density function for different time intervals (year, month), which are given in Table 2. The average wind speeds V_{AV} and their root mean square deviations σ are also added to Table. 2.

When calculating the average indicators of a WT productivity, we assume that a conventional vertical-axis WT with the following technical characteristics is used: rated power P_{WR}=1800 W, cut-in wind speed V_{MIN}=1,5 m/s, rated speed V_R=3 m/s, maximum wind speed V_{MAX}=12 m/s. It should be noted that WTs with such characteristics are already offered for sale by manufacturers [9].

The typical dependence of the WT power curve $P_W^* = f(V^*)$ is assumed. This dependence can be described by the following simplified expression [9, 23]

$$P_W^* = \begin{cases} 0, & if \quad V^* \le V_{MIN}/V_R, \\ \left(V^*\right)^3, & if \quad V_{MIN}/V_R < V^* < 1, \\ 1, & if \quad 1 \le V^* \le V_{MAX}/V_R, \\ 0, & if \quad V^* > V_{MAX}/V_R \end{cases}, \tag{6}$$

where $P_W^* = P_W / P_{WR}$, $V^* = V / V_R$; P_W, P_{WR} – the current and rated value of WT power, respectively; V – the current value of wind speed.

The average productivity P_{WAV} of WT was calculated using the density function of the Weibull distribution (4) according to the formula [11]

$$P_{WAV} = P_{WR} \int_{V_{MIN}}^{V_{MAX}} f(V) P_W^* dV, \tag{7}$$

where the value of wind speed varies from V_{MIN} to V_{MAX} with discreteness of 1m/s.

Table 2 compares the average P_{WAV} power with the P_{WAVF} power, which was calculated from the actual wind speed values for the observation periods (month, year) and converted to power using expression (6). A comparison of the values of P_{WAV} and P_{WAVF} showed a sufficiently high degree of coincidence, the calculation error δ_P does not exceed 8.9%. At the same time, the P_{WAV} power value is in most cases higher than the P_{WAVF} power value (sign "-" in the Table 2).

The average electricity generation of WT W_{WAV} for the time interval T (year, month) was determined by the expression

$$W_{WAV} = TP_{Wav} = TP_{WR} \int_{V_{MIN}}^{V_{MAX}} f(V) P_W^* dV. \tag{8}$$

In Table 2, the W_{WAV} values, in turn, were compared with the actual W_{WAVF}, generation, which was calculated by the numerical trapezoid method using the actual P_{WAVF} power values (the calculation error δ_W does not exceed 9%).

Conclusions

The possibility of developing small wind power generation in the suburbs of Kyiv to ensure the energy security of the region is substantiated based on the use of archival data on wind speed from open sources. Determination of the averaged wind characteristics for several locations in the Kyiv region allowed us to identify promising areas for the development of small wind energy generation, which includes the northwestern region of the Kyiv region. In particular, in the city of Bucha, which was selected for further research, the average annual wind speed for all years of observation exceeds 3 m/s, and the specific wind load exceeds 20 W/m^2.

Based on the histogram of the wind speed distribution for Bucha with a grouping of wind speed intervals of 0.5 m/s, it was found that the starting wind speed for stable operation of the WT in the given location should be in the range of 2.0...2.5 m/s and the wind speed corresponding to the rated power of the WT should be 6.05...6.72.

The wind speed data were approximated by a two-parameter standard Weibull distribution function. The parameters of the Weibull distribution were determined by the method of mean standard deviation for different time intervals (year, month). The performance of a conditional wind turbine with a given power characteristic was evaluated. The average productivity of the WT and the average value of the generated electricity was calculated using two methods: the Weibull distribution and the numerical method based on actual wind speed data. A comparison of the calculation results showed that the error does not exceed 9%. The results obtained can be useful: for determining the locations most promising for the development of small-scale energy; in calculating the parameters of combined (wind-solar) power systems during simulation modeling.

The direction of further research is to use the obtained results to prepare the initial data for modeling the operation modes of WT of arbitrary power.

Table 2. Results of calculation of WT productivity

Month	Jan.	Febr.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
V_{AV}, m/s	3.72	3.38	3.86	3.37	2.98	3.10	3.11	2.86	3.20	3.29	3.60	3.88	3.36
σ, m/s	1.53	1.4	1.66	1.51	1.38	1.3	1.44	1.34	1.37	1.66	1.67	1.65	1,53
k	2,63	2,61	2,50	2,39	2,30	2,58	2,32	2,27	2,51	2,10	2,31	2,52	2.34
c, m/s	4.19	3.80	4.35	3.80	3.36	3.5	3.51	3.23	3.61	3.72	4.06	4.37	3.82
P_{WAV}, W	1405.6	1400.9	1489.0	1360.7	1222.8	1315,4	1271.8	1174.6	1334.6	1283.1	1401.1	1495.8	1358,3
P_{WAVF}, W	1466,5	1377,3	1488,1	1323.3	1144,3	1237,6	1188,8	1078,3	1281,8	1226,3	1342	1474,7	1302
δ_P, %	4,3	-1,6	0,0	-2,8	-6,8	-6,3	-6,9	-8,9	-4,1	-4,6	-4,4	-1,4	-4,3
W_{WAV}, kWh	1012,0	941,4	1107,8	979,7	909,7	947,1	946,2	873,9	960,9	923,8	1042,4	1112,8	11898,7
W_{WAVF}, kWh	1091,1	961,6	1111,7	953,8	851,3	891,0	884,6	802,3	922,4	914,2	964,6	1097,1	11446,0
δ_W,	7,8	2,1	0,3	-2,7	-6,8	-6,3	-6.9	-8,9	-4,2	-1,0	-8,1	-1,4	-3.9

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Conflicts of Interest*: The authors declare no conflict of interest.*

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REFERENCES

[1] Hilorme T., Sokolova L., Portna O., Lysiak L., Boretskaya N., The model of evaluation of the renewable energy resources development under conditions of efficient energy consumption *IBIMA 2019: Education Excellence and Innovation Management through Vision 2020*, 2019, 7514 – 7526 doi: 10.5171/2019.923814

[2] Omelchenko V., Ukraine's renewable energy sector before, during and after the war. [Electronic resource]. Available at: https://razumkov.org.ua/en/articles/ukraines-renewable-energy-sector-before-during-and-after-the-war. 11.11.2022

[3] Skrypnyck A., Kozhan D., Using nodal specific transportation costs to determine economically beneficial distributed generation source location areas in radial electrical power distribution systems, *Przegląd Elektrotechniczny*, 97 (2021), No. 3, 101–105

[4] Alsamamra H. Shoqeir J., Assessment of Wind Power Potential at Eastern-Jerusalem, Palestine, *Open Journal of Energy Efficiency*, 9 (2020), 131-149. doi: 10.4236/ojee.2020.94009

[5] Hernandez E., Cordoba E., García G., Comparative Analysis of the Weibull Model and Observed Wind Data in the City of Floridablanca, Colombia, *TECCIENCIA*, 13(2019). Available at: https://revistas.ecci.edu.co/index.php/TECCIENCIA/article/view/468

[6] Saif Serag, Khalid Ibaaz Adil Echchelh, Statistical study of wind speed variations by Weibull parameters for Socotra Island, Yemen, *The International Conference on Innovation, Modern Applied Science & Environmental Studies (ICIES2020),* E3S Web Conf., 234 (2021) 00045. Available at: https://doi.org/10.1051/e3sconf/202123400045

[7] Ukrainian small windmills - autonomous saviors or suitcases without handles? [Electronic resource] - Available at: https://ua-energy.org/uk/posts/ukrainski-mali-vitriaky-avtonomni-riativnyky-chy-valizy-bez-ruchky. 31.08.2021

[8] Shavolkin O., Shvedchykova I., Gerlici J., Kravchenko K., Pribilinec F., Use of Hybrid Photovoltaic Systems with a Storage Battery for the Remote Objects of Railway Transport Infrastructure, *Energies*, 15 (2022), 4883. https://doi.org/10.3390/en15134883

[9] Shvedchykova I., Romanchenko J., Melkonova I., Melkonov H., Pisotskii A., Possibilities of Electricity Generation Using Small Wind Generators in Eastern Ukraine," *2022 IEEE 8th International Conference on Energy Smart Systems (ESS)*, Kyiv, Ukraine, 2022, 239-242, doi: 10.1109/ESS57819.2022.9969319

[10] Mikhaylenko O.Y., Shchokin V.P., Melnyk O.E., Kuzmenko A.S., Structural and parametric identification of the statistical model of wind speed distribution in the urban environment, *Scientific Notes of Vernadsky TNU. Series: Technical sciences,* Vol. 30 (69), Part 2 (2019), No. 2, 31-41 (in Ukranian)

[11] Smerdov A.A., Bulba E.M., Statistical characteristics of wind speed in the region of Poltava, *Bulletin of Poltava State Agrarian Academy*, 2011, No. 1, 153-157 (in Ukranian)

[12] Volkova O.O., Tretyakov O.S., Chervanov I.G., Modeling the wind potential of the local area of the Forest-Steppe for the needs of wind energy using GIS technologies, *Ukrainian Geographical Journal,* 2015, No. 4, 10-16. Available at: http://nbuv.gov.ua/UJRN/UGJ_2015_4_4 (in Ukranian)

[13] Osadchii V.I., Skrypnyk O.Y., Oshurok D.O., Skrypnyk O.A., Wind resources of Ternopil region, *GEOINFORMATIKA,* 2017, No. 4 (64), 50-61 (in Ukranian)

[14] Shevchenko O., Snizhko S., Big city wind regime. *Visnyk Kyivskogo nacionalnogo universytetu imeni Tarasa Shevchenka, Geografiya,* Bulletin of Taras Shevchenko National University of Kyiv, Geography, 3 (72), 2018, 13-20 (in Ukranian)

[15] Kostogryzova N.O., Dubrovskaya V.V., Shklyar V.I., Statistical analysis of the results of wind speed measurement, *Energy: economics, technology, ecology,* 2014, No. 2. Available at: https://ela.kpi.ua/bitstream/123456789/10127/1/10_Kostohrizova_NO_Statistical_analysis.pdf (in Ukranian)

[16] Photovoltaic geographical information system. Available at: https://re.jrc.ec.europa.eu/pvg_tools /en / tools.html#SA

[17] Arkhypova L.M., Mandryk O.M., Moskalchuk N.M., Prykhodko M.M., Radlovska K.O., Renewable energy resources in the system of sustainable development of Carpathian region of Ukraine, *Journal of Physics: Conference Series*, 1781 (2021). https://doi.org/10.1088/1742-6596/1781/1/012010

[18] Okopnyi L., Kolesnikov A., Justification of the use of wind power plants for enterprises of Ternopil region, *Socioeconomic problems and the state*, 2012, vol. 1 (6), 74-81. Available at: http://sepd.tntu.edu.ua/images/stories/pdf/2012/12olspto.pdf (in Ukranian)

[19] Suwarno S., Zambak M.F., The Probability Density Function for Wind Speed Using Modified Weibull Distribution, *International Journal of Energy Economics and Policy*, *11*(6), 2021, 544–550. https://econjournals.com/index.php/ijeep/article/view/11625.

[20] Teimourian H., Abubakar M., Yildiz M., Teimourian A., A Comparative Study on Wind Energy Assessment Distribution Models: A Case Study on Weibull Distribution, *Energies*, 2022, 15, 5684. https://doi.org/10.3390/en15155684

[21] Damian Głuchy, Grzegorz Trzmiel, Analysis of the impact of wind turbine power characteristics on the amount of generated energy, *Przegląd Elektrotechniczny*, 2022, Vol. 98, No. 11, 296–300

[22] Shavolkin O., Shvedchykova I., Kolcun M., Medved' D., Improvement of the Grid-Tied Solar-Wind System with a Storage Battery for the Self-Consumption of a Local Object, *Energies,* 15, 5114, 2022. https://doi.org/10.3390/en15145114

[23] Shavolkin O., Shvedchykova I., Kolcun M., Medved' D., Variant of Implementation of a Grid-Tied Solar-Wind System with a Storage Battery for Self-Consumption of Local Object, *2022 IEEE 8th International Conference on Energy Smart Systems (ESS)*, Kyiv, Ukraine, 2022, 184-189, doi: 10.1109/ESS57819.2022.9969234