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THE COMBINED METHOD OF LOCAL WIND POWER POTENTIONAL ESTIMATE WITH THE EMPHASIS ON ITS EFFICIENT UTILIZATION ON UKRAINIAN TERRITORY

Робота присвячена порівняльному і розрахунковому аналізу різних факторів, що визначають локальний вітровий енергопотенціал. Показано, що крім метеорологічної вітрової статистики одночасно необхідно розглядати сукупність територіальних, технічних, технологічних, економічних, екологічних та інших факторів. Отримано кілька аналітичних співвідношень, що дозволяють розрахувати річну вітрову енерговіддачу та інші енергетичні характеристики. Сформульовано практичні рекомендації стосовно підвищення ефективності використання вітрової енергії в Україні.

Ключові слова: вітроенергетичний потенціал, територіальні особливості, аналітичне подання, комбінований підхід, параметричний аналіз, вітряна енерговіддача, підвищення ефективності.

Работа посвящена сравнительному и расчетному анализу различных факторов, которые определяют локальный ветровой энергопотенциал. Отмечается, что кроме метеорологической ветровой статистики необходимо одновременно рассматривать совокупность территориальных, технических, технологических, экономических, экологических и других факторов. Получен ряд аналитических соотношений, которые позволяют рассчитывать годовую ветровую энергоотдачу и другие характеристики ветра. Сформулированы практические рекомендации, касающиеся повышения эффективности использования ветровой энергии в Украине.

Ключевые слова: ветроэнергетический потенциал, территориальные особенности, аналитическое представление, комбинированный подход, параметрический анализ, ветровая энергоотдача, повышение эффективности.

This work is devoted to comparative and calculational analysis of different factors which determine local wind power potential. It is shown that apart from the meteorological wind statistics it is necessary to consider simultaneously the combination of territorial, technical, technological, economic, ecological and other factors. Several analytical expressions allowing of calculate the annual wind energy output and other wind characteristics are presented. The practical recommendations, related to more efficient use of wind energy in Ukraine is given.

Key words: Wind potential, territorial aspects, analytical representation, combined approach, parametric analysis, wind energy output, increasing of efficiency.

Symbol index: V – wind velocity; V_N – nominal velocity; V_∞ – free stream velocity; V_0 – velocity far ahead of rotor; p – pressure; p_∞ – pressure in free stream; $\bar{p} =(p-p_\infty)/q_\infty$ – pressure coefficient; q – dynamic pressure, q=0.5ρV^2; t – time; T – annual time = 8760 hours; R – radius, radial distance; S – area; S_1 – rotor swept area; P – power; P_N – nominal power; P_1 – power transmitted to the rotor; P_0 – wind power in a free stream; P – power density; C_p – power coefficient; L – length, distance; H – height; ω – angular velocity; λ – tip speed ratio, $\lambda=\omega R/V_0$; E – energy; $\bar{E}$ – energy per unite swept area; $f(V)$ – wind speed frequency distribution.

Subsripts and abbreviations: ∞ – free stream parameters; 0 – parameters far upstream of the rotor; 1 – parameters in the plane of rotation; c – average quantities; m – maximum values; WT – wind turbine; HAWT – horizontal axis wind turbine; VAWT – vertical axis wind turbine; WPD – wind

power density; MAWS – mean annual wind speed; WEA – wind energy association; WTS – wind turbine site.

Introductory remarks. A knowledge of local characteristics of the wind with respect to its commercial utilization is indispensible for successfully planning of any wind energy project. Detailed information about local wind resources is relevant to the following topics:

– Selection of a particular site which is suitable for deploying wind turbines;

– Decision of how many and what types of WT can be installed at the particular site area;

– Performance evaluation of the energy output and cost effectiveness of the wind energy system;

– Operational requirements related to the use of produced energy;

– Planning and realization of the full system design.

Obtaining the reliable wind data is considered as the first and most important step in any planning for the use of WT. The importance of further studies of local wind resources can be illustrated by the fact, that these problems is widely discussed in scientific publications devoted to the subject. First of all, should be mentioned Wind Atlases and Wind Resource Maps (for example [2; 4 – 8]) which indicates the geographical distribution of the main wind characteristics around the globe, as well as in different countries and regions. Wind Power Atlas, containing the detailed statistical data has been recently prepared for Ukrainian territory [3]. The analysis of wind characteristics and the ways of wind energy extraction is discussed in many works [14 – 18; 32; 34; 35]. Several publications are devoted to the estimate of wind power potential at the Ukrainian territory [9 – 13]. The analysis of wind power potential on the offshore and urban territories is presented in [16; 34; 35; 37; 39 – 42]. In some of the above mentioned works the analytical modeling of wind characteristics is presented and widely discussed.

The necessity of further study of regional wind power potential is determined by the rapid development of wind energy production industry during the last few decades. It is known that since the mid of eighties and up to now the total wind machine capacity in the world has been increased from the value of about 1000 MW to 230 GW. Nowadays, the share of energy which is produced by wind turbines in the world is about 1.5%. But in some countries such share is much greater. The World Wind Energy Association (WWEA) named the list of countries which have the greatest installed WT capacity (more than several gigawatts). This list includes: Chaina, U.S.A., Germany, Spain, India, Italy, France, Great Britain, Canada and Portugal. The group of countries within the Europian WEA and other organizations developed the ambitions program «Wind force 10» aimed at reaching 10% share of total wind energy production in 2020, and 20% share in 2040. Freshly presented data show that this program goes on ahead of schedule.

Ukraine started to develop its own wind energy utilization industry couple decades ago but it is still far behind of the leaders in this field. Nowadays our country has 12 grid-connected wind turbine power plants with total installed capacity about 750 MW. These plants are equipped with WT having the nominal power within the range from 100 kW to 2.5 MW. Until 2011 the most of WT have been manufactured at the industrial enterprise «Yuzhnoye» (Dnipropetrovsk) on a purchased license principle. Reasently WT with power capacity of 2.5 MW started to manufacture in Kramatorsk. Most of the existing WT are installed along the shores of Azov and Black seas, in Crimean peninsula, as well as in Mikolayev, Odessa, Zaporizhzhia, Donets'k, Lugans'k, Cherson provinces and in Karpatian region. According to the «Program of Energy Production Development»,

which was adopted by Ukrainian Cabinet of Ministers, this country is supposed to produce at the wind power plants annually 0.6 TWh of energy in 2015, 1.9 TWh – in 2020, 3.8 TWh – in 2025 and 7.4 TWh – in 2030. Apart from grid-connected wind machines in Ukraine there exist large number of stand-alone WT. They are usually aimed at providing energy for smaller units and private consumers.

Total and local wind power potential. It is known that Earth atmosphere captures annually 1.5×10^{12} kWh of radiated solar energy. Approximately about 2% of it is converted info the energy of atmospheric circulations. The calculated wind power is one hundred times more then annual output of all power stations installed on this globe. The total wind power potential can be subdivided info several parts. First of them is called «Gross potential» – N_g. It is part of wind energy which is available and can be used annually on the territory of a proper region (continent, country etc). The second part is called «Technical potential» – N_T. It is measured by the total volume of electrical or other type of energy output which can be obtained with the use of contemporary technical means: wind turbines with the proper characteristics and size of the area of a given region which is suitable for deploying of such turbines. It can be presented in the form

$$N_T = N_G \cdot C_p \cdot \left(A_1 / A_2\right) \cdot \eta_1 \cdot \eta_2 . \tag{1}$$

Here $C_p=P_1/P_0$ is power coefficient of WT, P_0 is dynamic power of the wind, P_1 is wind power transmitted to the WT rotor, η_1 and η_2 are the drive-traine and electric generator efficiencies be respective. A_2 is the total area of a given region and A_1 is the area on which WT can be installed. Statistical estimate of these areas relation is $A_1/A_2\approx0.1 - 0.3$. The third component is economical potential N_E, which is the part of N_T and it is considered as commercially acceptable. $N_E\approx0.5\%$ of N_T. The annual value of N_T on Ukrainian territory is estimated as 30 GWh.

The presented here figures characterizing wind power potential (WPP) are very approximate. In order to get its more correct estimate it is necessary to consider many factors which determine its value. The comparative and calculation analyses of various factors impact on the estimate of local wind power potential is the main task of a presented paper.

The factors determining the local WPP. The main factor is the meteorological complex, which includes measured and modeled wind characteristics. Mean annual wind speed (MAWS) belongs to the basic measured wind parameters. The probability density of wind velocity distribution and its analytical representation, wind power density, annual energy output and some others could be considered as modelled wind characteristics.

Territorial factor determines geographical position of a given region and spatial distribution of its areas with high and moderate WPP, which are suitable for WT installation. The local terrain characteristics also belongs to territorial aspects. Technical, technological, economic, ecological and specific site-related factors should be also included in the combined analysis of a given problem. We start with the more detailed analysis of meteorological data which is the main source of information, determining the local WPP. It is known that people started to observe such atmospheric phenomena and characteristics as wind velocity, air temperature, pressure, density, humidity, persipition etc many years ago.

Such characteristics were measured and evaluated at the thousands of meteorological stations which are positioned in many geographical locations around the globe. It is known that it takes at least 25 – 30 years of data collection in order to estimate long-term values of weather or climate features. It is also necessary to note that up to the mid of XX century wind data were measured and evaluated almost exclusively from meteorological point of view, i.e. they were devoted to analysis of climate patterns and preparing the

weather forecast. These data are very important but, at the same time, they can not always be used as sufficient when one is considering the commercial exploitation of wind resources. The specialist in the field are confident that some meteorological data which have been accumulated for a long period of time should be corrected or supplemented with newly obtained information, [20].

Such actions is needed because in the past some meteorological stations used unreliable measuring equipment; wind characteristics at the altitude of 50 m and higher have not been always observed; the influence of surface irregularities like local relief, and obstacles were not always taken into account; the frequency of daily observations were different from one station to another and it could make difficult to obtain correct averaged in time wind parameters. That is why the further study of local wind energy resources is very important.

Now it is necessary to discuss the basic wind characteristics with the emphasis on more efficient wind energy utilization in Ukraine. We start with such parameter as wind velocity. It is necessary to know its value and direction, its temporal and spatial variability. The obtained results can be presented with the use of wind maps, tables, histograms, wind-roses and other means. Meteorological statistics include measured and modelled characteristics. The mean annual wind speed (MAWS), wind speed frequency distribution and its analytical representation, wind power density and some others are considered as modeled characteristics. Average wind speed for a proper period of time can be obtained with the use of relation

$$V_C = \frac{1}{n}\sum_{i=1}^{n} V_i \,. \tag{2}$$

Here n is the number of measurements. In order to get reliable result it is necessary to follow standard and generally accepted procedure of measuring. It can be shown that for successful extraction of wind energy it is necessary to have wind velocity $V_C \geq 4$ m/s on the height H=10 m over the ground. As far as rotor hub of contemporary WT is usually positioned at the heights H=40÷80 m the calculated wind velocity in this case will be greater than 4 m/s.

Wind frequency distribution function $f(V)$ is important local wind characteristics. As far as wind velocity is continuous random value, the function $f(V)$ more correctly is called probability density function. Probability of wind speed can be viewed in two ways. First of them is called cumulative probability $F(V)$ and the second one – probability density function $f(V)$. Mathematically, they are related by

$$\frac{dF(V)}{dV} = f(V). \tag{3}$$

The normalization of $f(V)$ is given by

$$\int_0^{\infty} f(V)dV = 1 \,. \tag{4}$$

The mean value of V (mathematical expectation value) will be

$$M(V) = V_c = \int_0^{\infty} Vf(V)dV \,. \tag{5}$$

Functions $F(V)$ and $f(V)$ are modelled on the basis of obtained experimental data. For this purpose several analytical expressions have been suggested. The most frequently used is Weibull two-parametric representation

$$F(V) = \exp\left[-\left(\frac{V}{A}\right)^k\right], \tag{6}$$

$$f(V) = \frac{k}{A}\left(\frac{V}{A}\right)^{k-1} \cdot \exp\left[-\left(\frac{V}{A}\right)^k\right]. \tag{7}$$

Here k is form-parameter and A is the scaling factor. In order to represent local frequency distribution it is necessary to determine k and A with the use of measured meteorological data. Unfortunately, such procedure in the most cases is quite cumbersome. There exist some semiempirical approaches to determine k and A. It can be shown that for the case of k variation within the interval from 1.5 to 3.0 the value of A is proportional to V_c :

$$A \approx 1.12 V_c . \tag{8}$$

The Raleigh representation of $f(V)$ is obtained for the case, when k=2

$$f(V) = \frac{\pi}{2}\left(\frac{V}{V_c^2}\right)\exp\left[-\frac{\pi}{4}\left(\frac{V}{V_c}\right)^2\right]. \tag{9}$$

The analysis of a measured wind frequency distribution demonstrates reasonable good ability of Weibull and Raleigh functions to fit the actual data. At the same time, neither function is able to follow variation of V in the vicinity of calm (when V=0). The experience show, that duration of calm is never equals to zero. In this case it is necessary to find such kind of $f(V)$ representation which will be more close to reality in all range of velocity variation. The more convenient for this purpose to use graphical representation of experimental data.

Very important for this purpose can be systematic experimental data presented in [17], which was published in 1894. Author of this work analysed data for a five-year period (1887 – 1891), which have been collected at 19 meteostation on the territories of Russia, Germany and Austria. These data are presented in Fig.1.

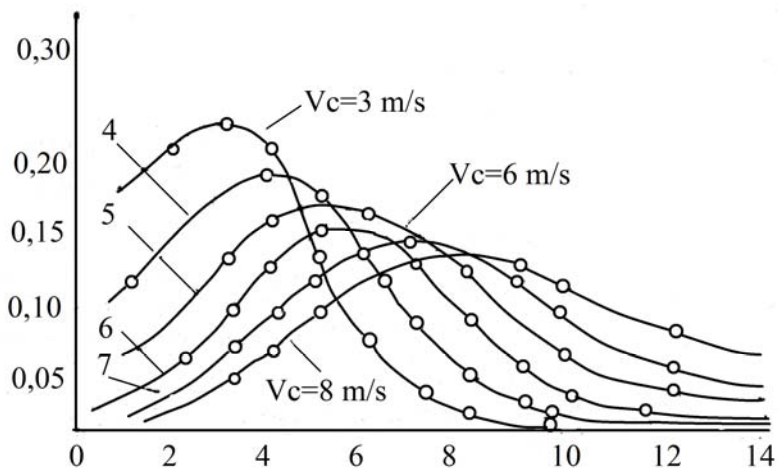

Fig. 1. Graphical representation of WSFD

It should be observed that maximum value of function $f(V)$ in Fig.1 always corresponds to the main annual wind speed V_c. In other words, the analytical representation of $f(V)$ is determined only by one parameter,–V_c. With the use of this important fact we suggest the following expression for $f(V)$

$$f(V) = f_m \exp[-g(V - V_c)^2]. \tag{10}$$

Here f_m is a maximum value of $f(V)$ for a given V_c. For the left-hand part (index «L») and right-hand part of the curve in Fig.1 (index «R»), we will have

$$g = g_L = \frac{\ln(f_1 / f_m)}{(V_1 - V_c)^2}, \tag{11}$$

$$g = g_R = \frac{\ln(f_2 / f_m)}{(V_2 - V_c)^2}. \tag{12}$$

Here V_1=2 m/s; V_2=1.5V_c; f_1 and f_2 are the values of $f(V)$, which correspond to V_1 and V_2 respectively.

Couple words is necessary to add in order to explain physical interpretation of WSFD. It is necessary to note that there exist several different ways of its presentation; one of them – with the use of continuous analytical expression and the second one – by drawing the histogram with the use the co-called «method of bins».

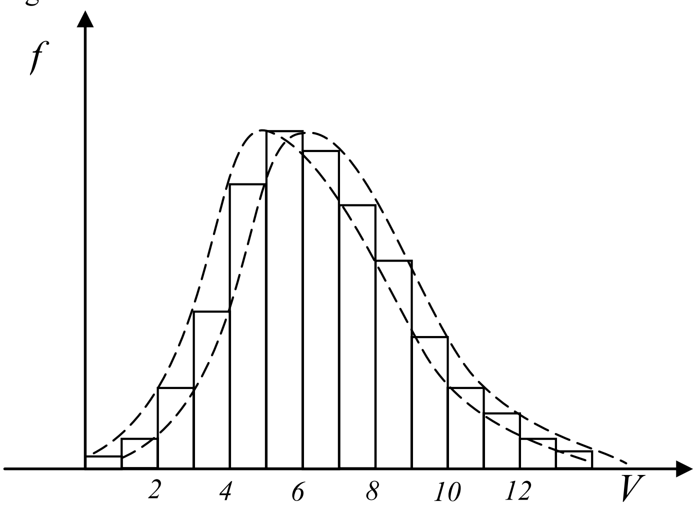

Fig. 2. Presentation of WSFD by the histogram

Bin is actually the subinterval $\Delta V_i = V_i - V_{i-1}$. The width of the bin is usually equals 1 m/s. The length of the bin $f(V_i)$ is the relative number of hours $\bar{t}_i = t_i / T$ per one year (T=8760 hours), when V_i lies within the interval ΔV_i. In the case of continuous presentation of WSFD $\bar{t}_i$ corresponds to a fixed value of V_i.

Now we will discuss some other modelled meteorological parameters. It is known that power of the wind (P_0), passing through an area (S) perpendicular to wind velocity direction, is given by

$$P_0 = 0.5 \rho V^3 S, \tag{13}$$

where ρ is the air density. The most important parameter, which characterises the local wind potential, is called «Wind power density» – WPD. It is the mean annual wind power per unite area of a free stream tube.

$$\overline{P}_c = 0.5\rho\int_0^\infty V^3 f(V)dV . \qquad (14)$$

It can be shown that mathematically expected value of a cubed wind speed is

$$V_c^3 = \int_0^\infty V^3 f(V)dV . \qquad (15)$$

In this case we will have

$$\overline{P}_c = 0.5\rho V_c^3 . \qquad (16)$$

This parameter strongly depends on the height over the ground due to the speed variation in the shear flow. Such dependence can be illustrated by the data of Table 1.

Table 1

WPD on a different altitudes *H*

V_c (*m/s*)	*H* (*m*)	$N\overline{P}_c$, (W/m^2)	$T\overline{P}_c$, (W/m^2)
4.5	15	2010	390
	60	3640	700
5.0	15	2810	520
	60	5100	860
5.5	15	3200	620
	60	5810	1020

In this table $N\overline{P}_c$ is the nominal *WPD* in a free stream and $T\overline{P}_c$ is technical *WPD*. $T\overline{P}_c$ is usually estimated as `~20% of $N\overline{P}_c$ and depends on the wind power utilization technique.

The presented in Table 1 data allows to estimate the rated power and size of rotor swept area before installing WT at a given site.

Territorial aspect is the next important factor which is necessary to discuss in detail. It is known that the territory of Ukraine is 603.5 sq km. According to local Wind Power Atlases and Wind Maps about one-fifth of this territory is suitable for wind power utilization. Unfortunately, large-scale Wind Maps alone can’t provide correct local wind characteristics. They usually represent the wind speed over the flat homogeneous terrain and requires adjustment to local conditions. Some territories, which have satisfactory wind conditions can’t be used, because on them the wind energy production is not economically viable or they have unsuitable terrain. From this point of view presented on Wind Maps territories having high wind potential should be reduced. At the same time Ukraine has reserve territories which still are not used for wind energy production. First of all, it is so-called «offshore territories». Ukraine is the second after Norvey having vast territories with shallow waters. Development of the offshore wind power plants in based on the advantages of such territories. Here they are:

– higher wind speeds which generally increase with distance from the shore;

– availability of large continuous areas suitable for major wind plants;

– less turbulent air flow due to smooth water surface and small roughness length (z_0 = 0.003–0.005 m) which allows to harvest wind energy more efficiently.

Starting from the beginning of nineties the offshore wind energy production develops very rapidly in such countries as Denmark, Great Britain, Germany, Sweden, Norway, Belgium, China and others. At present time there exist a large number of the offshore wind parks. Top twenty of them have at each wind park total wind power capacity up to several hundreds megawatts. At a given moment Ukraine still does not have any wind park and from this point of view it has the real opportunity to increase significantly wind energy production on its territory. It is necessary to name the main Ukrainian offshore areas and water basins, which can be used for this purpose. First of all, it is necessary to include to this category Syvash lake which is adjacent to Crimean peninsula. It is one of the unique geographical phenomena with the very salt and swallow waters. Its area is 2560 sq km and average velocity over its territory is more than 6 m/s. Up to now this area still is not involved in economic activity. The other available shallow sea bed strip lies along coastal line of Azov and Black seas. Here is necessary to name also the artificial water reservoirs adjacent to hydropower stations on Dnipro river. The greatest of them are Kremenchug basin (2252 sq km) and Kachovka basin (2155 sq km). There are more than 40 smaller shallow reservoirs on Ukrainian territory. For the development of Ukrainian offshore wind power plants can be also employed large estuarities on Dnipro and Dnister rivers. The typical wind park is shown in Fig. 3.

Fig. 3. One of the wind parks on the Baltic sea

Having in mind, that at the suitable territories the density at WT installation is approximately 10 mW/sq km, it is easy to estimate additional wind power resources, which can be used in future. Apart from advantages of the offshore wind energy production there exist several problems, which is necessary to solve. First of all, such wind energy projects are more expensive. Technological procedure is more complicated, especially on the stage of installation and maintenance. It is necessary of mention some other difficulties in the development: the threat of stormy winds and high wave – braking loads, more intensive corrosion of WT structural parts and so on. But the successful practical use of the offshore territories in many countries, as well as development of special national pro-

grams show that such branch of wind turbine industry have a bright future. The principles of wind energy extraction on the offshore territories of Ukraine is discussed in [39].

Fig. 4. Wind turbines WS-12 are installed on the roof of shopping center in Raisio, Finland

Another kind of wind recourses can be converted into energy by deploying wind turbines at the urban territory, i.e. in built environments. There are three variants in the selection of suitable wind turbine site. WT can be installed on the roof or the building of structure, alongside the building and in ducts through adjacent buildings. We further will discuss the first variant because it has the proper advantages. The idea of mounting WT on the roof was born a long time ago. It was based on the principle of using so called «hill-top» effect. But the complicated technical and technological problems did not permit to solve this problem in the past. Only several years ago such wind energy project was implemented into reality. Several countries (France, Italy, Finland and others) successfully deploy WT on the urban territory. In Fig. 4 is shown couple of Savonius rotors which are mounted on the roof of commercial building.

The main purpose of such projects is bringing the local source of energy closer to prime consumer. Such low-cost energy could be used independently from general electric grid. At the same time it can be also fed into grid, reducing the external energy demand. It is known, that average mind speed over the urban territory in lower then in rural areas. But in the proper point at the roof of the structure wind velocity can be greater then its global value over the urban territory. It was shown in the works in which experimental and calculation data are presented, [22]. The pressure coefficient $\overline{p} = 0.5(p - p_\infty)/\rho V_\infty^2$ on the flat roof of the building is usually negative. In this case local velocity V will be greater than ifs global value V_∞. It can be shown with the use of Bernoully equation:

$$V = V_\infty \sqrt{(1 - \overline{p})}\,. \tag{17}$$

Analysis of wind statistical data shows that in the most cities of Ukraine mean annual wind speed is greater then 4.0 m/s. For example in Kerch $V_c = 4.48$ m/s; in Odessa $V_c = 4.51$ m/s; in Donetsk $V_c = 4.66$ m/s and so on. With the use of (17) we can see,

that many Ukrainian cities have moderate but reliable wind potential. The study of prevailing wind direction presents the opportunity to install on the roof special devices – concentrators. They allow to direct and increase wind velocity ahead of WT and improve its energy output. It is clear, that on the urban territory can't be used high-powered and large wind turbines. The experience shows that size of WT should not be greater than 1/10 of the building height. The parametric analysis of different WT which are suitable for urban environment is given in [37]. It is shown that small-powered WT with vertical axis of rotation is more suitable for this purpose. They don't need to be pointed into the wind, more adapted to work in turbulent flow and do not suffer from the frequent wind direction changes. Savonius rotor, Darrieus H-rotor and its modifications, rotor with helicoidal blades could be recommended for this purpose. By the way, the wide variety of such small-powered wind turbines which are presented at the world market is given in [33; 36].

In development the urban-oriented, wind-power projects it is necessary to overcome the proper difficulties. Such difficulties arise due to existence of several problems: low average wind speed, vibration of WT which can be transmitted to the building where it is mounted; interference with electronic equipment etc. In order to prevent strong vibration several technical means are suggested, for example,-the use of elastic platform and so on. It is already worked out different measures aimed at reduction not negative impact of WT on the building and it's residents. Specialists in the field are confident that with the use of contemporary technical means wind energy production on the urban territory will soon become the commercial reality.

The technical and technological aspect of WPP estimate is based on the analysis of different WT peculiarities, their maintenance and operational characteristics. It is known that the most of wind power plants are deployed at the open onland terrain, where average velocities is over 4.5 m/s. They are usually equipped with high-powered HAWT. The nominal power of such turbines is gradually increasing. It leads to increasing of rotor swept area. At the same the rotor blade length over 90 m is not recommended due to serious technological problems and high structural stresses. From this point of view the VAWT can be considered as more acceptable in the future. On the territories with low and moderate average wind speeds ($V_c \leq 4$m/s) could be used stand-alone and low-capacity WT. Sometimes the combined projects, like WT + diesel generator or WT + solar panel are preferable. The analysis of contemporary WT, which are presented on the market, shows for example, that multibladed small-powered WT with the starting velocity V_s=2 m/s and unlimited cut-out velocity V_k could have noted advantages. Most of the offshore wind-power plants is now equipped with HAWT having megawatt capacity. At the same time, the calculation analysis of the offshore Syvash lake area, presented in, shows that VAWT in this case could have proper advantages over HAWT [39].

It is already admitted earlier that small-powered VAWT can be more preferable when they are used on the urban territories and mounted on the top of the buildings.

The economic aspects of wind power potential estimate is extremely important. A great member of studies have been performed to develop the standard method of such estimate. Unfortunately the acceptable method still is not completely worked out, but it is commonly agreed that the general purpose of it is not only to determine economic performance of a given design, but also to compare it with conventional and renewable energy systems. The main economic indicator of the wind energy project is its cost, which can be broken into several parts: costs of research and development studies, costs of design, fabrication, tests, shipment, installation, exploitation, repairs, insurance etc. First of

all, it is necessary to note that the use of relative (or specific) cost of different items is more convenient for the practical use. For this purpose the proper reference parameter (RP) is used. It can be for example, nominal power, swept area, mass etc.

Fabrication (production) costs sometimes is called «ex-fabric costs». It is usually considered with respect to separate structural elements: 1) rotor (including blades, hub, pitch and yaw control mechanisms etc); 2) mechanical drive-traine (gar-box, rotor shaft, nacelle etc); 3) electric system (electric generator, invertor-, if needed, - control system, cabling etc); 4) tower (plus foundation). The total specific costs of WT fabrication (ex- factory cost) lies approximately with the range of 600 – 1000 US dollars per kilowatt. It was decreasing since the early nineties, but couple years ago started slightly to increase [28].

The table 2 borrowed from [34] could serve as an example of separate subsystems and components costs of WT.

Table 2

Fabrication costs of WT parts

Type of WT	Subsystem	Mass(kg)	Costs in US dollars	Proportion	Specific costs
HAWT P_N=750 kW D=48 m hub height-55m	Rotor	12800	110800	34.5%	13 $/kg
	Drive train	17700	202850	37.06%	6 $/kg
	Electric System	4450	37500	12.41%	30 $/kw
	Tower	38000	49400	16.48%	1.3 $/kg
	total		300550	100%	
HAWT P_N=1500 kW D=70 m hub height-80m	Rotor	34100	284300	21.03%	8 $/kg
	Drive train	46200	289500	39.92%	6 $/kg
	Electric System	8500	172500	18.33%	50 $/kw
	Tower	150000	195000	20.73%	1.3 $/kg
	total		941300	100%	

In order to obtain the sales price it is necessary to add the total fabrication costs and surcharge for overhead (~ 45%). The to total fabrication costs of HAWT and VAWT do not sufficiently differ, but costs of structural parts are different.

Research and development costs are usually apportioned to sales prices and they are not more then 10% of its. Sales prices of electrics lies in the vicinity of $ 0.1/kw and depend on the repairment period (10÷20 years). Costs of the offshore wind power project is ~ 50% greater than on land variant. But the price of electricity is approximately the same.

During the last couple decades the costs of wind-power projects were gradually decreasing. But the use of economy of scale and «assembly line principle» (like in automobile industry) still is questionable. On the macroeconomic level it is necessary to take into account so-called «avoided payments» for the reduction of fossile fuel consumption. For the external energy dependent Ukraine it is very important economic factor. The use of renewable energy sources prevents the environmental pollution and global warming. Moreover, it is transmitted into people health benefits. It is necessary to assign a financial value to such benefits. That is why national governments is many countries are deploying the special intensive for the realization of wind-energy projects: guarantied prices for sales of electricity (green tariffs), tax credits and other measures. Similar legislative acts

have been adopted in Ukraine. The green tariff in Ukraine, adopted in 2008, is 1.23 UA grivnas per Kilowatt-hour. It is greater than the payments for electricity generated at the conventional power stations.

Environmental impact factor should be taken into account from different points of view. On one hand, the utilization of wind energy unreversably deserves the attribute «environmentally friendly». On the other hand, it can't be considered without estimate of its impacton the environment. To the negative influence factors should be included such phenomena as: noise emission, interference with electronic equipment, possible threat caused by flying off damaged rotor blades, shadow effects and visual impact on the landscape. It is necessary to note that in contrast to the large conventional power plants, the environmental impact of WT affects only their immediate surrounding.

The most important acoustic parameter describing the overall noise intensity at the location of perception (immission point) is indicated as amplitude-weighed level. It is designated by the symbol dB (A). The permissible sound pressure level (denoted by L_A) is usually prescribed by national legislations and lies within the interval 40 – 65 dB (A). Noise source (for example, WT) is characterized by sound power level (L_W). There exists the empirical relation between L_A and L_W.

$$L_W = L_A + 10\lg(4\pi R_i^2)dB(A) + 6dB(A) \tag{18}$$

Here L_A is measured sound pressure at the immition point, R_i is the distance from this point to the center of the rotor (m). The nature of sound is represented by a frequency of three octave spectrum (16 – 2000 Hz). Infrasound frequency is less than 16 Hz, and ultrasonic frequency is greater than 2000 Hz. Between these limits lies the audible noise. Infrasound emission is the most typical phenomenon for the contemporary WT. The most harmful for humans is considered the frequency ~7 Hz. The sound emission is determined by the rotating blades and by the drive-train. Rotor generates "hissing" and "whooshing" noises and they are difficult to avoid. Drive-train noise could be reduced with a proper structural design measures.

The typical sound power level for contemporary WT is ~95 – 100 Hz(A) of nominal WT power P_N ~500 Kw, and ~105-108 Hz(A) for P_N ≥2000 Kw.

On the distance of more than 300 m from the WT the sound pressure P_A emitted by such sources is usually reduced to permissible level [23; 24; 25].

The interference of WT with such equipment, as computer, radio, television and others have been examined in detail since the high-powered wind machines have been installed near the residential area. It was found that the use of special filters during the connection of the appliances to external electric grid, gradual transfer to digital TV's and obtaining the TV signals from satellite almost completely solve such problems. The impact of WT on animals life (birds, fish and others) should be taken into account but sometimes this problem is overestimated by environmentalists. It is found, for example, that the death-rate of the birds due to collision with rotor blades is not more frequent than in collisions with airplanes or due to the contacts with high-voltage transmission lines. The experience shows that «local» birds quickly learn to identify the moving obstacle and fly around it. Special attention should be paid to such Ukrainian territory as Syvash lake because birds are migrating and nestling at this area. It is shown in [39] that use of slowly rotating megawatt-powered VAWT on this offshore site is preferable from this viewpoint. The serious threat to fish from offshore WT is not registered.

The vibration problem was analyzed when urban wind power projects were considered.

The visual impact on the landscape in principle is not avoidable especially in the densely populated area. In any case this problem should be solved in concordance with local community.

The shadow impact sometimes is also included into negative environmental phenomena. But this impact is miserable because the shadow occurs only in the immediate vicinity of WT. At the same time, the reflection of sun rays from the rotating blades could be seen far away from WT. Such reflection sometimes produce flickering stroboscopic effect when it falls into an observer. Due to the short time of this action it can be considered as an acceptable phenomenon. The site-related issues should include the combination of all above mentioned factors. Their analysis provides the opportunity to select appropriate WT site. The information about all available sites enables the designers, investors and producers to estimate correctly the local and total wind power potential in Ukraine. Meteorological data about wind characteristics at the selected site should be known at least for a period of 20 – 30 previous years. Sometimes it is necessary to spend additional 2 – 3 years in order to collect more detailed information. It is necessary to determine: mean annual wind speed and it's seasonal variation, wind-speed frequency distribution $f(V)$ and it's analytical representation, wind-power density $\overline{P}_c$, prevailing wing direction, etc. Sometimes it is necessary to know the relative time share of stormy wind speeds (V>25 m/s) and calms (V<2 m/s), air density, temperature, the character of precipitation and other data.

Territorial factor is directly related to geographical position of WT site. It can be onland, offshore zones, or urban territory. It is necessary to know the size of such territories, which are suitable for WT installation, as well as such site peculiarities as relief, local terrain characteristics, obstacles on surrounding territory and so on.

Technical and technological aspects of site-related factors is determined by the type of selected for exploitation WT`s, the character of they fabrication, installation, maintenance and operations. Local infrastructure (grid – connection procedure, building the access roads etc) should be included into technical aspects. Economic and ecological factors have been already discussed in detail. It is necessary only to add that in some cases the given site can't be used due to unsuitable economic or ecological conditions in spite of the favorable meteorological situation.

At last, we should are ready to name the main combined parameter, which more distinctly determine wind power potential at a given site. It is maximized annual wind energy output per swept area of a given WT.

$$\overline{E}\left(\text{kwh/m}^2\right)=\frac{\rho T}{2000}\int_{V_s}^{V_N} V^3 C_p(V) f(V)dV+\frac{P_N T}{S}\int_{V_N}^{V_k} f(V)dV . \qquad (19)$$

Here ρ (kg/m^3) is the air density, T=8760 hours is the year time, $C_p(V)$ is power coefficient of WT, $f(V)$ is wind speed frequency distribution, P_N – nominal power of WT, V_s, V_N, V_k, are starting, nominal and cut-out wind velocities respectively. The calculation of $\overline{E}$ could be considered as optimization procedure. It consist of two stages [32]. First stage is devoted to optimization of WT rotor and aimed at the selection of a maximum value of power coefficient $C_p(V)$. On the second stage the maximum value of $\overline{E}$ for a WT with given P_N (which is installed at the selected site), should be found at the proper value of V_N, which in this case is variation parameter. As an example, maximum of $\overline{E}$ is

found for VAWT with P_N=1000 kW which is supposedly installed on the offshore territory of Syvash lake (where V_c=6 m/s).

The results of calculations is presented in Fig. 5.

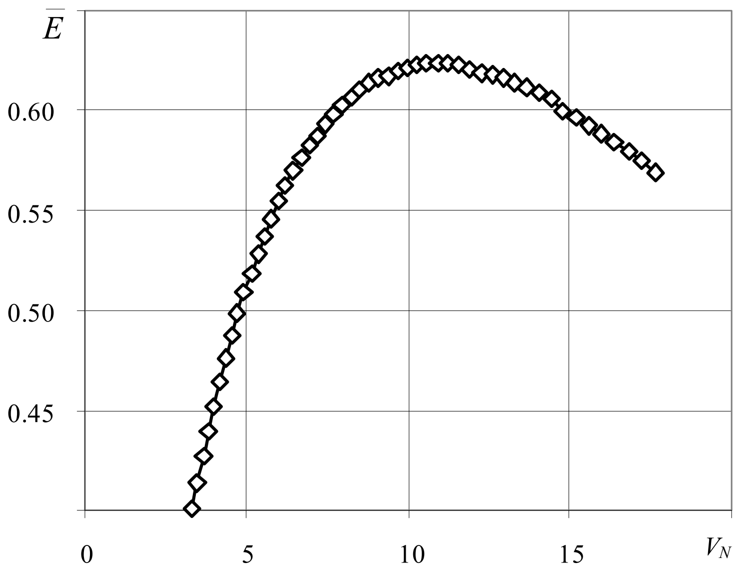

Fig. 5. Annual wind energy output (KWh/m²) of WT with P_N=1000 KW as a function of nominal wind velocity V_N(m)

It can be seen that maximum value of $\overline{E}$ is obtained, when V_N=11 m/s.

Conclusions. The main results of the performed analysis can be formulated as follows:

– it is shown that only combination of meteorological, territorial, technical, technological, economic and ecological factors can provide correct estimate of local wind-power potential, especially when it is oriented on a particular wind turbine site conditions;

– during the selection of the suitable site it is necessary to take into account the corresponding legislative acts of national government and consent of local community authorities;

– on the basis of combined approach it was shown that Ukrainian wind-power potential can be sufficiently increased when offshore zones of swallow waters and urban areas will be considered as reserve territories for WT installation;

– the annual wind energy output $\overline{E}$ per the swept area, of WT is recommended as a main combined parameter, which determines the local wind-power potential. This parameter includes principal characteristics of WT and local wind conditions. As an example, with the use of combined parameter the maximized value of $\overline{E}$ was obtained for the case, when VAWT with nominal power P_N=1MW is supposedly installed on the offshore territory of Syvash lake.

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ЧИСЛЕННАЯ РЕАЛИЗАЦИЯ ОБОБЩЕННОГО МЕТОДА БЛОХА-ГИНЕВСКОГО

На основі аналогії між функціями Гріна та оберненими матрицями в методі граничних елементів запропоновано алгоритм, що узагальнює метод Блоха-Гіневського та дозволяє ефективно чисельно розв‘язувати крайові задачі для рівняння Лапласа у багатозв'язних областях складної геометричної форми. Запропонований алгоритм може бути застосовано для чисельного розв‘язку задач гідродинамічної взаємодії.

Ключові слова: Метод Блоха-Гіневського, потенціальна течія ідеальної нестисливої рідини, метод граничних елементів, функція Гріна.

На основе аналогии между функциями Грина и обратными матрицами в методе граничных элементов предложен алгоритм, обобщающий метод Блоха-Гиневского и позволяющий эффективно численно решать краевые задачи для уравнения Лапласа в многосвязных областях сложной геометрической формы. Предложенный алгоритм может быть применен для численного решения задач гидродинамического взаимодействия.

Ключевые слова: Метод Блоха-Гиневского, потенциальное течение идеальной несжимаемой жидкости, метод граничных элементов, функция Грина.

On the base of simplicity of Green's functions and inverse matrices in boundary element method, it is proposed an algorithm, which generalizes Blokh-Ginevskiy's method and gives an opportunity to effectively, numerically solve boundary-value problems for Laplace equation in multiconnected complex geometrical shape domains. The proposed algorithm can be applied for numerical solution of hydrodynamic interaction problems.

Key words: Blokh-Ginevskiy's method, potential ideal incompressible fluid flow, boundary element method, Green's function.

Введение. Настоящая работа продолжает серию работ авторов [1–6], посвященных применению методов вычислительной теории потенциала к задачам гидродинамического взаимодействия. Задачи данного класса возникают всякий раз, когда в потоке присутствуют независимые объекты – обтекаемые тела, твердые стенки, вихревые образования, свободные поверхности, границы раздела несмешивающихся жидкостей, контактные разрывы скоростей, ударные волны, пограничные слои и т. д. Простое перечисление взаимодействующих объектов показывает степень сложности рассматриваемой проблемы, учитывая, что даже простой расчет каждого из гидродинамических эффектов, связанных с упомянутыми объектами, может вызвать определенные затруднения, а расчет их взаимодействия неизбежно потребует столь значительных усилий и ресурсов, что не всегда может быть осуще