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EVALUATION OF THE EFFICIENCY OF WIND GENERATORS IN THE CONDITIONS OF PARTICIPATION IN THE DAILY ELECTRICITY MARKET

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In its development, the global energy sector is constantly demonstrating the growth of electricity consumption. Traditional power plants in this process ensure an increase in greenhouse emissions and aggravation of climate problems, which are becoming more relevant every year. Against this background, modern alternative energy sources, namely wind power plants, contribute to reducing the impact of traditional power plants and promote solutions to address environmental problems. The development of the global wind energy industry is accompanied by an intensive increase in the unit capacities of wind power generators. The paper analyzes the efficiency of a wind power plant based on modern wind generators for predetermined location conditions, taking into account operating costs based on operating experience and based on the assessment of the power plant's participation in the balancing electricity market and taking into account the "green tariff". Calculations of technical and economic indicators of a hypothetical 4-unit wind power plant with various wind generators under the wind conditions of a predetermined industrial site located in the Carpathian region of Ukraine were carried out. The calculations take into account modern typical characteristics of wind generators, additional operating costs and the estimated cost of electricity in the conditions of a balancing electricity market and in the conditions of the application of the "green tariff" for the comparison of overall efficiency.

Additional operating costs, including equipment maintenance and disposal of worn turbine blades, were considered and found to have minimal impact on the overall cost structure, contributing only 5-7% to total expenses. The findings confirm the efficiency of constructing wind farms with modern wind generators in the Carpathian region, particularly when integrated into the balancing energy market, supporting the transition to renewable energy and reducing reliance on traditional fossil fuels.

Key words: *wind power plant, wind generators, real wind conditions, performance characteristics, payback period.*

Eq. 4. Fig. 1. Table. 4. Ref. 9.

1. Problem formulation

The development of the global energy sector in terms of the installed capacity of alternative renewable sources of electricity and their production shows stable growth. In these conditions, wind energy shows a significant growth rate of influence on the level of global electricity production. In recent years, mainly alternative and renewable sources of electricity have been reported to be used in certain countries during periods of reduced electricity load schedules of power systems [1]. In such periods, the share of electricity obtained from alternative sources was up to 87%. The use of wind power plants together with them reduces the consumption of traditional primary energy resources, while contributing to the technological development of territories, creating jobs, and reducing the amount of CO_2 emissions. The development of world energy is accompanied by an increase in the unit capacities of wind generators. At the same time, new experience in the operation of power plants is being formed, which is associated with the manifestation of additional factors that affect the overall efficiency, in particular, wind energy. Factors affecting the performance of wind farms are the constant growth of the unit capacity of wind generators, along with the additional costs of wind farms for repairs and spare parts and related logistics. This information, which determines the efficiency of the wind power plant, should be taken into account in the processes of designing and planning the operation of the power plant, taking into account the conditions of a specific region.

The current stage of development of the Ukrainian wind energy industry has significantly lower development indicators than the world average. In 2018, wind farms in Ukraine produced 974 MWh of electricity, while the share of wind energy in the overall balance was 0.62% and 0.9% in the total capacity of generators. This reduces CO_2 emissions by 490,000 tons. In 2023, the nominal capacity of wind generators reached 1900.8 MW. The development of power generation in Ukraine will continue to require a reduction in dependence on fossil fuel types, its import, and reduction of emissions into the atmosphere.

2. Analysis of recent research and publications

The efficiency of the wind farm is determined by a group of indicators that allows taking into account certain factors for making specific technical decisions. Such factors include the existing legislation, the results of engineering research, logistics costs, especially in the conditions of mountain ranges, the results of wind potential studies, etc. [3,4]. It is also necessary to take into account the global trends in the prices of wind generators, which as of 2023 amounted to 800-900 thousand € per MW of installed capacity. At the same time, there were noticeable changes in the market conditions for the sale of generated electricity. At the same time, the performance indicators of the wind farm are affected by the requirements of the national legislation on the "green tariff", which is connected with the use of products of domestic manufacturers. The specified factors of influence on the efficiency of wind farms in the energy system encourage a deeper analysis of the situation that developed during 2023-24.

3. The purpose of the article

The purpose of the work is to obtain an assessment of the efficiency of a wind farm with modern wind generators under the conditions of a specific location of a construction site in the Ukrainian Carpathians, taking into account additional operating costs based on operating experience and current forms of realization of generated electricity in the form of a payback period for capital investments. During the assessment of operating costs, the previous experience of long-term operation of other wind power plants in the conditions of power systems, which is accompanied by additional financial costs for repair and maintenance of equipment, should be taken into account. Such costs can make up to 50% of the direct costs associated with unplanned replacements of equipment elements. Only capital elements – gearboxes, electric generators, turbine blades – can generate a cost of up to €10,000 per turbine per year [2]. In addition, the work takes into account the impact of the implementation conditions of production on the efficiency of the wind farm as of 2024 - with the use of a "green tariff" or the participation of the power plant in the daily balancing electricity market [3,7].

4. Results of the researches

The initial stage of obtaining an estimate of the performance of a wind farm in real conditions is the characterization of a designated area for an industrial site. In order to obtain wind characteristics for a specific site in the upper reaches of the Carpathian ridges of Ukraine (coordinates of the site - (lat., lon.) 49.2470; 22.8763), it is possible to accept the actual probability distribution of wind speed according to the analytical Weibull distribution obtained earlier as a result of a long-term measurable campaign in the form of:

$$\Phi_V = \frac{k}{C}\left(\frac{V}{C}\right)^{k-1} e^{\left(-\frac{V}{C}\right)^k}, \quad (1)$$

where Φ_V is the functional distribution of wind probability, %; k is scattering coefficient; C is the scaling factor, which is determined by the average wind speed and is approximately $C=(2V/\pi)^{1/2}$; V is the wind speed estimated from the measurement results, m/s. The given characteristic of the distribution of wind characteristics of the site was previously obtained from open sources [3,4]. We will accept the results of the Vortex© Factoria de Calculs SL computer program Vortex MAPS(™) as the initial data for calculating the wind characteristics of the above-mentioned construction site. As a result of using Vortex company data, an annual analytical Weibull distribution was obtained for the specified area in the form of Fig. 1 with the following characteristics: the Weibull k value $k = 2.13$, average wind speed – $V_a = 7.34$ m/s.

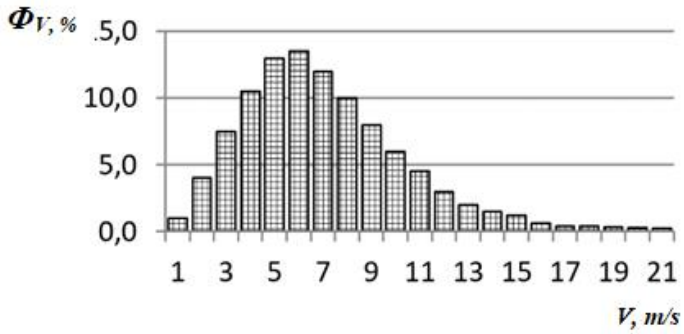

Fig. 1. Analytical Weibull distribution of the selected area

The given characteristics were obtained for a measuring tower with a height of 100 m. To convert to the actual height of the wind generator, Hellman's law should be applied [5]:

$$V_{h2} = V_{h1} \cdot \left(\frac{H_2}{H_1} \right)^b, \quad (2)$$

where H_2 – the height of the wind generator under study; H_1 is the height of the tower at which the measurements were made; V_{h2}, V_{h1} is corresponding wind speeds; b is indicator of the nature of the terrain profile for wind generator installation (b = 0.13÷0.31).

The intensity and dynamism of the development of the global wind energy markets stimulate the wind turbine market and the emergence of new offers from manufacturers of this equipment with higher performance and power indicators. Wind generators of significant power from well-known world manufacturers differ to a certain extent from each other, which makes it possible to choose based on comparative characteristics. The final choice of the wind turbine type depends on the evaluation of performance and profitability, and therefore efficiency in real operating conditions. As of 2024, the current nominal capacities of wind generators are 5.5–7.5 MW. Let's consider the technical and economic indicators of a hypothetical wind farm located on the above-mentioned site. To calculate the indicators of the wind farm, we will take two types of wind generators – Vestas V172-7.2 MW and V162-6.2 MW [6]. The parameters of the selected wind generators are listed in Table 1.

Table 1

Parameters of wind turbines

Characteristic	Vestas V172	Vestas V162
Nominal power, MW	7.2	6.2
Rotor diameter, m	169	162
Tower height, m	170	169
Rotor coverage area, m²	22698	20612
Average energy production, for 4 turbines, MWh.	95869.4	82554.2
The cost of 1 pc. wind turbine generator, million €	5.976	5.146
Operating costs for 4 turbines, €	1153270	909700
Additional operating costs for 4 turbines, €	40.000	40.000

The estimated power of the wind generator for a specific case of the installation site is determined by the following parameters: wind speed at the height of the wind turbine axis, air density, daily indicators of maximum and minimum wind speed [5]:

$$P = k \cdot \rho \cdot V^3 \cdot S/2, \quad (3)$$

where k – the turbine efficiency factor; ρ is air density at the nominal height, kg/m³; V – the value of the wind speed, m/s; S – the wind flow capture area, m².

The performance characteristics of the types of wind turbines specified for analysis can be obtained from the manufacturer's passport data. The production of electricity by a wind generator can be defined as follows:

$$E = \int_{V_{\min}}^{V_{\max}} \left[\tfrac{1}{2} \rho S V^3 C_t \phi_V T \right] dV, \quad (4)$$

where: ρ – air density; S – the area of the wind turbine; C_t – a parameter that characterizes the efficiency of the wind generator's use of wind energy [6].

For a hypothetical wind farm with the selected wind generators, the annual production indicators for the specified site in the conditions of mountain ranges, taking into account the Weibull distribution (1), (2) and the wind characteristics given by (3), (4) are as follows (table. 1).

The calculated indicators of the annual production of the wind power plant make it possible to obtain an approximate estimate of the efficiency of a 4-aggregate plant in the conditions of a defined area for two types of wind generators.

The amount of capital investments in the construction of a wind power plant can be obtained on the basis of expert assessments, taking into account the costs of wind turbines worth €0.85 million/MW [5], the design cost – €0.9 million, generation licensing – €0.4 million, the cost land acquisition – €0.26 million, transport, construction and installation support – 15% of the cost of wind turbines.

Operating costs can be roughly estimated at 8.5% – including expenses for wages, for dispatching services, for depreciation deductions, for rent and investment deductions for the development of the territory, for taxes. At the same time, an amount of €10,000 per wind turbine during the year should be additionally allocated to operational costs, which is determined by the need for post-accident recovery of the power plant equipment [2].

On the one hand, the cost of electricity generated at wind farms in Ukraine is determined by the "green" tariff, which is approved by the Government and amounts to UAH 3.95/kWh as of June 1.2024 [7]. Based on the annual output of the wind power plant, this provides an opportunity to calculate the profitability characteristics.

Table 2

Results of the calculation of the technical and economic indicators of the wind farm based on the "green tariff"

Type of wind generator	"Green" tariff for June 1, 2024, UAH/kWh	Total cost, thousand €	Annual profit, thousand €	Payback period, years
4 x Vestas V172-7.2 MW	3.95	29.84	71406.1	3.6
4 x Vestas V162-6.2 MW		26.03	9236.2	4.0

On the other hand, the cost of electricity generated at wind farms in Ukraine can be estimated by the purchase price for electricity on the daily balancing electricity market. For comparison, similar results under conditions of sale of products on the balancing electricity market are shown in Table 3, where the market price for June 1, 2024 is taken into account [8] are given in table 3.

Table 3

Results of the calculation of the technical and economic indicators of the wind farm based on the price of the balancing market

Type of wind generator	The price of electricity on the daily balancing market on June 1, 2024 UAH/kWh	Annual profit, thousand €	Payback period, years
4 x Vestas V172 -7.2 MW	5.4	12626.7	2.6
4 x Vestas V162 -6.2 MW		9761.2	2.9

The "levelized cost of energy" indicator (LCOE) is determined on the basis of market data and reflects the current cost of all costs for the production of one unit of energy, i.e. this indicator represents the ratio of annual capital and operating costs, divided by the years of operation of the equipment, to the total annual output of the wind farm [9]. For our case, on the basis of previous data and for 10-year operation of an imaginary station, it is possible to obtain the data listed in Table 4.

Table 4

Results of the calculation of the LCOE

Type of wind generator	*LCOE on 10-th year*, €/MWh
Vestas V172 -7.2 MW	42.3
Vestas V162 -6.2 MW	41.8

The technical and economic indicators of the wind farm correlate well with previously obtained data [3, 4, 9], calculated on the basis of expert assessments, should be perceived as estimated characteristics of the

quantity, which cannot be absolutely accurate due to the approximation of the initial data and the use of expert assessments of the components, arbitrarily selected value of the price on the balancing electricity market in Ukraine.

The technical and economic indicators of the wind farm show slight differences from the previously published practical results of the operation of the wind power plant [4]. This provides an opportunity to draw a conclusion about the similarity of the obtained results with the possibility of using estimated data in the consumption part and measured data on the wind load of the specified site for the wind power plant.

It should be noted that the consideration of additional operating costs for the post-accident restoration of wind generators in the amount of €10,000 per turbine does not significantly affect (within 5-7%) the annual operating costs, as well as the payback period of capital investments.

Adoption of a technical and economic engineering decision on the construction of a wind power plant must be implemented on the basis of a technical and economic justification for the construction of a real wind farm. The results calculated in the work make it possible to take into account modern peculiarities in the regulatory framework and the existing exchange rate, and they correlate with the results of a real power plant in similar conditions. This further emphasizes the significant effectiveness of the construction of a wind farm with modern wind generators in the Carpathians of Ukraine.

5. Conclusions.

The characteristics of capital investments, operating costs, annual electricity production were obtained, the gross profit during the annual operation of the wind power plant with options for installing wind generators was calculated. This makes it possible to estimate the payback time of an investment in the construction of a wind farm. So, for a 4-unit station with Vestas V172-7.2 MW generators, the payback time is 3.6 years, and with Vestas V162-6.2 MW type wind generators - 4.0 years, as well as for Vestas V172-7.2 MW in operating conditions "green tariff" and, respectively, 2.6 years and 2.9 years under conditions of sale of electricity at the prices of the balancing market per day. Additional operating costs for the disposal of worn wind turbine blades do not have a significant impact on the overall cost indicators and amount to 5-7% of the total costs. The obtained results allow us to confirm the effectiveness of the construction of wind farms with modern wind generators in the area of the Ukrainian Carpathians, especially under the condition of working in a balancing energy market per day.

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ОЦІНКА ЕФЕКТИВНОСТІ ВІТРОГЕНЕРАТОРІВ В УМОВАХ УЧАСТІ У ДОБОВОМУ РИНКУ ЕЛЕКТРОЕНЕРГІЇ

Світова енергетика у своєму розвитку безупинно демонструє зростання споживання електроенергії. Традиційні електростанції у цьому процесі забезпечують збільшення парникових викидів та загострення кліматичних проблем, що з кожним роком збільшують свою актуальність. На цьому фоні сучасні альтернативні джерела енергії, а саме вітрові електростанції, сприяють зниженню впливу традиційних електростанцій та спонукають до розв'язанню екологічних проблем. Розвиток світової вітроенергетики супроводжується інтенсивним зростанням одиничних потужностей генераторів вітрових електростанцій. В роботі проведено аналіз ефективності вітрової електростанції на основі сучасних вітрогенераторів для наперед визначених умов розташування з урахуванням експлуатаційних витрат на основі досвіду експлуатації та на основі оцінки участі електростанції в балансуючому ринку електроенергії та з урахуванням «зеленого тарифу». Здійснено розрахунки техніко-економічних показників уявної 4-агрегатної вітроелектростанції з різнотипними вітрогенераторами за вітрових умов наперед заданого промислового майданчика, що розташований в регіоні Карпат України. В розрахунках враховано сучасні типові характеристики вітрогенераторів, додаткові експлуатаційні витрати та оціночну вартість електроенергії в умовах балансуючого ринку електроенергії та в умовах застосування «зеленого тарифу» для порівняння загальної ефективності.

Додаткові експлуатаційні витрати, включаючи технічне обслуговування обладнання та утилізацію зношених турбінних лопаток, були розглянуті та виявлено, що вони мають мінімальний вплив на загальну структуру витрат, вносячи лише 5-7% у загальні витрати. Отримані дані підтверджують ефективність будівництва ВЕС із сучасними вітрогенераторами в Карпатському регіоні, особливо за умови інтеграції в ринок балансуючої енергії, підтримки переходу на відновлювані джерела енергії та зменшення залежності від традиційного викопного палива.

Ключові слова: *вітроелектростанція; вітрогенератор; реальні вітрові умови; характеристики продуктивності; термін окупності.*

Ф. 4. Рис. 1. Табл. 4. Літ. 9.

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