№ 3 (130) / 2025
Техніка, енергетика, транспорт АПК
Vol. 130, № 3 / 2025
UDC 621.311.24: 621.314
DOI: 10.37128/2520-6168-2025-3-17

ASSESSMENT OF WIND TURBINE EFFICIENCY BASED ON LCOE

Kostiantyn POKROVSKIY, Candidate of Technical Sciences, Associate Professor
Lviv Polytechnic National University

ПОКРОВСЬКИЙ Костянтин Борисович, к.т.н., доцент
Національний університет «Львівська політехніка»

The paper investigates the techno-economic efficiency of wind power plants using the Levelized Cost of Energy (LCOE) as an integrated performance indicator under real operating and market conditions. The applicability of LCOE as a comparative criterion for modern wind turbines deployed in mountainous regions of Ukraine is substantiated. A hypothetical four-unit wind farm located in the Ukrainian Carpathians is modeled using site-specific wind characteristics derived from a Weibull distribution and open-source datasets. Three state-of-the-art high-capacity wind turbine models are considered: Enercon E-126 7.58 EP8, Vestas V164-8 MW, and Gamesa SG 7.0-170.

Annual energy production, capital expenditures (CAPEX), operational expenditures (OPEX), and projected gross profits are calculated assuming electricity sales on the Ukrainian balancing market. The model incorporates additional costs associated with unscheduled maintenance and post-accident equipment recovery. LCOE values are determined for each wind farm configuration over a ten-year operational horizon. The results indicate closely aligned LCOE values in the range of 0.043–0.044 €/kWh for all turbine types, confirming their high economic competitiveness under the specified conditions.

Sensitivity analysis demonstrates that contingency costs related to equipment restoration exert only a marginal influence on overall efficiency, affecting financial indicators by no more than 5–7%. The obtained results correlate well with empirical data from operating wind farms in comparable environments. The study confirms the technical and economic feasibility of deploying modern high-capacity wind turbines in the Ukrainian Carpathians. The proposed methodological framework can serve as a practical tool for preliminary techno-economic assessment of prospective wind farm sites under real market conditions.

Key words*: wind power plant; wind turbine; LCOE; levelized cost of energy; performance indicators; techno-economic efficiency; payback period*.

Eq. 2. Fig. 1. Table. 3. Ref. 8.

1. Problem formulation

The global energy sector has consistently seen steady increases in electricity consumption. Conventional power plants contribute to rising greenhouse gas emissions, worsening climate challenges. Wind farms, on the other hand, help mitigate the environmental impact of fossil-based generation[1]. The worldwide wind energy industry is advancing rapidly, marked by the growth of turbine unit capacities. This study evaluates the efficiency of a wind power plant using modern turbines, applying the Levelized Cost of Energy (LCOE) metric under specific site conditions. Operational costs and turbine type comparisons are taken into account. A hypothetical four-unit wind farm located in the Carpathian region of Ukraine was modeled under local wind conditions. The analysis incorporates typical turbine characteristics, additional operating expenses, and projected energy production costs during the early years of operation.

2. Analysis of recent research and publications

The efficiency of wind power plants (WPPs) is determined by a set of interrelated technical, economic, and regulatory characteristics that enable informed engineering and investment decisions. These factors include existing legislation, results of engineering surveys, logistical costs – particularly significant in mountainous regions – as well as the outcomes of wind potential assessments [1, 2]. It is also necessary to consider global price trends for wind turbines, which in 2023 ranged from €800,000 to €900,000 per megawatt of installed capacity [3]. The combined influence of these factors on the performance of wind farms within power systems necessitates a deeper analysis of industry developments observed during 2024–2025, with

Article received 24.10.2025. Article accepted 08.12.2025. Article published 25.12.2025.

particular emphasis on the Levelized Cost of Energy (LCOE) as the key criterion for investment decision-making [4].

Recent studies emphasize that the evolution of wind energy systems is increasingly driven by digitalization, predictive analytics, and life-cycle cost optimization [5, 6]. Researchers highlight that the integration of digital twin technologies, condition monitoring systems, and data-driven maintenance strategies enables more accurate forecasting of turbine performance and degradation processes over time. Such approaches significantly reduce uncertainty in estimating operational expenditures and downtime, which directly affect the LCOE indicator [5]. In mountainous and complex-terrain regions, where wind variability and logistical constraints are pronounced, these tools become especially important, as they allow operators to adapt control strategies and maintenance schedules to site-specific conditions, thereby improving both technical reliability and economic outcomes [6].

Furthermore, contemporary literature increasingly focuses on the role of market mechanisms and regulatory frameworks in shaping the economic efficiency of wind power plants [7]. Studies demonstrate that participation in balancing and day-ahead electricity markets introduces additional revenue volatility, but also creates opportunities for higher profitability when combined with flexible operational strategies [7, 8]. The LCOE metric is therefore complemented by market-oriented indicators that reflect real trading conditions, grid integration costs, and ancillary service provision. This shift from static feed-in tariff models toward competitive market participation necessitates more comprehensive techno-economic models that incorporate price dynamics, curtailment risks, and grid constraints [4, 8]. As a result, modern assessments of wind farm efficiency increasingly rely on hybrid approaches that merge classical energy yield calculations with market simulations and risk analysis, providing a more realistic basis for investment decision-making.

3. The purpose of the article

The purpose of this study is to evaluate the efficiency of wind power plants (WPPs) equipped with modern wind turbines under the specific site conditions of the Ukrainian Carpathians. The assessment accounts for additional operational costs and uses the Levelized Cost of Energy (LCOE) as a comparative indicator.

When estimating operating expenses, it is essential to consider the long-term experience of other wind farms, which often involves additional financial outlays for equipment repair and maintenance. Such costs may reach up to 50% of direct expenditures associated with unplanned replacements of equipment components. Major elements – including gearboxes, power wind generators, and turbine blades–alone can incur annual expenses of up to €8,000 - 10,000 per turbine [2].

4. Results and discussion

The Levelized Cost of Energy (LCOE) represents the present value of all expenses associated with producing a single unit of electricity over the entire lifetime of a project. In general terms, LCOE (expressed in EUR/MWh or EUR/kWh) is defined as the ratio of the sum of discounted costs incurred throughout the project's operational period to the sum of discounted electricity generated:

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (1)$$

where: I_t – investment expenditures (CAPEX) in year; M_t – operating and maintenance costs (OPEX) in a year; F_t – fuel costs in a year tt (typically zero for wind power plants); E_t – electricity produced in a year; r – discount rate; n – project lifetime in years.

In a simplified form, often applied for preliminary assessments – particularly during the initial years of operation – LCOE can be expressed as the ratio of total annual costs to the annual volume of electricity generated.

$$\mathrm{LCOE} \approx \frac{\text{Annual Capital Costs} + \text{Annual Operating Costs}}{\text{Annual Energy Production}} \quad (2)$$

The initial phase of evaluating the operational performance of a wind farm under real-world conditions involved a detailed characterization of the designated industrial site. For the site located in the upper reaches of the Ukrainian Carpathian ridges (coordinates: 49.2470 N, 22.8763 E), the wind speed probability was modeled using the analytical Weibull distribution. This distribution was derived from long-term measurement data previously identified in open-source records [3, 4]. Primary data for calculating the wind characteristics at the proposed construction site were obtained through the Vortex© MAPS™ computational framework. The simulation yielded an annual analytical Weibull distribution for the specified coordinates with a shape factor k = 2.13 and an average wind velocity V_a = 7.34 m/s [3]. These parameters correspond to a measurement height of 100 m. To adjust these values to the specific hub height of the wind turbine, Hellman's law [4] was utilized, ensuring the accuracy of the vertical wind profile extrapolation.

The rapid expansion and dynamic evolution of global wind energy markets have catalyzed the development of high-performance turbines with enhanced power ratings. According to 2025 industry standards, the nominal capacities of leading-edge wind generators typically range from 7.0 to 8.0 MW. Given the variations in technical specifications among major global manufacturers, a comparative analysis is essential for optimizing turbine selection based on site-specific performance and economic viability. To evaluate the technical and economic efficiency of a prospective wind farm at the designated site, three turbine models were selected for comparative modeling: the Enercon E-126 7.58 EP8, the Vestas V164-8 MW, and the Gamesa SG 7.0-170 [5]. These units represent the current technological frontier in high-capacity wind energy conversion. The core operational parameters and performance metrics for the selected turbines are summarized in Table 1, and serve as the baseline for subsequent profitability and output simulations.

The projected power output of a wind turbine at a specific installation site is governed by several critical parameters, including the wind velocity at the hub height, local air density, and the diurnal variations in wind speeds. These indicators were evaluated using conventional analytical methods.

Performance specifications for the turbine models selected for this study were extracted from the manufacturers' official technical datasheets. The potential electricity generation for each unit was calculated using the standard power equation, which incorporates air density, the rotor swept area, and the power coefficient (C_p) representing the aerodynamic efficiency of the generator [4, 5].

For the hypothetical power wind farm at the designated high-altitude site, the estimated annual energy production (AEP) was determined by synthesizing the site-specific Weibull distribution parameters with the operational power curves of the turbines. The resulting performance indicators, adjusted for the unique topographic conditions of the Carpathian mountain ranges, are summarized in Table 1.

Table. 1

Parameters of 4 wind turbines on a wind farm

Characteristic	Enercon E-126 7.58 EP8	Vestas V164-8 MW	Gamesa SG7.0-170
Nominal power of WTG, MW	7.58	8.0	7.0
Average electric energy production, MWh.	100929.2	106521.6	93206.4
The cost of 1pc. WTG, mln. €.	6.29	6.64	5.81
Operating costs, €	1 278 204	1 346 811	1 183 460

The projected annual energy yield facilitates a preliminary efficiency assessment of a four-unit wind power plant configured for the specific site conditions. This evaluation considers the performance of two distinct wind turbine models. The total capital expenditure (CAPEX) for the wind farm's development was derived from expert appraisals and industry benchmarks. Key cost components include:

- Wind Turbine Procurement: Estimated at €0.83 million/MW [4].
- Project Design and Engineering: Fixed at €0.9 million.
- Generation Licensing: Allocated at €0.4 million.
- Land Acquisition: Budgeted at €0.26 million.
- Logistics and Installation: Calculated as 15% of the total wind turbine procurement cost.

Operational expenditures (OPEX) are estimated at 8.5% of the investment. This figure encompasses labor costs, dispatching services, depreciation, land lease payments, local development contributions, and applicable taxes.

Table. 2

Results of the calculation of the indicators of the WPP based on the price of the real balancing market

Type of wind generator	The price of electricity on the daily balancing market on 09.01.2025 UAH/kWh	Annual profit, €
4 x Enercon E-126 7.58 EP8	7.0	14 567 103
4 x Vestas V164-8 MW		15 374 252
4 x Gamesa SG7.0-170		13 452 470

Furthermore, an additional contingency fund of €10,000 per turbine per annum is integrated into the OPEX to account for unscheduled maintenance and post-accident equipment recovery [2].

For the purpose of economic modeling, the revenue from generated electricity is benchmarked against the purchase prices on the Ukrainian day-ahead and balancing electricity markets. A comparative analysis of the financial outcomes, based on the market price recorded on June 1, 2025 [6] is presented in Table 2.

The Levelized Cost of Energy (LCOE) metric was employed to evaluate the economic competitiveness of the project based on current market dynamics. This indicator quantifies the average cost per unit of electricity throughout the facility's lifecycle. Specifically, it is calculated as the ratio of total annualized capital and operational expenditures to the wind farm's total annual energy output [4]. In this study, the LCOE was determined based on the previously established financial parameters and a projected operational period of 10 years for the hypothetical power plant. The synthesis of these variables, reflecting the total lifecycle costs relative to the cumulative generation, is detailed in Table 3.

Table. 3

Results of the calculation of the LCOE

Type of WTG	Calculated LCOE on 10-th year, €/kWh
4 x Enercon E-126 7.58 EP8	0,04368
4 x Vestas V164-8 MW	0,044
4 x Gamesa SG7.0-170	0,04353

The techno-economic performance metrics of the proposed wind farm demonstrate a high degree of correlation with established empirical data [3, 4, 7]. It should be noted, however, that these indicators serve as approximate quantitative estimates. Their inherent variability stems from the use of expert assessments for specific cost components and the fluctuations in the Ukrainian balancing electricity market prices used in this simulation.

Minor discrepancies between the current findings and previously documented operational results [4] do not undermine the study's validity. On the contrary, the proximity of these results confirms the reliability of using a hybrid data approach – combining estimated consumption metrics with measured site-specific wind load data–for preliminary site assessments.

Sensitivity analysis reveals that the inclusion of specialized contingency costs, such as the €10,000 per turbine allocated for post-accident restoration, has a marginal impact on the overall financial profile. Specifically, these costs influence annual operating expenditures and the investment payback period by only 5–7%, suggesting that such maintenance risks do not compromise the project's fundamental economic viability.

Furthermore, calculating the LCOE over a 10-year operational horizon enhances the flexibility of the preliminary efficiency appraisal. While this study provides a robust framework based on open-source wind potential data and expert cost evaluations, the final engineering and investment decision should be predicated on a comprehensive techno-economic justification (TEJ) tailored to the specific logistics and real-time market conditions of the construction site.

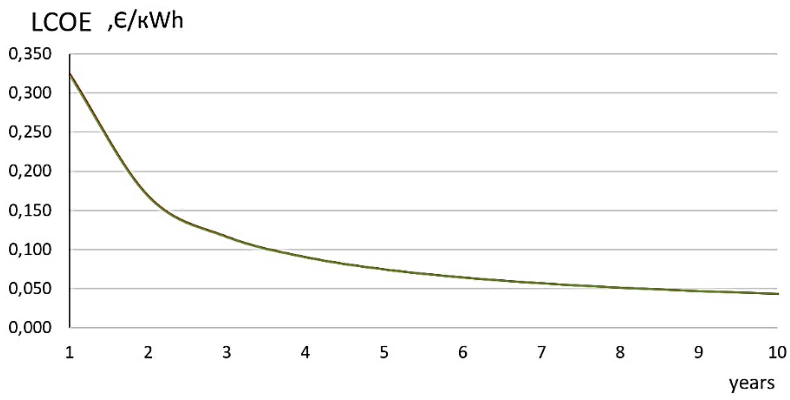

Fig 1. Dependence of LCOE of wind farms with different wind turbines on the operating time.

The analytical results presented in this study reflect current regulatory frameworks and prevailing exchange rate dynamics, ensuring the contemporary relevance of the findings. The high correlation between these calculations and the operational data from existing wind power plants in analogous environments reinforces the credibility of the proposed model.

Furthermore, the findings underscore the substantial technical and economic feasibility of deploying advanced high-capacity wind turbines within the Ukrainian Carpathian region. Given the favorable wind load profiles and the performance metrics of modern equipment, the strategic development of wind farms in this mountainous terrain represents a highly efficient pathway for expanding Ukraine's renewable energy capacity.

5. Conclusion

The paper obtained the characteristics of capital investments (CAPEX), operating costs (OPEX), and annual electricity production, calculated the gross profit for the annual operation of a wind power plant, using wind turbine installation options for calculating LCOE. This makes it possible to estimate the LCOE parameter of a wind power plant with 4 generators for comparison: Enercon E-126 7.58 EP8, Vestas V164-8 MW, and Gamesa SG 7.0-170, operating under the conditions of selling electricity at the prices of the real balancing market in Ukraine per day. The results of the calculations provide additional flexibility in assessing the efficiency of wind power plants under real conditions. The results obtained allow us to confirm the efficiency of building wind power plants with modern wind turbines in the Ukrainian Carpathians, especially when operating on the real balancing energy market on a daily basis.

References

1. BP P.L.C. (2022). *2021 at a glance*. URL: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-at-a-glance.pdf [in English].
2. Wood Mackenzie. (2019). *Unplanned wind turbine repairs to cost industry $8 billion+ in 2019*. URL: https://www.woodmac.com/press-releases/unplanned-wind-turbine-repairs-to-cost-industry-8-billion-in-2019 [in English].
3. Pokrovskyi, K. (2024). Evaluation of the efficiency of wind generators in the conditions of participation in the daily electricity market. *Engineering, Energy, Transport AIC, 3*(126), 80–85. DOI: https://doi.org/10.37128/2520-6168-2024-3-9 [in English].
4. Zobaa, A. F., & Bansal, R. C. (2011). *Handbook of renewable energy technology*. World Scientific. [in English].
5. Wind turbine models. (2025). URL: https://en.wind-turbine-models.com/turbines [in English].
6. Finance.UA. (2025). *Rynkovi tsiny na elektroenerhiiu v Ukraini staiut vyshche za yevropeiski* [The market price for electricity in Ukraine has become the highest in Europe]. URL: https://news.finance.ua/ua/rynkova-cina-na-elektroenerhiyu-v-ukraini-stala-naybil-shoyu-v-yevropi [in Ukrainian].
7. Mykhailenko, O., & Tkachuk, T. (2018). *LCOE vidnovliuvanykh dzherel enerhii v Ukraini* [LCOE of renewable energy sources in Ukraine]. GO "Laboratoriia Chystoi Enerhetyky". URL: https://reform.energy/media/1037/fc28e1186ade16bab68428627c1d3ab0.pdf [in Ukrainian].
8. Leng, J., Zhang, H., Yan, D., Liu, Q., Zhang, D., & Zhao, R. (2019). *Digital twin-driven manufacturing cyber-physical system for parallel controlling of smart workshop*. [in English].

ОЦІНКА ЕФЕКТИВНОСТІ ВІТРОГЕНЕРАТОРІВ НА ОСНОВІ LCOE

У статті досліджено техніко-економічну ефективність вітрових електростанцій на основі показника зведеної вартості електроенергії (LCOE) з урахуванням реальних умов експлуатації та ринкових факторів. Обґрунтовано доцільність застосування LCOE як інтегрального критерію для порівняння сучасних вітроенергетичних установок у гірських районах України. Проведено моделювання роботи гіпотетичної вітрової електростанції, що складається з чотирьох агрегатів, розміщених у Карпатському регіоні, з використанням статистичних параметрів вітрового режиму, отриманих на основі розподілу Вейбулла та відкритих джерел даних. Для аналізу обрано три високопотужні моделі вітрогенераторів: Enercon E-126 7.58 EP8, Vestas V164-8 MW та Gamesa SG 7.0-170.

Розраховано річний виробіток електроенергії, капітальні витрати (CAPEX), експлуатаційні витрати (OPEX) та прогнозний валовий прибуток за умов реалізації електроенергії на балансуючому ринку України. У модель інтегровано додаткові витрати, пов'язані з аварійним обслуговуванням та ремонтом обладнання. Визначено значення LCOE для кожної конфігурації вітрової електростанції на десятирічному горизонті експлуатації. Отримані результати свідчать про близькі значення LCOE для всіх розглянутих типів турбін у межах 0,043–0,044 €/кВт·год, що підтверджує їх високу економічну конкурентоспроможність.

Показано, що вплив додаткових витрат на відновлення обладнання має обмежений характер і не перевищує 5–7 % загальних показників ефективності. Результати моделювання узгоджуються з даними діючих вітрових електростанцій та підтверджують доцільність розміщення сучасних вітроустановок у Карпатському регіоні. Запропонований підхід може бути використаний як *інструмент попередньої техніко-економічної оцінки перспективних майданчиків будівництва вітрових електростанцій в Україні.*

Ключові слова: *вітроелектростанція, вітрогенератор, LCOE, приведена вартість електроенергії, показники продуктивності, техніко-економічна ефективність, термін окупності.*

Ф. 2. Рис. 1. Табл. 3. Літ. 8.

INFORMATION ABOUT THE AUTHOR

Kostiantyn POKROVSKIY – Candidate of Technical Sciences, Associate Professor of Electric Power Engineering and Control Systems Department of NU "Lvivska polytechnika" (48/5 ak. Saharova St., Lviv, 79013, Ukraine., e-mail: kpokrov@gmail.com, https://orcid.org/0000-0003-4151-5820).

ПОКРОВСЬКИЙ Костянтин Борисович – кандидат технічних наук, доцент кафедри Електроенергетики та систем керування НУ «Львівська політехніка» (48/5,акад. Сахарова, Львів, 79013, Україна, e-mail: kpokrov@gmail.com, https://orcid.org/0000-0003-4151-5820).