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WIND TURBINES AND FARMS USING AI FOR ENERGY STORAGE

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The article provides a comprehensive overview of wind turbine technologies, including both onshore and offshore systems, focusing on aspects such as grid integration, trends in the levelized cost of energy (LCOE), and applications of artificial intelligence (AI) in areas like forecasting, diagnostics, control, and digital twins from 2015 to 2025. The importance of energy storage solutions, such as battery energy storage system (BESS), liquid air energy storage (LAES), compressed air energy storage (CAES), power-to-x/H_2 (P2X/H_2), and pumped storage, is also discussed in relation to enhancing system flexibility and increasing the market value of wind energy. The text identifies research gaps and priorities for research and development. Wind energy remains cost-competitive, with onshore wind continuing to be among the lowest cost options for new energy capacity (weighted LCOE ≈ $0.034/kWh globally). Cost variations are mainly influenced by capacity factor (CF), the weighted average cost of capital (WACC), and execution risks. The scale of capacity and maturity of the supply chain are improving, particularly for offshore wind (12–20+ MW/turbine). However, costs and timelines are sensitive to logistics, weather conditions, and the availability of installation vessels. High-voltage direct current (HVDC) technology is becoming the standard for exporting offshore power, and transitioning to meshed/multi-terminal systems require interoperability across different vendors (InterOPERA) and standardized FAT/SAT/HIL testing. Ensuring grid-forming capabilities and converter compatibility is essential for the stability of low-inertia power systems, necessitating harmonized testing profiles and certification requirements at the wind turbine generator (WTG)/wind power plant (WPP)/HVDC levels. Artificial intelligence is increasingly being utilized in operations, achieving optimal results by combining forecasting methods (long short-term memory networks (LSTM)/ gated recurrent units (GRU)/Transformers) with fault detection and diagnosis (FDD)/ remaining useful life (RUL) predictions and wake steering techniques. These results are measured not only by the change in annual energy production but also by their impact on service profiles and network constraints.
Current and evolving ENTSO-E requirements include fault ride-through capabilities (low-voltage ride-through (LVRT) and high-voltage ride-through (HVRT)), active power (P) and reactive power (Q) control (Volt-VAR/Volt-Watt), ramp-rate constraints, primary and secondary frequency control (FCR/FRR), as well as limits on harmonics, flicker, and distortion. Converter-based generation units must ensure low short-circuit power (weak grid) and during disturbances, highlighting the increasing significance of dynamic models (root-mean-square simulation (RMS)/electromagnetic transient simulation (EMT)) and compliance validation during both commissioning and operation.
Keywords: renewable energy, wind turbines, offshore, AI/ML, forecasting, diagnostics, digital twin, wake control, BESS, hydrogen, LCOE, HVDC.

Радек П., Валовськи Г., Сиротюк С., Гальчак В., Станицький Т., Сиротюк Г. Вітрові турбіни та вітроелектростанції з використанням штучного інтелекту для накопичення енергії
Подано узагальнений аналітичний огляд розвитку вітроенергетичних технологій у період 2015–2025 рр., що охоплює наземні та морські вітроустановки, питання їх інтеграції в електричні мережі, динаміку показника приведеної вартості електроенергії протягом життєвого циклу (LCOE), а також застосування методів штучного інтелекту. Особливу увагу приділено використанню ШІ для прогнозування генерації, технічної діагностики, оптимізації керування та створення цифрових двійників вітрових електростанцій.
Розглянуто роль систем накопичення енергії (BESS, LAES, CAES, P2X/водень, гідроакумулюючі електростанції) у підвищенні гнучкості енергосистеми та зростанні ринкової цінності вітрової генерації. Визначено основні наукові прогалини та пріоритети науково-дослідної та дослідно-конструкторської роботи, зокрема в частині інтеграції відновлюваних джерел енергії, до енергосистем із низькою інерційністю.
Економічна конкурентоспроможність вітроенергетики зберігається: наземна вітроенергетика залишається серед найдешевших джерел нових генеруючих потужностей (середньозважений LCOE ≈ 0,034 дол./кВт·год у глобальному

масштабі). Діапазон вартостей визначається переважно коефіцієнтом використання встановленої потужності (CF), вартістю капіталу (WACC) та ризиками реалізації проєктів. Масштабування потужностей і зрілість ланцюгів постачання зростають, особливо в офшорному сегменті (12–20+ МВт на турбіну), однак строки та витрати залишаються чутливими до логістики, погодних «вікон» і доступності спеціалізованих монтажних суден.
Передача потужності від морських ВЕС дедалі частіше базується на технології HVDC; перехід до багатовузлових і мережевих рішень потребує міжвендорної сумісності та стандартизованих випробувань FAT/SAT/HIL. В умовах низької інерційності мереж ключового значення набувають grid-forming перетворювачі та узгоджені вимоги сертифікації. Найкращі результати впровадження ШІ в експлуатації досягаються при поєднанні прогнозування (LSTM/GRU/Transformer), діагностики несправностей і залишкового ресурсу (RUL), а також керування вітровими шлейфами з урахуванням впливу на AEP, сервісні режими та мережеві обмеження.
Актуальні та перспективні вимоги ENTSO-E охоплюють здатність до роботи при аваріях (LVRT/HVRT), керування активною та реактивною потужністю, обмеження швидкості зміни потужності, первинне й вторинне регулювання частоти, а також нормативи гармонік і флікера. Для генераторів на базі перетворювачів зростає значення динамічного моделювання (RMS/EMT) і перевірки відповідності під час пусконалагодження та експлуатації.
Ключові слова: відновлювана енергетика, вітрові турбіни, офшорна вітроенергетика, штучний інтелект / машинне навчання, прогнозування, діагностика, цифровий двійник, керування вітровим слідом, системи накопичення енергії, водень, LCOE, HVDC.

Problem statement. Wind energy maintains high growth dynamics and has exceeded the threshold of ~1 TW of installed capacity; 2023 will bring approximately 117 GW of new installations, as confirmed by industry reports and agency services [7; 20]. Initial estimates and market updates indicate that the trend of high growth has continued into 2024, although it still remains below the level necessary to achieve the ambition of tripling renewable energy capacity by 2030 [7; 19].

In parallel, cost reviews and techno-economic benchmarks show that wind remains cost-competitive with new conventional capacity: the International Renewable Energy Agency (IRENA) report documents falling capital costs and low LCOE values for onshore wind, with some variations due to the cost of capital and supply chains [4]. Independent analyses by Lazard (LCOE+ 2024/2025) place onshore wind at the lower end of the cost spectrum of generation technologies on a subsidy-free basis [11; 12]. The National Renewable Energy Laboratory (NREL) Annual Technology Baseline 2024 parameterizations (cost profiles, capacity utilization factors, O&M) remain the primary reference point for projections to 2050 – both in the utility-scale and distributed wind scenarios [13; 14; 16; 17].

In 2024–2025, system bottlenecks (permits, grid access, stability of support mechanisms) and financing conditions (WACC) will come to the fore. As the share of weather-dependent sources increases, so does the market value of flexibility: balancing services (FCR/FRR), reactive power regulation capacity, and integration with energy storage, which reduce curtailment and smooth the generation profile [4; 5; 13]. The maturity of battery technologies and advances in safety, degradation, and life-cycle cost (LCOS) are confirmed by the latest scorecards and operational evaluations [4; 15]. As a result, wind + storage hybridization improves project bankability and facilitates meeting grid code requirements in systems with decreasing inertia and increasing converter share [5; 13; 15].

Analysis of recent research and publications. Architectures and capacity scale. HAWTs (horizontal axis turbines) dominate the wind energy market, while VAWTs (vertical axis turbines) remain niche and demonstrative – mainly due to aerodynamics, scale, and supply chain maturity [7; 13; 17]. In the onshore class, typical unit capacities have grown from ~2–3 MW to 5–7 MW between 2015 and 2025, and in the offshore class from ~6–8 MW to 12–20+ MW thanks to larger rotor diameters, taller towers, and better load control [7; 13; 17; 18].

Two main generator configurations are used, namely direct-drive (usually PM, fewer moving parts, higher nacelle mass) and geared (lighter generator, but complex gearbox loaded with variable wind profiles). The choice influences the efficiency curve, O&M strategy, and reliability profile (bearings/gears vs. multi-pole—new generator) [13; 17]. Both approaches standardize on active pitch and yaw systems, integrated with load sensors and SCADA data, enabling advanced load control and AEP (also under "wake control") [13; 21; 22].

The trend is toward increasing rotor diameter and the use of hybrid composites (glass/carbon) and joining technologies for very long offshore blades (transport/installation). Tower heights are increasing (onshore) to take advantage of better wind profiles and reduce ground-level phenomena [7; 13; 17].

Onshore, the standard foundations include reinforced concrete options, either monolithic or segmented, as well as geotechnically adapted foundations. Project development is increasingly moving towards areas that accommodate taller towers and longer blades, while also navigating environmental and spatial restrictions [7; 13]. In shallow or temperate waters, permanent foundations are prevalent, with monopiles (diameter increasing to class XL) and jackets being commonly used. For deeper waters, the adoption of floating platforms such as spar buoys, semisub, and tension-leg platforms (TLP) is on the rise. Market and technical reports suggest a rapid increase in power unit capacity, which necessitates the use of heavy installation equipment and the standardization of offshore interfaces [7; 18]. Additionally, within the internal grid of the farm, the voltage of array cables is increasing to 66 kV, compared to the previous 33 kV, thereby reducing losses and the number of distribution bays [18].

For long distances and increasing offshore export capacity, HVDC (VSC) is being used, which improves controllability, reactive power balance, and stability in systems with decreasing inertia. Horizon 2025+ encompasses multi-terminal/meshed HVDC projects at sea (North Sea/Baltic Sea), requiring multi-vendor interoperability (frameworks and standards developed, among others, in InterOPERA) [6; 10; 18]. On the system side, ENTSO-E emphasizes research and implementation of grid-forming and compatibility in converter-dominated networks [5]. At the farm level, turbine coordination is used (curtailment, P/Q control, FCR/FRR support), and in recent years – thanks to jet models and operational data – wake steering (yaw/pitch deflection) has become common practice to increase AEP and reduce load. These methods are described and quantified in the NREL/WES literature [21; 22]. High-frequency SCADA streams and vibration/temperature sensors are standard, powering diagnostics, production forecasting, and digital twins. The datasets and cost/CF parameterizations in NREL ATB 2024 provide a reference for modeling LCOE/NPV/IRR scenarios for various configurations (onshore/offshore fixed/floating) [13; 17].

From 2015 to 2025, wind power has seen significant growth in turbine scale, with onshore capacities reaching 5–7 MW and offshore turbines 12–20+ MW, along with larger rotor diameters [7; 13; 17; 18]. The share of HVDC transmission is increasing, with preparations for multi-terminal and meshed networks requiring interoperability standards [6; 8; 10]. Wind farm infrastructure is being modernized to 66 kV, improving power quality and controllability (P/Q) [18], while integrated farm and wake control strategies (AEP↑, loads↓) [21; 22] enhance energy production and reduce mechanical loads. Reference data and models, such as ATB 2024, provide a foundation for techno-economic analyses and investment planning [13; 17].

Setting the task. Current and evolving ENTSO-E requirements include fault-ride-through (LVRT/HVRT), P/Q control (Volt-VAR/Volt-Watt), ramp-rate constraints, primary and secondary frequency control (FCR/FRR), as well as harmonic, flicker, and distortion limits. Converter-based generating units must maintain low short-circuit power (weak grids) and under disturbance conditions, which increases the importance of dynamic models (RMS/EMT) and compliance validation during commissioning and operation [5; 8].

As export power and distances from shore increase, the share of HVDC (VSC/MMC) increases, providing independent active/reactive power control, improved stability in systems with decreasing inertia, and reduced losses on long routes. Internal farm networks are being upgraded from 33 kV to 66 kV, resulting in reduced losses and fewer distribution bays. Market reports also point to the need for standardization of maritime interfaces and coordination with transmission grid operators [18; 21]. In the North Sea and Baltic Sea regions, the concept of meshed/multi-terminal HVDC with multi-node and multi-vendor connections is being developed. A key issue is multi-vendor interoperability (control compatibility, DC protection, communication standards, and FAT/SAT testing), which is addressed, among others, by the InterOPERA program (technical framework, specifications, verification procedures) [6; 10].

To ensure frequency and voltage stability in a converter-dominated system, TSOs/DSOs and offshore grid operators expect grid-forming capabilities: converter operation as a "voltage source" (VSM/droop/matching control), synchronization without relying solely on PLLs, provision of short-circuit power, black starts, and immunity to interactions with other converters and HVDC. ENTSO-E identifies this as a research and implementation priority for 2024–2034 [5], and offshore integration reviews provide practical implications for the selection of control, filtering, and coordination with HVDC [17].

A modern farm control unit implements transmission system operator commands (AGC/availability), distributes P/Q references to turbines, enforces ramp-rate and power factor PF profiles, and manages curtailment and network constraints (voltage, cable currents, transformer thermals). In practice, wind farms increasingly provide system services – from frequency regulation to voltage support – and acceptance test requirements include both RMS and EMT scenarios (fast disturbances, harmonics, converter-HVDC interactions) [5; 8; 18].

A large share of converters requires: designing filtration and resonance damping (cables, transformers, filters); scanning impedance at the load (current path stability for harmonics); coordination of P/Q control algorithms between turbines, the farm, and HVDC terminals to avoid oscillations and uncontrolled reactive power flows [5; 8; 18]. Integrating BESS/LDES at the farm's coupling point increases flexibility, enabling FCR/FRR, fast-frequency response, ramp smoothing, power profile firming, and curtailment reduction. Operational evaluations and scorecards confirm the possibility of stable provision of such services with proper management of degradation and the temperature profile of the storage system [15]. The model benefits and parameterization for long-term scenarios are well described in the NREL ATB 2024 reference sets [13].

Farm-to-grid integration is entering a stage where grid-forming capabilities and HVDC interoperability are becoming as critical as classic FRT requirements and P/Q control. For offshore projects, with power scaling and increasing distances, HVDC is the default solution, and for the EU market, it is a prerequisite for constructing meshed offshore grids. Onshore and offshore, plant-level control and (increasingly often) energy storage facilities determine the ability to provide ancillary services, which enhances project bankability and system stability [5; 6; 8; 10; 13; 15; 18].

Presentation of the main material. AI/ML is key in four areas: wind and production forecasting (nowcasting 5–30 min, short-term 1–48 h, medium-term up to 7 days); fault diagnosis and component RUL estimation from SCADA/vibration/thermal data; digital twins (drivetrain, blades, pitch/yaw systems); farm-level control – including wake steering and coordination of active/reactive power and grid constraints (often in model predictive control (MPC)/ reinforcement learning (RL) schemes and taking into account operational constraints) [8; 18; 21; 22].

In practice, SCADA series (P, Q, v_{wind}, ρ, θ_{yaw}, $T_{nacelle}$), meteorological data (stations/lidars, NWP), qualitative signals (curtailment, alarms), and calendar features are combined. Models: from "classic" (GBM, RF) through LSTM/GRU to Transformers (temporal encoders, attention with NWP data), often in hybrid systems (nowcast → short-term cascades) [1; 23]. Validation: serial (walk-forward), without time leakage; MAE/RMSE/nMAE metrics, for probabilistic versions: pinball loss, CRPS, quantile calibration. Reviews from 2024–2025 confirm that the benefits of sequential models increase with data density and quality (SCADA + NWP), and that local features (layout/wake) and ensembling provide advantages [1; 23]. FDD (Fault Detection & Diagnosis) utilizes SCADA features (bearing/gear temperature trends, slip, vibration, currents) and supervised and unsupervised learning methods (classification/anomaly). RUL relies on sequential or Bayesian models, with forecast uncertainty and decision costs (maintenance planning vs. failure risk). Although the review literature focuses primarily on power forecasting, the same ML framework is being transferred to diagnostics; NREL reports identify O&M digitization as one of the pillars of LCOE reduction [1; 18].

Digital twins (DT) combine physical models (aerodynamics/structure) with data models (ML) and SCADA/vibration streams, enabling load estimation, drift detection, and real-time parameter updates (so-called "physics-ML hybrids"). Market and integration reports for offshore applications note accelerated digitalization, which supports service planning and operations in decreasing inertia networks [8; 18]. Wake steering – yaw/pitch coordination at the farm level minimizes wake losses and - with weather/layout data – allows for increased AEP when controlling blade and gearbox loads. NREL market research and studies, as well as WES publications, demonstrate that wake steering has significant value potential in the US energy markets and is a candidate for an operational standard for modern wind farms [21; 22]. In real-world implementations, algorithms must respect grid codes (ramp-rate limits, volt-variable, and frequency-of-transfer (FRT)) and interoperability with HVDC (offshore). Therefore, in practice, MPC with constraints and/or RL policies trained on EMT/RMS simulators are used, followed by safety rules and operator supervision [5; 8; 18].

Data pipeline and machine learning operations (MLOps) (implementation practice): data ingest and quality: SCADA standardization, outlier detection, gap-filling, dataset versioning; feature store and experiments: feature engineering automation, experiment tracking, and distribution drift validation (data/model drift); model risk and interpretability: SHAP/Permutation for array models; for sequences - time window analysis (saliency) and counterfactual testing; operation: online metric monitoring (nMAE, CRPS), degradation alarms, periodic retraining, and compliance auditing. This framework is consistent with the integration trends (TSO requirements, P/Q control quality, HVDC operation) described by ENTSO-E and NREL [5; 8; 18].

Key challenges include: data availability and standardization (making SCA-DA available for benchmarking – Table), generalization across farms (transfer learning), integration with grid and HVDC codes, and co-optimization with storage facilities (firming/provisioning FCR/FRR), as confirmed by integration reports and storage facility performance assessments [5; 8; 13; 15].

NREL research indicates that wake steering can increase energy yield and reduce land occupancy by as much as to several dozen percent, depending on the location and market [6; 10; 20].

In practice, three main variants are encountered: co-located (the storage facility and the wind farm share a connection), behind-the-meter (ESS "behind the meter" of the wind farm, with full control coordination), and front-of-the-meter (ESS as an independent resource at the same grid node). Each option differs in billing rules, connection constraints, and service mix (energy + FCR/FRR/FFR, voltage regulation, black-start) [13; 15].

Value added and system services. Wind + ESS hybridization: smoothes the power profile and reduces curtailment/wind-spillage; enables the provision of frequency containment reserve (FCR)/ frequency restoration reserve (FRR)/ fast frequency response (FFR), voltage services, and daily arbitrage; improves bankability (reduced revenue risks, better alignment with grid codes), which is reflected in LCOE/LCOS analyses and market scenarios (Lazard, NREL ATB; operational evaluations) [11; 13; 15].

Table. List of typical tasks and metrics [own work]
Таблиця. Перелік типових завдань і показників оцінювання [власна розробка]

AI Task	Input Data	Horizon	Models	Metrics	Notes/SOTA
Power forecast	SCADA, meteo, lidar	15 min–48 h	LSTM/GRU, Transformer	MAE/RMSE/nMAE	Transformers, hybrid MTL
Fault Detection	SCADA, Vibration, Temperature	Continuous	Autoencodery, CNN, XGBoost	F1/AUC	Explainable AI for Alarms
Component RUL	Running times, workloads	Days–months	Bayes, RNN, survival	MAPE, Brier	Models with uncertainty
Wake control	Wind roses, layout	Online	MPC/RL + FLORIS	ΔAEP, obgravity	Increased AEP, reduced workload

Storage technologies – status and parameters: BESS (Li-ion/LFP; ascending Na-ion): mature supply chains, fast response (ms–s), typical times 0.5–4 h; impact on LCOS determined by C-rate, temperature, cycle depth, and aging profiles. DNV reports and New York State Energy Research and Development Authority (NYSERDA) evaluations provide current observations on degradation, safety, and operational efficiency [4; 15]; LAES / CAES (LDES): longer times (multiple hours/day), no electrochemical degradation, but lower η round-trip; literature reviews present efficiency ranges, TRL status, and design bottlenecks [2; 3]; PHS (Pumped-Storage Hydropower): bulk resource, high power, proven reliability; design-dependent costs and location considerations [9; 13]; P2X/H□: conversion of wind surpluses to hydrogen (electrolysis) and further use (ammonia, heat, mobility or el-el recombination via fuel cells/GT). Provides cross-sectoral flexibility at the expense of lower el-el cycle efficiency; system and cost approaches are discussed in cost and scenario reports [9; 13].

Typical ranges (indicative, according to reviews and reports): BESS Li-ion/LFP: η ~ 85–92 %, ms–s response, 4–10,000 cycle life (depending on profile); decreasing costs, but sensitive to WACC and BoS [4; 11; 13; 15]; LAES: η ~ 55–70 %, 1-minute response, high mechanical durability; attractive for LDES and cold climates [2; 3]; CAES/AA-CAES: η ~ 45–70 % (higher for adiabatic concepts), 1-minute horizon; geological requirements or cost of pressure storage [2; 13]; PHS: η ~ 70–85 %, s–min response, very high durability; location constraints [9; 13]. For wind farms, the most commonly considered are BESS 1–2 h (firming, FCR/FRR) and LDES 6–12 h (LAES/CAES/PHS – trough/peak shift; daily-seasonal integration). The heuristic: $E_{ESS} = P_{ESS} \times t_{duration}$, and P_{ESS} is selected based on the analysis of the ramp distribution and the farm's "curtailment" profile (SCADA + NWP) [13; 15].

Control and mixed-integer programming (MIP)/MPC include: SoC management (system service slots vs. arbitration); respecting ramp-rate limits, P/Q, and connection constraints; coordination with the HVDC (offshore) and WPP controller of the farm, usually implemented by MPC (with constraints) or MIP/rule-based schedules supported by prediction (SCADA + NWP). In practice, operational supervision (degradation, temperature, BMS) and "derating" of services are necessary to maintain the guarantee [13; 15; 18].

The location of the storage (behind/before the meter) determines the allocation of losses and revenues (energy vs. ancillary services). In offshore, the integration of ESS ↔ HVDC and 66 kV voltages in in-farm cables is growing in importance, requiring consistency between P/Q algorithms and constraint mechanisms (cable/transformer thermal management) [8; 18].

Operational reports (NYSERDA) and industry assessments (DNV) emphasize requirements for fire safety, gas detection, fire insulation, emergency discharge strategies, and compliance (acceptance testing, monitoring) – key for operator/insurer acceptance [4; 15].

The LCOE of wind energy and the LCOS of storage systems together form a value stack: arbitrage, ancillary services, penalty reduction/curtailment, and incentivized delivery profiles (PPA/service markets). Lazard and NREL ATB indicate that profitability depends on WACC, service prices (FCR/FRR), grid tariffs, and the expected operating profile (number of cycles) [11; 13].

From a risk perspective, key factors include performance guarantees (calendar and cyclical), degradation (temperature/C-rate), parts availability, and, in offshore applications, service logistics and integration with HVDC. Operational evaluations (NYSERDA) provide empirical performance and availability indicators for ESS fleets, making financial models realistic [15].

Conclusions. The cost competitiveness of wind energy continues to be strong. Onshore wind remains in the lower cost range for new capacity (weighted LCOE ≈ $0.034/kWh globally). The cost is primarily influenced by CF, WACC, and execution risks. Capacity scale and supply chain maturity are improving, especially for offshore wind (12-20+ MW/turbine). However, costs and project timelines are sensitive to factors such as logistics, weather conditions, and the availability of installation vessels. HVDC is becoming the standard method for exporting offshore power, and the shift to meshed/multi-terminal systems requires interoperability among various vendors (InterOPERA) and standardized FAT/SAT/HIL testing. To ensure the stability of low-inertia systems, it is essential to maintain compatibility between grid-forming technologies and converters. Harmonized testing profiles and certification requirements at the WTG/WPP/HVDC levels must be established. AI is now being integrated into operations, achieving the best results when combining forecasting methods (such as LSTM/GRU/Transformers) with FDD/RUL assessments and wake steering techniques. Success is measured not only by the change in ΔAEP but also by the effects on service profiles and network constraints. Hybridization with energy storage (primarily BESS 1-2 h, and for LDES: LAES/CAES/PHS) enhances the energy value by providing firming, FCR/FRR/FFR. This approach reduces curtailment and increases bankability, while also requiring reliable coverage for degradation and safety within the LCOS. February

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