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ANALYSIS OF THE EFFICIENCY OF A BI-ROTOR WIND POWER INSTALLATION FOR AUTONOMOUS POWER SUPPLY SYSTEMS

АВТОНОМДЫ ЭЛЕКТРМЕН ЖАБДЫҚТАУ ЖҮЙЕЛЕРІНЕ АРНАЛҒАН БИРОТОРЛЫ ЖЕЛ ЭНЕРГЕТИКАЛЫҚ ҚОНДЫРҒЫСЫНЫҢ ТИІМДІЛІГІН ТАЛДАУ

АНАЛИЗ ЭФФЕКТИВНОСТИ БИРОТОРНОЙ ВЕТРОЭНЕРГЕТИЧЕСКОЙ УСТАНОВКИ ДЛЯ АВТОНОМНЫХ СИСТЕМ ЭЛЕКТРОСНАБЖЕНИЯ

M.B. Tustykbayev [1]*, **B.N. Absadykov** [1], **E.S. Askarov** [2]
[1]Kazakh National Research Technical University named after K.I. Satbayev University, Almaty, Kazakhstan
[2]International University Of Transportation And Humanities, Almaty, Kazakhstan
*Corresponding author: Bakhyt Absadykov, e-mail: b.absadykov@satbayev.university

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wind turbine, small-scale distributed generation, autonomous power supply, bi-rotor turbine, Betz limit, Digital Twin, isolated microgrid, energy storage, power coefficient.

ABSTRACT
This work presents an analysis of ways to improve the efficiency of low-power autonomous power supply systems through the selection of the optimal aerodynamic and electromechanical design for wind turbines. Based on a literature review and theoretical concepts expanding upon the classical Betz limit, the study examines methods for overcoming operational challenges in isolated microgrids under turbulent and low-wind conditions, as well as approaches to assessing battery degradation. The potential feasibility of achieving a power coefficient of up to 81.4% in two-stage turbines is substantiated. The scientific novelty lies in the comprehensive analysis and conceptual identification of the coaxial counter-rotating bi-rotor configuration as the most promising solution for small-scale distributed generation. The practical significance of the work consists in systematizing data on the potential of integrating Digital Twin technology to optimize aerodynamic performance, enable predictive monitoring, and facilitate intelligent energy storage management, which conceptually elevates wind turbines to the class of highly reliable systems.

Түйінді сөздер:
жел энергетикалық қондырғысы, шағын үлестірілген энергетика, автономды электрмен жабдықтау, биროторлы турбина, Бец шегі, цифрлық егіз, оқшауланған микрожелі,

ТҮЙІНДЕМЕ
Бұл жұмыста жел энергетикалық қондырғыларының оңтайлы аэродинамикалық және электромеханикалық схемасын таңдау арқылы қуаты шағын автономды электрмен жабдықтау жүйелерінің тиімділігін арттыру жолдарын талдау ұсынылған. Әдебиеттерге шолу және классикалық Бец шегін дамытатын теориялық тұжырымдамалар негізінде турбулентті және әлсіз желдер кезінде оқшауланған микрожелілерде пайдалану қиындық-тарын еңсеру әдістері, сондай-ақ аккумуляторлық батареялардың

энергия жинақтағыштар, жел энергиясын пайдалану коэффициенті.

тозуын бағалау тәсілдері қарастырылады. Екі сатылы турбиналарда жел энергиясын пайдалану коэффициентін 81,4 %-ға дейін жеткізудің әлеуетті мүмкіндігі негізделеді. Ғылыми жаңашылдық шағын үлестірілген энергетика үшін ең перспективалы шешім ретіндеосьтес қарсы айналатын биротορлы компоновканы кешенді талдаудан және тұжырымдамалық ерекшелеуден тұрады. Жұмыстың практикалық маңыздылығы аэродинамикалық сипаттамаларды оңтайландыру, предиктивті мониторинг және жинақтағыштарды зияткерлік басқару үшін цифрлық егіз технологиясын енгізу әлеуеті туралы деректерді жүйелеуде жатыр, бұл тұжырымдамалық түрде жел турбиналарын жоғары сенімді жүйелер класына шығарады.

Ключевые слова:
ветроэнергетическая установка, малая распределенная энергетика, автономное электроснабжение, биротoрная турбина, предел Беца, цифровой двойник, изолированная микросеть, накопители энергии, коэффициент использования энергии ветра.

АННОТАЦИЯ
В работе представлен анализ путей повышения эффективности автономных систем электроснабжения малой мощности посредством выбора оптимальной аэродинамической и электромеханической схемы ветроэнергетических установок. На основе обзора литературы и теоретических концепций, развивающих классический предел Беца, рассматриваются методы преодоления сложностей эксплуатации в изолированных микросетях при турбулентных и слабых ветрах, а также подходы к оценке деградации аккумуляторных батарей. Обосновывается потенциальная возможность достижения коэффициента использования энергии ветра до 81,4% в двухступенчатых турбинах. Научная новизна заключается в комплексном анализе и концептуальном выделении соосной контрвращающейся биротoрной компоновки как наиболее перспективного решения для малой распределенной энергетики. Практическая значимость работы состоит в систематизации данных о потенциале внедрения технологии цифрового двойника для оптимизации аэродинамических характеристик, предиктивного мониторинга и интеллектуального управления накопителями, что концептуально переводит ветротурбины в класс высоконадежных систем.

INTRODUCTION

Global trends in wind energy development

The use of the kinetic energy of air masses has a history spanning thousands of years, inextricably linked to the development of human civilization. The first documented evidence of wind power to propel sailing vessels on the Nile River dates back to 5000 BC, and by 200 BC, simple wind-powered water pumps were already being used in China to irrigate agricultural land. During this same period, the first vertical-axis windmills appeared in what is now Iran and Afghanistan, used for grinding grain in arid climates. In the 11th–13th centuries, these technologies reached Europe: Dutch engineers created massive wind pumps to drain lakes and reclaim land from the sea, and windmills became a vital driver of Europe's pre-industrial economy.

The transition from purely mechanical work to electricity generation occurred in the late 19th century. The first experimental wind turbines were built by Austrian Josef Friedländer in 1883, Scottish professor James Blyth in 1887, and American Charles Brush in 1888. Following the oil crisis of the 1970s, interest in wind energy as an independent energy source increased exponentially, spurring the development of large industrial turbines.

The first quarter of the 21st century has become an era of global energy transition. Awareness of the climate threats associated with greenhouse gas emissions and the depletion of readily available hydrocarbon reserves have placed wind energy at the forefront of decarbonization of the global economy. The evolution of the industry over the past twenty-five years has demonstrated unprecedented growth rates. According to official data from the Global Wind Energy Council (GWEC, 2025), the global wind turbine fleet has exceeded 1.1 TW of installed capacity, with wind currently providing approximately 8% of all global electricity generation.1

A clear geographic polarization is evident: while Europe was the undisputed leader at the turn of the 2010s, by 2025, the dominant position has shifted to Asian countries, primarily China, whose corporations have seized the initiative in the megawatt-scale offshore installation segment and produce more than half of all turbines globally. The technological vector of "big" (utility-scale) wind energy is aimed exclusively at scaling unit capacity: rotor diameters of modern offshore machines already exceed 250 meters, and the capacity of a single unit reaches 15-18 MW. However, this gigantomania is accompanied by an exponential growth of problems. The installation of such giants requires unique vessels, the transportation of blades by land is practically impossible without the reconstruction of road infrastructure, and the issue of recycling used composite blades (made of fiberglass and carbon fiber) still does not have an environmentally friendly and cost-effective mass-scale solution.

Specifics and challenges of small-scale distributed generation

In the shadow of gigantic offshore and onshore wind farms lies an equally important sector: small-scale distributed energy (Small Wind), aimed at independent consumers (Tarasiuk et al., 2025; Babina, 2012). In many regions of the world with low population density (Arctic and subarctic zones, high mountains, isolated islands, vast steppe and desert areas), the construction of long power transmission lines from centralized power plants is completely economically impractical. Such autonomous facilities—cell phone towers, meteorological and seismic stations, border outposts, farms, remote villages, and private homes—are in dire need of reliable, independent energy sources. The global market for small wind turbines is expected to reach record levels by 2030, as demand for decentralized energy systems steadily grows (Tarasiuk et al., 2025). Traditionally, diesel generation has been used for such facilities, but the logistics of fuel delivery (often by helicopters or all-terrain vehicles during winter seasons) make the cost per kilowatt-hour astronomical. Wind turbines offer an alternative, but blindly copying "large" wind energy technologies and simply scaling them down has proven to be an engineering dead end. Low-power wind turbines (typically in the range of 1 to 50 kW) are forced to operate in the harsh aerodynamic conditions of the near-surface layer of the atmosphere (at tower heights of 10 to 30 meters). This layer is characterized by extreme turbulence caused by air mass friction with the earth's surface. Here, a pronounced velocity gradient (vertical wind shear) is present, along with numerous aerodynamic shadows and turbulence from buildings, trees, and complex terrain. Moreover, surface winds are characterized by constant, chaotic changes in direction. The priority for an autonomous wind turbine is not generating maximum peak power during hurricane-force winds, but rather the ability to ensure a stable and continuous power supply at low and medium wind speeds (3–6 m/s), which statistically prevail 70–80% of the year in most continental regions. An autonomous station requires absolute operational reliability, as access for repair crews is often impossible for several weeks or months. Any mechanical failure or prolonged downtime due to weak winds leads to deep battery discharge, the shutdown of life support systems, and the need for emergency startup of backup generators (Tarasiuk et al., 2025). This necessitates a fundamental rethinking of classic aerodynamic designs and a transition to innovative multi-rotor concepts.

MATERIALS AND METHODS

Theoretical foundations and comparative analysis of classical WT designs

Wind energy engineering has historically developed within two main paradigms: horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT). Each concept has its own theoretical basis and specific limitations. Horizontal-axis propeller-type wind turbines account for the overwhelming share of the global market. Their aerodynamic principle is based on the generation of lift force when air flows around profiled blades (Babina, 2012; Kashem et al., 2021) The blade profile has an aerodynamic shape, resulting in a higher flow velocity over the convex part of the blade than under the flat part. According to Bernoulli's law, this generates lift, which causes the rotor to rotate. The undeniable advantages of HAWTs include high theoretical efficiency. Modern three-bladed turbines can achieve Cp – wind power coefficient values of approximately 0.45–0.50, which brings them very close to the theoretical Betz aerodynamic limit for a single disk (Betz, 1920; Kashem et al., 2021). They are also characterized by high speed, which reduces the requirements for the multiplier and reduces the generator size. However, for autonomous systems, such installations exhibit a number of critical drawbacks. The most important of these is a catastrophic dependence on flow direction. In surface turbulence, the wind changes direction every second. The attitude control system has inertia and inevitably lags. This results in "oblique flow," which reduces the swept area and causes flow separation at the blades. Experiments have shown that in a turbulent environment, small HAWTs lose up to 40-50% of their design output (Babina, 2012). Destructive gyroscopic moments are additional drawbacks. Alternating cyclic loads during nacelle rotation bend the mast and break out bearings. Furthermore, HAWTs are characterized by high starting speeds (3.5-5 m/s), making them useless in light wind zones. An alternative paradigm is vertical-axis turbines: Savonius and Darrieus rotors (Babina, 2012; Habib et al., 2023). The main advantage of VAWTs for standalone installations is their absolute omnidirectionality. Cylindrical symmetry allows them to capture wind from any direction without the need to rotate the nacelle. The absence of a wind-orientation mechanism increases the overall reliability of the unit. The vertical shaft arrangement allows heavy electromechanical equipment to be located at the very bottom, dramatically reducing the load on the mast and simplifying maintenance (Babina, 2012; Kashem et al., 2021). However, these advantages come with fundamental drawbacks. VAWTs have low overall efficiency. As shown in a comprehensive analysis of the efficiency of horizontal and vertical turbines, Savonius and Darrieus rotors have very high aerodynamic drag coefficients, which significantly reduces their overall efficiency compared to propeller-driven counterparts. As a result, the overall efficiency of VAWTs for real installations is a modest 0.15–0.35 (Babina, 2012; Habib et al., 2023). This specific flow pattern generates strong vibrations. Pulsations in the lift force cause uneven torque, which leads to bearing wear. Finally, classic Darrieus models lack self-starting. When stationary, they cannot spin up on their own, draining the batteries' scarce energy (Habib et al., 2023).

Energy storage systems (Batteries) in autonomous microgrids: The physics of interaction

Justifying the efficiency of any stand-alone wind turbine is impossible without a thorough understanding of the operation of the buffer storage system. A stand-alone wind turbine never directly powers the load. It is integrated into a complex circuit: the wind generator generates alternating current, which is rectified, fed to a battery bank via an intelligent controller, and then converted by an inverter for the load. In this circuit, the battery is the most vulnerable, expensive, and critical element (Tarasiuk, 2025). Deep-cycle traction batteries are used for stand-alone systems. The choice of battery chemistry is dictated by operating conditions. Lead-acid AGM (Absorbent Glass Mat) batteries are characterized by a low initial cost and the ability to deliver ultra-high currents. However, they have a limited service life and are critically vulnerable to chronic undercharging. In calm conditions, the plates quickly become coated with lead sulfate, and capacity drops. Gel lead batteries are more resistant to deep discharges, but require precision from the controller: excess voltage causes gassing and swelling. The most advanced solution is lithium iron phosphate ($LiFePO_4$) batteries, which offer exceptional service life and no memory effect. Engineering calculations for the required capacity of these batteries are based on a comprehensive assessment of load power, runtime, inverter efficiency, Depth of Discharge (DOD), temperature corrections, and the Peukert effect (Kumar, 2023). Despite careful calculations, the most pressing problem remains electromagnetic cogging in permanent magnet generators. In light winds, the kinetic energy of a single rotor in a traditional turbine is simply insufficient to overcome magnetic attraction. As a result, the terminal voltage is zero, the controller cannot open the circuit, and the batteries reach critical discharge. Under such conditions, battery life is reduced several times faster than expected (Kumar, 2023; Tarasiuk, 2025). This makes it vital to transition to multi-rotor concepts with significantly increased starting torque.

Evolution towards spatial and coaxial multi-rotor systems (MRWT)

Understanding the mechanical limitations of a single wind turbine led science to the concept of dividing the swept area—the creation of multi-rotor wind turbines. The idea is to place multiple small rotors on a single support structure, which, according to the square-cube law, reduces overall weight. In recent decades, researchers have been actively modeling various configurations. Trirotor systems create positive aerodynamic interference, tetrarotor systems demonstrate phenomenal reliability due to redundancy, and hexarotor matrices generate a cumulative barrier (Chronis et al., 2022). However, spatial networks are completely unsuitable for small-scale autonomous power generation due to their monstrous design. The abundance of trusses creates colossal drag, and the steering mechanisms experience extreme stress in turbulent conditions. Scientific thought has arrived at an elegant compromise: combining the advantages of multiple rotors but placing them compactly – one behind the other on a single axis. Thus, the concept of a bi-rotor coaxial counter-rotating wind turbine was born (Nardecchia et al., 2021). When discussing the transition to bi-rotor systems, it is impossible to ignore the fundamental contribution of Kazakhstani science. Professor Sh. A. Ershin and his scientific school conducted in-depth theoretical and applied research in the field of vertical-axis bi-rotor turbines (Ershin et al., 2015). Based on their theory of turbulent flow aerodynamics, a team of scientists developed and patented innovative carousel-type wind turbines with two coaxial, autonomous counter-rotating shafts. The practical triumph of these ideas was the creation of the "Bolotov Windrotor" by engineer A. V. Bolotov (Bolotov & Bolotov, 2018). This coaxial turbine achieved a near-perfect efficiency of 48% for vertical-axis systems, capturing flows of any intensity and generating current in winds of only 2 m/s. The experience of their long-term integration proves that the bi-rotor paradigm is the most justified choice for distributed energy.

RESULTS AND DISCUSSION

Justification of the absolute efficiency of the bi-rotor WT (CRWT- Counter-Rotating Wind Turbine)

The selection of the coaxial bi-rotor configuration as the optimal solution for autonomous microgrids is based on three fundamental pillars: an aerodynamic breakthrough, innovative electromechanics, and ideal dynamic balancing.

Aerodynamic superiority: Beyond classical limits

Classical theory mathematically proves that a turbine cannot extract more than 59.26% of the kinetic energy of an air flow (Betz, 1920). When passing through the blades of a single wind turbine, the flow swirls, and the kinetic energy of this parasitic rotation is irretrievably lost in the wake. A bi-rotor system radically changes hydrodynamics. The rear rotor, with reverse-pitch blades and counter-rotating, captures the swirling air mass, "straightens" the flow, and converts the lost energy into shaft rotation. Linear momentum theory, expanded by B.G. Newman, demonstrated that the theoretical power limit for a coaxial system increases to 64% (Newman, 1986). Further theories using Computational Fluid Dynamics (CFD) have shown that with careful selection of induction coefficients, the theoretical maximum for a two-stage turbine reaches 81.4%, which is 22% higher than the Betz limit (Agrawal, 2010; Chantharasenawong, 2008). Counter-rotation causes rapid breakdown of tip vortex sheets, providing intense mixing of air layers and accelerating wake velocity recovery by 46.5% compared to conventional HAWTs (Cioni et al., 2024).

Electromechanical Superiority: Double Rotation Generator

The birotor wind turbine implements a revolutionary paradigm: a generator with a rotating stator (Neagoe et al, 2023; Niu et al., 2022). The front rotor rotates the inductor (magnets), and the rear rotor rotates the armature (windings) in the opposite direction. The relative rotation speed of the magnetic field is equal to the sum of their magnitudes.

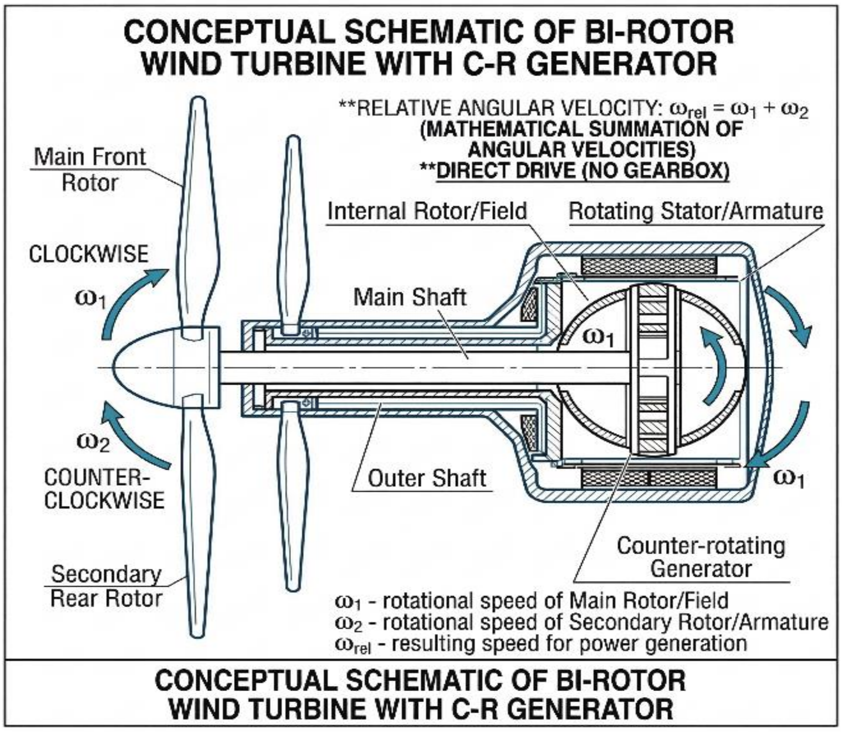

Figure 1. Schematic diagram of a bi-rotor wind turbine with a counter-rotating electric generator (rotor-stator)

Note – compiled by the authors in AutoCad

This doubles the electromotive force, allowing the generator to begin charging the battery at wind speeds half that of a single turbine (1.5–2 m/s) (Neagoe et al, 2023). This speed addition effect eliminates the need for a mechanical gearbox (direct drive) and allows the counter torques to easily break the magnetic sticking of the teeth, providing a soft and early start (Niu et al., 2022).

Dynamic stabilization and compensation of reactive torque

In a single-rotor turbine, the reactive torque tends to twist the mast. In a bi-rotor design, two counter-rotating wheels create two reactive torques directed in opposite directions. With proper design, these torques cancel each other out directly at the generator's central unit (Mihnenkov et al., 2002). The resulting torsional load tends to zero, allowing the use of ultra-light telescopic towers. The mutual cancellation of these torques completely eliminates the occurrence of destructive gyroscopic precession during sudden changes in wind direction.

Application of digital twin technology in the development and operation of bi-rotor wind turbines

The relevance of introducing the digital twin concept into the renewable energy sector stems from the need to dramatically improve the efficiency and predictively forecast autonomous installations (Massel et al., 2019; Kumar et al., 2023).

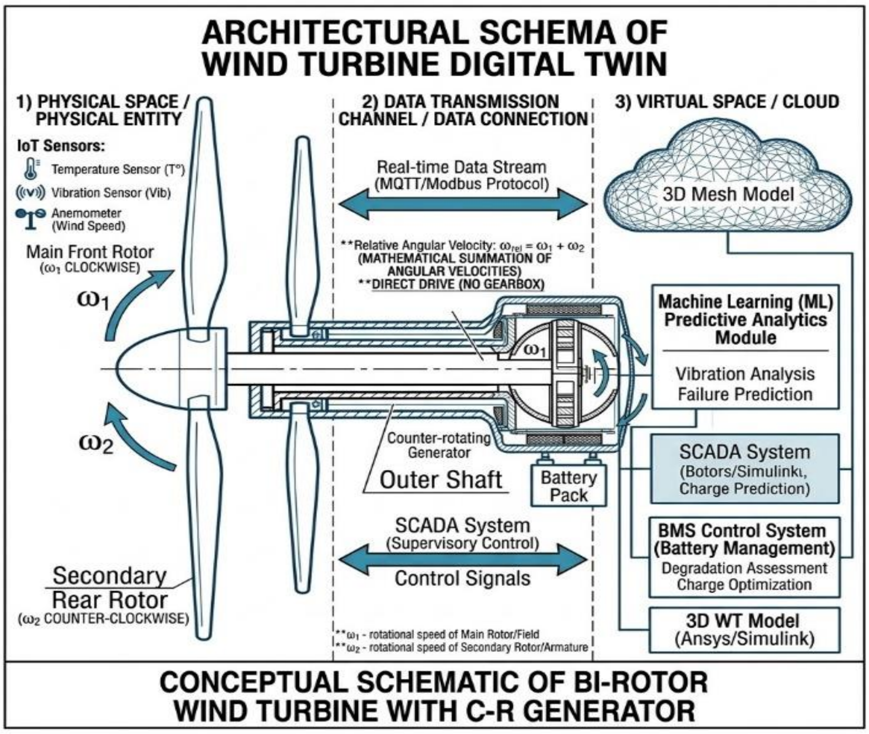

Figure 2. Three-level architecture of the Digital Twin system for an autonomous wind turbine

Note – compiled by the authors in AutoCad

A digital twin is a living, virtual copy of a physical object that synchronizes with it in real time. When developing an autonomous bi-rotor wind turbine, the use of this technology solves several fundamental problems. First, during the design phase, a digital copy of the turbine is created for Computational Fluid Dynamics - CFD simulations, enabling the selection of the mathematically ideal distance between coaxial wind wheels without the need for expensive full-scale prototypes (Massel et al., 2019). Second, during the operational phase, the integration of an IoT sensor network enables predictive maintenance. Neural network algorithms detect microdefects in bearings long before they occur, predicting wear and preventing sudden, emergency failures far from civilization (Kumar et al., 2023). Finally, a crucial function is the intelligent management of energy storage devices. Integrating a digital twin with a Battery Management System (BMS) enables precise assessment of the battery's State of Health (SOH). The twin adapts the controller's operating algorithms to anticipate periods of calm, protecting batteries from deep discharge and significantly extending their lifespan (Kumar et al., 2023).

Environmental and economic justification, acoustic safety, and predictive maintenance strategies for birotor wind turbines

The mass introduction of birotor wind power plants for decentralized power supply requires not only confirmation of their aerodynamic efficiency, but also a comprehensive environmental and economic justification. The life cycle of small-scale power plants is associated with strict standards of acoustic impact on humans and the need to minimize total operating costs throughout the entire 25-year period of operation. Noise pollution is one of the most critical limiting factors when placing wind turbines near farms and private residential areas. According to the recommendations of the World Health Organization (WHO), structural noise is recognized as the second most important environmental risk factor for human health after atmospheric air pollution (Evrard & Ecotière, 2024). Classical horizontal-axial turbines, in addition to the audible aerodynamic noise generated by the separation of the turbulent boundary layer at the trailing edge of the blades, produce a significant amount of infrasound (acoustic vibrations with a frequency below 20 Hz). Since low-frequency waves have an extremely low degree of atmospheric attenuation, they can travel vast distances and penetrate dense building structures, causing people to experience a subjective feeling of internal vibration, headaches, and sleep disturbances (Oštrina et al., 2023). Although the direct threat to health from the infrasound of small wind turbines has not been scientifically proven and remains the subject of discussion, the cumulative effect of the operation of several single-rotor turbines can create zones of acoustic discomfort (Evrard & Ecotière, 2024). In this aspect, birotor architecture demonstrates an undeniable environmental advantage. Firstly, due to the increased energy extraction coefficient, the birotector system develops rated power with a smaller rotor diameter. This proportionally reduces the circumferential velocity at the ends of the blades, which are the main source of high—frequency whistling. Secondly, the mutual rotation of the front and rear impellers acts as an active acoustic dissipator. The periodic intersection of the oncoming blades effectively "breaks up" the low-frequency vortex structures, shifting the spectrum of the generated noise to the high-frequency region. High-frequency sound waves fade rapidly in the atmosphere and are absorbed by the natural terrain. Measurements show that the sound pressure from coaxial installations at a distance of 10 meters rarely exceeds the threshold of 40 dBA, which is comparable to background noise in a quiet office and allows them to be mounted directly on the roofs of residential buildings.The economic feasibility of any generating equipment is assessed using the universal integral indicator LCoE (Leveled Cost of Energy) — the normalized cost of electricity generation throughout the entire life cycle. For isolated Arctic and steppe power systems, which are completely dependent on the complex logistics of fuel delivery, the LCoE index of traditional autonomous diesel generation reaches astronomical values. The integration of renewable energy sources makes it possible to reduce this financial barrier several times. In a comparative analysis of the economic models of classical single-rotor turbines and multi-rotor systems, birotor complexes demonstrate high investment attractiveness. The addition of a second rotor and the introduction of a sophisticated dual-rotation generator increase the initial capital cost (CAPEX) by 15-20% compared to the basic configuration (Oukara et al., 2024). However, in the long run, this surplus is completely eliminated. Due to the accelerated recovery of the satellite footprint and utilization of the energy of the parasitic swirl of the air stream, the annual electricity generation of the biotor system increases by 25-30% while maintaining the same sweeping area. In terms of 20 years of operation, this increase more than compensates for the initial investment, radically reducing the final LCoE and speeding up the payback period of the project. Regular operating and maintenance (O&M) costs account for the lion's share in the cost structure of wind power (Donnelly et al., 2024). In traditional horizontal wind turbines, the most vulnerable, difficult and expensive to maintain link is a mechanical step-up gearbox (multiplier). Gearbox gears are susceptible to micropitting, require expensive regular replacement of synthetic oil and installation of filtration systems to remove condensate and solid particles. Moreover, at temperatures below -30 ° C, the oil thickens, which leads to jamming of the transmission and catastrophic breakdowns. The architecture of a birotor wind turbine with a dual-rotation generator allows you to gracefully solve this problem by implementing the Direct Drive concept. Reliability studies show that gearless turbines have significantly lower failure rates and minimize total operating costs (O&M) throughout their service life. The complete absence of a mechanical transmission puts the installation in the category of maintenance-free systems. For autonomous and remote facilities, where the logistics cost of calling a repair team can be many times higher than the cost of the replacement part itself, switching to direct drive is the only economically feasible solution.The maximum reduction in operating costs in autonomous microgrids is achieved due to the synergy of biotor mechanics and cyberphysical control systems. The classic reactive approach (repair of equipment after its actual breakdown) is absolutely unacceptable for autonomous life support stations due to unacceptably long downtime. At the same time, preventive maintenance (replacement of parts strictly on schedule, regardless of their condition) leads to unjustified overspending of expensive spare parts. The digital twin technology provides a painless transition to a Predictive Maintenance strategy. The integration of heterogeneous data streams (collecting telemetry, vibration accelerometer readings, thermocouples, and encoders) allows the digital model to continuously analyze the physical condition of the unit. Mathematical algorithms detect anomalies and early signs of degradation (for example, fatigue microcracks of blades or insulation defects of windings) long before their transition to a critical stage. The introduction of predictive monitoring based on digital twins reduces total maintenance costs by 47% compared to the reactive approach and increases the operational readiness coefficient of the complex to 99.5%. In the future, the total digitalization of small birotor installations will open the way to blockchain tokenization algorithms for distributed energy resources. This will allow the creation of peer-to-peer microgrids in which excess generated electricity will be automatically redistributed and traded between neighboring autonomous consumers using smart contracts, which will create an additional source of income and accelerate the return on investment.

Structural reliability, mechanical load calculation, and standardization of small birotor wind turbines.

In addition to aerodynamic and electromechanical advantages, the full-scale implementation of birotor wind turbines for autonomous life support systems requires rigorous assessment of their structural reliability, fatigue strength, and precision dynamic balancing. The design and operation of small-capacity wind turbines (with an effective swept area of less than 200 square meters and an operating voltage of up to 1000 V) are strictly regulated by international and adapted national regulations, in particular GOST R 54418.2 (corresponding to the international standard IEC 61400-2) (GOST R 54418.2-2014, 2015). This standard defines uncompromising requirements for the engineering integrity of subsystems, overspeed protection algorithms, and the mechanical strength of components under extreme wind loads (storms) and blade icing. The bi-rotor turbine concept, despite its aerodynamic perfection, poses a number of complex challenges for design engineers. Unlike traditional single-rotor systems, the mechanical "heart" of a bi-rotor unit is a highly loaded coaxial shaft assembly, where the outer hollow shaft rotates counter to the inner solid shaft. With the two rotor masses rotating in opposite directions, the loads on the radial support and thrust bearings are generated not only by the static weight of the generator and the aerodynamic thrust force, but also by a complex set of dynamic factors. This matrix of influences includes high-frequency centrifugal forces, as well as Coriolis effects, which inevitably arise during feathering (changes in the airflow vector and nacelle rotation). Classic analytical formulas for calculating the basic dynamic service life (rating life) of rolling bearings under such conditions prove inadequate. Accurately determining local stresses in the contact zone of rollers and treads under asymmetric loads from two independent aerodynamic masses requires the use of advanced multi-body dynamic modeling (Multi-Body Simulation) and finite element analysis (FEA) (Kim et al., 2017). A critical technological step in ensuring the design life of a bi-rotor design is the precision dynamic balancing of both wind turbines. Even minimal uneven mass distribution (imbalance) in composite blades rotating in opposite directions can generate destructive high-frequency resonant vibrations. In a birotor design, the rotational speeds of the front and rear wheels generate vibrations that are transmitted unimpeded to the central shaft and support mast. This inevitably leads to accelerated fatigue failure of the metal structures, degradation of winding insulation, and premature failure of the dual-rotor generator. Dynamic balancing in the factory is performed based on the construction of precise vector diagrams of mass distribution. This allows for the precise addition of corrective weights to minimize the level of structural noise, eliminate vibrations, and significantly increase the service life of bearing assemblies. The electromechanical reliability of a coaxial system also critically depends on maintaining a precise torque balance. In an ideal operating mode, the electromagnetic braking torque generated by the front wind wheel on the inductor should be almost completely balanced by the counter-reactive torque of the rear wind wheel, transmitted to the stator. The moment equation ensures smooth operation of the entire generator set, eliminates spontaneous twisting of the nacelle around the tower, and prevents damage to the power collector cables. As comprehensive fault-tolerance reviews demonstrate, replacing the traditional mechanical multiplier with a direct drive in a birotor design eliminates the most vulnerable transmission component, radically reducing the likelihood of catastrophic mechanical failures. However, this solution places increased demands on the quality of neodymium magnets, their protection against demagnetization during overheating, and the thermal stability of the generator's armature windings. Thus, an in-depth structural reliability analysis confirms that, with strict adherence to design standards (GOST), the use of finite element modeling, and high-quality dynamic balancing, birotor wind turbines are capable of providing phenomenal mean time between failures, outperforming classic geared counterparts even in the harshest climatic conditions of isolated regions (Umnov, 2018).

CONCLUSION

An analytical review demonstrates that the use of conventional wind turbines in the stand-alone microgrid sector faces insurmountable aerodynamic and design barriers. The evolution of multi-rotor systems has logically led engineering to an optimal compromise—the coaxial counter-rotating (bi-rotor) wind turbine. The rationale for the high efficiency of this solution is based on four key factors: Aerodynamic breakthrough: Overcoming the Betz limit and achieving a theoretical KEUC (Kinetic Energy Utilization Coefficient) of up to 81.4% by utilizing the swirling wake, which provides a significant increase in output.

• Electric synergy with storage: The dual-rotation generator doubles the relative speed, eliminates the multiplier, solves the problem of starting sticking, and begins charging the battery in light winds.

• Dynamic survivability: Mutual compensation of reactive moments and damping of gyroscopic loads relieve the mast and increase vibration resistance.

• Cyber-physical integration: The use of digital twins radically improves airflow optimization, predictive failure forecasting, and battery management.

• Thus, the development and research of a bi-rotor wind turbine using a digital twin is the most promising, economically feasible and scientifically significant direction for further research.

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Авторлар туралы мәліметтер
Информация об авторах
Information about authors

Түстікбаев Мақсат Бақытжанұлы – докторант, Сәтбаев университеті, Қазақстан Республикасы, Алматы қаласы.
Тустыкбаев Максат Бахытжанович – докторант, Сатпаев университет, Республика Казахстан, город Алматы
Tustykbayev Maxat Bakhytzhanovich – PhD student, Satbayev University, Almaty, Republic of Kazakhstan.
e-mail: maqsat.tustykbayev@gmail.com,
ORCID: https://orcid.org/0009-0006-9551-9295,

Абсадықов Бақыт Нәрікбайұлы – техника ғылымдарының докторы, профессор, Сәтбаев университеті, Алматы қ., Қазақстан
Абсадыков Бахыт Нарикбаевич – доктор технических наук, профессор, Сатпаев университет, г. Алматы, Казахстан
Absadykov Bakhyt Narikbayevich – Doctor of Technical Sciences, Professor, Satbayev University, Almaty, Republic of Kazakhstan
e-mail: absadykov@mail.ru
ORCID: https://orcid.org/0000-0001-7829-0958

Асқаров Ерлан Сейтқасымұлы – техника ғылымдарының кандидаты, қауымдастырылған профессор, Халықаралық көлік-гуманитарлық университеті, Алматы қ., Қазақстан
Аскаров Ерлан Сейткасымович – кандидат технических наук, асс. профессор, Международный транспортно-гуманитарный университет, г. Алматы, Казахстан
Askarov Erlan Seitkasymovich – Candidate of Technical Sciences, Associate Professor, International Transport and Humanitarian University, Almaty, Republic of Kazakhstan.
e-mail: erlan57@mail.ru,
ORCID: https://orcid.org/0000-0003-4487-4458