

**ФАН ВА ТЕХНОЛОГИЯЛАР
ТАРАҚҚИЁТИ**
**РАЗВИТИЕ НАУКИ И
ТЕХНОЛОГИЙ**



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РАЗВИТИЕ НАУКИ И ТЕХНОЛОГИЙ

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Ушбу журналда чоп этилган материаллар тахририятнинг ёзма рухсатисиз тўлиқ ёки қисман чоп этилиши мумкин эмас. Тахририятнинг фикри муаллифлар фикри билан ҳар доим ҳам мос тушмаслиги мумкин. Журналда ёритилган материалларнинг ҳаққонийлиги учун мақолаларнинг муаллифлари ва реклама берувчилар масъулдирлар.

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REVIEW OF PERFORMANCE AND APPLICATIONS OF HYBRID WIND TURBINES

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Annotation. This article provides a comprehensive review of the performance, design principles, recent advancements, applications, and challenges associated with hybrid wind turbines, specifically focusing on the integration of Savonius and Darrieus turbine designs. Hybrid turbines leverage the strengths of drag-based and lift-based mechanisms, enabling efficient energy production across a wide range of wind speeds.

Key words: hybrid wind turbines, Savonius-Darrieus turbines, propulsion, lift, wind energy, aerodynamic optimization.

ОБЗОР ЭФФЕКТИВНОСТИ И ПРИМЕНЕНИЯ ГИБРИДНЫХ ВЕТРОВЫХ ТУРБИН

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Аннотация. В данной статье представлен всесторонний обзор эффективности, принципов проектирования, последних достижений, областей применения и связанных с ними проблем гибридных ветряных турбин, с особым акцентом на интеграцию конструкций турбин Савониуса и Даррье. Гибридные турбины используют преимущества механизмов, основанных на тяговой и подъемной силе, обеспечивая эффективное производство энергии в широком диапазоне скоростей ветра.

Ключевые слова: гибридные ветряные турбины, турбины Савониуса-Даррье, тяговая сила, подъемная сила, ветровая энергия, аэродинамическая оптимизация.

GIBRID SHAMOL TURBINALARI SAMARADORLIGI VA QO‘LLANILISHINI KO‘RIB CHIQISH

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Annotatsiya. Maqolada gibrid shamol turbinalarining samaradorligi, dizayn tamoyillari, so‘nggi yutuqlari, qo‘llanilishi va ularga bog‘liq qiyinchiliklar bayon etilgan. Ayniqsa, Savonius va Darrieus turbinalari dizaynlarini birlashtirishga alohida e‘tibor qaratiladi. Gibrid turbinalar tortish va ko‘tarish kuchlariga asoslangan mexanizmlarning kuchli tomonlarini birlashtirib, keng shamol tezligi diapazonida samarali energiya ishlab chiqarishni ta‘minlaydi.

Kalit so‘zlar: gibrid shamol turbinalari, Savonius-Darrieus turbinalari, shamol energiyasi tizimlari, barqaror energiya yechimlari, aerodinamik optimallashtirish.

As the world faces increasing environmental challenges and a growing demand for renewable energy, wind power has emerged as a crucial player in the transition to sustainable energy systems. Among various wind turbine designs, the Savonius wind turbine holds a unique position due to its simplicity, robustness, and ability to function effectively in low wind speeds. Originally invented by Finnish engineer Sigurd Savonius in 1922 [1], the turbine is known for its vertical-axis configuration and drag-based design, making it particularly suited for small-scale and decentralized energy generation. Unlike the more common horizontal-axis wind turbines (HAWTs), which rely on lift forces for rotation, Savonius turbines utilize the difference in drag forces acting on their semi-cylindrical blades. This allows them to operate in low and variable wind conditions, capturing energy from urban wind flows, mountain passes, and other turbulent environments.

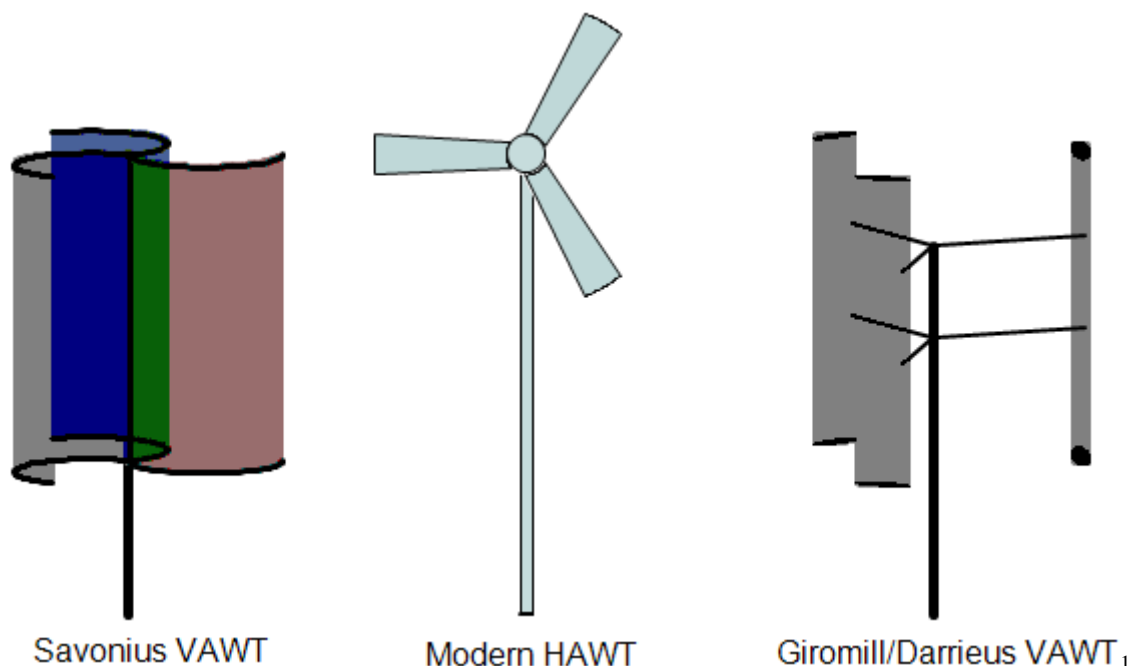


Fig. 1. The Three Principal Types of Wind Turbine: Savonius VAWT, Modern HAWT, and Darrieus VAWT

Despite their lower efficiency compared to HAWTs, their ability to start at low wind speeds and operate independently of wind direction makes them an attractive option for applications where reliability and simplicity are prioritized. Savonius turbines are also gaining attention for their role in urban environments and off-grid solutions. Their compact size and low operational noise make them suitable for integration into infrastructure such as streetlights, building rooftops, and water pumping systems. Recent advancements in computational fluid dynamics (CFD), blade geometry optimization, and hybrid configurations have further enhanced their performance, expanding their potential applications [2]. This review explores the performance of Savonius wind turbines, emphasizing their design characteristics, aerodynamic efficiency, applications, and recent advancements. By delving into these aspects, the study aims to provide a comprehensive understanding of how Savonius turbines can contribute to the growing demand for renewable energy solutions.

Design and Working Principle. The Savonius wind turbine operates on the principle of drag-based aerodynamics. It consists of two or more vertically aligned semi-cylindrical blades that form an "S" shape when viewed from above. This unique blade geometry creates a differential drag force as the wind strikes the turbine. The concave side of the blade captures more wind energy, generating a high drag force, while the convex side faces less resistance, resulting in a net rotational

¹ <https://celloexpressions.com/ts/dynamic-documentation/intro/>

torque. This drag-driven design allows the turbine to rotate even in low wind speeds, making it highly effective in areas with inconsistent or low wind velocity [3].

Unlike horizontal-axis wind turbines (HAWTs) that rely on lift-based aerodynamics, the Savonius turbine's reliance on drag ensures consistent performance in turbulent or multi-directional wind conditions. The vertical-axis configuration eliminates the need for yaw mechanisms, which are typically required in HAWTs to align with the wind direction. Additionally, the simplicity of the design makes Savonius turbines easier to construct, maintain, and deploy in remote or low-resource settings [4].

The efficiency of a Savonius turbine depends heavily on specific design parameters. For example, the overlap ratio, which represents the distance between the two blades, significantly affects the aerodynamics. An optimal overlap ratio (typically between 0.1 and 0.2) can minimize turbulence and maximize torque [5].

Similarly, the aspect ratio (the ratio of blade height to diameter) influences the turbine's swept area and power generation capability. Taller blades with higher aspect ratios capture more wind energy, making them more efficient for power generation [6]. The introduction of innovative design modifications has further enhanced the performance of Savonius turbines. For instance, helical blades, as opposed to traditional straight blades, improve rotational smoothness and reduce vibration, leading to higher efficiency and durability [7]. The integration of hybrid designs, such as combining Savonius turbines with Darrieus turbines, leverages the drag and lift principles to improve overall performance [8].

Despite these advancements, Savonius turbines typically have lower power coefficients compared to lift-based turbines, with typical values ranging from 0.15 to 0.30. However, their ability to start at low wind speeds (as low as 2 m/s) and operate in multi-directional winds makes them ideal for small-scale, urban, and off-grid applications. The straightforward construction and use of locally available materials further enhance their appeal for rural and developing regions [9]. By leveraging these design principles and addressing efficiency limitations through modern innovations, the Savonius wind turbine continues to play a vital role in decentralized and sustainable energy solutions.

Hybrid turbines, while offering significant advantages, face several challenges and limitations that must be addressed to maximize their efficiency and applicability. One of the primary challenges is the increased design complexity. Hybrid turbines integrate multiple systems, such as Savonius and Darrieus designs, each with distinct aerodynamic principles. Ensuring these systems work harmoniously rather than interfering with each other requires advanced engineering and optimization. Aerodynamic interactions between the drag-based and lift-based components can cause inefficiencies if not properly managed, and determining the optimal proportions of each system to maximize performance across varying wind conditions necessitates detailed computational simulations and physical testing.

This complexity extends to the structural design, as the combined system must maintain stability under different wind speeds and directions. Another significant limitation is the higher initial cost associated with hybrid turbines. These systems require more materials than standalone designs, increasing costs for blades, shafts, and structural supports. Additionally, the sophisticated design process, which often involves extensive testing and advanced modeling, further adds to the expense. Manufacturing hybrid turbines typically involves higher precision and quality control standards, which can also elevate costs. Maintenance expenses are another concern, as the combined system has more moving parts, potentially leading to higher wear and tear over time.

Operational challenges also arise with hybrid turbines. The added weight of integrating two systems can strain the supporting structure, bearings, and foundation. This issue becomes particularly significant in larger-scale hybrid turbines where the overall mass increases substantially. Furthermore, the scalability of hybrid turbines is limited by their complexity, making them less feasible for large-scale power generation applications. They are generally more suited to

small- to medium-scale installations, such as urban or off-grid settings, where their combined strengths can be fully utilized. Efficiency optimization is another limitation, as hybrid turbines are designed to operate across a wide range of wind speeds and conditions. While this adaptability is advantageous, it can result in suboptimal performance under specific conditions where a single-design turbine might excel.

Achieving a balance between the low-speed performance of Savonius components and the high-speed efficiency of Darrieus components is a continuous challenge for designers. Despite these challenges, hybrid turbines represent a promising technology for sustainable energy generation. Continued advancements in materials, computational modeling, and manufacturing techniques are helping to mitigate these limitations. Researchers are exploring lighter and stronger materials to reduce weight, as well as innovative blade designs to improve aerodynamic efficiency. By addressing these challenges, hybrid turbines have the potential to play a significant role in the renewable energy sector, particularly in areas with variable wind conditions. However, overcoming their inherent limitations remains critical to their broader adoption and long-term success.

Recent advancements in hybrid wind turbine technologies have significantly improved their performance, efficiency, and applicability in various settings. One of the most notable innovations is the use of helical blade designs in Savonius-Darrieus hybrid turbines. Unlike traditional straight blades, helical blades provide smoother rotation and minimize pulsations, which not only improves aerodynamic efficiency but also reduces mechanical stress on the turbine's structure. This advancement has been shown to increase the power coefficient and durability of hybrid turbines, making them more reliable in both urban and remote applications [10].

Computational Fluid Dynamics (CFD) simulations have played a critical role in optimizing hybrid turbine designs. Advanced modeling techniques now allow engineers to simulate complex aerodynamic interactions between the drag-based and lift-based components of hybrid turbines. These simulations enable the fine-tuning of blade geometry, overlap ratios, and turbine dimensions, which enhances performance while minimizing turbulence and energy losses [11].

Another significant area of advancement is the development of lightweight and high-strength materials. The use of composite materials, such as carbon fiber and reinforced polymers, has led to a reduction in the overall weight of hybrid turbines while maintaining their structural integrity. These materials not only improve the turbine's mechanical efficiency but also extend its lifespan, reducing maintenance costs over time. Additionally, innovations in manufacturing processes, such as 3D printing, have facilitated the production of complex and precise turbine components at a lower cost [12].

Hybrid turbines are also benefiting from the integration of smart technologies. Sensors and monitoring systems are now being incorporated into turbine designs to provide real-time data on performance, wind conditions, and mechanical stress. This data can be analyzed using machine learning algorithms to optimize the operation of hybrid turbines, ensuring maximum energy output under varying conditions. Furthermore, these systems can predict maintenance needs, reducing downtime and preventing costly repairs [13].

Hybrid configurations have also become a focus of research, with efforts to combine different types of turbines, such as vertical-axis Savonius and horizontal-axis Darrieus, to leverage the strengths of each design. Some hybrid turbines now feature adaptive systems that adjust their operation based on wind conditions, switching between drag and lift mechanisms as needed. This adaptability has significantly widened the operational wind range of hybrid turbines, making them suitable for regions with unpredictable wind patterns [14].

Lastly, the coupling of hybrid turbines with energy storage systems has emerged as a key advancement. By integrating batteries or flywheel storage, hybrid turbines can store excess energy generated during high wind conditions and release it during periods of low wind, ensuring a consistent power supply. This innovation addresses one of the most critical challenges in wind energy systems—intermittency—and enhances the reliability of hybrid turbines for standalone and

grid-connected applications [15]. These advancements collectively demonstrate the potential of hybrid wind turbines to become a cornerstone of renewable energy solutions. With continued research and development, hybrid turbines are expected to play a more significant role in addressing global energy challenges, particularly in decentralized and off-grid systems. However, further work is needed to optimize their scalability and reduce costs to make them more accessible for widespread adoption.

Applications of hybrid wind turbines are diverse and continually expanding as advancements in design and technology enhance their adaptability and efficiency. One of the most common applications of hybrid turbines is in small-scale power generation, where their ability to operate efficiently in low and variable wind conditions makes them ideal for powering individual homes, small businesses, and off-grid installations. In rural and remote areas, hybrid turbines are often employed to supply electricity to communities that lack access to conventional power grids. Their low maintenance requirements and robust design make them particularly well-suited for such settings, where access to repair and replacement parts may be limited [16].

In urban environments, hybrid wind turbines are gaining traction due to their compact size, low noise levels, and ability to harness wind energy in turbulent conditions. They are increasingly integrated into the infrastructure of smart cities, mounted on rooftops, streetlights, and buildings. These installations not only generate renewable energy but also contribute to the aesthetic and environmental appeal of modern urban landscapes. Additionally, hybrid turbines are often paired with solar panels to create hybrid renewable energy systems, further enhancing their efficiency and reliability in urban applications [17].

Another significant application of hybrid turbines is in water pumping systems. Their ability to provide consistent torque, even at low wind speeds, makes them ideal for mechanical water pumping in agricultural and rural contexts. In many parts of the world, particularly in developing regions, hybrid turbines are used to draw water for irrigation and drinking purposes, reducing dependency on fossil fuels and grid electricity [18].

Hybrid turbines are also finding use in coastal and offshore wind energy projects, where they can take advantage of strong and consistent wind patterns. The robustness of their design allows them to withstand harsh environmental conditions, such as saltwater corrosion and high wind speeds, making them an attractive option for offshore renewable energy systems. These turbines can be deployed as standalone units or as part of larger wind farms to increase energy generation capacity [19].

In the industrial sector, hybrid turbines are employed to provide power to small- and medium-scale enterprises, particularly in regions with unreliable grid electricity. Their ability to store excess energy through integrated battery systems ensures a continuous power supply, reducing operational disruptions and energy costs. Similarly, hybrid turbines are used in military applications, where reliable and portable energy systems are crucial for field operations in remote areas [20].

Hybrid turbines also play a vital role in research and educational settings, where they are used as demonstration tools for studying renewable energy systems. Their relatively simple design allows students and researchers to explore the principles of wind energy conversion, hybrid configurations, and energy optimization techniques. Additionally, they serve as a testbed for innovative designs and materials, contributing to the development of more efficient renewable energy technologies [21]. Hybrid wind turbines offer a wide range of applications that address the growing global demand for clean and sustainable energy. Their versatility, durability, and adaptability make them suitable for use in diverse settings, from rural and remote areas to urban environments and offshore installations. As research and development efforts continue to improve their performance and cost-effectiveness, hybrid turbines are expected to play an increasingly important role in achieving global energy sustainability.

Conclusion. Hybrid wind turbines represent a significant step forward in the evolution of renewable energy technologies. By combining the strengths of multiple turbine designs, such as the drag-based Savonius and lift-based Darrieus turbines, hybrid systems effectively address many of the limitations inherent in standalone turbines. These turbines provide a unique combination of high starting torque, efficiency across a wide range of wind speeds, and adaptability to varying environmental conditions. Their versatility makes them particularly suitable for decentralized energy generation in remote and rural areas, urban settings, offshore installations, and industrial applications. One of the key advantages of hybrid turbines lies in their ability to operate efficiently in both low and high wind conditions, ensuring consistent energy production in regions with variable wind patterns.

This adaptability is further enhanced by advancements in design, such as helical blades, lightweight materials, and computational optimization, which have improved their aerodynamic performance, reduced mechanical stress, and extended their operational lifespan. Additionally, the integration of smart technologies, including sensors and real-time monitoring systems, has enabled better operational control and predictive maintenance, reducing downtime and enhancing reliability. Despite their numerous advantages, hybrid wind turbines are not without challenges. Their design complexity, higher initial costs, and scalability limitations are areas that require continued research and development. However, these challenges are increasingly being addressed through innovative approaches, such as the use of composite materials, hybrid configurations with solar panels, and the development of modular designs that make hybrid turbines more accessible and cost-effective. The role of hybrid turbines in achieving global energy sustainability cannot be overstated. As the world grapples with the urgent need to transition to cleaner and more sustainable energy sources, hybrid turbines offer a practical solution to meet energy demands while reducing greenhouse gas emissions.

Their deployment in off-grid installations, urban environments, and offshore wind farms demonstrates their potential to diversify and strengthen renewable energy portfolios. Moreover, their application in water pumping, rural electrification, and industrial processes highlights their ability to address critical energy needs across various sectors. Looking ahead, hybrid wind turbines are poised to play an increasingly important role in the global renewable energy landscape. Continued investment in research and development, coupled with supportive policy frameworks and public-private partnerships, will be crucial in overcoming existing limitations and scaling up their adoption.

As advancements in materials, manufacturing, and energy storage systems continue to emerge, hybrid turbines will become even more efficient, reliable, and cost-competitive. In the broader context of global energy transition, hybrid turbines exemplify the innovative solutions needed to address the challenges of climate change and energy security. Their ability to provide clean, decentralized, and adaptable energy solutions makes them an indispensable tool in the pursuit of a sustainable future. By bridging the gap between efficiency and accessibility, hybrid wind turbines have the potential to transform how we harness wind energy, contributing significantly to a greener and more resilient energy system. With their growing role in renewable energy strategies, hybrid turbines will undoubtedly remain a cornerstone in the quest for sustainable development and energy equity worldwide.

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