REVIEW OF EXPERIMENTAL RESEARCH INVESTIGATIONS AND THE WORKING PRINCIPLE OF SMALL VERTICAL AXIS WIND TURBINES
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REVIZIA INVESTIGAȚILOR DE CERCETARE EXPERIMENTALĂ ȘI PRINCIPIUL DE FUNCȚIONARE AL TURBINELOR EOLIENE MICI CU AX VERTICAL

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ABSTRACT
This review paper provides a comprehensive analysis of the working principles of wind turbines, with a specific focus on experimental research studies for Vertical Axis Wind Turbines (VAWTs). Wind turbines are essential in harnessing renewable energy, and understanding their operational mechanisms is crucial for optimizing efficiency and performance. The paper outlines the basic working principles of both Horizontal Axis Wind Turbines (HAWTs) and VAWTs, with a deeper exploration of the latter due to its unique advantages in urban and low-wind conditions used in agriculture. The review critically examines recent experimental research on VAWTs, including various design modifications, aerodynamic performance studies, and energy efficiency improvements. Key parameters such as blade shape, turbine configuration, and site-specific factors are discussed, drawing on findings from experimental setups in laboratory and field conditions. The paper also highlights challenges in scaling VAWTs, including structural integrity, noise reduction, and cost-efficiency. Future trends and advancements in VAWT technology are considered, aiming to enhance their viability as a competitive solution for renewable energy generation in households, companies and agricultural farms. Cost-effectiveness, noise reduction, and structural durability remain significant barriers to the widespread adoption of VAWTs, despite promising advancements. This underscores the need for additional research into scalable designs, advanced materials, and optimal configurations for a variety of environmental conditions.

ABSTRACT
Această lucrare de oferă o analiză cuprinzătoare a principiului de funcționare ale turbinelor eoliene, cu un accent special pe studiile experimentale de cercetare pentru turbinele eoliene cu ax vertical (VAWT). Turbinele eoliene sunt esențiale în valorificarea energiei regenerabile, iar înțelegerea mecanismelor lor operaționare este crucială pentru optimizarea performanțelor. Lucrarea conturează principiul de bază de lucru atât ale turbinelor eoliene cu ax orizontal (HAWT) cât și al clor cu ax vertical (VAWT), cu o explorare mai profundă a acestora din urmă datorită avantajelor unice în condiții urbane și de vânt scăzut ce pot fi utilizate in agricultura. Studiul examinează critic cercetările experimentale recente privind VAWT, inclusiv diverse modificări de proiectare, studii de performanță aerodinamică și îmbunătățiri ale eficienței energetice. Sunt discutați parametri cheie, cum ar fi forma palei, configurația turbinei și factorii specifici locului, bazându-se pe constatările din configurații experimentale în condiții de laborator și de teren. Lucrarea evidențiază, de asemenea, provocările în scalarea VAWT, inclusiv integritatea structurală, reducerea zgomotului și eficiența costurilor. Sunt luate în considerare tendințele și progresele viitoare în tehnologia VAWT, cu scopul de a spori viabilitatea acestora ca soluție competitivă pentru generarea de energie regenerabilă în gospodarii, companii si ferme agricole. Eficiența din punct de vedere al costurilor, reducerea zgomotului și durabilitatea structurală rămân bariere semnificative în calea adoptării pe scară largă a VAWT-urilor, în ciuda progreselor promițătoare. Acest lucru subliniază necesitatea unor cercetări suplimentare privind designurile scalabile, materialele avansate și configurațiile optime pentru o varietate de condiții de mediu.

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INTRODUCTION

Wind energy is a key pillar in the global transition toward renewable and sustainable energy systems, offering a clean and inexhaustible alternative to fossil fuels (*Arutyunov et al., 2017*). With increasing concerns over climate change, energy security, and environmental sustainability, wind turbines have gained widespread adoption as reliable sources of electricity generation. Advances in turbine technology continue to improve efficiency and reduce costs, thereby accelerating their integration into both large-scale power grids and small, decentralized energy systems (*Franković et al., 2001*).

Wind turbines function by converting the kinetic energy of moving air into mechanical energy, which is subsequently transformed into electrical energy (*Hau et al., 2006*). This process involves several key stages:

- *Wind capture*: The turbine blades, designed with aerodynamic profiles, intercept wind flow and convert it into rotational motion. The efficiency of this process depends on wind speed, blade geometry, and orientation (*Kusiak et al., 2010*).

- *Mechanical energy conversion*: The rotational energy of the blades is transferred through the rotor hub and main shaft to a generator, where it is transformed into electrical energy via electromagnetic induction (*Cheng et al., 2014*).

- *Electricity generation*: Within the generator, a system of magnets and copper coils produces an electric current as the rotor turns, which is directed to the grid for consumption (*Kan et al., 2021*).

- *Energy conversion and control*: Most turbines produce alternating current (AC), which is conditioned—typically through transformers or inverters—to match grid requirements. Advanced control systems adjust rotor orientation and blade pitch to optimize performance under varying wind conditions (*Yaramasu et al., 2015*).

- *Transmission and distribution*: Generated electricity is routed through substations and delivered to end users via the electrical grid. In larger wind farms, this process may involve energy storage systems and voltage regulation to maintain grid stability (*Hossain, 2021*).

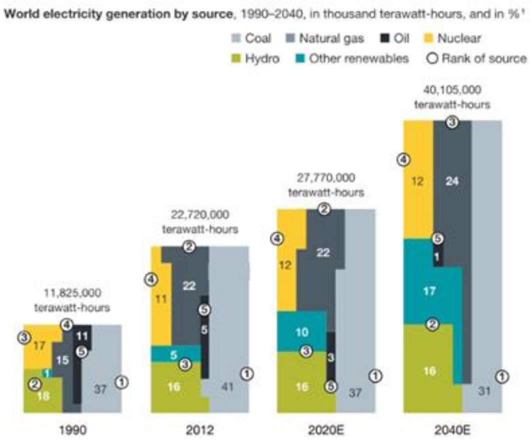

Fig. 1 - Evolution of electricity generation sources
(*www.mckinsey.com*)

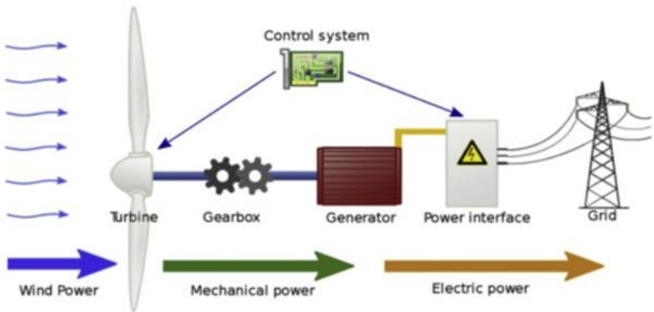

Fig. 2 - The operating principle of wind turbines
(*Gupta et al., 2021*)

While the basic principle remains consistent across all wind turbines, their configurations vary significantly, influencing their efficiency, cost, and suitability for different environments. The two primary types are horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs).

HAWTs are the most prevalent, particularly in utility-scale wind farms. In these systems, the rotor shaft is aligned horizontally, and the blades rotate in a vertical plane (*Mohammadi et al., 2016*). The blade design, often modeled after aircraft wings, optimizes lift-to-drag ratio for maximum energy capture at high altitudes (*Dal Monte et al., 2013*). These turbines are known for their high efficiency and scalability, though they can be challenging to maintain due to their large size and offshore or remote locations.

Table 1

Advantages and disadvantages of Horizontal Axis Wind Turbines (*Eftekhari et al., 2022*)

Advantages	Disadvantages
- *High efficiency*: HAWTs are generally more efficient than other types of wind turbines. - *Proven technology*: They have been in operation for decades, and their performance is well known. - *Large-scale production*: HAWTs can be scaled up for large wind farms, making them ideal for commercial energy production.	- *Complicated maintenance*: HAWTs are often located in remote or offshore locations, requiring significant maintenance and repair costs. - *Noise and visual impact*: These turbines can be noisy and are sometimes criticised for their visual impact on landscapes.

In contrast, VAWTs feature vertically oriented blades that rotate around a shaft perpendicular to the ground. Common designs include the Savonius and Darrieus models. A key advantage of VAWTs is their ability to capture wind from any direction, eliminating the need for yaw mechanisms. Their compact and accessible design makes them well-suited for turbulent, low-wind urban environments (*Kragten, 2004*).

Table 2

Advantages and disadvantages of Vertical Axis Wind Turbines (*Kragten, 2004*)

Advantages	Disadvantages
- *Omnidirectional*: VAWTs can capture wind from any direction, eliminating the need for the turbine to be constantly adjusted. - *Lower maintenance expenses*: Because the mechanical components of VAWTs are located closer to the ground, they are easier to maintain than HAWTs. - *Suitability for urban areas*: Their compact design and ability to operate in turbulent and low-speed winds make them more suitable for urban environments.	- *Lower efficiency*: VAWTs are generally less efficient than HAWTs, especially in large-scale power generation. - *Mechanical complexity*: VAWT designs can be more complex, leading to potential reliability issues and higher production costs.

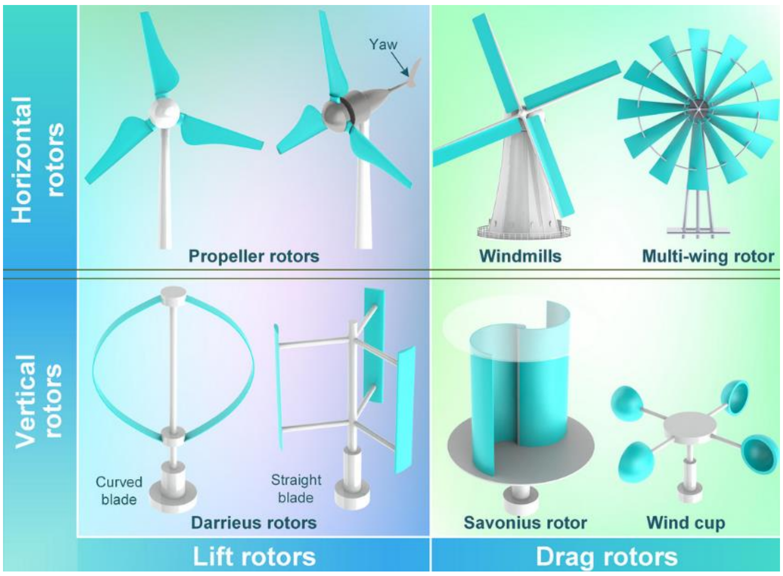

Fig. 3 – Wind turbines types (*Wang et al., 2023*)

A distinct subcategory within wind energy systems is small wind turbines, typically intended for domestic or small commercial applications. These systems are often horizontal-axis designs, though vertical-axis models are also used where spatial or wind conditions favor them. Small turbines are installed on rooftops or in open areas to provide localized power generation.

Table 3

Advantages and disadvantages of Small Wind Turbines (*Probst et al., 2011*)

Advantages	Disadvantages
- *Energy independence*: They allow homeowners or small businesses to generate their electricity and reduce grid dependency.	- *Limited power generation*: small turbines may not generate enough electricity to meet the power needs of larger buildings or multiple homes.
- *Cost-effective for small installations*: For smaller energy needs, these turbines are more cost-effective than large-scale installations.	- *Wind dependence*: These turbines are highly dependent on local wind conditions, which can be variable.

This introduction provides an overview of the principles, configurations, and applications of wind turbines, setting the stage for deeper exploration into their design optimization. In particular, as interest grows in sustainable urban energy systems, vertical-axis wind turbines are attracting renewed attention due to their adaptability and compact footprint. The following sections will focus on modeling and enhancing the performance of such turbines, with a particular emphasis on computational approaches and design refinement.

SPECIFICITY OF WIND TURBINES. WIND TURBINE TECHNOLOGIES

Wind energy has emerged as one of the most popular and rapidly growing renewable energy sources worldwide. Concerns about climate change and the environmental impact of fossil fuels have fueled the need for sustainable alternative resources. Wind turbines stand out from other renewable energy sources due to their efficiency, scalability, and environmental reasons (*Savino et al., 2017*). This section investigates wind turbine technology, focusing on their many varieties, the concepts behind their operation, their advantages, and current technical developments. Wind turbines are divided into two categories: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs) (*Paraschivoiu et al., 2018*). Both types convert the kinetic energy of the wind into mechanical energy that is then used to create electricity. However, their design, application, and efficiency vary greatly.

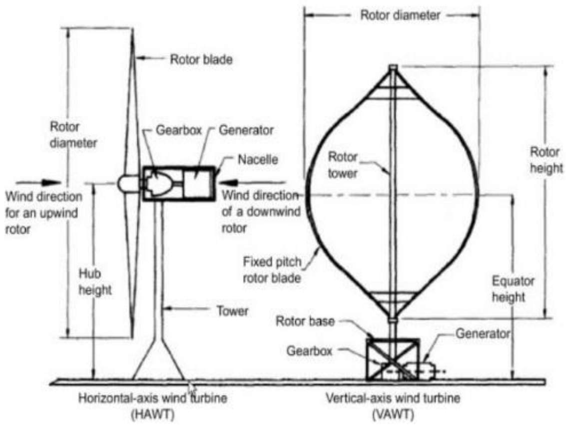

Fig. 4 - The Basics of HAWT and VAWT Configurations (*Ismail et al., 2021*)

Horizontal axis wind turbines are the most common and commonly used in large-scale commercial wind farms. These turbines have their blades attached to a horizontal shaft, and the entire turbine is aligned with the direction of the wind. HAWTs are often considered the most efficient form of wind turbine due to their aerodynamic design (*Sedaghat et al., 2014*). They generally have three blades that are designed to capture the most wind energy. HAWT blades rotate along a horizontal axis and can generate huge amounts of power, making them suitable for use in areas with regular wind speeds, such as coastal or offshore areas. On the other hand, vertical axis wind turbine blades rotate around a vertical axis that is perpendicular to the ground (*Chaudhary et al., 2014*). VAWTs are suitable for areas with irregular or turbulent wind patterns because, unlike HAWTs, they do not require orientation into the wind. Because they can be positioned closer to the ground, VAWTs offer advantages in terms of maintenance, although they are often smaller and less efficient than horizontal ones (*Xisto et al., 2016*). In addition, VAWTs are often quieter and have a smaller aesthetic impact, which may increase their acceptability in residential and urban environments (*Kumar et al., 2018*).

The essential concept behind wind turbines is the transfer of kinetic energy from the wind into mechanical energy, which is then converted into electrical energy by the generator (*Wang et al., 2018*). The operation of a wind turbine can be divided into several parts (*Li et al., 2011*). The first is wind capture, in which wind turbines use enormous blades to capture the kinetic energy of the wind. When wind blows over the blades, it generates lift and drag forces, causing them to rotate (*Schaffarczyk et al., 2017*). This rotational motion powers the turbine generator. The rotating blades are attached to a shaft, which is connected to a gearbox. The gearbox increases the rotational speed of the shaft to reach the speed required by the generator. The mechanical energy is transmitted to the generator and converted into electrical energy (*Keung et al., 2008*).

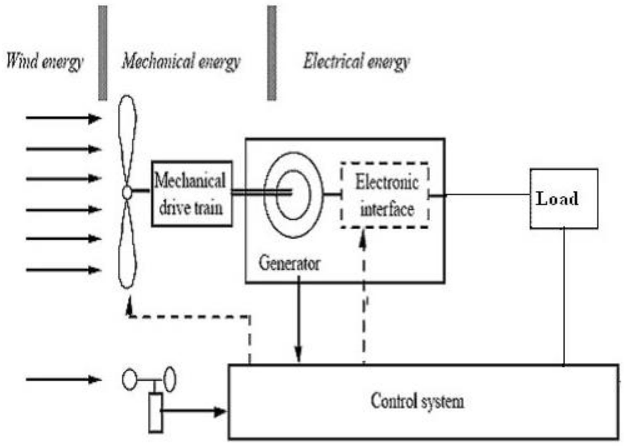

Fig. 5 - Wind energy conversion scheme (*Rambabu et al., 2012*)

The generator, which normally consists of a rotor and a stator, works on the concept of electromagnetic induction. The shaft rotates, causing the rotor to rotate inside the stator, generating energy. The electricity produced is then sent through wires to the grid or to a local power system. Modern wind turbines are equipped with advanced control systems that improve their performance (*Balat et al., 2009*). These systems use wind speed, direction, and other environmental parameters to determine the turbine's orientation, blade pitch, and energy output. This increases efficiency and reduces damage in adverse weather conditions. Due to their many advantages, wind turbines are becoming an increasingly important part of the world's transition to renewable energy. Unlike fossil fuels, wind energy does not emit greenhouse gases or air pollutants while it is operating. Since wind turbines have a low environmental impact, they are a crucial tool in the fight against climate change and reducing the carbon footprint (*Pryor et al., 2010*). In addition, wind energy has become one of the most affordable sources of renewable energy in recent decades due to the huge reduction in costs. The design, materials, and manufacturing methods of wind turbines have improved, making wind energy more competitive with traditional sources such as nuclear, coal, and gas (*Abbasi et al., 2017*).

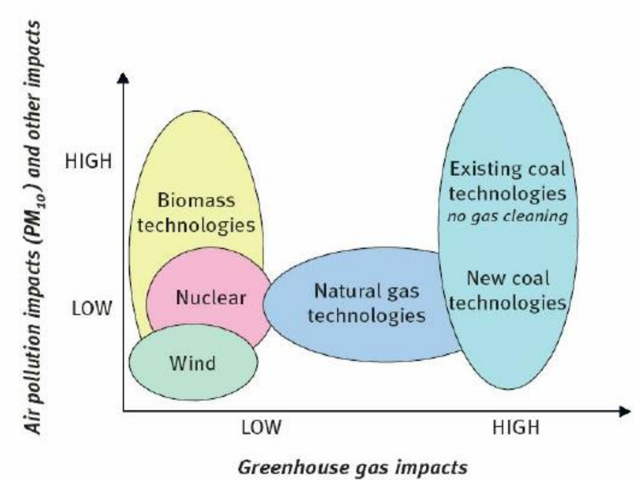

Fig.6 - Comparison of energy sources
(Van Kuik et al., 2008)

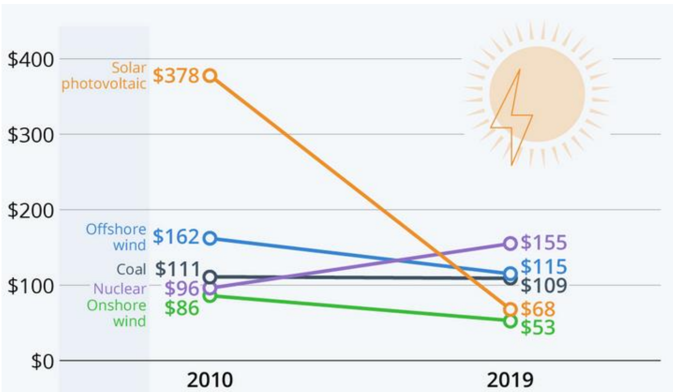

Fig.7 - Decreasing the cost of renewable energy
(*https://www.statista.com/chart/26085/price-per-megawatt-hour-of-electricity-by-source/*)

By investing in wind energy, nations can reduce their dependence on imported fossil fuels, improving their economic stability and energy security.

Producing wind energy locally can help the renewable energy industry create jobs and reduce dependence on international energy markets. Around the world, the wind energy sector has generated millions of jobs in production, installation, operation, and maintenance (*Aldieri et al., 2017*). The need for skilled personnel in a variety of disciplines, including engineering, logistics, and research, is growing with the demand for wind turbines.

In recent years, significant technological developments have taken place in the operation and design of wind turbines. Thanks to these advances, wind energy is now more economical, reliable, and efficient (*Kaldellis et al., 2011*). Some contemporary wind turbines have rotor diameters of over 200 meters, demonstrating the significant increase in wind turbine size. Since offshore wind farms have a lot of space and wind resources, these larger turbines are of great help there (*Bilgili et al., 2022*).

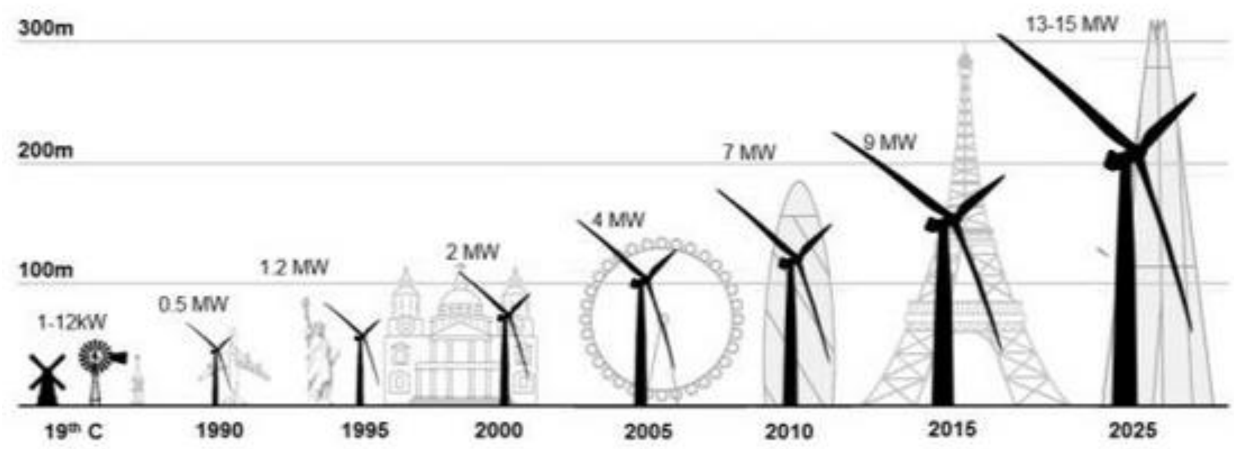

Fig. 8 - Evolution of wind turbine size (*Pisanò et al., 2019*)

Floating wind turbines are an innovative technology that allows wind turbines to be installed in deeper oceans, where conventional fixed-bottom turbines are impractical. These turbines are fixed to the seabed by floating platforms and can be erected in places with strong and persistent winds, far from shore. Floating wind technology has the potential to open up vast new areas for wind energy generation.

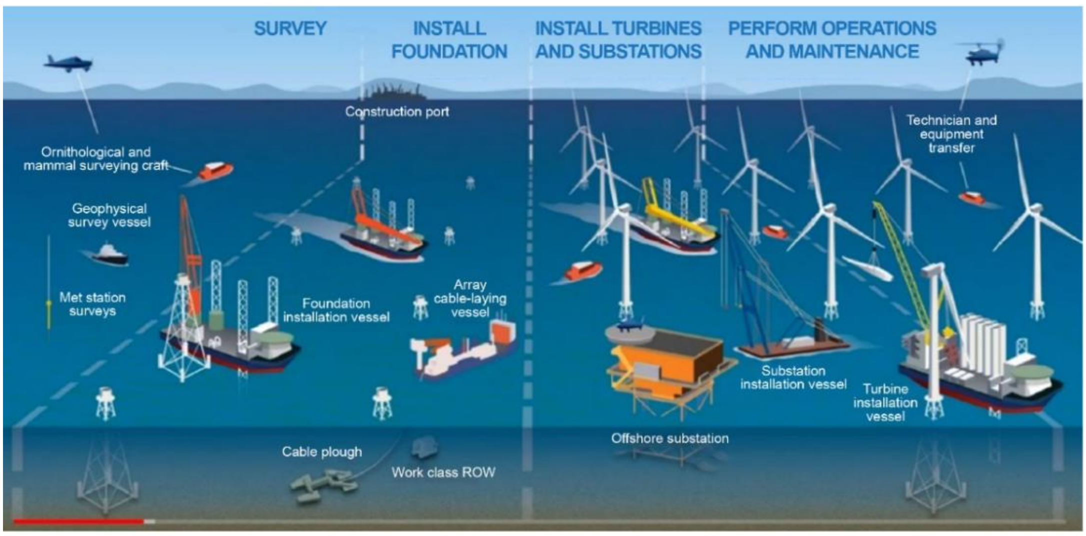

Fig. 9 - Offshore wind turbine installation (*Ryu et al., 2022*)

Because wind power is intermittent, its production is dependent on the availability of wind. However, more efficient integration of wind power into the electricity grid is possible with the development of smart grid technology. Energy storage devices, sophisticated forecasting methods, and wind power can all be used by smart grids to control the fluctuation of wind power and provide a constant and reliable source of energy (*Abbey et al., 2008*).

To increase efficiency, the design of turbine blades has changed dramatically. More wind energy can be captured at lower speeds due to the aerodynamic efficiency, reduced length, and weight of modern blades. Innovative features such as fins, which reduce drag and improve performance, are also included in some blades (*Chehouri et al., 2015*).

In addition to size increases and floating offshore installations, recent breakthroughs in materials science have had a substantial impact on wind turbine performance. The adoption of carbon fiber-reinforced polymers (CFRPs) and other advanced composites has led to lighter yet stronger blades, improving aerodynamic efficiency and durability while reducing maintenance needs (*Sun et al., 2025*). These materials also contribute to the feasibility of longer blades without compromising structural integrity.

Additive manufacturing (3D printing) is beginning to revolutionize turbine component production. It allows for complex, custom geometries that were previously unfeasible and enables localized manufacturing, reducing costs and transportation emissions (*Sivamani et al., 2020*).

Another major breakthrough is the integration of artificial intelligence (AI) and machine learning algorithms in wind turbine control systems. These smart controllers optimize blade pitch, yaw, and even predict maintenance needs based on real-time environmental data and turbine health metrics (*Al Noman et al., 2022*). Predictive maintenance, enabled by AI-driven condition monitoring, significantly reduces downtime and increases turbine lifespan.

Modular turbine designs are also emerging as a way to reduce installation complexity and allow for easier transportation, especially in remote or urban environments (*GU et al., 2021*). In offshore installations, autonomous robotic systems are being developed for turbine inspection, repair, and cleaning, reducing the need for human intervention in harsh marine conditions.

Looking ahead, several trends are poised to define the next generation of wind energy technology:

- *hybrid renewable systems*: Future wind turbines will increasingly be integrated into hybrid energy systems, combining wind with solar, hydrogen production, or battery storage. These systems enhance grid stability and ensure continuous energy supply during low-wind periods (*Mohamed*, 2023).

- *vertical axis wind turbine farm optimization*: As urban and distributed generation grows, VAWTs may see renewed attention. New research into aerodynamic interaction in VAWT arrays is improving their efficiency when placed in close proximity, enabling more compact and urban-friendly wind farms (*Barnes et al., 2019*).

- *bio-inspired blade design*: Nature-inspired designs—like humpback whale tubercles or bird wings—are being mimicked to reduce drag, increase lift, and enhance performance in turbulent wind conditions (*Hassan et al., 2023*).

- *dynamic blade morphing*: Research into smart materials such as shape-memory alloys and piezoelectrics is paving the way for turbine blades that adapt in real time to changing wind conditions, optimizing power capture (*Baghdadi et al., 2020*).

- *end-of-life and recycling innovations*: With sustainability at the forefront, the development of fully recyclable turbine blades and circular economy strategies for decommissioned components will become increasingly important (*Kouloumpis et al., 2020*).

- *high-altitude wind energy* (HAWE): Technologies such as airborne wind turbines (e.g., tethered drones or kites) are being explored to capture stronger, steadier winds at higher altitudes, potentially revolutionizing onshore energy production (*Breban et al., 2020*).

In a short period of time, wind turbine technology has advanced significantly, becoming a major force in the global energy transition due to advances in design, operation, and efficiency. With increasing accessibility and scalability, wind energy could contribute significantly to global energy supply.

Even so, ongoing developments in infrastructure and technology are helping to eliminate obstacles such as intermittency and grid integration. Wind turbines will be essential for reducing dependence on fossil fuels, preventing climate change, and building a sustainable energy future as the globe continues to embrace renewable energy.

WORKING PROCESS OF VERTICAL AXIS WIND TURBINES - COMPARATIVE ANALYSIS OF SAVONIUS AND DARIEUS TURBINES

Wind energy has become one of the most promising renewable energy sources in the modern world as sustainable ways are sought to meet energy demands. The vertical axis wind turbine (VAWT) is a special and often overlooked option among the different types of wind turbines. The VAWT is much more versatile than the horizontal axis wind turbine, which is more popular due to its design, which allows it to harness wind energy from any direction, especially in regions with irregular wind patterns (*Ashwill et al., 2012*).

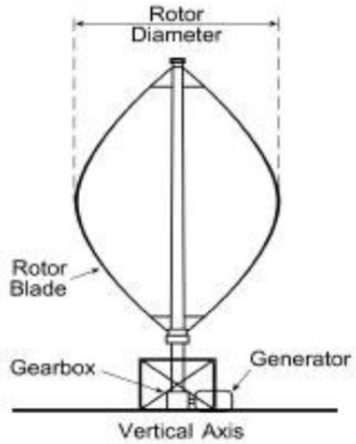

Fig. 10 - VAWT (*Salem, 2016*)

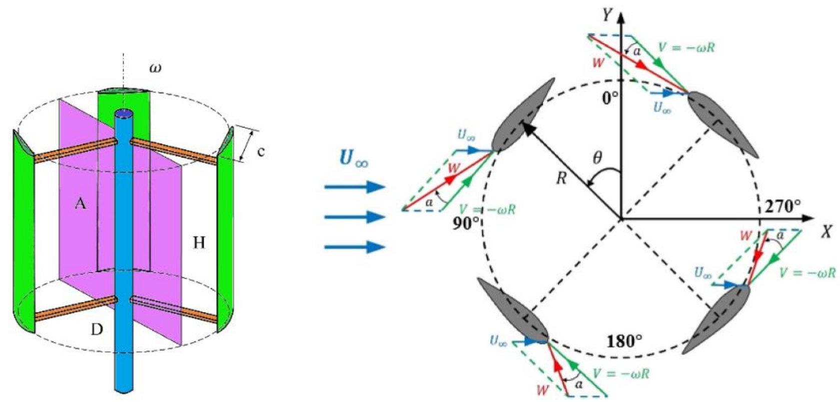

Fig. 11 - Force distribution on a VAWT (*Abbasi et al., 2024*)

The moment the wind hits the blades of a VAWT is when the action begins. The design of a VAWT ensures that it can capture wind energy regardless of the direction of the wind, unlike conventional turbines that must be pointed into the wind. This feature makes a VAWT an excellent option for urban settings where airflow can be disrupted by buildings or other obstacles, and wind flows are erratic.

VAWTs differ fundamentally in their construction in that their blades rotate along a vertical axis instead of a horizontal one. The shape of these blades varies depending on the type of turbine. Similar to the wings of an airplane, the blades in some designs are designed as curved sails that provide lift. In others, the blades are designed to produce drag, much like a cup or spoon that catches the wind. These two types are called Darrieus and Savonius turbines, respectively.

The entire process from wind to electricity is a smooth, uninterrupted cycle. An environmentally friendly alternative to conventional energy sources such as coal or natural gas, the energy produced by VAWTs is clean and renewable. One benefit of this system is that VAWTs are more suitable for residential and urban environments, as they are quieter and less invasive than their horizontal equivalents. Furthermore, compared to traditional turbines, which often have parts located at high altitudes, the VAWT design ensures that its mechanical components are easily accessible, making maintenance simpler and less expensive (*Abdolahifar et al., 2024*).

VAWTs have many disadvantages, despite their benefits. Their lower efficiency compared to HAWTs is one of their main disadvantages, especially in regions with regular wind patterns. In addition, the durability of the blades can occasionally be affected by mechanical stresses caused by the rotational forces acting on them. To increase the turbine's performance and longevity, experts are still working to improve the design by using stronger materials and improving the aerodynamics of the blades (*Kragten, 2024*).

An important feature that makes the VAWT unique among turbine designs is its ability to capture wind from all directions. A rotating mechanism, which orients the turbine towards the wind, is not required for VAWTs, unlike HAWTs, which must be orientated towards the wind. This ensures that the turbine will continue to operate efficiently in settings where wind direction changes frequently (*Lee et al., 2018*).

The small size of the VAWT offers an additional benefit. The turbine is an excellent option for cities with limited space, as it can be located in smaller areas and can operate well in stormy or low-wind conditions. Whether installed on a rooftop or incorporated into the architecture of a building, the VAWT is a discreet yet efficient source of renewable energy. Furthermore, by reducing dependence on fossil fuels, VAWTs contribute to a sustainable future (*Bashir et al., 2021*). Finding sustainable, reliable, and scalable energy solutions is more crucial than ever as cities expand and populations grow. With its practical and environmentally beneficial energy solution, VAWTs have great potential in this field. Although still in development, VAWTs have already shown promise in small-scale applications, and research is still ongoing to increase their effectiveness and design. VAWTs could become increasingly widespread in urban energy networks as engineers strive to maximize turbine performance, providing a creative response to the problems associated with contemporary energy use (*Aresti et al., 2013*).

The vertical axis wind turbine is an interesting and efficient way to capture wind energy. VAWTs have enormous potential for the future of renewable energy due to their small size, ease of maintenance, and ability to capture wind from any direction. Although there are still issues, mainly with sustainability and efficiency, these are being addressed by ongoing technological developments. With the introduction of clean, renewable energy in cities and small-scale applications around the globe, VAWTs may become increasingly significant in the coming years as we move towards a more sustainable energy future (*Kavade et al., 2017*).

Fig. 12 - Applications of VAWT in urban environments (*Tasneem et al., 2020*)

The type of wind turbine known as vertical axis wind turbines (VAWTs) has attracted interest in both research and real-world applications. Two well-known types of VAWTs, among the many designs, are the Savonius and Darrieus turbines. The efficiency, adaptability for specific applications, operating processes, and design complexity of these two categories vary greatly. Based on their operating principles, benefits, disadvantages, and applicability to different applications and climatic situations, they can be compared (*Abid et al., 2015*).

Among the vertical axis wind turbines, the Savonius turbine is one of the most basic designs. Two or more semi-cylindrical blades arranged in an "S" shape and fixed on a vertical axis usually make up its rotor. For strength and longevity, these blades are often composed of metal or composite materials. A Savonius turbine operates on the basis of drag forces. The curved blades rotate when the wind hits them due to wind pressure. Due to the configuration of the blades, the turbine always rotates because one side of the rotor experiences a greater drag force than the other (*Akwa et al., 2012*).

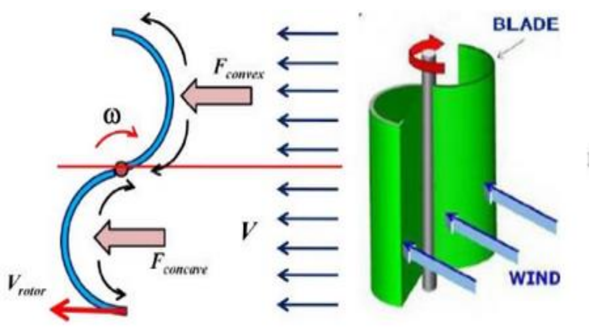

Fig. 13 - Diagram of a Savonius VAWT (*Khandagale et al., 2017*)

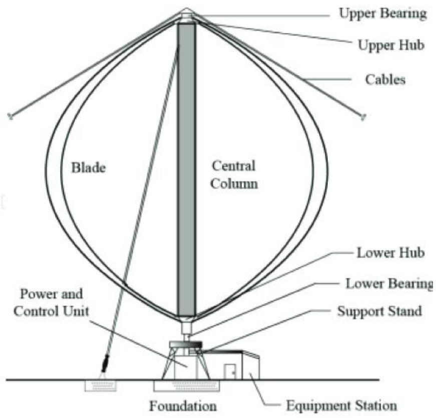

Fig. 14 - Diagram of a Darrieus VAWT *(Li, 2019*)

Often called an "egg beater" because of its unusual design, the Darrieus turbine has vertical blades that are usually curved and mounted on a vertical shaft. Like an airplane wing, the blades are often shaped with aerodynamic profiles to increase lift forces. The Darrieus turbine works on the basis of aerodynamic lift, which produces rotational motion by varying the air pressure on the opposing surfaces of each blade (*Tjiu et* *al., 2015*). The lift force works in a direction that causes the turbine to rotate when the wind blows over the blades. Since the Darrieus turbine cannot start rotating at low wind speeds without external help, it often requires a starting mechanism. It is well known that the Savonius turbine is not as efficient as other types of wind turbines. The main reason for this is that it uses drag forces, which are less efficient than lift-based methods. The efficiency of the Savonius turbine is typically between 10% and 20%, depending on environmental conditions and design differences. However, it has the particular benefit of being able to start rotating at low wind speeds, making it suitable for locations with frequent low wind speeds (*Menet et al., 2004*). The Savonius turbine is also frequently used in settings such as cities or smaller wind farms, where reliability and robustness are more important than efficiency. Compared to the Savonius turbine, the Darrieus turbine often offers higher efficiency. Unlike the Savonius design, which uses drag forces, it uses lift forces, which are more efficient. Depending on the system configuration, wind speed, and blade design, the efficiency of the Darrieus turbine can range from 25% to 45% (*Zereg et al., 2024*). However, in low-wind areas, the Darrieus turbine is less successful because it requires higher wind speeds to start spinning. Large-scale wind power generation is feasible due to its high efficiency and ability to generate more electricity in steady wind.

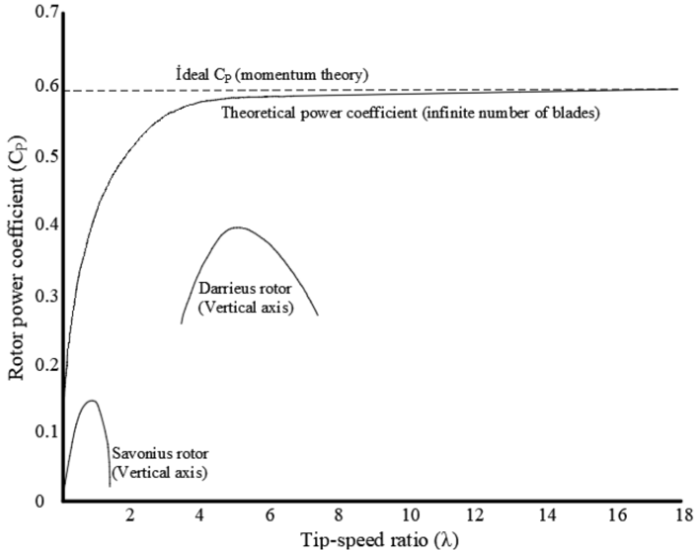

Fig. 15 - Efficiency comparison between Savonius and Darrieus VAWTs (*Muratoğlu et al. , 2019*)

Table 4

Advantages and disadvantages of the Savonius turbine(*Shende et al., 2022*)

Advantages	Disadvantages
- *Low wind speed*: One of the most significant advantages of the Savonius turbine is its ability to start operating at low wind speeds. This makes it ideal for areas where wind conditions are inconsistent or low. - *Simple design*: The Savonius turbine has a relatively simple design and is easy to manufacture, making it cost-effective. This simplicity also leads to easier maintenance and repairs. - *Durability*: Savonius turbines are known for their durability and can withstand high winds and turbulent conditions, making them suitable for harsh environments. - *Vertical axis*: The vertical axis design allows the turbine to operate regardless of wind direction, making it more versatile in environments where wind direction is variable.	- *Low efficiency*: Due to its dependence on drag forces, the Savonius turbine has a relatively low efficiency compared to lift-based designs. This limits its power generation capacity. - *Limited power output*: The design of the Savonius turbine typically results in a lower power output compared to other wind turbines, making it unsuitable for large-scale power generation. - *Noise*: Savonius turbines tend to produce more noise compared to Darrieus turbines, which can be a negative factor in residential or urban areas.

Table 5

Advantages and disadvantages of the Darrieus turbine (*Paraschivoiu et al., 2002*)

Advantages	Disadvantages
- *High efficiency*: the Darrieus turbine operates on aerodynamic lift, which is more efficient than the drag-based operation of the Savonius turbine. This leads to a higher power generation potential. - *Higher power output*: Due to its more efficient operation, the Darrieus turbine can generate much more power than the Savonius turbine, making it more suitable for large-scale applications. - *Compact design*: Although larger than the Savonius turbine, the Darrieus turbine can still be compact in terms of footprint, making it suitable for urban and offshore installations where space is limited. - *Less noise*: the Darrieus turbine typically produces less noise than Savonius turbines, making it more suitable for residential or urban environments.	- *High wind speed*: One of the main disadvantages of the Darrieus turbine is that it requires higher wind speeds to start rotating, making it less efficient in low-wind regions. - *Complex design*: The Darrieus turbine is more complex to manufacture and often requires additional components, such as a starting mechanism, making it more expensive to install. - *Structural challenges*: Darrieus turbines can suffer mechanical stresses due to high loads on the blades, which can lead to fatigue over time, leading to maintenance challenges.

In low-power, small-scale applications where efficiency is not the main concern, the Savonius turbine is frequently used. In cities with irregular wind conditions, the Savonius turbine is frequently used due to its low wind speed. Due to its design, it can work well in places with complicated wind patterns. For off-grid installations or as additional energy sources for homes, farms (*Glasberg et al., 2024*), or industrial sites, the Savonius turbine is perfect. The Savonius turbine is suitable for applications such as water pumping, where constant rotation at low speed is required, due to its robustness and simplicity.

(*www.engineeringnews.co.za*)

(*https://greenoteka.eu*)

Fig. 16 - Savonius in an urban environment

The higher efficiency and power output of the Darrieus turbine make it more suitable for large-scale applications. In utility-scale wind farms that require a lot of power, the Darrieus turbine is frequently used. When wind conditions are consistent, it can produce more electricity and is more efficient than smaller turbines. For offshore sites, where wind speeds are often higher and more reliable, the Darrieus turbine is perfect due to its robust design and increased power output. To summarize, both Savonius and Darrieus wind turbines have various benefits and uses due to their design, efficiency, and operating circumstances. The Savonius turbine works well in low-wind environments, providing a low-cost and long-lasting solution for small-scale applications, while the Darrieus turbine has higher efficiency and power, making it more suitable for large-scale wind power generation in areas with more consistent wind conditions. Each turbine has a place in the renewable energy landscape, and the decision to choose between them is largely determined by individual energy requirements, environmental circumstances, and available space.

Hybrid vertical axis wind turbines (VAWTs), which integrate Savonius and Darrieus rotor designs, aim to capitalize on the advantages of both configurations—namely, the high starting torque of the drag-based Savonius turbine and the superior aerodynamic efficiency of the lift-based Darrieus rotor (*Hosseini et al., 2019*). This combination enhances self-starting capabilities while maintaining favorable power output at higher wind speeds, making hybrid models particularly attractive for small-scale and urban wind energy applications. The synergy between the two mechanisms contributes to improved rotational stability, smoother power generation across varying wind conditions, and better overall performance compared to standalone designs. Researchers have explored a variety of geometric configurations—such as blade overlap, angular positioning, and rotor placement—to optimize the interaction between the components. Numerical and experimental investigations have demonstrated that these hybrid systems offer a balanced compromise between torque generation and power coefficient, addressing key limitations inherent to each individual turbine type.

SYNTHESIS OF EXPERIMENTAL RESEARCH ON WIND TURBINES AND THEIR WORKING PROCESS

As a clean and sustainable alternative to fossil fuels, wind energy has emerged as a key source of renewable energy in the fight against climate change (Barthelmie et al., 2021). Wind turbines have emerged as a key component of this energy shift, transforming wind energy from kinetic to mechanical and ultimately electrical forms. However, extensive experimental research is needed to ensure that these turbines are efficient, reliable, and capable of operating in a variety of situations. Testing a turbine involves more than just determining how efficiently it produces energy; it also involves evaluating its performance, robustness, and safety in a range of real-world scenarios (He et al., 2022).

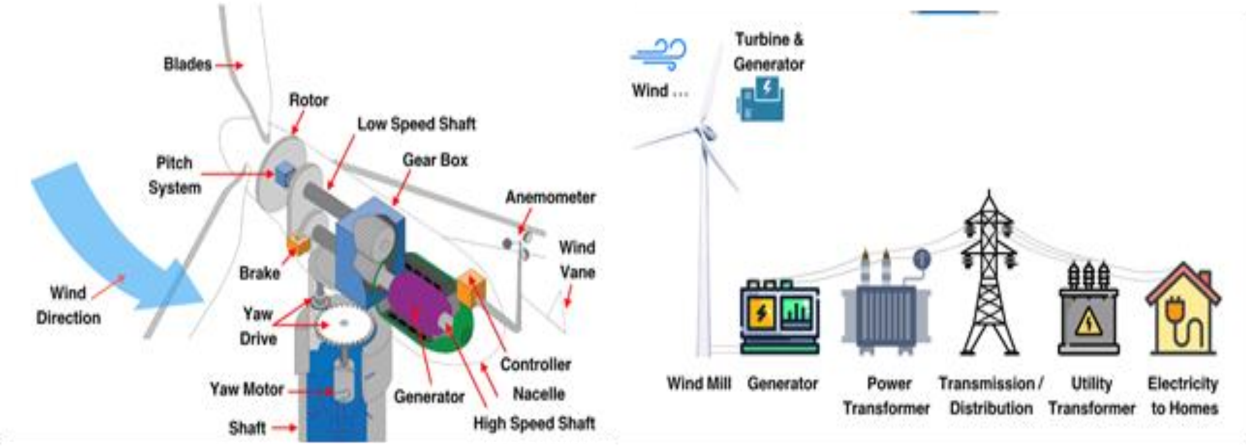

Fig. 17 - Wind turbine diagram
(*https://www.electricaltechnology.org/2021/08/wind-power-plant.html.*)

The fundamentals of wind turbine mechanics need to be understood before getting into the finer points of experimental testing. The parts of a conventional wind turbine include a tower, nacelle, generator, rotor, and blades. The blades rotate as the wind passes over them. A generator is turned by this rotational motion, and the mechanical energy is converted into electrical energy. Wind speed, the turbine operating under different conditions, and the design of the blades are some of the variables that affect the efficiency of this energy conversion (*Elizondo et al., 2009*). Testing these turbines in controlled, real-world settings is necessary to maximize performance and reliability.

To ensure that wind turbines meet the required performance and safety criteria, experimental testing is essential. These tests are primarily designed to evaluate the turbine's ability to generate electricity under a range of wind conditions (*Gaunt et al., 2012*). By monitoring the turbine's response to mechanical loads and severe weather conditions, engineers also aim to assess the structural integrity of the machine. This facilitates the identification of potential defects, predicts the turbine's durability, and ensures its safe operation. In addition, experimental testing helps improve turbine designs by improving overall efficiency and reliability through refinement of materials, control systems, and aerodynamic characteristics (*Bottasso et al., 2014*).

Key elements, including energy production, efficiency, and reliability under varying wind speed and climate conditions, can be measured by engineers through testing. Testing can identify a turbine's power curve, for example, which shows the relationship between wind speed and energy production. This curve helps optimize the turbine design and provides insights into its operating limits (*Carrillo et al., 2013*).

Laboratory testing, field testing, and accelerated life testing are the three main testing approaches that can be used to analyze the complex process of wind turbine testing (*Bastankhah et al., 2017*). Each of them contributes in a different way to the evaluation of different turbine performance factors. Laboratory tests usually focus on specific parts of the wind turbine, such as the generator, nacelle, and blades. The aerodynamic characteristics of the blades are investigated in wind tunnels, and additional tests are conducted to evaluate mechanical performance, stress resistance, and material durability in simulated environments. Before the turbine is assembled and placed in the field, the intention is to understand how each component functions.

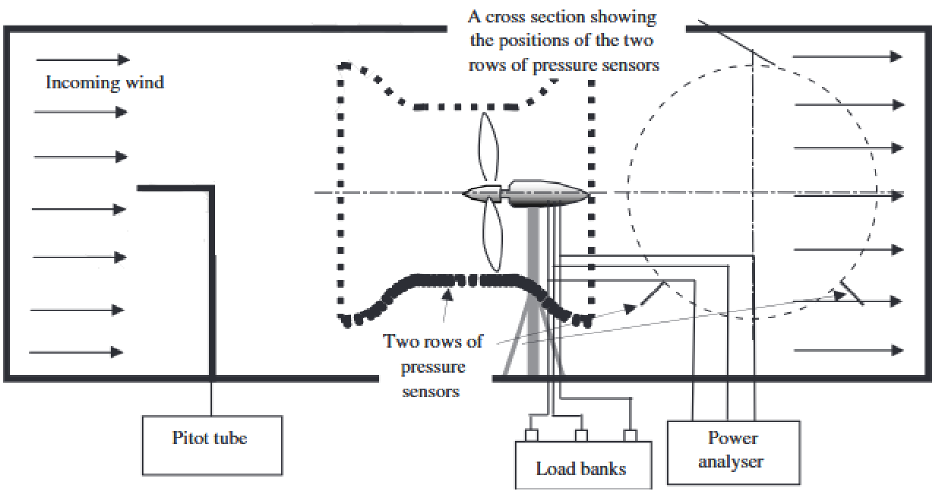

Fig. 18 - Wind turbine testing diagram in wind tunnel (*Agha et al., 2018*)

As an alternative to laboratory testing, field testing involves putting turbines in realistic settings to evaluate how well they perform in wind conditions. Measuring energy production at different wind speeds, evaluating turbine performance under varying wind load conditions, and monitoring long-term performance are common examples of such tests. Field testing allows engineers to see how turbines respond to variables that are difficult to replicate in a laboratory, including turbulence, humidity, and temperature changes.

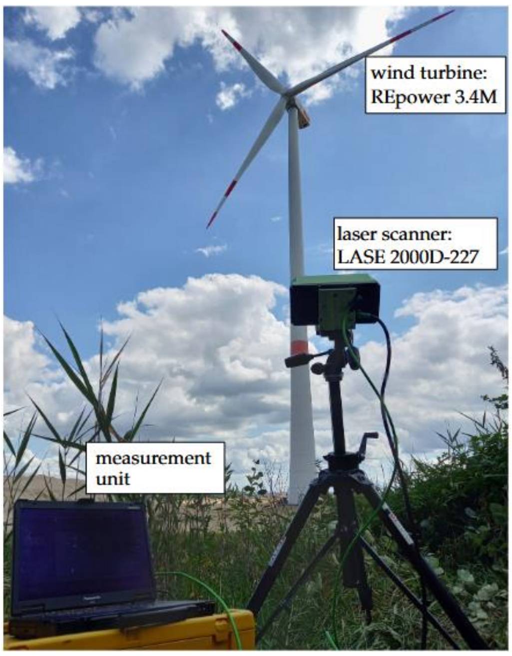

Fig. 19 - Field testing setup (*Helming et al., 2021*)

The data must be examined thoroughly after it has been collected. Key performance parameters such as the power curve, efficiency, and capacity factor are of particular interest to engineers. While efficiency shows how much of the wind energy is converted into electricity, the power curve allows engineers to see how much power a turbine produces at different wind speeds. Engineers can assess the overall performance of the turbine by analyzing the capacity factor, which shows how efficiently the turbine generates energy relative to its maximum potential.

It is also essential to test for noise and vibration. The structural integrity of the turbine can be compromised by excessive vibration or noise, which could lead to mechanical failure or environmental problems in populated areas. Engineers can improve turbine designs to minimize noise and wear by monitoring these variables during experimental testing (*Shinagam et al., 2020*).

Wind turbine testing presents certain challenges. The instability of the wind itself is the main challenge. Because wind direction, speed, and turbulence are so variable, it is difficult to reproduce constant conditions in both laboratory and field experiments. Wind is rarely as predictable as one would like, and conditions in the field can vary rapidly, even though wind tunnels provide controlled environments for some studies. Although engineers frequently use sophisticated forecasting models to predict wind patterns, unpredictability is still a persistent problem.

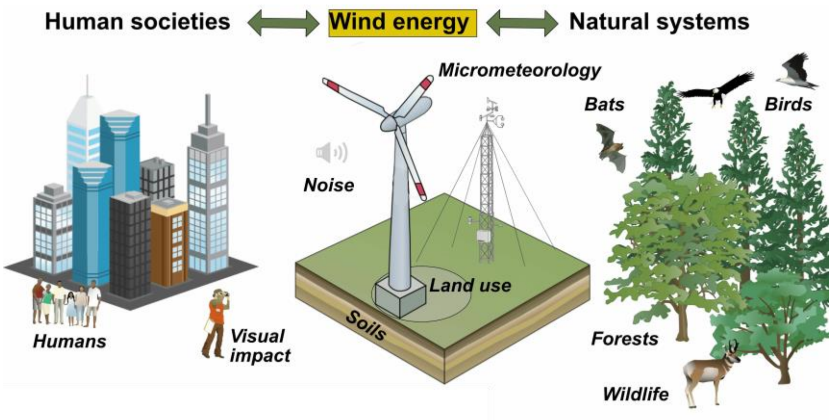

Fig. 20 - Testing challenges and environmental factors (*Sander et al., 2024*)

There are also logistical issues, especially with outdoor tests. Turbines are often located in remote areas, far from maintenance teams or test facilities. The testing procedure could be further complicated by the high cost of installation, maintenance, and transportation. In addition, wind turbines are heavy and bulky, making them difficult to move and install, especially in hilly or offshore wind farms (*Vis et al., 2016*). Another important factor is safety. Field tests can be dangerous for personnel, especially when carried out in adverse weather. Therefore, strict safety procedures must be followed to ensure that people are protected during the testing procedure (*Jin et al., 2016*). Potential risks such as strong winds, electrical failures, or even structural failure of a turbine component during testing must be considered by engineers.

The results of experimental tests have significant ramifications for the future of wind energy and turbine design. Engineers have gained important knowledge through testing, which has led to notable increases in turbine cost-effectiveness, efficiency, and reliability. Modern turbines now have higher energy conversion efficiencies, for example, due to advances in materials science, control systems, and blade design. In addition, superior testing techniques have produced turbines that are more resilient to harsh weather conditions (*Sun et al., 2022*), such as the hot, dry climate of desert regions or the icy winds of the North Sea.

SYNTHESIS OF EXPERIMENTAL RESEARCH ON THE WORKING PROCESS OF SAVONIUS TURBINES

The interest in wind energy has increased significantly due to the search for renewable and sustainable energy sources. Among the types of wind turbines, the Savonius wind turbine (SWT), a vertical axis wind turbine (VAWT), stands out for its ease of use, efficiency in low wind conditions, and low production costs (*Zemamou et al., 2017*). Aerodynamic drag forces drive the turbine, making it perfect for small-scale energy production. However, a large number of experimental tests are required to exploit its potential fully and maximize its performance (*Akwa et al., 2012*).

The original form of the Savonius wind turbine, created in the 1920s by the Finnish engineer Sigurd Savonius, consists of two or more vertically positioned curved blades (*Zoucha et al., 2023*). The drag force generated by the wind hitting the blades of a Savonius turbine allows it to harness wind energy, unlike horizontal-axis wind turbines. The blades are typically spoon-shaped, with one side facing the wind to "catch" it and the other side acting as a drag force to rotate the turbine (*Gall et al., 2023*). Wind energy is converted into mechanical energy as the blades rotate about a vertical axis as a result of the wind interacting with them. Because the Savonius turbine relies on drag forces rather than lift, it is often less efficient than horizontal-axis turbines, while still being successful at low wind speeds (*Dewan et al., 2021*). However, the turbine's simple design and ability to operate in irregular and fluctuating wind conditions make it a desirable choice for small-scale energy applications, especially in off-grid, domestic, or urban environments.

To better understand and improve the performance of Savonius wind turbines, experimental testing is essential. The complexity of real-world wind conditions and turbine performance cannot be fully captured by theoretical models and simulations, although they can provide some insight (*Wenehenubun et al., 2015*). Researchers can evaluate elements such as power output, efficiency, and the impact of environmental conditions through physical tests, which improve design and operation methods. Real-world information about the turbine's power output, efficiency under different wind conditions, and the impact of turbulence and mechanical wear are all provided through testing. Engineers can improve turbine performance and make it more reliable and efficient for specific applications by adjusting important design parameters through experimental testing, such as rotor height, number of blades, and blade curvature (*Zhou et al., 2013*). To determine whether the turbine is suitable for practical use, researchers conduct long-term experiments in a variety of climatic situations to evaluate its longevity and mechanical durability. The best economical and efficient design for a given situation can be found by comparing several turbine designs, combinations, and materials through experimental testing (*Shamsuddin et al., 2022*).

Savonius wind turbines can be experimentally tested in several ways, each designed to evaluate a specific facet of the turbine's performance. Wind tunnel testing, field testing, and computational fluid dynamics (CFD) simulations are the most commonly used techniques (*Ferrari et al., 2017*).

By carefully adjusting wind direction, speed, and turbulence in a controlled wind tunnel, researchers can evaluate how a turbine responds to particular circumstances. Wind tunnel testing is useful for determining power coefficients, evaluating aerodynamic forces acting on blades, and fine-tuning turbine shape (*Ross et al., 2011*). Although wind tunnel testing provides controlled settings and repeatability, it cannot accurately capture the complexity of environmental circumstances seen in the real world.

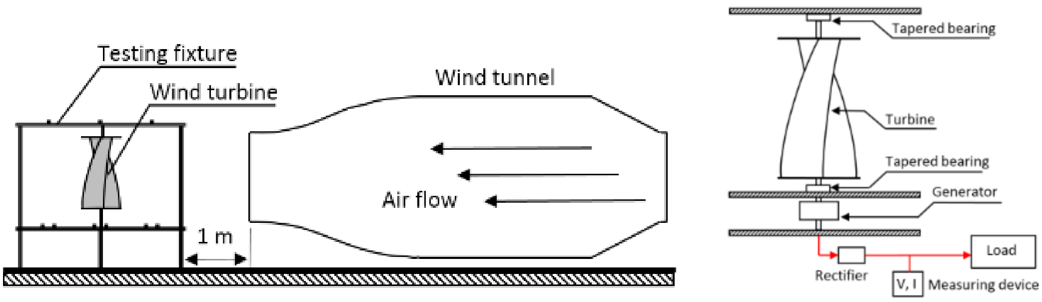

Fig. 21 - Wind tunnel setup for testing Savonius wind turbine
(*Zakaria et al., 2019*)

To track the performance of Savonius turbines over time, field testing involves placing them in real-world outdoor environments. Field tests provide information about the turbine's performance in a variety of wind conditions, including turbulence, gusts, and changing wind directions, unlike wind tunnel experiments. The turbine's behavior in different climates, reliability, and long-term performance are all evaluated through field tests.

A useful technique for simulating wind flow around turbine blades and predicting aerodynamic performance is computational fluid dynamics simulations. In addition to helping researchers refine design features, including blade shape, size, and length, these models provide information about the distribution of aerodynamic forces, drag, and lift (*Dobrev et al., 2011*). Although CFD can help improve the design before physical testing, it may not be able to account for all environmental factors that influence turbine performance.

Turbine output and mechanical load must be measured during field and wind tunnel testing to determine efficiency. Researchers can measure the turbine's rotational speed and torque using instruments such as dynamometers and torque sensors. In addition to providing information to evaluate the turbine's overall performance and energy production, these measurements allow the calculation of the power coefficient (Cp) (*Kadam et al., 2013*).

Several experimental investigations have provided useful information on the performance of Savonius wind turbines. Key findings from these investigations include blade configuration, blade curvature, rotor height, power coefficient, and efficiency.

The number of blades in a Savonius turbine has a large influence on its performance. While two-blade variants are popular due to their simplicity, three- or four-blade turbines offer better torque and stability at low wind speeds. However, this may increase drag and decrease the turbine's efficiency. According to experimental results, the appropriate number of blades is determined by the intended use, with fewer blades being more efficient in higher wind speeds and more blades providing greater efficiency at lower speeds (*Chaichana et al., 2019*).

The curvature of the turbine blades is another crucial component that affects its aerodynamic performance. Blades with steeper curvatures create more drag, which can increase the rotational speed but can also cause mechanical stress, leading to increased wear rates. Blades with shallower curvatures, on the other hand, generate less drag but may be less efficient in transferring wind energy into rotational motion (*Chan et al., 2018*). Experimental investigations suggest that moderate curvature is usually the most effective for balancing drag and performance; however, modifications may be necessary depending on the circumstances and turbine size.

The height of the turbine rotor, or the distance between the center of rotation and the tip of the blades, is also important in influencing performance. Taller rotors can gather wind from a wider region, increasing the power generation capacity. However, increasing the rotor height can increase the complexity and expense of the turbine, with performance gains decreasing beyond a certain point. The rotor height should be adjusted based on the anticipated wind conditions and the unique power requirements of the application, according to tests (*Tahani et al., 2017*).

The power coefficient (C_p) is a useful indicator of the efficiency of a wind turbine. Experimental tests have indicated that the C_p of Savonius turbines typically ranges between 0.2 and 0.3, which is lower than that of horizontal axis wind turbines. However, experimental investigations have shown that by carefully optimizing the design, including changes in blade shape, spacing, and rotor height, it is feasible to increase the power coefficient and improve overall efficiency (*Gad et al., 2014*).

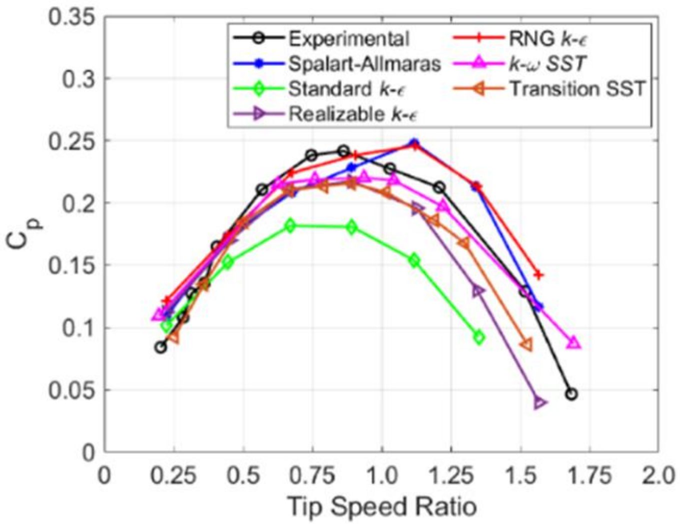

Fig. 22 - Power coefficient (Cp) vs. tip speed ratio (TSR) (*Dewan et al., 2023*)

The Savonius wind turbine is a viable alternative for sustainable energy generation, especially in low to very high wind conditions, where conventional wind turbines have great difficulty operating. Experimentation has provided vital information on its performance characteristics, including blade geometry, rotor height, and energy efficiency. This information can be applied to improve turbine designs, making them more efficient and reliable for real-world applications (*Roy et al., 2017).*

SYNTHESIS OF EXPERIMENTAL RESEARCH ON THE WORKING PROCESS OF DARRIEUS TURBINES

Wind energy, previously considered an alternative energy source, is rapidly becoming a cornerstone of global efforts to reduce dependence on fossil fuels. Wind turbines have played a major role in the renewable energy revolution, and among the various designs investigated, the Darrieus wind turbine stands out for its novel approach to capturing wind energy. Unlike standard horizontal-axis wind turbines (HAWTs), which operate on a horizontal axis, the Darrieus turbine has a vertical axis that allows it to capture wind from any direction (*Du et al., 2019*). While offering fascinating benefits in some situations, the Darrieus turbine faces a number of obstacles that have required substantial experimental study to increase its performance, efficiency, and practicality.

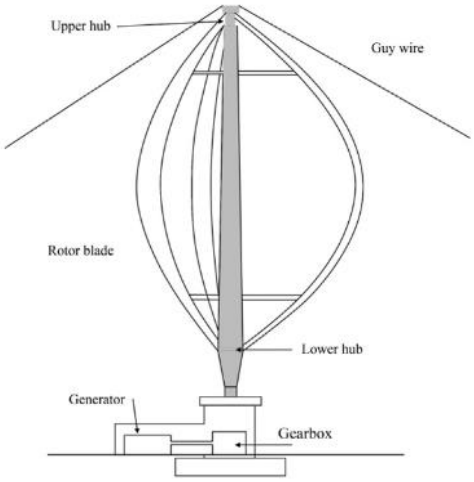

Fig. 23 - Power coefficient (Cp) vs. tip speed ratio (TSR) (*Tasneem et al., 2020*)

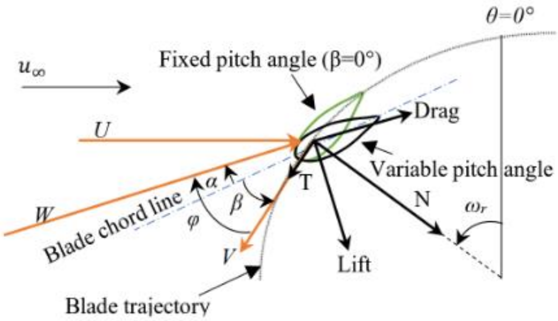

Fig. 24 - Aerodynamic forces on the blade of a Darrieus turbine (*Abdalrahman et al., 2021*)

The Darrieus wind turbine, invented by French engineer Georges Darrieus in the 1920s, is notable for its characteristic curved blades connected to a central vertical shaft. This design sets it apart from conventional turbines. One of the main benefits of the Darrieus turbine is its ability to collect wind from any direction, avoiding the need for a turning mechanism, which is necessary for horizontal-axis turbines to cope with wind (*Malael et al., 2021; Castelli et al., 2011*). While this may seem like a significant benefit, the turbine has long struggled with efficiency, starting torque, stability in varying wind conditions, and structural durability. Experimental research has become critical in an attempt to optimize its design and overcome these obstacles. Much of the initial research on Darrieus turbines has focused on understanding their aerodynamic characteristics. Scaled-down versions of Darrieus turbines are being tested in wind tunnels under controlled wind conditions, and the results provide valuable insight into how many aspects influence turbine performance (*Bedon et al., 2015*). One of the most important findings from these studies is the link between blade shape and efficiency. Curvature, aspect ratio (the ratio of blade length to blade width), and number of blades all play an important role in determining how much energy a wind turbine can generate. Researchers have found that blades with a higher aspect ratio are more efficient at converting wind energy into mechanical power, but their design must be balanced with concerns about structural integrity. The blade profile, whether flat or curved, also influences the lift-to-drag ratio, which is a significant component of turbine efficiency (*Mohamed et al., 2019*).

However, one of the major problems faced by Darrieus turbines is the difficulty of starting. Unlike horizontal-axis turbines, which can start rotating with a light breeze, the Darrieus turbine frequently fails to overcome its inertia when wind speed is low. Early experiments identified this "starting problem" as a significant drawback (*Asr et al., 2016*). In response, various solutions have been sought, some of which have been tested both in the laboratory and in the real world. One way is to include a small starter motor or Savonius rotor in the base of the Darrieus turbine. The Savonius rotor works as a traction-based device, providing the initial torque needed to start the system. In initial experiments, this hybrid technique has produced encouraging results, with the Savonius rotor providing enough torque to start the Darrieus turbine even in low wind conditions (*Chegini et al., 2023*).

The design of Darrieus turbines is further complicated by a phenomenon known as "stall.". When the wind exceeds the ideal range for turbine operation, lift decreases. Due to the enormous working forces, turbine efficiency can drop drastically, and in the worst cases, the blades can be damaged (*Fujisawa et al., 2001*). One of the main objectives of experimental research has been to overcome this obstacle. To maximize performance, several experimental setups have investigated the possibilities of active control systems, such as variable pitch blades, which change the angle of attack in real time. Dynamic stall control, which uses sophisticated control algorithms to modify the torque or blade angles in response to changing wind conditions, has been the subject of several investigations. Research into the use of these technologies on a large scale is still ongoing, despite their enormous potential.

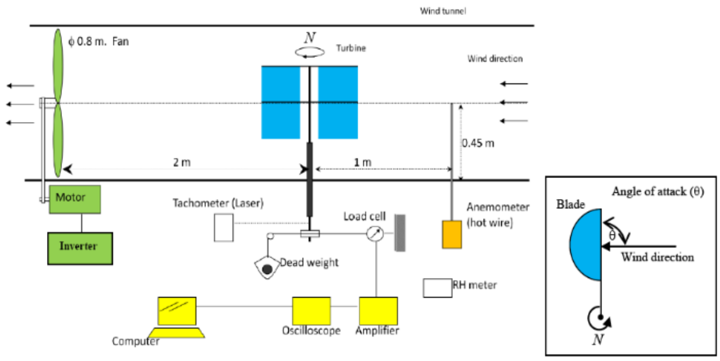

Fig. 25 - Darrieus type wind turbine test setup in the wind tunnel (*Chaitep et al., 2011*)

A crucial method for assessing the practicality of Darrieus turbines has been field testing, despite these difficulties. Turbines are exposed to the unpredictability of real wind conditions during field tests, unlike wind tunnel tests, which provide a controlled environment. In particular, the behavior of the turbine in turbulent wind conditions is one of the performance patterns that is often revealed by the results of these tests (Ferroudji et al., 2016). The vertical axis design of Darrieus turbines makes them particularly vulnerable to vibrations, which over time can cause structural damage. These vibrations can lead to fatigue, reduced efficiency, and, in some cases, failure. They are created by the oscillations of the blades as they move through the wind. Consequently, much of the experimental research in this field has focused on reducing these vibrations through the use of damping devices, including tuned mass dampers, which reduce the oscillations of the turbine blade. The use of materials with better mechanical properties and lighter weight for turbine blades has improved mechanical stability and provided pertinent information on materials science (Olivera et al., 2024).

Fig. 26 - Combination of Darrieus and Savonius wind turbines
(*https://www.windsystemsmag.com/news/first-vertical-axis-wind-turbine-awarded-certification/*)

Along with these experimental methods, computational fluid dynamics (CFD) simulations have emerged as a powerful tool for understanding Darrieus turbine airflow (*Malael et al., 2024*). To reproduce how air moves over the turbine blades, CFD simulations require complex mathematical models. These models provide researchers with a deep understanding of the aerodynamic forces acting on the turbine, allowing them to identify inefficient or turbulent airflow regions. In a wind farm configuration, CFD has been particularly useful in understanding the dynamics of Darrieus turbines, or the turbulent air left behind the moving blades, and how these flows can affect the operation of neighboring turbines (*Dumitrescu et al., 2015*). CFD has played a key role in guiding experimental research and optimizing turbine configurations by modeling various design changes, such as changing the geometry of the blades or changing the distance between the blades. Increasing the turbine's power coefficient, which measures how well the turbine can convert wind energy into mechanical energy, is one of the main goals of all this research. A wind turbine can only capture 59.3% of the wind's kinetic energy, according to a theoretical restriction called the Betz limit (*Huleihil et al., 2012*). Experimental studies have shown that improvements in blade design and the mitigation of energy losses from friction and turbulence can bring the efficiency of Darrieus turbines closer to their potential limits, even though they frequently operate below this theoretical maximum. According to some research, the power coefficient of the Darrieus turbine could significantly outperform conventional designs and reach values Cp of up to 0.4 or 0.5 with an ideal design. The figure below illustrates turbine efficiency and ideal operating range using a power coefficient versus tip speed ratio (TSR) graph.

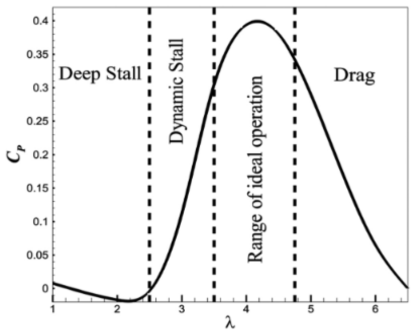

Fig. 27 - Darrieus rotor performance CP versus blade tip speed ratio (*Sagharichi et al., 2016*)

Despite the progress, many obstacles still need to be overcome before Darrieus turbines can be considered a viable alternative for large-scale wind power generation. Field testing, for example, is an expensive and time-consuming operation, with findings often affected by local wind conditions, which are difficult to recreate in controlled environments. Furthermore, while the use of modern materials such as carbon fiber composites holds great potential to increase turbine strength and reduce weight, these materials come at a high cost that must be justified by the long-term performance and longevity of the turbine.

CONCLUSIONS

Vertical Axis Wind Turbines (VAWTs) have been thoroughly examined in this review, with a focus on experimental studies and current developments in their efficiency, performance, and design. Although large-scale wind energy generation is dominated by Horizontal Axis Wind Turbines (HAWTs), VAWTs offer a special opportunity due to their space efficiency and versatility, especially in urban, low-wind, and agricultural areas.

Numerous important areas where VAWT technology is developing, including turbine configuration, blade design, and aerodynamic performance enhancements, have been brought to light by the examination of experimental investigations. Despite their potential, these developments are frequently hampered by issues with cost-effectiveness, noise reduction, and structural integrity—all of which are crucial for the broad use of VAWTs.

Addressing these challenges through innovative engineering solutions and advancements in materials science could significantly enhance the viability of VAWTs. As the demand for renewable energy sources continues to grow, ongoing research and development will be essential in overcoming these obstacles and unlocking the full potential of vertical axis wind turbines.

These issues must be resolved in future advancements, with an emphasis on scalability and integration into various contexts. To ensure that VAWTs can compete with conventional wind turbines and make a significant contribution to the generation of renewable energy, it will be essential to optimize their designs for durability, reduce operating costs, and increase their energy efficiency.

To sum up, VAWTs have a lot of promise as an alternative energy source, especially in areas where conventional wind turbine designs might not be as successful. Unlocking their full potential requires ongoing experimental study in addition to technological and material advancements. VAWTs may become more important in the shift to decentralized and sustainable energy systems for homes, companies, and the agricultural sector if current constraints are addressed.

This could lead to greater adoption and integration of VAWTs into various environments, ultimately contributing to a more resilient and sustainable energy landscape. As research continues to evolve, innovative designs and applications may emerge that further enhance the viability of vertical axis wind turbines in the renewable energy market.

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