INNOVATIONS IN SMALL WIND TURBINES: A COMPREHENSIVE REVIEW OF VERTICAL AXIS DESIGN AND EXPERIMENTAL FINDINGS
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INOVAȚII ÎN DOMENIUL TURBINELOR EOLIENE DE MICI DIMENSIUNI: O REVIZIE CUPRINZĂTOARE A PROIECTĂRII TURBINELOR EOLIENE CU AX VERTICAL ȘI A REZULTATELOR EXPERIMENTALE

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ABSTRACT
This paper provides an overview of the recent developments on small wind turbines in terms of their distinguishing characteristics, experimental research and structural and operational development of small vertical axis wind turbines. Emphasizing their decentralized generation capability, cost savings, and sustainability, the first part discusses the characteristics of small wind turbines. Then the review paper goes through a synthesis process of experimental research work on small wind turbines to evaluate their performance, technological advancements evolved in line with actual world problems encountered. The paper also describes what was achieved by way of small vertical-axis wind turbine design, material problems, and aerodynamic theories that control their operation. Finally, the study provides a review of experimental research studies that were conducted on the performance of small vertical axis wind turbines.
The study also shows the functioning methods of small vertical axis wind turbines examined by means of experimental research, which investigate their efficiency under different environmental circumstances and where they may be optimized. Emphasizing the interdependence between theory and practice, this paper examines answers wind turbine researchers have already looked at. A small part of international research data seeking to improve the efficiency and design of small wind turbines is collated here.

REZUMAT
Această lucrare oferă o imagine de ansamblu asupra dezvoltărilor recente ale turbinelor eoliene mici în ceea ce privește caracteristicile lor distinctive, cercetarea experimentală și dezvoltarea structurală și operațională a turbinelor eoliene mici cu ax vertical. Subliniind capacitatea lor de generare descentralizată, costuri și durabilitatea, in prima parte a lucrarii sunt prezentate caracteristicile turbinelor eoliene mici. Analiza trece printr-un proces de sinteză a lucrărilor de cercetare experimentală asupra turbinelor eoliene mici pentru a evalua performanța acestora, progresele tehnologice evoluând în concordanță cu problemele reale întâlnite in timpul functionarii turbinelor. Lucrarea descrie, de asemenea, ceea ce s-a realizat prin proiectarea unei turbine eoliene mică cu ax vertical, problemele legate de selectia materialelor și teoriile aerodinamice care controlează funcționarea acestora. În cele din urmă, studiul oferă o trecere în revistă a studiilor experimentale de cercetare care au fost efectuate asupra performanței turbinelor eoliene cu ax vertical. Studiul arată, de asemenea, metodele de funcționare ale turbinelor eoliene cu ax vertical examinate prin cercetări experimentale, care investighează eficiența acestora în diferite circumstanțe de mediu și unde pot fi optimizate. Subliniind interdependența dintre teorie și practică, această lucrare examinează solutiile existente la care cercetătorii de turbine eoliene au ajuns deja. O mică parte din datele cercetării internaționale care încearcă să îmbunătățească eficiența și proiectarea turbinelor eoliene mici este inclusa in lucrare.

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INTRODUCTION

Wind power is currently among the most promising and sustainable sources of energy today. Wind turbines are essential in tapping into the use of natural resources to generate energy with the growing need for renewable energy sources. The technology in the devices is able to convert wind energy into electrical energy and present a clean source compared to fossil fuels, according to Brown et al. (*Brown et al., 2015*). Apart from reducing the use of non-renewable energy sources and greenhouse gas generation, wind power stands for environmental sustainability.

The main function of a wind turbine is to harness the energy of the wind and transfer it into the form of motion and afterwards into mechanical form and finally into electrical form. The principle on which it works is simple: the turbine's blades are pushed by the wind and rotated to create motion, as Ning et al. explained in their paper (*Ning et al., 2014*). Figure 1 shows the key components of a horizontal-axis wind turbine. The main components are the tower, nacelle, rotor, generator, and the blades. In the rotor's core is fitted the generator, which functions because the turbine's blades are spinning around it. The generated electrical power from the generator can be utilized on-site or transmitted through the power network.

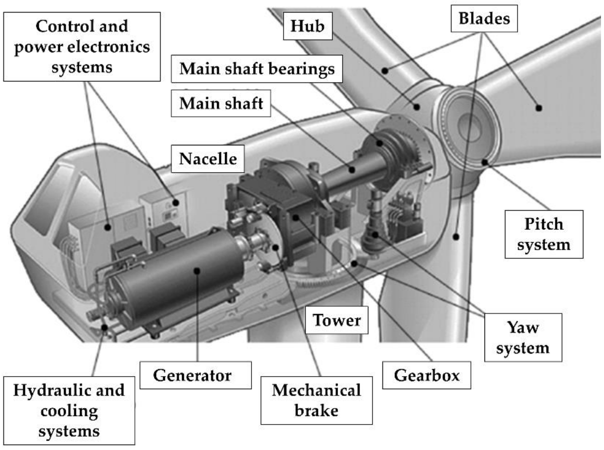

Fig. 1 - Diagram of key components of a wind turbine (*Civera et al., 2022*)

Designed to resemble the wings of an airplane in most instances, the blades capture the energy in the air (wind). The blades, along with the hub they are attached to, make up the rotor. The nacelle, the housing atop the tower, contains the generator and gearbox among the main components. The tower positions the turbine to elevated levels where the speed of the air is stronger and safer. The mechanical energy has to be transferred to electrical energy by the generator, as Enevoldsen et al. stated in their paper regarding the study of an extensive dataset consisting of 35 years of multi-megawatt wind turbine inventions (*Enevoldsen et al., 2019*). The wind delivers mechanical rotation energy in the form of spinning the blades around the rotor. A gear alters the speed in rotation after the mechanical energy is transferred to it via a shaft. The rotation is amplified to a functional speed with the aim of producing power. The mechanical energy is transferred from the gear to the generator, where electromagnetic induction is utilized to transform it into electrical energy. An interesting study belongs to Xiaohui et al., who presented in their paper an algorithm for calculating the magnetic transient effects in a wind turbine tower struck by lightning (*Xiaohui et al., 2010*).

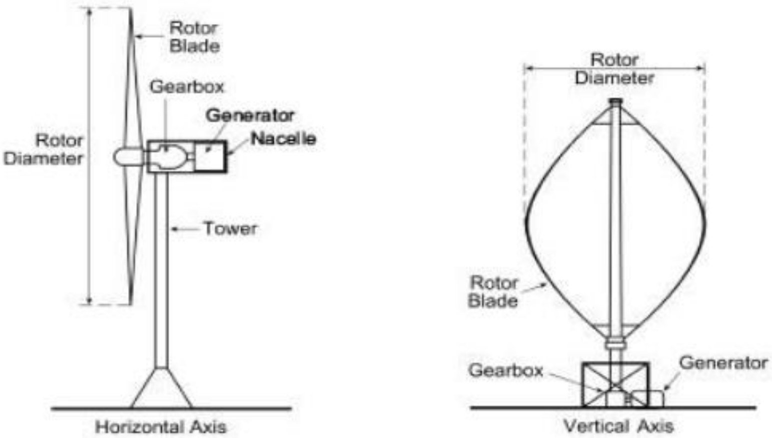

Fig. 2 - Horizontal axis wind turbine vs. vertical axis wind turbine (*Salem et al., 2016*)

HAWT (horizontal axis wind turbines) and VAWT (vertical axis wind turbines) are the two major types of wind turbines. In figure 2 are presented the resemblances between these two types. Although both are utilized to generate electricity from wind energy, they have different design, efficiencies, and applications. Eriksson et al. presented in their paper a comparative study of three wind turbines: a horizontal axis wind turbine and two vertical axis wind turbines; the Darrieus turbine and the H-rotor. Their study includes aspects like structural dynamics, control systems, maintenance, manufacturing and electrical equipment (*Eriksson et al., 2008*).

Just like propeller blades, the blades in the most prevalent type of turbine are mounted on a horizontal axis. Such turbines are mounted on tall towers in order to avail themselves of the stronger winds higher up in the air. They are suitable for onshore and offshore use due to high efficiency in high winds. However, they require a mechanism to alter the direction of the turbine so the blades may face the direction in which the wind blows, as also Elkodama et al. stated in their paper (*Elkodama et al., 2023*). The blades on vertical-axis wind turbines, on the other hand, rotate on a vertical axis. Such turbines are suitable for regions where the wind flows are turbulent or irregular because they neither require turning and can harvest the wind from any direction as Khammas et al. suggest in their paper (*Khammas et al., 2015*). Due to the fact that VAWTs are smaller and compact in nature, they may be utilized where there is limited space in urban areas or even within residential areas. Although they provide improved quietness and flexibility compared to HAWTs, they typically exhibit lower efficiency. They are utilized in ordinary-scale energy use; however, in the best conditions in terms of winds, they are less efficient in comparison to ordinary-scale large-size HAWTs.

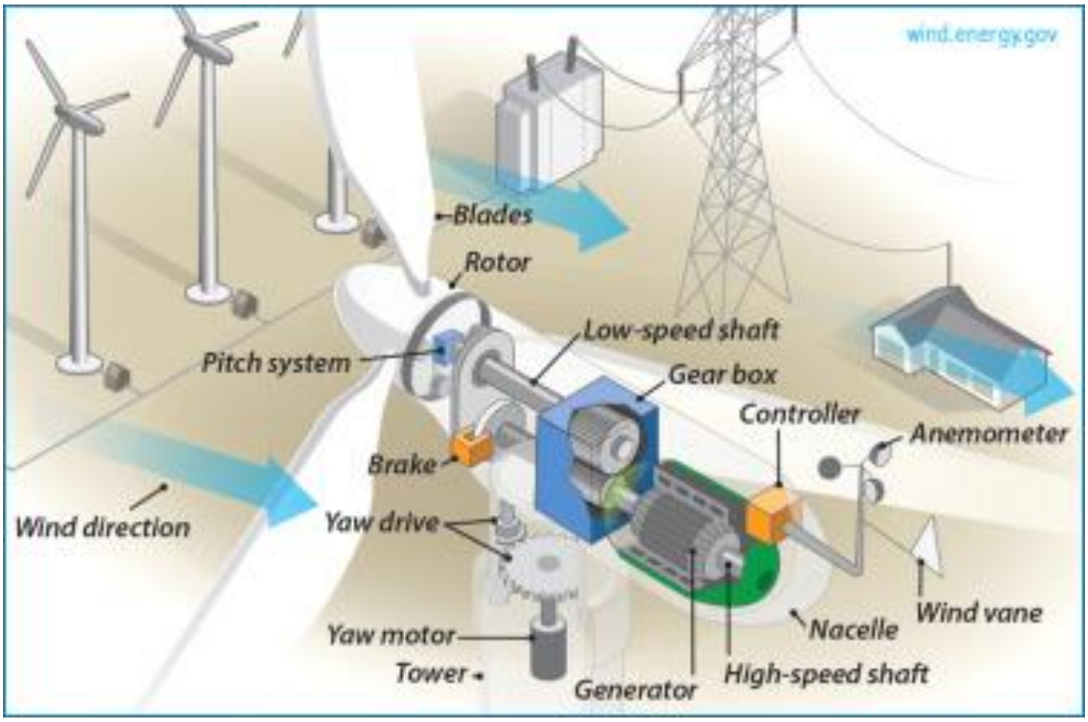

Fig. 3 - The process of generating energy through wind turbines
(*Junginger et al., 2020*)

There are several similarities and dissimilarities between the two categories, but the energy generation process is basically the same (as Figure 3 shows). HAWTs are efficient in energy conversion in regions with consistent and powerful winds. They are the turbines preferred for use in large-scale wind farms due to their long blades, which enable them to capture more energy (*Adams et al., 2011*). They would be difficult to service but are prone to wear and tear in extreme weather conditions. A very interesting study on the structural health monitoring of a HAWT was conducted by Adams et al., focusing on a Micon 65/13 horizontal-axis wind turbine.

Although VAWTs are less efficient in regions with powerful winds, they are suitable for use in residential or urban regions because they are compact and better suited to handle changes in the direction of the wind.

Having major components closer to the ground, they are easier to service. Kragten A. in his report presents the main advantages and disadvantages of a Darrieus wind turbine rotor and concludes that because of many disadvantages and only a few advantages, Darrieus is less efficient than a HAWT (*Kragten A., 2004*), and because of that, this type of wind turbine is not suitable for use in large-scale power production because they have low efficiency in energy conversion.

The graphic below depicts a categorization of the primary types of wind turbines based on their power coefficient at various tip speeds. Currently, the horizontal-axis wind turbine and vertical-axis wind turbine Darrieus type are more typical and widely employed on a large scale.

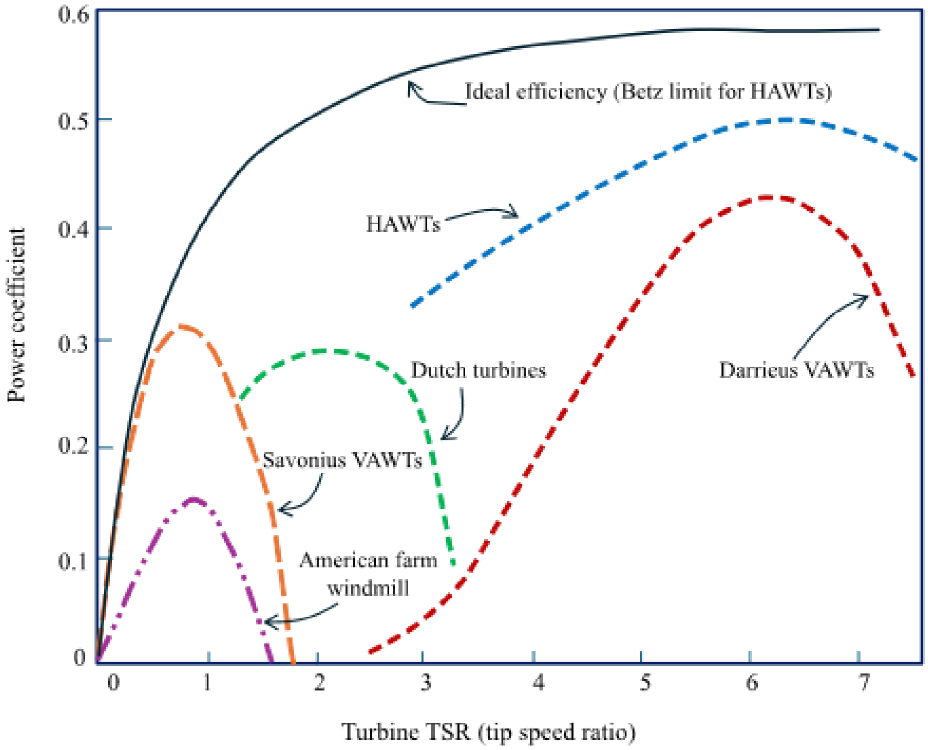

Fig. 4 - Comparison of HAWT and VAWT efficiency
(*Abdolahifar et al., 2024*)

Wind turbine technology in the last decades has seen tremendous improvement with advances in efficiency, design, and material technology. Wind turbine blades today are longer than 100 meters and much larger in size relative to the last generation (*Winters et al., 2018*). Low-speed winds are not a problem for such large-scale machines; now even at low wind speeds they produce a great amount of power. Apart from improving the durability of the turbine, advances in material technology in the form of light but strong composite material have reduced production costs. It is well known that the driving force behind the renewable energy revolution is represented by the wind farms. Figure 5 shows a wind farm where the horizontal-axis wind turbines are installed to replace fossil fuels with emissions-free electricity.

Advances in technology in offshore in the form of floating turbines allow it to be installed in the deep seas where the traditional fixed-based ones are no longer installable. Wu et al. present in their paper the state-of-the-art geotechnical and structural issues that affect offshore wind turbine foundations (*Wu et al., 2019*). The floating turbine expands the ability to produce power in areas previously inaccessible. Further, with the addition of smart grid technology, the wind turbine operates in the larger power network at optimal performance and enhances distribution and overall reliability in the network, aspects seen by Johnson et al. even from 1976 (*Johnson et al., 1976*). In Figure 6 three type of offshore floating wind turbine foundations are presented.

Fig. 5 - Wind farm (*https://drawdown.org/solutions/onshore-wind-turbines*)

Although they are promising, wind turbines are also detrimental. Possibly one of the greatest detriments is the fact that the wind is not always available. Wind speed is inconsistent, and there could be some locations where there are stretches of little or no wind at all, which generates intermittent energy generation. *Szlivka et al., (2017),* presents the advantages and disadvantages of different types of wind turbines and their use in urban environments, with an emphasis on small wind energy systems that generate under 100 kW.

Storage facilities for the surplus energy generated during windy days, such as batteries or pumped hydro storage, are on the agenda as solutions. Environmental impact brought about by wind turbines is the other issue. They are thought to be cleaner than fossil fuels but can also impact wildlife in the immediate area, particularly birds and bats that may become entangled in the spinning blades. Krijgsveld et al. evaluated the collision rate of birds with contemporary, big 1.65 MW wind turbines for three months in fall and winter. They concluded that the collision rate was 0.08 birds per turbine per day on average (range 0.05-0.19) (*Krijgsveld et al., 2009*). The construction and upkeep of wind farms themselves also impact the immediate environments.

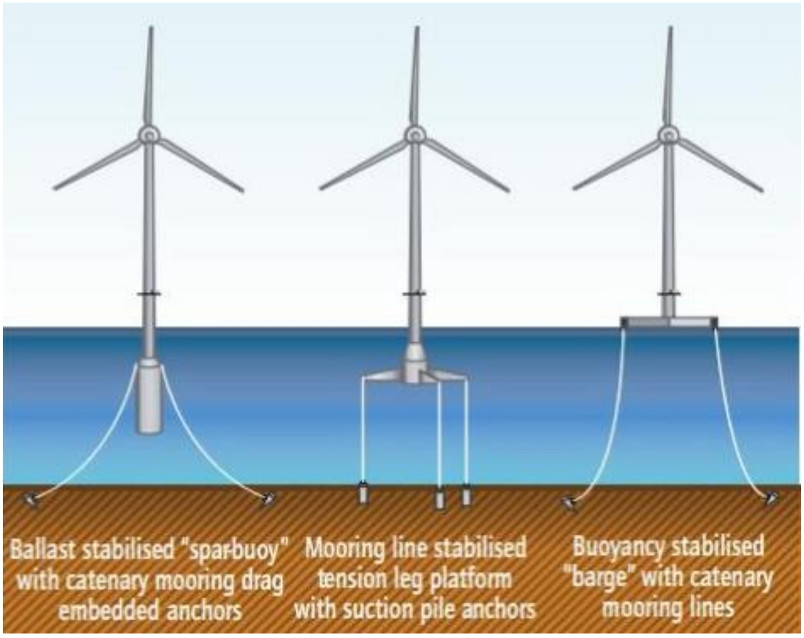

Fig. 6 - Offshore floating wind turbine
(*Wiser et al., 2011*)

The sound generated by the big wind turbines and their aesthetic effect are other issues. In his paper, *Liu, (2017)*, reviews the aerodynamic and mechanical noise mechanisms of wind turbines, as well as de-noising methods used in health condition monitoring. The study concludes that new time-frequency analysis techniques in signal processing are still needed to effectively de-noise signals based on the unique characteristics of wind turbines. There has been opposition to the sight of wind farms in some areas, and the sound generated by the turbine blades can be bothersome to residents in the vicinity. While such concerns are contentious, technological advancements have made the noise levels less.

The installation of wind turbines can also involve high upfront costs, especially for large commercial farms. Wind turbines generally have low maintenance and operational costs; however, high initial costs in certain locations may pose a barrier to deployment. Sieros et al. investigated the cost-effectiveness of wind turbines with rotor diameters up to 250 m and hub heights over 150 m. Their conclusion was that the total optimization issue, including all additional expenses, had optimal solutions on a bigger scale (*Sieros et al., 2012*). Figure 7 depicts the cost history over 12 years and clearly shows a decline in cost per kW.

However, the future of wind turbines is promising. As research and development continue, wind turbines are increasingly economical, efficient, and environmental. Wind energy, along with other renewable sources such as solar energy, is expected to be a core component in global efforts to reduce dependence on fossil fuels and mitigate the effects of global warming. *Badwawi et al., (2015),* published a comprehensive review paper that summarizes major research on optimal sizing design, power electronics topologies, and control strategies. The paper also presents the state of the art for both grid-connected and stand-alone hybrid solar and wind energy systems.

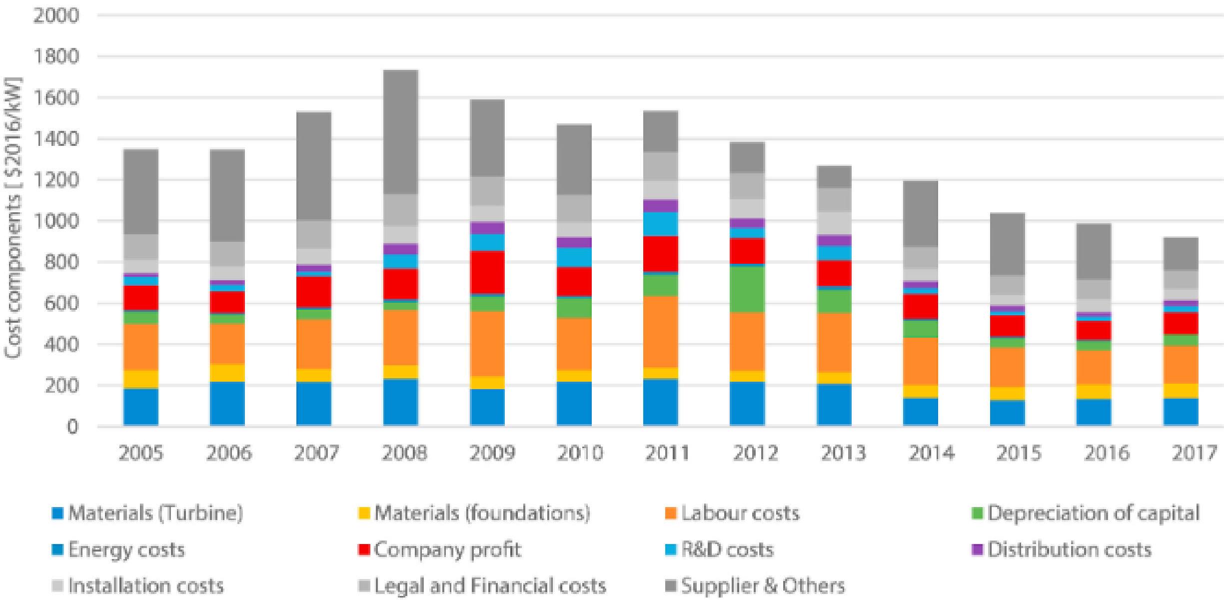

Fig. 7 - Cost comparison (initial investment vs. operating cost)
(*Elia et al., 2020*)

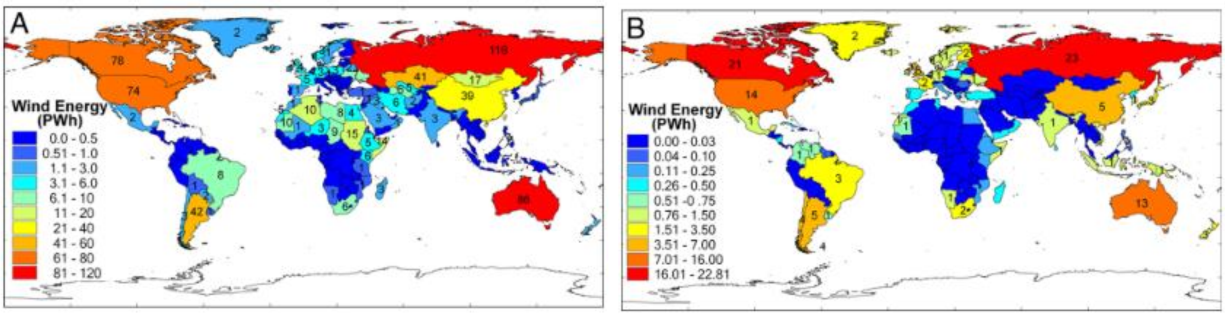

Fig. 8 - Global wind energy potential (A - Onshore. B - Offshore.)
(*Lu et al., 2023*)

Wind turbines are among the most significant technologies supporting the transition from non-renewable to sustainable energy. As the ability to harness wind energy is a cornerstone of the renewable energy portfolio, both horizontal-axis and vertical-axis wind turbines are utilized, each offering distinct advantages. With ongoing technological advancements, wind turbines are expected to become more efficient and serve as a critical foundation in global efforts to mitigate climate change. Despite persistent challenges, such as the intermittency of wind power and its environmental impacts, the continued development of wind energy technology is projected to secure wind turbines a dominant role in clean energy production for the foreseeable future. However, location remains a crucial factor for the effective operation of wind energy systems. Figure 8 illustrates the global zones suitable for wind energy development, including both onshore and offshore applications.

Small wind turbines are increasingly being installed on farms as an inexpensive, clean source of energy. Farmers can reduce their consumption of grid electricity and decrease their energy bill by powering homes with electricity produced from a clean source. Small wind turbines have the capability of offering a stand-alone power source to drive farm lighting, irrigation (Figure 9), and machinery in rural or off-grid settings.

By harnessing wind power, an environmentally friendly and zero-hazardous pollutant-emitting source of power, small wind turbines conserve running expenses while promoting environmental efficiency. This serves to reduce the carbon footprint of farming activities. Small wind turbines can also be coupled with other renewable power systems, such as solar power, to make hybrid systems that can offer a round-the-clock power supply.

Small wind turbines are inexpensive since farmers themselves also get subsidized or encouraged by the government for using renewable technology. Apart from fulfilling the sector's energy requirement, farm wind power is helping to promote larger efforts to green the agricultural sector and mitigate the effects of climate change.

Fig. 9 - Small wind turbine in a farm
(*https://midwestwindmillcompany.com/product/small-farm-windmill*)

INTRODUCTION ON THE SPECIFICITY OF SMALL WIND TURBINES

Medium and small wind generators have attracted much excitement for application as an alternative energy source for small-scale off-grid scenarios. Small wind turbines convert wind into electricity as one step in achieving a more sustainable way of living: providing cleaner alternatives for traditional energy. An overview of challenges, solutions, and future needs in the wind energy domain is presented by Wallenius et al. in their paper (*Wallenius et al., 2016*). Small wind energy generation also offers numerous pros and few cons, in spite of becoming even more useful as concerns about climate change and energy security grow.

They all have that common principle: converting wind energy into mechanical energy, even at very small sizes. According to Bashir, the wind turbine is a promising technology because of its enormous energy potential, environmental friendliness, and minimal maintenance operation when compared to traditional energy generation, and future study on wind turbines should focus on the wind turbines' recycling capacity (*Bashir, 2022*).

As it is shown in figure 10, the wind turbines consist of three main parts: generator, rotor blades, and supporting structure (tower). The speed of the rotation of the blades is caught by the generator shaft. Then, through electromagnetic induction, it gets transformed into usable energy for homes or companies.

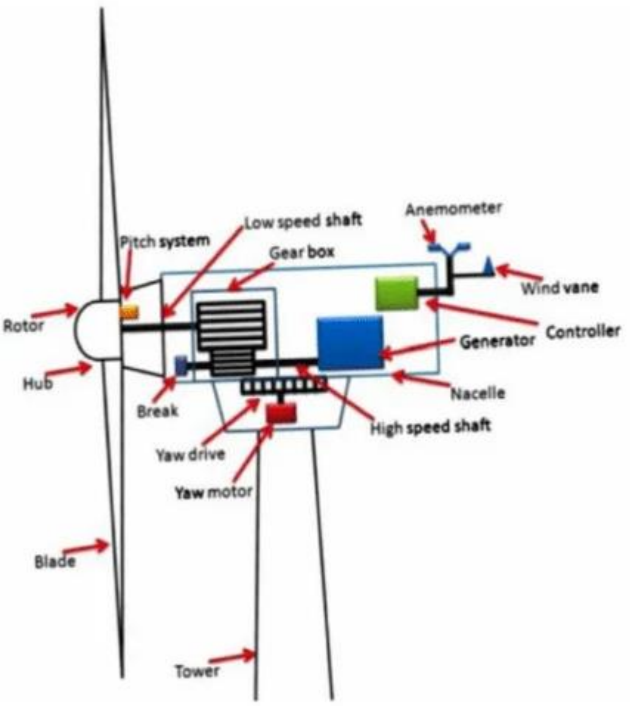

Fig. 10 - Basic components of a wind turbine
(*https://electricalsphere.com/wind-energy-basic-component-and-site-selection*)

Small-scale wind turbines are primarily classified, like all types of wind turbines, according to their axis of rotation, i.e., vertical-axis wind turbines (VAWTs) or horizontal-axis wind turbines (HAWTs). Typically, large installations as well as small ones most often go in for horizontal-axis wind turbines (HAWTs). Rotor blades of these wind turbines rotate in the horizontal plane, much like a normal aircraft propeller. The horizontal-axis wind turbines are specifically more effective in areas where the direction of the wind is relatively constant and predictable, such as open rural areas with ample space and high-speed wind, largely from farmland or coastal locations, as Kabak et al. specified in their paper, where an algorithm in order to determine the suitable regions where the wind turbines would be located was used (*Kabak et al., 2022*).

Vertical-axis wind turbines (VAWTs) can be more effective at collecting wind because they rotate their blades around a vertical axis and can thus take winds from any direction. Due to buildings and obstacles on the ground level, wind directions can be random at times in an urban setting, which is why such applications are suitable for VAWTs. *Alqahtani, (2024)*, published an intriguing article in which the primary goal was to close the gap in process parameter optimization required to transform wind energy wake from highway traffic into electrical energy using vertical-axis wind turbines. VAWTs are not known to be as popular as HAWTs. However, they tend to be a lot more silent, smaller, and thus preferred for residential endeavors.

Both types of turbines have varied benefits based on the region and application, although they function on the same principle. Small wind turbines have a wide availability of application areas due to their adaptation and can be used to offer renewable energy in remote rural areas where small businesses and private homes can depend on it as a reliable alternative to normal energy sources. To back up this claim, Battisti et al. produced research in which they evaluated the effectiveness of small wind turbines in urban settings (*Battisti et al., 2018*). As a consequence, a new constraint for estimating the quantity of energy that a wind turbine will create in a certain location was proposed.

In a good wind resource area, a small wind turbine can provide a sufficient amount of electricity for the energy needs of a typical home. Normally, these systems are combined with solar panels to create a hybrid energy solution that optimizes energy production during both day and night. Hence, even if the sun or the wind doesn't provide the required power, homes can still be powered because of high power output resulting from both sources being harnessed. Small wind turbines will support the sustainable energy supply for remote or rural sites where grid connection is impossible or very expensive. The results of using a small wind turbine system to build environment lamps to comply with the green building approach can be found in *Ozgener, (2006*).

Besides, it can be proved beneficial for small businesses, particularly when they are stably and remotely located. For example, wind turbines can be installed at farms and small manufacturing sites to share the burden of energy expenses. It will help them reduce their dependency upon fossil fuels, which is particularly central since energy is costly and unreliable in certain areas. A review paper summarizing the different studies that have been carried out on the application of SWT technology in the built environment to study the inflowing wind characteristics, their performance, and to detect the knowledge gap, and also exploring the degree to which the international design standard of SWTs, IEC 41400-2, was written by Anup et al. (*Anup et al., 2019*).

Small wind turbines are the perfect choice for remote places where it is extremely expensive to have electricity lines installed. In places that are not part of the national power grid, a small wind turbine can be a power lifeline (*Singh et al., 2013*). Consider isolated villages, research facilities, homes, and even rescue missions after natural disasters—these all can use wind power to create electricity. For example, wind power can provide the energy required for daily living in coastal towns or mountain resorts or even remote research stations in distant corners of the Globe. By integrating energy storage devices with wind energy, isolated systems can be developed to ensure energy security in areas that would otherwise rely on costly and unreliable fuel supplies *(Simic et al., 2013)*. A few examples of small wind turbines that are easily incorporated into urban settings because of their distinctive shapes and low noise pollution are shown in Figure 11.

Fig. 11 - Example of a residential small wind turbine installation
(*https://www.linkedin.com/pulse/does-small-wind-turbine-your-home-increase-thomas-vogel*)

A small vertical-axis wind turbine captures the wind energy naturally and can hence decrease reliance on fossil fuels. These types are essential for the reduction in carbon footprint and stopping climate change. The production of wind turbines as well as their installation is very low in carbon when compared to those emissions that have been produced in the very long term in coal, oil, or gas power plants. However, as Lenzen et al. stated in their paper, despite the fact that the construction and technology of most current wind turbines are rather consistent throughout a wide range of power ratings, existing life-cycle assessments of their energy and CO_2 intensity indicate significant variances (*Lenzen et al., 2002*).

Ultimately, reducing energy costs is one of the most attractive benefits of small wind turbines, although these wind turbine types, after being installed, require less maintenance and operation. The construction of residential systems can be quite costly; however, in the long run, the costs will be offset with savings on energy bills. For example, initial investment can be supported by subsidies, tax credits, and government incentives, thus making wind energy more affordable for consumers. The Global Framework for Climate Services (GFCS) is leading global initiatives to enhance the quality, availability, and application of climate data and forecasts to support renewable energy producers in decision-making processes *(Terrado et al., 2017)*. Many households and companies will hence generate more of their own power, thereby decreasing their dependence on the utility system, and therefore saving up a considerable amount of money. Small wind turbines are expected to last for decades with very little maintenance, usually sporadic maintenance required by most systems, and an expected operating time of 20 to 30 years. Based on the power loss criterion of wind turbines, *Hu et al., (2025),* proposed a yaw system control strategy aimed at improving power output and extending turbine lifespan. When calculating the wind power loss threshold and delay time threshold, the proposed control strategy in their research uses historical data from the wind turbine. From this, they can directly control wind power loss and enhance wind turbine output.

Unlike solar panels, which might need some component repairs or routine cleaning, wind turbines rarely require frequent maintenance. Basic maintenance includes ensuring that the turbine remains aligned with the wind, noting the inspection of the electrical part of the system, as well as ensuring that the blades are clear of defects. Many small turbines tend to be built to withstand tormenting weather conditions, e.g., high winds, rain, and snow; hence, such turbines are strong and very suitable for many settings (*Gonçalves et al., 2021*). As Gonçalves et al. reported in their study, the highest values of wind energy output occurred on stormy days, implying that these high-impact storms had a favorable influence on wind energy production.

Small wind turbines indeed have their share of challenges, but they also come with their benefits. While they can prove to be cost-effective over time, a small wind turbine can be costly to construct at present, such as in the case of using a wind turbine system that also includes all mounting poles and electrical connections. Such systems are often financially out of reach for most businesses and homes. The most significant challenges are believed to be linked with social acceptance, transportation and installation logistics, and medium-term sustainability of the economic and political backing of wind energy as per McKenna et al. study (*McKenna et al., 2016*). In certain locations, however, these costs can be reduced through various incentives, tax credits, and rebates that make wind energy much more cost-effective.

The power output of small wind turbines has further dependence on wind speed at the site. Wind speed and direction are also the most important and of prime importance in determining the productivity of a turbine. In locations where there are very limited wind resources, the turbine will not generate enough power to make the project worthwhile. For this reason, the local wind conditions must be assessed prior to making a decision to install a turbine, as Mangos specifies in his doctoral dissertation (*Mangos, 2024*).

Despite all the advantages, the noise pollution is still created when it operates, especially in larger systems, though new wind turbines are typically quieter than their predecessors. People or businesses within residential areas may be disturbed by this. There are also visual issues, as some people may not prefer a wind turbine on their property because they do not want the appearance of it. Extensive research on the issues of noise pollution linked to the use of wind turbines was undertaken by Ruggiero et al. The paper concerns a predictive software program and experimental frequency spectrum and time history acoustic noise generated by wind turbines (*Ruggiero et al., 2015*).

A promising alternative for renewable energy production, small wind turbines are energy independent, cost-effective, and eco-friendly. With the improving technology, these systems are quieter, more efficient, and faster to install. The ability of small wind turbines to provide renewable power over a wide range of uses, from household use at home to rural regions, cannot be overstressed, even in the presence of issues such as installation costs and site location, aspects that are presented in Fingersh et al.'s report (*Fingersh et al., 2006*). Small wind turbines play a significant role in the global energy transformation as the world seeks cleaner alternatives to fossil fuels in creating a more sustainable and robust energy future.

SYNTHESIS OF EXPERIMENTAL RESEARCH ON SMALL WIND TURBINES

Small wind turbines (SWT) are very important units for producing decentralized renewable energy sources and are sustainable opportunities for rural and away-from-the-grid communities. Unlike the large turbine designs, these small wind turbines are designed to service small businesses and applications that are domestic and agricultural in nature, where the critical factors are reliability and efficiency (*Glasberg et al.,* *2024*). Experimental testing is crucial to render these machines safe, long-lasting, and operationally efficient so as to fill the gap between theoretical designs and real-world performance. A typical example of the corresponding wind turbine class for each application can be seen in Figure 12. As Bianchini et al. suggested in the paper, a house requires a small wind turbine of around 1.5 kW, and one up to 15 kW can be used in a farm.

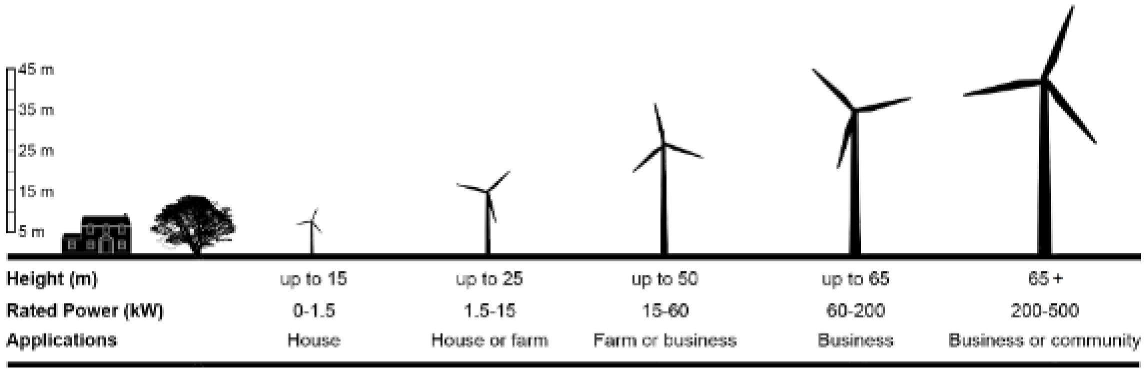

Fig. 12 - Small wind turbines vs large wind turbines (*Bianchini et al., 2022*)

In addition to maximizing turbine performance and compliance with regulation, experimental testing also ensures the validation of computer models. Environmental conditions commonly simplify computational fluid dynamics (CFD) and other theoretical models, and thus, a difference between predicted and actual performance exists (*Dumitrescu et al., 2015*). Experimental testing rectifies the gaps by providing empirical data in simulated and actual environments. In addition, such tests ensure turbines withstand turbulence, dynamic wind loads, and weather conditions for more extended periods, making them safer and more reliable. Representative research in the field belongs to Syawitri et al., who have conducted a flow field analysis to gain insight into the inherent flow physics, such as dynamic stall behavior, using hybrid RANS-LES turbulence models (*Syawitri et al., 2021*).

Field testing, hybrid approaches, and wind tunnel testing are the three broad categories into which small wind turbine test procedures are grouped. Torque, tip speed ratio (TSR), power coefficient (Cp), etc., are tested methodically. The models tend to be on a small scale, and sophisticated measuring devices such as particle image velocimetry (PIV) provide information about the air patterns surrounding the blades of the turbine. In their scientific paper, Edwards et al. used experimental PIV visualization in a wind tunnel on a three-bladed small vertical axis wind turbine experimental model to experimentally validate the CFD numerical simulation results (*Edwards et al., 2015*). An interesting experimental test was conducted by Nietiedt et al., which consists of using two optical measurement systems to simultaneously record fluid (PIV system) and deformation (photogrammetry system) information in one global coordinate system. Their setup can be seen in Figure 13.

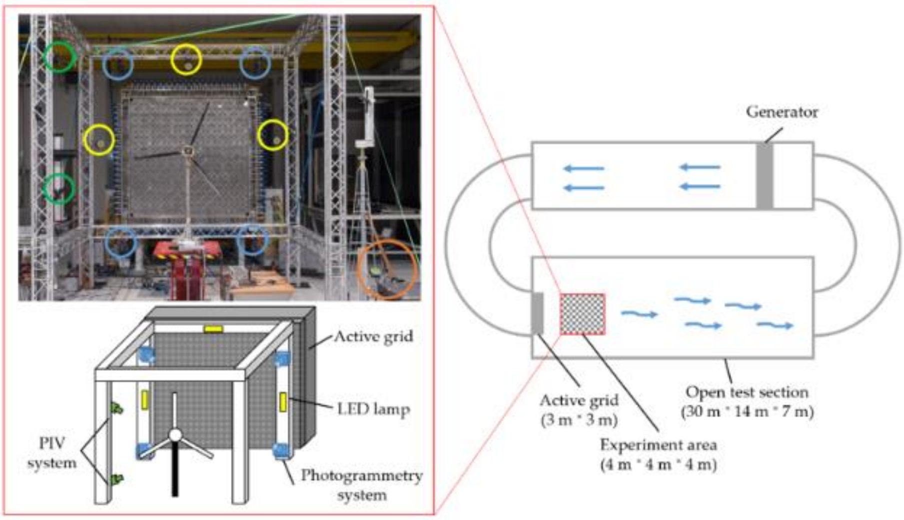

Fig. 13 - Wind tunnel with scale turbine models, airflow visualization (*Nietiedt et al., 2022*)

By placing turbines in their proper operating environments, field testing enhances wind tunnel research. This method takes into account variables such as wind direction, temperature changes, and environmental barriers such as trees or buildings. To evaluate material fatigue, erosion, and noise production under real-world operating conditions, long-term field experiments are crucial. The figure below depicts a stand-alone solution for this sort of study, which may be used practically anywhere on the globe. These solutions include a small wind turbine and a compact housing unit that contains all electronics, energy storage, data collection, and remote-control systems.

Fig.14 - Field test site with small wind turbines installed
(*https://nachhaltigwirtschaften.at/en/iea/technologyprogrammes/wind/iea-wind-task-27-workingperiod-2018-2019.php.*)

To offset individual limitations, hybrid test procedures—blending field testing with wind tunnel testing—are increasingly employed. Such procedures, economical and time-efficient, are accurate by utilizing wind tunnels for first-order parameter optimization and field testing for field validation without compromising on precision. In their paper, LeBlanc et al. report the procedures utilized in the development of a model of an H-type vertical axis wind turbine, which include physical measurement of the as-built form, experimental test updates to the models, and lastly, tests to model correlation on a component-by-component basis, as well as a completely assembled system, bringing in the ideas of "machine learning" and "digital twins" (*LeBlanc et al., 2020*). Emerging technologies, such as machine learning-based data analysis and digital twins, have further increased the strength of hybrid testing systems.

Yilmaz's work compares CFD simulation and experimental data to gain better knowledge of basic rotor aerodynamics principles for designing an aerodynamically efficient small wind turbine rotor by establishing the optimum design tip speed ratio (TSR) and number of blades. Figure 15 depicts part of his results.

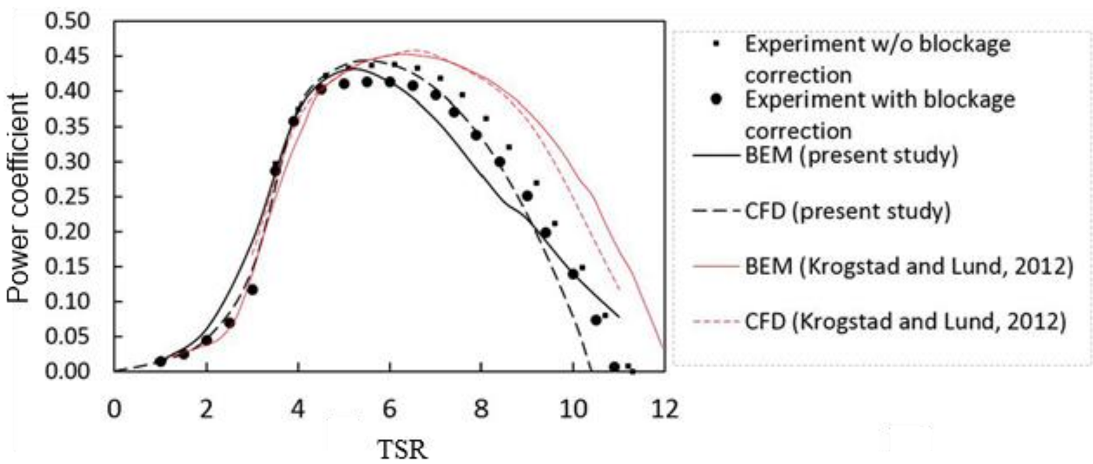

Fig. 15 - Power coefficient as a function of TSR (*Yilmaz., 2022*)

While it has its benefits, experimental testing has its disadvantages, such as very high costs, uncertain climatic conditions, and scaling issues. It requires a high cost to set up wind tunnels or test facilities in the field, and the cost is further increased through the use of high-accuracy sensors and data acquisition systems. The inhomogeneity in the field test condition makes it difficult to process data, and scaling issues in wind tunnel tests could lead to incorrect conclusions when applying the results to full-scale turbines.

High-definition sensors augment precise data, allowing real-time monitoring of important factors while the machine learning software detects patterns and anomalies from complex data sets, improving predictive modelling. Hybrid platforms, which combine virtual simulation and actual-world testing, such as digital twins, offer a cost-effective, scalable substitute for conventional practices (*Pimenta et al., 2020*).

A paper that examines the state-of-the-art of predictive digital twin platforms for wind energy systems based on a five-year review of literature, challenges, and limitations, and debates future research directions belongs to the Kandemir et al. They organize their review based on popular approaches like physics-based modeling, data-driven approaches, and hybrid modeling. Figure 16 is their depiction of a wind turbine development process that entails the digital twin technology.

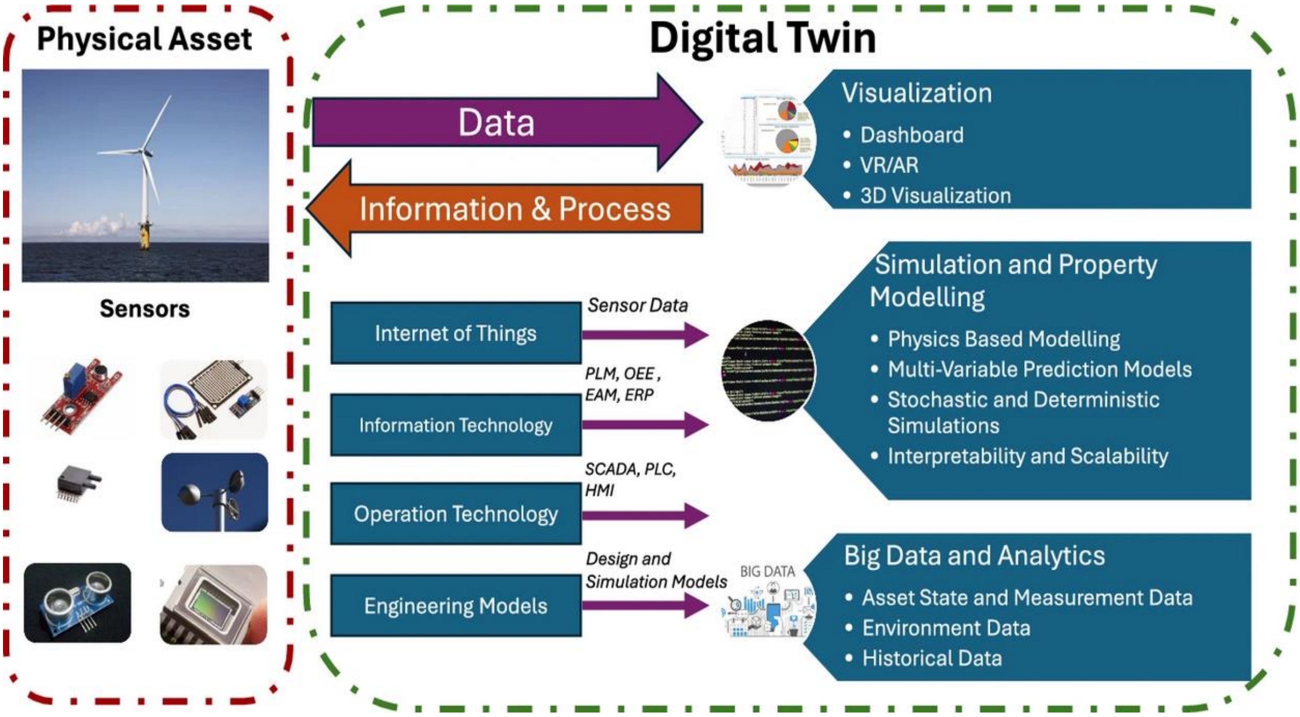

Fig. 16 - Wind turbine testing with digital twin technology (*Kandemir et al., 2024*)

The experimental testing of efficient and effective SWTs and their interaction with theory provides useful verification of theoretical expectations, guiding design improvements and performance limits consistent with safety and efficiency requirements across development stages. New technologies such as sensors, data analytics, and hybrid tests are changing the domain. These technologies could potentially be turning points for the sustainable future of human beings as they considerably increase the affordability and scalability of small wind turbines.

RESEARCH SYNTHESIS ON THE STRUCTURE OF SMALL VERTICAL AXIS WIND TURBINES

A couple of decades ago, wind power increased its popularity as an alternative and renewable energy compared to other energy resources. One of the most promising types of wind turbines is the vertical axis wind turbines (VAWTs), which are recommended for small-scale applications (*Mălăel et al., 2015*). These turbines are the simplest to operate, require lower maintenance, and are the most environmentally friendly. Vertical-axis wind turbines can be located in residential and urban settings where wind and space conditions are less uniform due to their vertical axis.

The basic working principle of vertical-axis wind turbines is the same as that of horizontal-axis wind turbines, which is transforming wind energy into mechanical energy, which will then be used to generate electricity.

The major difference is noticed in the rotor direction. The VAWT turbine blades rotate around a vertical axis of rotation. There exist different VAWT designs, such as the Savonius and Darrieus (*Garmana et al., 2021*). For efficiency, the curved blades of the Darrieus turbine are comparable to the aerodynamic surfaces of an airplane wing. However, due to its simplicity and strength, the Savonius turbine—a semicircular blade with a simpler thrust design—is frequently used in low-wind conditions where other wind turbines struggle even to start. Figure 17 illustrates the principal types of vertical-axis wind turbines. They can gather wind from any direction and thus operate very efficiently with changing winds. Each type has its own advantages and applications, depending on the siting and intended energy output.

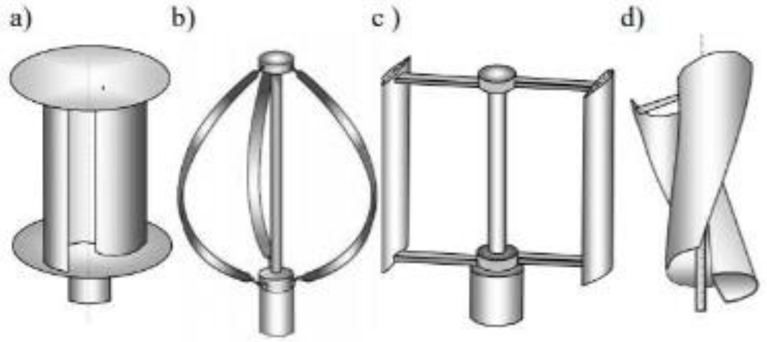

Fig. 17 - VAWT models: a) Savonius type, b) Darrieus type, c) H type, d) spiral type
(*Polak et al., 2006*)

Power rating, typically a few watts to a few kilowatts, defines small VAWTs. The turbines are utilized in domestic, rural, or off-grid applications. Small VAWTs can be inefficient, unreliable, and prone to structural issues - challenges highlighted in several recent studies *(Wood et al., 2011)* - particularly when their design does not align with the characteristics of the installation site. The efficiency and longevity of small VAWTs depend largely on their structural design. These turbines involve close attention to numerous parameters, ranging from material and blade shapes to aerodynamics. Of the most needed is the ability of the turbine to harness energy in low-speed wind, a condition that also comes in abundance for wind systems of small scales (*Clausen et al., 2023*).

The material and form of the blade on the turbine will have a direct impact on the mode of operation of the turbine. Darrieus turbine blades (Figure 18), for example, possess an airfoil cross-section and thus are more aerodynamically efficient and can provide more energy. Manufacturing such blades can be more expensive and complicated, though.

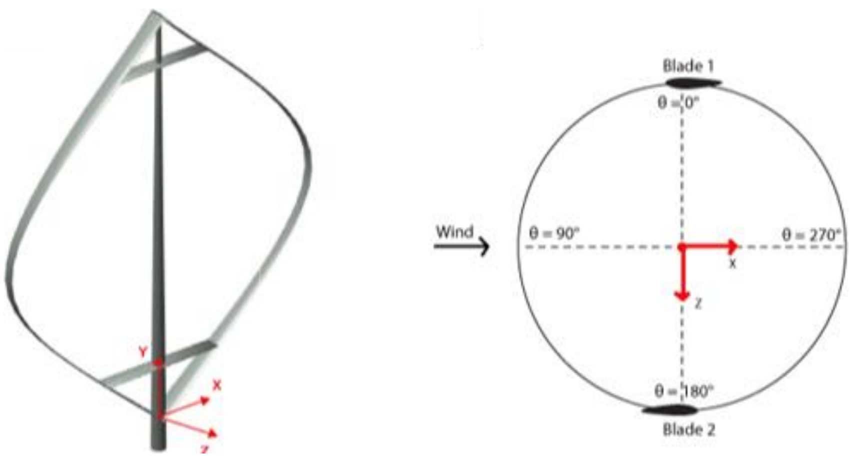

Fig. 18 - Cross-section of the aerodynamic profile of a Darrieus turbine blade
(*Sakib et al., 2021*)

The blade shape, rotor size, and blade number can affect the aerodynamics in small VAWTs. Three-bladed Darrieus turbines have been found to be a good balance between stability and efficiency. Due to its simplicity and ability to start rotating from low wind speeds, the Savonius type, despite its lower efficiency, is still predominantly used for small applications. The choice of material for the support frame of the turbine is also an important aspect in small VAWT design.

In addition to providing strength to withstand wind forces as well as other weather conditions, the blades, rotor, and support frame must also be light enough to allow for easy start-up and smooth running of the system. Fiberglass, composite, steel, and aluminum are the popular materials for manufacturing small VAWTs. Material science and aerodynamics research, as *Condruz et al. (2019*) have shown, and aerodynamics development have improved the vertical axis wind turbine efficiency. A comparison of materials for turbine blades is presented in Figure 19. Though the materials that can be used in the wind turbine blade manufacturing are composites, metals, wood, foams, and even polymers.

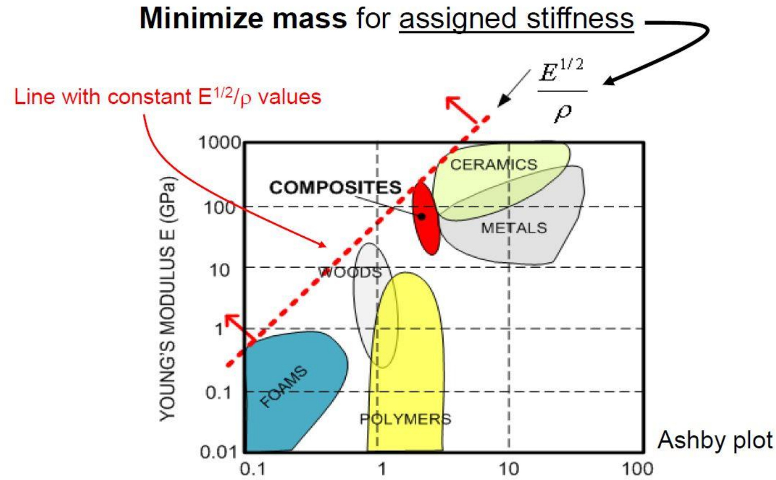

Fig. 19 - Comparison of materials for turbine blades: metal and composite materials
(*https://www.windfarmbop.com/why-wind-turbine-blades-are-made-of-composite-materials/*)

With its lightweight and corrosion-resistant properties, aluminum is very applicable for use on an urban scale on a small scale. On the other hand, steel is primarily used in large-scale developments due to its high strength, but it can also be employed in small VAWTs to meet stability requirements, provided that weight distribution is carefully managed. Their strength-to-weight ratios and resistance to environmental degradation also make fiberglass and composites increasingly sought after. Stability of turbine construction is vital, particularly as wind force changes fairly regularly in VAWTs. Computer-aided and advanced structural analysis techniques like finite element modelling (FEM) have been researched for their ability to optimize structural design. Such simulation makes it possible to accurately predict stress levels, vibration, and likely points of failure within the turbine structure. *Marzec et al., (2023)*, wrote a paper on structural topology optimization of the H-Rotor wind turbine coupled with the one-way Fluid Structure Interaction (FSI) approach. They aim to minimize the volume of the maximum stressed and deformed blades. The results consist of comprehensive information about unstable flow fields around the operating wind turbine coupled with the optimized topology of the interior of the blade without changing the external aerodynamic profile. Part of their results, blade deformations, are presented in Figure 20.

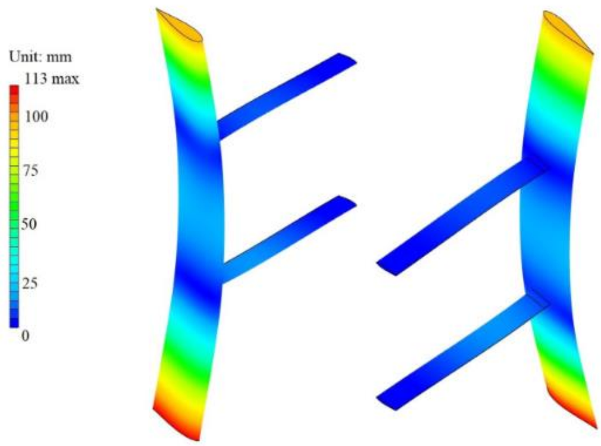

Fig. 20 - Finite element analysis of the VAWT rotor
(*Marzec et al., 2023*)

Small VAWTs' capacity to withstand the stresses of bending and torsion without malfunction is a major worry for engineers. One way to address that is by looking at hybrid turbine designs and multiple blades. The performance of a small vertical axis wind turbine depends on a few key factors: the wind conditions, the design of the turbine itself, and the control systems. To get the most out of small VAWTs, researchers have concentrated on boosting that power coefficient—the measure of how efficiently a turbine can turn wind energy into mechanical power. And that's because wind speeds in domestic and urban areas are notoriously unpredictable; there is a lot of turbulence and wind change in direction. That's why small VAWTs are designed to respond quickly. Savonius turbines, for example, may not produce as much power as Darrieus turbines, but they do operate efficiently at lower wind speeds—and that's a real advantage (Figure 21). A research study that aims to reveal the effect of the rotor radius ratio on the performance of the hybrid vertical axis wind turbine Savonius-Darrieus, using the Computational Fluid Dynamics methods, belongs to Irawan et al. Their results consist of the increase in the rotor radius ratio value causing an increase in the initial torque coefficient but a decrease in the maximum power coefficient value.

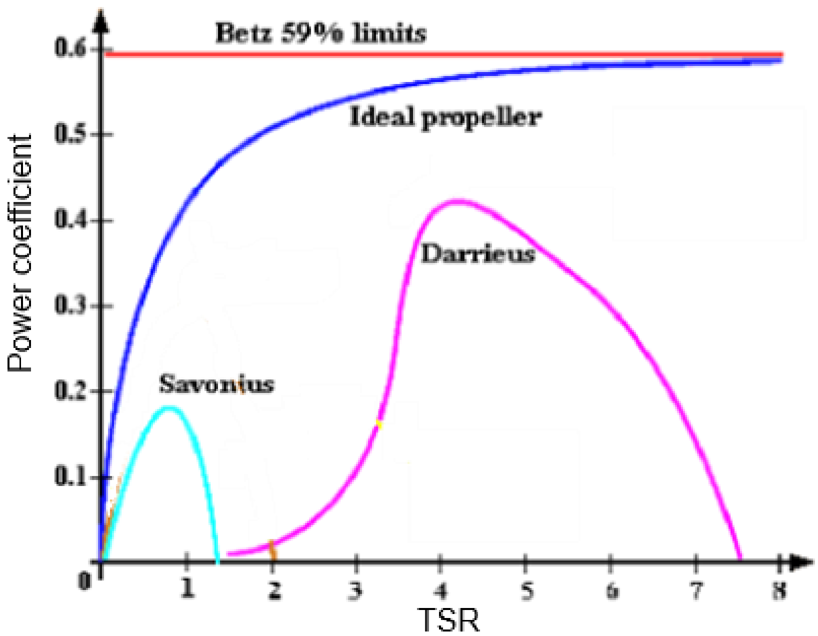

Fig. 21 - Darrieus vs Savonius efficiency
(*Irawan et al., 2023*)

Major design specifications of small vertical-axis wind turbines (VAWTs) include wind speed cut — the lowest speed at which the turbine starts to produce electricity. At this point, technologies like variable speed systems and pitch control come into play because these control systems maximize small VAWTs for a broader range of wind conditions. Small VAWTs generally aren't as efficient as large horizontal-axis wind turbines (HAWTs) because of the inherent aerodynamic losses of the vertical axis. Drag forces that build up as the blades rotate in the wind — especially when the wind speed isn't ideal — can reduce efficiency even further.

Researchers have been trying to drive efficiency up by pitching the blades, using hybrid designs (*Malael et al., 2018*), and implementing control strategies to cut down on drag resistance. Smart grid tech can be used to optimize turbine performance in real-time, based on the latest wind data. But one of the biggest challenges in designing a small VAWT is making sure the structure lasts a long time. That's because small turbines are most susceptible to the kind of mechanical fatigue that comes from variable loads and stresses—turbulence, wind gusts, and other environmental conditions. Blades, bearings, and other mechanical parts can break down and degrade over time. That's why ensuring durability is one of the biggest challenges in the development of small VAWTs. Ali et al. investigated structural optimization of sea-capable VAWTs designed for long-term reliable operation. Based on their analysis, the maintenance cost would be minimized with considerable savings without compromising structural integrity in the marine environment if their optimized combination is utilized. The outcomes of their structural fatigue analysis are demonstrated in the figure below.

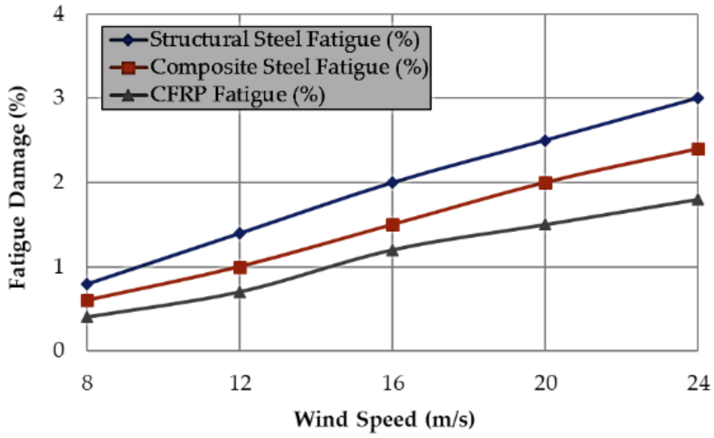

Fig. 22 - Structural fatigue analysis
(*Ali et al., 2024*)

Compact VAWTs depend on some pretty sophisticated bearing systems, vibration-damping technologies, and materials that can withstand fatigue much better. That's not the only thing driving adoption of these turbines in urban areas, though; aesthetics and noise pollution are just as much a factor. A major design challenge for urban wind turbines is the noise generated during operation. A study examining the power produced and noise generated by two small wind turbines that were tested inside a wind tunnel is one of Hays et al. Their suggested configuration showed a 9% increase in power generation and noise reduction of up to 7 dB(A) *(Hays et al., 2019)*. Another paper that deals with the vertical axis wind turbine noise generation is *Yue, (2023*), in which URANS equations were used to numerically investigate the noise level for VAWT at three different wind speeds (Figure 23).

In residential areas, some of those compact designs — especially the ones with fewer blades — can be pretty loud. Engineers are refining those designs to reduce noise generation and adding features that do just that. And because in many places, people care deeply about how wind turbines look, aesthetics often ends up being a major factor in adopting small-scale wind turbines—especially in residential situations. Researchers are developing turbine designs that integrate seamlessly with their surroundings while maintaining high efficiency.

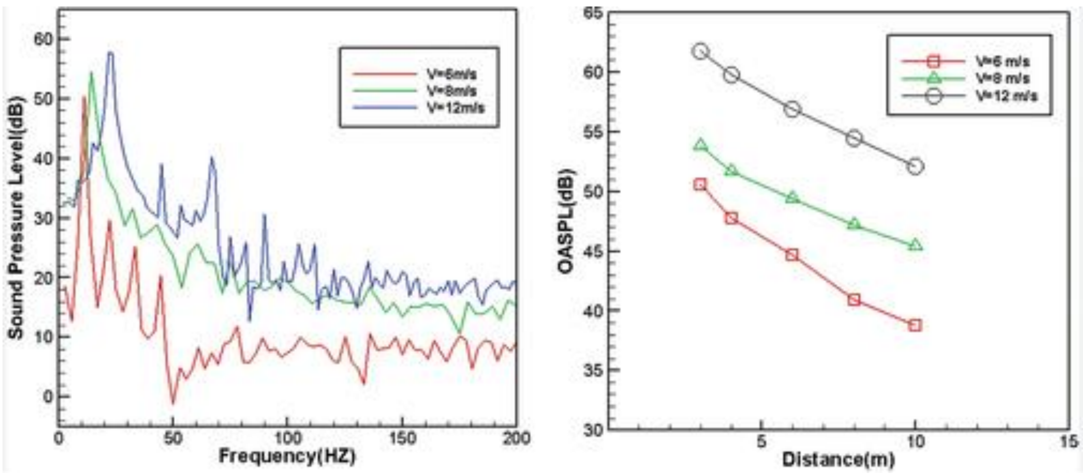

Fig. 23 - Noise levels for VAWT
(*Yue., 2023*)

Solving the problem of an increasing need for residential and off-grid energy, which can be renewable, is possible with the help of a small vertical-axis wind turbine. These turbines are still not the ultimate solution to generation without sporadic interference from the weather but are a step in the right direction that is reliable and can be efficient as well. Nevertheless, a whole lot of questions remain not only about the feasibility of their long-term use but also about whether they are a danger to the environment or not.

Currently, the possibilities of materials, aerodynamics, and control systems are being investigated as a means of overcoming these limitations and ensuring that the overall performance of small VAWTs gets better. The potential of small VAWTs in the renewable energy era, alongside innovation and consequent efficiency, especially in urban environments, which are normally characterized by inadequate wind speeds and little space, helps the situation to bounce back and take advantage of these possibilities. An interesting solution that can be integrated into the urban environment is presented in Figure 24. Three small wind turbine configurations can be easily mounted on a roof building.

Fig. 24 - Small vertical axis wind turbines installed in an urban area
(*https://www.cbc.ca/news/science/what-on-earth-wind-turbines-cities-1.6710512*)

SYNTHESIS OF EXPERIMENTAL RESEARCH ON THE WORKING PROCESS OF SMALL VERTICAL WIND TURBINES

The exponential growth of clean power generation has led to the widespread use of small wind turbines. These systems are present especially in places where the energy and space are limited, such as rural and urban areas. The vertical-axis wind turbine is among the most common wind turbine designs due to its straightforward construction, safety, low maintenance requirements, and ability to capture wind from all directions. The configuration also has several other advantages, particularly in urban areas where the wind can change its direction very often. In order to draw wind energy from any direction without a yaw system, VAWTs (*Mirecki et al., 2007*) represent a simplified solution due to their structural and mechanical structure. Energy conversion in VAWT is realized by using both drag and lift aerodynamic forces. The wind blows directly on the turbine blade's surface and causes the pressure reaction. The motion of the blades is resisted by drag, while lift is the force generated perpendicular to the wind direction, producing torque. An optimal turbine minimizes drag and maximizes lift, thereby achieving high efficiency. The balance between these two forces significantly impacts the energy capture efficiency of the turbine.

A famous example of most elementary turbines is the design of Savonius (Figure 25) turbines, which have the shape of cups, and the number of blades can be two or more (*Zemamou et al., 2017*). The most fitting use of these designs is the collection of energy from low wind rates. However, with the increase of wind velocities, its efficiency goes down as it highly depends on drag only.

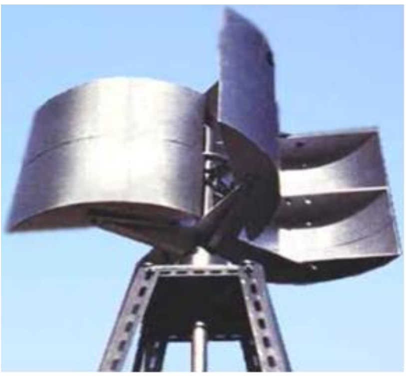

Fig. 25 - A basic Savonius design (*Aboufares et al., 2015*)

Fig. 26 - Darrieus WT
(*https://en.wind-turbine-models.com*)

Fig. 27 - Helical wind turbine design (*Kumar et al., 2019*)

Similar to an airplane wing, the Darrieus turbine uses curved blades in a form like "egg beater" to create power. The more efficient this type of design is when there are stronger winds, the more advanced mechanical parts it requires to work effectively. The conventional structure of this type of turbine is seen in Figure 26. The benefits of Darrieus and Savonius forms are combined into a helical turbine (Figure 27) to demonstrate a balanced performance. Its helix-shaped blade structure makes the system go through minimal mechanical stress while maximizing efficiency over a wide range of wind speeds.

Because there is no need for complex components to direct the turbine towards the wind, VAWTs can collect wind energy from any direction. When the wind is irregular and turbulent, this is beneficial for the power production of these devices. The gearbox and generator, and other components, tend to be placed at the base of the turbine, so it is easier to perform maintenance and reduce downtime. For urban applications where space is limited, VAWTs are preferable since they are generally smaller and can be accommodated in small areas. Anup et al. in their paper elaborate on the diversified studies that have been conducted on the application of SWT technology in the built environment for the purposes of finding out about the inflowing wind characteristics, their performance, and establishing the knowledge gaps (*Anup et al., 2019*). Their paper also delves into the validity of the international design standard for SWTs, IEC 41400-2, for urban installations.

A test rig must mimic different wind conditions to be able to test the performance of a small vertical axis wind turbine. Tests may be done outdoors or in a controlled condition wind tunnel based on the resources available and the level of precision required. Both the direction and speed of the wind can be kept under controlled laboratory conditions at the wind tunnel. Even if a controlled environment like this would be expensive, it is very convenient for reproducible research. When the turbine is outside, natural wind is applied to the turbine. Performance is less predictable and less controllable even if results are more realistic. The detailed outdoor small wind turbine configuration test facility is illustrated by Figure 28. Such a facility has been used in the research work conducted by Mostafavi et al. Outdoor experimental testing under real conditions and without the use of a control environment presented difficult effects such as variability of rotor speed, generation of noise, overloads, and any external environmental influence.

An interesting research work paper that documents comprehensive wind tunnel test results data collected on six airfoils of applicability to small wind turbines is *Selig et al., (2004*). The authors used airfoils like E387, FX 63-137, S822, S834, SD2030, and SH3055. They used the NASA Langley Low Turbulence Pressure Tunnel as their experimental facility.

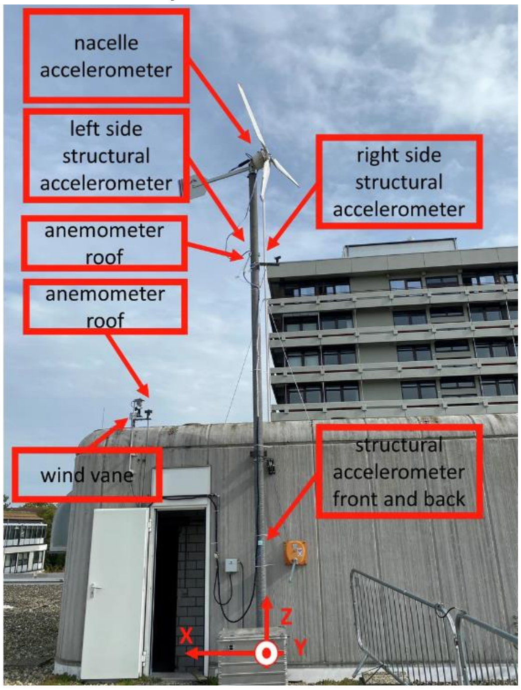

Fig. 28 - Small wind turbine - experimental setup (*Mostafavi et al., 2024*)

An anemometer is a very important measuring instrument used for assessing the turbine's efficiency under various conditions since it estimates the wind speed. Whereas an electrical output produced by the turbine is measured by a power meter, rotational torque transferred on the turbine shaft is measured by a torque meter. Experiments are conducted in the laboratory with the help of a data acquisition system that stores and records data from an anemometer, a torque meter, and a power meter for post-processing afterwards. Torque, rotational speed, and power output are taken when the turbine is tested with changing wind conditions. The primary goal of experimental testing is to measure how effectively the turbine converts wind energy into electrical energy under different operating conditions *(Migliore et al., 2004)*.

Low (2 m/s) to high (15 m/s) wind speeds are employed to test the turbine. Test wind speed ranges are employed to determine the optimal wind speed to attain maximum turbine efficiency. Wind speed measurements are made progressively higher for torque and power output. Different blade configurations are employed to test to observe the impact on performance. Savonius, Darrieus, and helical blades are compared *(Wakui et al., 2005)* under the same wind conditions to determine which of them is most appropriate for small-scale turbines. A comparison of Savonius, Darrieus, and the new configuration is done by Siddiqui et al. The results can be observed in the following graph in which the electrical power with respect to wind speed for each configuration is depicted.

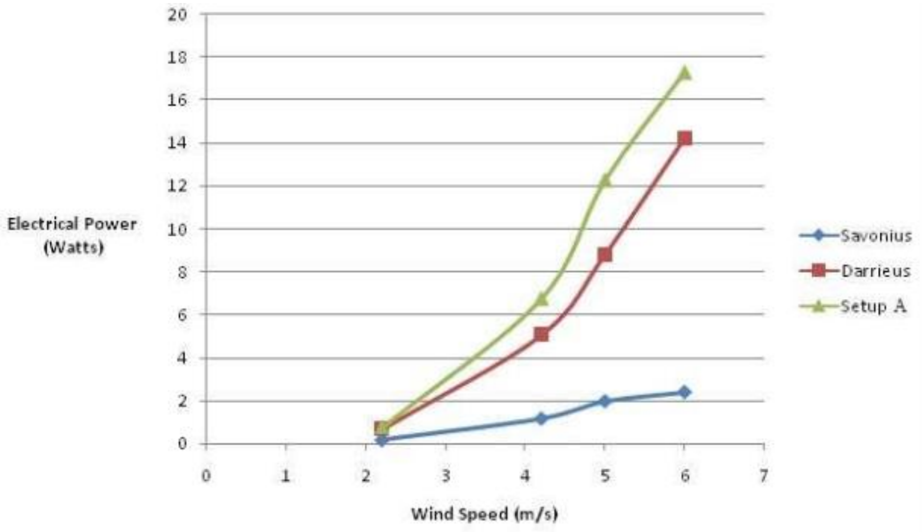

Fig. 29 - Performance comparison (*Siddiqui et al., 2016*)

Performance curves are obtained from the analysis of experimental data and depict the relationship between wind speed and power generation. Efficiency is quantified by the power coefficient (Cp), or the ratio of actual power generated to the theoretical maximum power available from the wind. Conclusions about small vertical axis wind turbine performance can be drawn from experimental test data (*Scungio et al., 2016*). Power output increases rapidly with rising wind speed to an optimum, a quite nonlinear relation between energy produced and wind speed. Performance is normalized after this because of aerodynamic and mechanical constraints.

At a moderate wind speed of about 8 to 12 m/s, the turbine is operating at its most efficient rate. The turbine can overspeed outside this range, decreasing its efficiency and possibly causing the system to be subjected to mechanical stress (Wood et al., 2001). With higher wind speed, there is greater rotational speed and torque. The rotational speed of the turbine stabilizes as it approaches its mechanical limits, but at extremely high wind speeds. This implies that at higher speeds, the rotational speed is stable, but torque increases with the wind speed.

The mechanism of the drag-based Savonius turbine was connected to less efficiency at higher wind speeds, while that of the helical blade of the Darrieus turbine led to maximum efficiency for a wide range of wind speeds. The shape of the blade and the angle of attack contributed significantly towards the optimization of the maximum lift increment and the minimum decrement in drag, thereby maximizing the overall efficiency of the turbine. A typical power versus speed curve of a wind turbine is shown in Figure 30. It is the representation of Mittal et al.'s research and it shows how the power mechanically taken from wind is dependent on rotor speed. Small turbines have been observed to have lower energy conversion efficiency than large commercial turbines (*Ozgener et al., 2006*), measured in terms of electrical power output to available wind energy. Small-scale systems are restricted, there are mechanical losses, and aerodynamic efficiency is poor. Notwithstanding this, small VAWTs are still very useful in decentralized power generation.

Experimental direct testing can provide vital information on the aerodynamic performance, performance parameters, and field applications of small vertical axis wind turbines. Since VAWTs with helical blades *(Han et al., 2018)*, among others, feature a simple configuration, are easy to service, and can capture winds from any direction, they are an ideal choice for low to moderate wind speeds. Although they have lower energy conversion efficiency compared to large turbines, small VAWTs offer compact size and simple installation, making them well-suited for domestic applications and small-scale power generation in areas with fluctuating wind conditions.

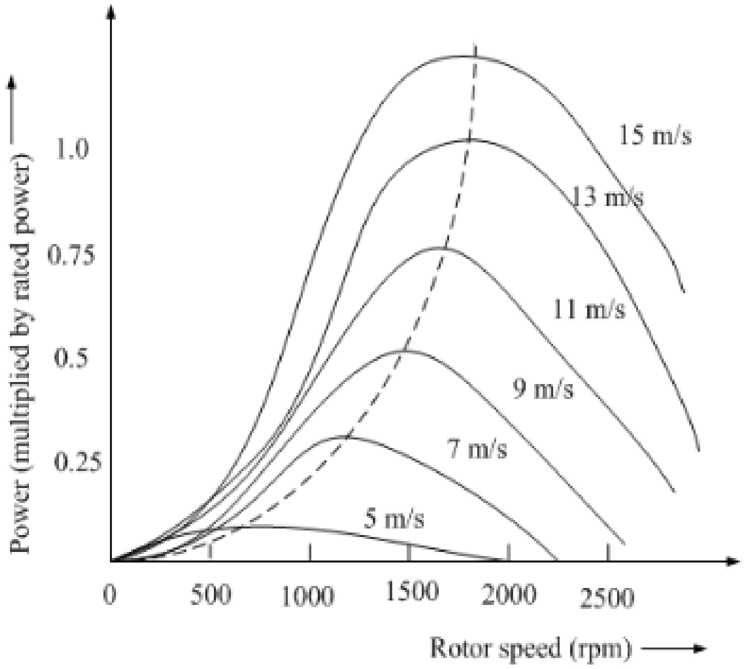

Fig. 30 - A typical power versus speed characteristic of a wind turbine (*Mittal et al., 2011*)

Research and development in small wind turbine technology will have to focus on improved blade design, reduction of mechanical losses, and use of optimized control systems in order to deliver optimum efficiency. On application of the advances, small vertical axis wind turbines can be an important part of the renewable energy industry that delivers sustainable energy solutions to urban and rural communities.

CONCLUSIONS

The paper is part of the documentation done for the PhD thesis, which has as the topic the research of a new wind turbine system integrated into the urban architecture. This review has highlighted the small wind turbine characteristics, including cost-effectiveness, environmental benefits, and suitability for various installation sites. The work is structured in four chapters that reveal the research done by the researchers in the field of small wind turbines. The first section belongs to the introduction on the specificity of small wind turbines with an accent on the advantages and disadvantages along with the challenges despite their benefits.

The synthesis of experimental research presented here highlights both the evolution and the barriers faced by small wind turbines in real-world applications. Issues such as energy conversion efficiency, reliability under various environmental conditions, and durability remain essential for optimizing small wind turbine systems. However, innovations in aerodynamic modelling, structural materials, and hybrid systems pave the way for improved performance in practical conditions.

Vertical-axis wind turbines offer clear advantages in urban areas and low-wind environments and are particularly well-positioned to play a leading role in these settings. With increasingly sophisticated design principles, new materials, and optimized work processes with ongoing research, small VAWTs can be more efficient and versatile in most areas of application. In the long term, ongoing improvement in small wind turbine technology is a giant opportunity for developing sustainable energy. The knowledge resulting from this review undoubtedly portrays areas to be investigated in the future, thereby giving ways for development and exploration in small wind energy systems.

REFERENCES

[1] Abdolahifar, A., & Zanj, A. (2024). Addressing VAWT Aerodynamic Challenges as the Key to Unlocking Their Potential in the Wind Energy Sector. *Energies*, 17(20), 5052.

[2] Aboufares, G. (2015). *Performance Characteristics of a Vertical Axis Wind Turbine Operating in Different Environmental Conditions* (Doctoral dissertation, University of Huddersfield).

[3] Adams, D., White, J., Rumsey, M., & Farrar, C. (2011). Structural health monitoring of wind turbines: method and application to a HAWT. *Wind Energy*, 14(4), 603-623.

[4] Ali, S., Park, H., & Lee, D. (2024). Structural Optimization of Vertical Axis Wind Turbine (VAWT): A Multi-Variable Study for Enhanced Deflection and Fatigue Performance. *Journal of Marine Science and Engineering*, 13(1), 19.

[5] Alqahtani, M. (2024). Optimization of VAWT installation with spatial and temporal complexity considerations. *Frontiers in Energy Research*, 12, 1373586.

[6] Andrew Ning, S., Damiani, R., & Moriarty, P. J. (2014). Objectives and constraints for wind turbine optimization. *Journal of Solar Energy Engineering*, 136(4), 041010.

[7] Anup, K. C., Whale, J., & Urmee, T. (2019). Urban wind conditions and small wind turbines in the built environment: A review. *Renewable energy*, 131, 268-283.

[8] Badwawi, R. A., Abusara, M., & Mallick, T. (2015). A review of hybrid solar PV and wind energy system. *Smart Science*, 3(3), 127-138.

[9] Bashir, M. B. A. (2022). Principle parameters and environmental impacts that affect the performance of wind turbine: an overview. *Arabian Journal for Science and Engineering*, 47(7), 7891-7909.

[10] Battisti, L., Benini, E., Brighenti, A., Dell'Anna, S., & Castelli, M. R. (2018). Small wind turbine effectiveness in the urban environment. *Renewable energy*, 129, 102-113.

[11] Bianchini, A., Bangga, G., Baring-Gould, I., Croce, A., Cruz, J. I., Damiani, R., ... & Orrell, A. (2022). Current status and grand challenges for small wind turbine technology. *Wind Energy Science*, 7(5), 2003-2037

[12] Brown, L. R. (2015). The great transition: Shifting from fossil fuels to solar and wind energy. *WW Norton & Company*.

[13] Civera, M., & Surace, C. (2022). Non-destructive techniques for the condition and structural health monitoring of wind turbines: A literature review of the last 20 years. *Sensors*, 22(4), 1627.

[14] Clausen, P. D., Evans, S. P., & Wood, D. H. (2023). Design, manufacture, and testing of small wind turbine blades. *Advances in wind turbine blade design and materials*. pp. 441-461. Woodhead Publishing.

[15] Condruz, M. R., Malael, I., Vintila, I. S., & Cernat, M. P. (2019). Manufacturing of advanced composite wind turbine blades for counter rotating vertical wind turbine. *Mater. Plast*, 57, 45-56.

[16] Dumitrescu, H., Cardos, V., & Malael, I. (2015). Boundary vorticity dynamics at very large Reynolds numbers. *INCAS Bulletin*, 7(3), 89.

[17] Edwards, J. M., Danao, L. A., & Howell, R. J. (2015). PIV measurements and CFD simulation of the performance and flow physics and of a small-scale vertical axis wind turbine. *Wind Energy*, 18(2), 201-217.

[18] Elia, A., Taylor, M., Gallachóir, B. Ó., & Rogan, F. (2020). Wind turbine cost reduction: A detailed bottom-up analysis of innovation drivers. *Energy Policy*, 147, 111912

[19] Elkodama, A., Ismaiel, A., Abdellatif, A., Shaaban, S., Yoshida, S., & Rushdi, M. A. (2023). Control methods for horizontal axis wind turbines (HAWT): State-of-the-art review. *Energies*, 16(17), 6394.

[20] Enevoldsen, P., & Xydis, G. (2019). Examining the trends of 35 years growth of key wind turbine components. *Energy for sustainable development*, 50, 18-26.

[21] Eriksson, S., Bernhoff, H., & Leijon, M. (2008). Evaluation of different turbine concepts for wind power. *Renewable and sustainable energy reviews*, 12(5), 1419-1434.

[22] Fingersh, L., Hand, M., & Laxson, A. (2006). Wind turbine design cost and scaling model (No. NREL/TP-500-40566). *National Renewable Energy Lab.(NREL)*, Golden, CO (United States).

[23] Garmana, A., & Arifin, F. (2021). CFD analysis for combination Savonius and Darrieus turbine with differences in the number of Savonius turbine blades. In *2021 International Conference on Artificial Intelligence and Mechatronics Systems (AIMS).* pp. 1-5. IEEE.

[24] Glasberg, D., Stratila, S., & Malael, I. (2024). A Numerical Analysis on the Performance and Optimization of the Savonius Wind Turbine for Agricultural Use. Engineering. *Technology & Applied Science Research*, 14(1), 12621-12627.

[25] Gonçalves, A., Liberato, M. L., & Nieto, R. (2021). Wind energy assessment during high-impact winter storms in southwestern Europe. *Atmosphere*, 12(4), 509.

[26] Han, D., Heo, Y. G., Choi, N. J., Nam, S. H., Choi, K. H., & Kim, K. C. (2018). Design, fabrication, and performance test of a 100-W helical-blade vertical-axis wind turbine at low tip-speed ratio. *Energies*, 11(6), 1517.

[27] Hays, A., & Van Treuren, K. W. (2019). A study of power production and noise generation of a small wind turbine for an urban environment. *Journal of Energy Resources Technology*, 141(5), 051202.

[28] Hu, Y., Luo, P., Yao, W., Zhou, L., Shi, P., Yang, W., & Han, H. (2025). Power increase and lifespan extension control strategy of wind turbine yaw system based on power loss. *Sustainable Energy Technologies and Assessments*, 74, 104172.

[29] Irawan, E. N., Sitompul, S., Yamashita, K. I., & Fujita, G. (2023). The effect of rotor radius ratio on the performance of hybrid vertical axis wind turbine Savonius-Darrieus NREL S809. *Journal of Energy and Power Technology*, 5(1), 1-12.

[30] Johnson, C. C., & Smith, R. T. (1976). Dynamics of wind generators on electric utility networks. *IEEE Transactions on Aerospace and Electronic Systems*, (4), 483-493.

[31] Junginger, M., Hittinger, E., Williams, E., & Wiser, R. (2020). Onshore wind energy. *Technological learning in the transition to a low-carbon energy system*. pp. 87-102. Academic Press.

[32] Kabak, M., & Akalın, S. (2022). A model proposal for selecting the installation location of offshore wind energy turbines. *International Journal of Energy and Environmental Engineering*, 13(1), 121-134.

[33] Kandemir, E., Hasan, A., Kvamsdal, T., & Abdel-Afou Alaliyat, S. (2024). Predictive digital twin for wind energy systems: a literature review. *Energy Informatics*, 7(1), 68.

[34] Khammas, F., Hussein Suffer, K., Usubamatov, R., & Mustaffa, M. T. (2015). Overview of vertical axis wind turbine (VAWT) is one of the wind energy applications. *Applied Mechanics and Materials*, 793, 388-392.

[35] Kragten, A. (2004). The Darrieus rotor, a vertical axis wind turbine (VAWT) with only a few advantages and many disadvantages. *Report KD215. Engineering Office Kragten Design, Populierenlaan*, 51, 5492.

[36] Krijgsveld, K. L., Akershoek, K., Schenk, F., Dijk, F., & Dirksen, S. (2009). Collision risk of birds with modern large wind turbines. *Ardea*, 97(3), 357-366.

[37] Kumar, P. M., Sivalingam, K., Narasimalu, S., Lim, T. C., Ramakrishna, S., & Wei, H. (2019). A review on the evolution of Darrieus vertical axis wind turbine: Small wind turbines. *Journal of Power and Energy Engineering*, 7(4), 27-44.

[38] LeBlanc, B., & Ferreira, C. (2020). Experimental characterization of H-VAWT turbine for development of a digital twin. *Journal of Physics: Conference Series.* Vol. 1452, No. 1, p. 012057. IOP Publishing.

[39] Lenzen, M., & Munksgaard, J. (2002). Energy and CO2 life-cycle analyses of wind turbines—review and applications. *Renewable energy*, 26(3), 339-362.

[40] Liu, W. Y. (2017). A review on wind turbine noise mechanism and de-noising techniques. *Renewable Energy*, 108, 311-320.

[41] Lu, X., & McElroy, M. B. (2023). Global potential for wind-generated electricity. *Wind energy engineering*. pp. 47-61. Academic Press.

[42] Malael, I., & Dragan, V. (2018). Numerical and Experimental Efficiency Evaluation of a Counter-Rotating Vertical Axis Wind Turbine. *Engineering, Technology & Applied Science Research*, 8(4).

[43] Mălăel, I., Dragan, V., & Vizitiu, G. (2015). The vertical axis wind turbine efficiency evaluation by using the CFD methods. *Applied Mechanics and Materials*, 772, 90-95.

[44] Mangos, O. (2024). *Contributions to the development of the wind energy potential of the Republic of Moldova (Contribuții la valorificarea potențialului energetic eolian al Republicii Moldova)* (Doctoral dissertation, Technical University of Moldova.

[45] Marzec, Ł., Buliński, Z., Krysiński, T., & Tumidajski, J. (2023). Structural optimisation of H-Rotor wind turbine blade based on one-way Fluid Structure Interaction approach. *Renewable Energy*, 216, 118957.

[46] McKenna, R., vd Leye, P. O., & Fichtner, W. (2016). Key challenges and prospects for large wind turbines. *Renewable and Sustainable Energy Reviews*, 53, 1212-1221.

[47] Migliore, P., & Oerlemans, S. (2004). Wind tunnel aeroacoustic tests of six airfoils for use on small wind turbines. *J. Sol. Energy Eng*., 126(4), 974-985.

[48] Mirecki, A., Roboam, X., & Richardeau, F. (2007). Architecture complexity and energy efficiency of small wind turbines. *IEEE Transactions on Industrial Electronics*, 54(1), 660-670.
[49] Mittal, R., Sandhu, K. S., & Jain, D. K. (2011). Grid voltage control of inverter interfaced wind energy conversion system (WECS). *International Journal of Environmental Science and Development*, 2(5), 337.
[50] Mostafavi, A., & Friedmann, A. (2024). Wind turbine condition monitoring dataset of Fraunhofer LBF. *Scientific Data*, 11(1), 1108.
[51] Nietiedt, S., Wester, T. T., Langidis, A., Kröger, L., Rofallski, R., Göring, M., ... & Luhmann, T. (2022). A Wind Tunnel Setup for Fluid-Structure Interaction Measurements Using Optical Methods. *Sensors*, 22(13), 5014.
[52] Ozgener, O. (2006). A small wind turbine system (SWTS) application and its performance analysis. *Energy Conversion and Management*, 47(11-12), 1326-1337.
[53] Pimenta, F., Pacheco, J., Branco, C. M., Teixeira, C. M., & Magalhães, F. (2020, September). Development of a digital twin of an onshore wind turbine using monitoring data. *Journal of Physics: Conference Series*. Vol. 1618, No. 2, p. 022065. IOP Publishing.
[54] Polak A., Barański M. (2006). Wind turbines comparison. *Electrical Machines*, pp. 147-151
[55] Ruggiero, A., Quartieri, J., Guarnaccia, C., & Hloch, S. (2015). Noise pollution analysis of wind turbines in rural areas. *International Journal of Environmental Research*, 9(4), 1277-1286.
[56] Sakib, M. S., & Griffith, D. T. (2021). Parked and operating loads analysis in the aerodynamic design of multi-megawatt-scale floating vertical axis wind turbines. *Wind Energy Science Discussions*, pp. 1-28
[57] Salem, M. E. M. (2016). Design of a pitch angle control system for a horizontal axis small wind turbine (Master thesis). Benha University. Benha Faculty of Engineering. Egypt
[58] Scungio, M., Arpino, F., Focanti, V., Profili, M., & Rotondi, M. (2016). Wind tunnel testing of scaled models of a newly developed Darrieus-style vertical axis wind turbine with auxiliary straight blades. *Energy Conversion and Management*, 130, 60-70.
[59] Selig, M. S., & McGranahan, B. D. (2004). Wind tunnel aerodynamic tests of six airfoils for use on small wind turbines. *J. Sol. Energy Eng*., 126(4), 986-1001.
[60] Siddiqui, A., Hameed, A., Mian, S. N., & Khatoon, R. (2016). Experimental Investigations of hybrid vertical axis wind turbine. *4-th International Conference on Energy, Environment and Sustainable Development (EEDS2016)*.
[61] Sieros, G., Chaviaropoulos, P., Sørensen, J. D., Bulder, B. H., & Jamieson, P. (2012). Upscaling wind turbines: theoretical and practical aspects and their impact on the cost of energy. *Wind energy*, 15(1), 3-17.
[62] Simic, Z., Havelka, J. G., & Vrhovcak, M. B. (2013). Small wind turbines–A unique segment of the wind power market. *Renewable Energy*, 50, 1027-1036.
[63] Singh, R. K., & Ahmed, M. R. (2013). Blade design and performance testing of a small wind turbine rotor for low wind speed applications. *Renewable Energy*, 50, 812-819.
[64] Syawitri, T. P., Yao, Y. F., Chandra, B., & Yao, J. (2021). Comparison study of URANS and hybrid RANS-LES models on predicting vertical axis wind turbine performance at low, medium and high tip speed ratio ranges. *Renewable Energy*, 168, 247-269.
[65] Szlivka, F., Molnár, I., & Sándor, G. (2017). Advantages and disadvantages of different types of wind turbines and their usage in the city. *Wind Energy Harvesting*.
[66] Terrado, M., González-Reviriego, N., Lledó, L., Torralba, V., Soret, A., & Doblas-Reyes, F. J. (2017). Climate services for affordable wind energy. *WMO Bull*, 66, 48-53.
[67] Wakui, T., Tanzawa, Y., Hashizume, T., & Nagao, T. (2005). Hybrid configuration of Darrieus and Savonius rotors for stand-alone wind turbine-generator systems. *Electrical Engineering in Japan*, 150(4), 13-22.
[68] Wallenius, T., & Lehtomäki, V. (2016). Overview of cold climate wind energy: challenges, solutions, and future needs*. Wiley Interdisciplinary Reviews: Energy and Environment*, 5(2), 128-135.
[69] Winters, J., & Saunders, Z. (2018). The largest wind turbine ever. *Mechanical Engineering*, 140(12), 31-31.
[70] Wiser, R. et al., (2011). *Wind Energy in IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, Cambridge and New York: Cambridge University Press.

[71] Wood, D. (2011). Small wind turbines. *Advances in wind energy conversion technology*. pp. 195-211. Berlin, Heidelberg: Springer Berlin Heidelberg.
[72] Wood, D. H. (2001). A blade element estimation of the cut-in wind speed of a small turbine. *Wind Engineering*, 25(2), 125-130.
[73] Wu, X., Hu, Y., Li, Y., Yang, J., Duan, L., Wang, T., ... & Liao, S. (2019). Foundations of offshore wind turbines: A review. *Renewable and Sustainable Energy Reviews*, 104, 379-393.
[74] Xiaohui, W., & Zhang, X. (2010). Calculation of electromagnetic induction inside a wind turbine tower struck by lightning. *Wind Energy*, 13(7), 615-625.
[75] Yilmaz, O. (2022). Increasing power coefficient of small wind turbine over a wide tip speed range by determining proper design tip speed ratio and number of blades. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 236(23), 11211-11230.
[76] Yue, Q. (2023). Aerodynamic noise prediction and reduction of H-Darrieus vertical axis wind turbine. *Australian Journal of Mechanical Engineering*, 21(3), 1093-1102.
[77] Zemamou, M., Aggour, M., & Toumi, A. (2017). Review of Savonius wind turbine design and performance. *Energy Procedia*, 141, 383-388.
[78] ****https://drawdown.org/solutions/onshore-wind-turbines*
[79] ****https://electricalsphere.com/wind-energy-basic-component-and-site-selection/*
[80] ****https://en.wind-turbine-models.com/turbines/93-dornier-darrieus-55*
[81] ****https://nachhaltigwirtschaften.at/en/iea/technologyprogrammes/wind/iea-wind-task-27-workingperiod-2018-2019.php.*
[82] ****https://www.cbc.ca/news/science/what-on-earth-wind-turbines-cities-1.6710512*
[83] ****https://www.linkedin.com/pulse/does-small-wind-turbine-your-home-increase-thomas-vogel*
[84] ****https://midwestwindmillcompany.com/product/small-farm-windmill*
[85] ****https://www.windfarmbop.com/why-wind-turbine-blades-are-made-of-composite-materials/*