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Review article

Performance study of low-speed wind energy harvesting by micro wind turbine system

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ABSTRACT

Wind energy constitutes a fundamental clean and sustainable energy asset, serving an essential function in the worldwide shift towards a low-carbon energy framework. Notwithstanding the technological innovations that have improved the accessibility and operational efficiency of wind power, the intrinsic variability of wind velocity and flow patterns continues to present considerable obstacles to the advancement of wind turbines that can rival conventional energy sources in terms of operational performance and reliability. To address these obstacles, the current research endeavor is dedicated to the augmentation of energy extraction from low-velocity wind environments through the implementation of micro-scale wind turbine systems. By utilizing maximum power point tracking (MPPT) algorithms, this study investigates the operational strategies of wind turbines subjected to variable wind conditions, with a particular focus on optimizing energy capture during low to moderate wind speeds. In addition, the research delineates targeted design recommendations aimed at improving the efficacy of small-scale wind turbines in low-velocity circumstances. A hybrid economic-environmental strategy is underscored as a viable approach to mitigate the unpredictability associated with wind energy, thereby integrating renewable energy systems with energy storage mechanisms. This research endeavor aims to facilitate the advancement of efficient, environmentally sustainable, and economically viable wind energy technologies that are meticulously tailored for small-scale implementations

1. Introduction

Due to important technical advancements and the requirement to meet the global sustainable development goals (SDGs), the energy demand has increased dramatically. Because they produce high amounts of pollution, traditional energy sources like coal and other fossil fuels have turned into serious environmental risks.

Global warming, rising carbon emissions, and the depletion of fossil fuel resources are the current problems facing the planet, (Olivier and Peters, 2020; Olabi et al., 2022). Besides, the availability of fossil fuels has significantly raised the cost of energy. Hence, economic poverty is associated with 733 million individuals who do not have access to energy; it is either directly or indirectly linked to economic poverty, (Nguyen and Su, 2022).

Interested individuals as well as bodies are starting to look at alternative energy sources as a means of moving away from fossil fuels and toward more environmentally responsible options, (Rios Villacorta et al., 2021); eventually, emissions of sulfur, carbon, and particulate matter are bad for the environment and for people. A cleaner and greener planet is not far-fetched if their use is restricted. In-depth research is also done on alternative power generation techniques to determine their effectiveness, accessibility, and utility, (Pavan Kumar

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and Bhimasingu, 2015).

By utilizing renewable resources, these alternative energy sources decrease air pollution and carbon emissions while reducing dependency on fossil fuels, (Davis.). Much of the research interest has been focused on renewable energy prospects and ways to make them more efficient and compliant due to the growing need for environmentally acceptable energy resources. Hence, long-term, and life-threatening issues like pollution and global warming have accelerated technological advancements in numerous fields, (McKenna et al., 2022).

Renewable energies are mostly represented by and obtained from sources such as solar, (Al-Manea et al., 2022; Qamar et al., 2022), wind (McKenna et al., 2022), hydro, and biomass ones, (Saravanan et al., 2022). Thus, an evaluation of the vertical axis wind turbine's effectiveness for home users is needed. Many nations are currently engaged in the gathering of energy from solar, wind, water, biomass, and tidal sources. This form of power generating will be more affordable for developing nations because it offers safer conditions for the production of electricity while also requiring less capital and maintenance.

Natural resources abound in wind energy, which also has the benefit of generating power, (Abbas et al., 2021). According to recent figures, throughout the last 10 years, the average yearly global temperature has increased at a rate of 1.14 C, coinciding with a rise in electricity generation, (Krishnan et al., 2023). The main cause for such an anomaly is the rise in CO2 emissions from burning fossil fuels each year. For that reason, a growing number of people are interested in renewable energy sources, such as wind, solar, and bioenergy, which together provide 28.1 % of the world's energy, due to their sustainability and low ecological impact.

Utilizing wind energy is free, and it does not pollute the environment after use. It is currently getting more attention than ever before because its use can successfully lower the use of fossil energy as well as greenhouse gas emissions, (Wang and Zhuang, 2017a; Wang et al., 2018). It therefore helps to meet the demand for energy while simultaneously promoting local growth and worldwide environmental preservation. Spending on renewable energy sources is rising globally, with wind energy being a vital renewable energy resource for boosting electrical power capacity. The International Energy Agency (IEA) claims that wind energy in 2020, broke all previous records ("IEA Wind TCP, 2020).

2. Wind turbine

The world's population has been growing quickly and, along with it, industries have been developing rapidly, which has in turn led to an increase in global energy consumption (Aldricy et al.). In this regard, the wind when compared to other renewable energy resources is thought to be one of the most promising and quickly expanding sources of energy for the production of electricity because it is plentiful, endless, and non-polluting (Abbas et al., 2021). There is a long history of using wind turbine models to harness wind energy as shown in Fig. 1.

Wind energy was not rediscovered as an alternative energy source until resistance to the use of oil, charcoal, or uranium in power generation grew, (Hau, 2008). One of the most advanced forms of renewable energy harvesting technology today is the wind turbine.

There is a significant lack of conventional energy, which has sparked interest in pollution-free renewable energy, (Lü et al., 2018). Economic feasibility is highly dependent on how well the system works to gather useful energy from naturally existing sources. One of the most advanced forms of renewable energy collecting technology today is the wind turbine. An overview of the general classification schemes that wind turbines can have been shown in Fig. 2.

Onshore turbines are more prevalent and have recently gained much appeal due to the steady wind that allows them to run continuously. Yet, the installation of large-scale wind turbines has resulted in an increase in global temperature, which is a significant barrier to reaching the intended sustainable goals (LSWT). By 2020, the installed capacity of wind power worldwide rose from 60.8 GW to 93 GW. Furthermore, the onshore industry utilized 86.9 GW, which represents a 59 % rise from 2019 upwards. Globally, wind energy accounted for 6.2 % of the total electricity supply in 2020, producing 1590 TWh, as will be shown ("IEA Wind TCP, 2020).

Wind turbine electricity can be distributed to users via the electric grid or consumed locally. Large wind turbines of today are multimegawatt machines with rotor diameters greater than 100 m. Consequently, it is essential to site wind-turbine installations in areas with high wind speeds because this results in a bigger generation of electrical energy, (Alkhalidi et al., 2022). Because of the steady wind and little turbulence, onshore, or close to the coast, it is usually the best place.

However, because these sites are frequently found in densely populated areas, installation of wind energy is frequently hampered by acceptance concerns, (Alfredsson and Segalini, 2017). In an urban environment, wind direction and speed are unpredictable because of different obstacles such as apartment buildings and skyscrapers, which can easily influence or lead them in different directions. Large wind turbines cannot run economically as a result of that.

Microwind turbines are therefore used to address these problems. Apart from all the sources of renewable energy, the production of electricity from renewable sources requires the use of greener energy technologies, such as micro wind turbines. A micro wind turbine is used to generate or produce low DC voltage power. In order to optimize wind turbine electrical output efficiency, a number of mechanical and

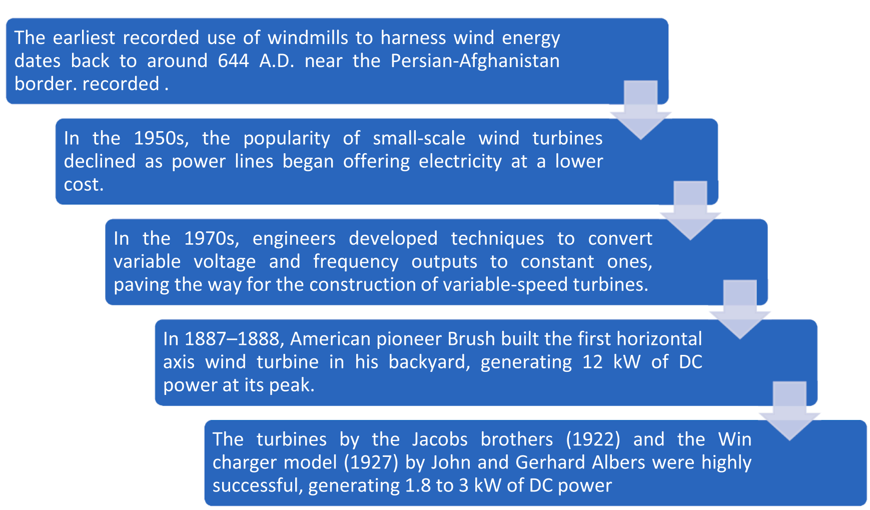

Fig. 1. Historical stages of turbine development.

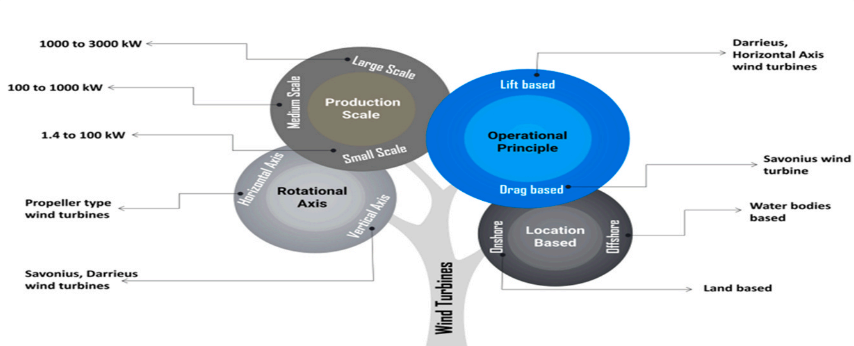

Fig. 2. Wind Tree: A broad classification of wind turbines.

electrical components need to be thoroughly inspected, (Minh Bui and Melis, 2013; Li et al., 2012). Additionally, micro wind turbines can be used in locomotives as alternative energy sources. In passenger trains, in particular, they can generate enough power to meet the needs of the hotel load, including air conditioning, lights, fans, and other appliances.

Compared to large wind turbines, micro wind turbines offer more benefits due to their near maintenance-free nature, dependability, and low cost, (Kumar Sahu et al., 2016; B. and Sengupta.). Because of the surrounding obstacles, SWTs usually operate in the lower atmospheric boundary layer, which is characterized by high turbulence and low wind speeds, (Battisti et al., 2018). Periods of stopping and starting are common for SWTs, (Akbari et al., 2022). Due to their low maintenance costs and ease of use, fixed pitch blades are found on the majority of SWTs, (Rutland, 1200 marine wind turbine, 2023).

Today, many nations strive to utilize wind energy at its peak production level. But in some nations, like Malaysia, the wind speed is insufficient to efficiently rotate the large wind turbines (WT) that are currently in place to generate useful power. This made it extremely difficult to generate electricity in these zones using wind power. Small-sized WTs can capture energy regardless of ideal wind speed conditions, in contrast to large WTs (Muhsen et al., 2020). Small wind turbines are therefore the most promising option for obtaining electricity from locations with low wind profiles. The most crucial part of the wind energy conversion process is played by wind turbine blades (WTB). They are of paramount importance because they take in the wind's kinetic energy and turn it into mechanical energy before transforming it into electrical energy by generators (Purusothaman et al., 2016).

There have been a few review studies on wind energy in Malaysia. These reviews, however, are not recent, and the majority of them focus primarily on renewable energy sources without going into great detail about the literature, (Ashnani et al., 2014; Foo, 2015). Just a small number of the previously mentioned studies focused on wind energy. Nevertheless, these studies looked into particular aspects like political and regularity support (Ho, 2016), technical issues, and spatial models and wind speed distribution, (Didane et al., 2016).

3. Impact of high wind speeds on wind turbine performance and safety

Wind energy is recognized as an intermittent energy resource, which significantly impacts the safety and stability of extensive grid-integrated wind power (WP) systems. Moreover, it is susceptible to losses that transpire during the transmission and distribution processes. The unpredictable nature of electricity generation, stemming from the variable fluctuations in wind speed, poses challenges for the safety and stability of electrical power grids when wind energy is incorporated on a large scale. As a result, precise forecasting of wind speed and wind power has increasingly assumed a vital role in mitigating wind power fluctuations within system dispatch planning. With the advancement of artificial intelligence methodologies, particularly deep learning, a growing array of deep learning-based models is being evaluated for wind speed (WS) and wind power (WP) forecasting, owing to their exceptional ability to address complex nonlinear challenges (Wang et al., 2021).

The classification of wind power generation as an intermittent energy source, arises from the chaotic variations in wind speed, rendering wind energy incapable of consistently satisfying power system demand. Intermittency is predominantly driven by the continuous and erratic fluctuations of wind speeds, compounded by the lack of tools that facilitate coherent forecasting. This phenomenon has been documented in numerous countries where the integration of wind power generation into the energy mix is substantial. The challenge of achieving precise wind speed predictions can be regarded as one of the primary factors contributing to uncertainties in wind energy production, particularly in long-term planning. For instance, wind speed exhibits variation with altitude; thus, the stochastic nature of wind is of considerable significance. When predictions overestimate wind speeds, leading to actual wind energy production falling short of expectations, a requirement arises for energy reserves or hydro capacity reserves to address potential deficits and maintain system reliability (Huang et al., 2024).

Large-scale wind turbines employ pitch control strategies to manage high-speed winds, while small-scale turbines often forego these due to cost concerns. Various methods for controlling turbines in high-speed winds are categorized as mechanical, electrical, or electromechanical. Mechanical methods utilize costly and inefficient devices for wind turbine control during adverse conditions. One such method involves measuring wind speed against nominal turbine speed and employing a braking mechanism to halt operation at excessive wind speeds, which ultimately limits power generation. The furling mechanism or yaw displacement is an electromechanical technique adjusting the turbine nacelle's position based on varying wind conditions. High-power turbines utilize pitch control mechanisms akin to yaw displacement to modify blade angles in response to wind speed. Although effective, electromechanical strategies are generally unsuitable for small-scale turbines due to their size and cost. Recently developed electrical methods, known as stall control techniques, allow turbines to operate continuously even in high winds and are divided into mechanical and electrical categories. Electrical stall methods demonstrate greater efficiency than mechanical ones, enabling energy capture during high wind conditions, with affordability achieved through the integration of appropriate observers into the controller (Barzegar-Kalashani et al., 2023a).

Future research could delve into the following domains: a) the development of a wind speed prediction framework rooted in temporal and spatial data. This framework will conceptualize a wind farm as a graph structure, with nodes symbolizing turbines and edges illustrating physical connections or spatial relationships (Huang et al., 2024). b) The integration of additional meteorological variables to evaluate their influence on wind speed data, enhancing the precision of wind speed forecasts. c) The proposed methodologies will be further applied to confront forecasting challenges in more complex environmental contexts (Wang et al., 2024).

4. Small scale wind turbines

The great potential of small- and mid-scale wind turbines has been recognized more and more in recent years. This is a noticeable circumstance despite the fact that most research interest has long been focusing on industry-scale wind turbines. Small and mid-scale wind turbines remain more popular and more affordable devices for small industries and nations that cannot afford the large wind farms' exorbitant costs.

Furthermore, location-based wind resources that can supply both a suitable capacity for the transmission of the generated energy and a sufficient amount of wind with continuous speed rank among the most crucial factors to think through when considering wind energy, (Akour et al., 2018a; Universities Power Engineering Conference (UPEC), 2009). Besides, because of the lack of suitable wind conditions, the geographic location of some nations limits the viability of establishing big wind farms in a few scenarios where cost is not the primary obstacle, (Herrera et al., 2019).

Wind farms face ongoing resistance. Smaller wind projects receive more favorable support than larger ones. This difference likely arises from the lesser noise and visual disturbance of small projects. Noise and aesthetic concerns often influence local public opposition to wind initiatives. A global trend is emerging towards renewable energy adoption for microgeneration, potentially leading to carbon-neutral electricity. Micro wind turbines are designed for localized electricity generation, typically in residential or small commercial environments (Zhang et al., 2023a).

They possess rotor diameters under 2.5 meters, including mini and micro turbines in urban settings. Importantly, small-scale wind turbines have low maintenance costs, high reliability, a wider operational wind range than larger turbines, and minimal environmental impacts (Pellegrini et al., 2021a)

Wind turbines are categorized by rotor diameters and power ratings, as detailed in Table 1. Small-scale wind turbines usually have rotor diameters from 0.5 m to 10 m and power ratings from 0.004 kW to 16 kW. Although small-scale turbines generate costlier electricity in low-wind regions, they can produce reliable energy when appropriately sized and positioned, particularly in urban areas. These turbines serve as a socio-economically beneficial energy source in many developing nations and can effectively provide power in remote areas of developed countries (Zhang et al., 2023a).

To enhance acceleration, turbines must be installed at a height of at least 1.3 times the building height. Research shows that roof-parallel obstructions negatively impact wind speed and turbulence. The study revealed that nearby trees create considerable uncertainty in airflow direction. Rooftop turbines should be placed on the tallest buildings to optimize performance. Additionally, wind flow should ideally be perpendicular to the roofline. Turbines positioned at least 1.3 times the building height exhibited enhanced performance, addressing identified challenges. Optimal results were observed when the turbine height was between 1.51 and 1.79 times the building's front elevation. The addition of a shroud or diffuser significantly improved turbine performance. A feasibility study assessed various turbine sizes in urban contexts, indicating a 70 % performance increase for rooftop turbines compared to ground-mounted ones. Performance further improved when the building was significantly taller than surrounding structures with optimized geometrical configurations. The sloping roof positively influenced wind velocities with an inclination angle of 8° compared to flat roofs (Aravindhan et al., 2023a).

Table 1
Classification of general HAWT related to the rotor diameters and power ratings (Zhang et al., 2023a).

Types of Turbines	Rotor diameter (m)		Wept area (m2)		Standard power rating (kW)	
	From	To	From	To	From	To
Micro	0.5	1.25	0.2	1.2	0.004	0.25
Mini	1.25	3	1.2	7.1	0.25	1.4
Household	3	10	7	79	1.4	16
Small	10	20	79	314	25	100
Medium	20	50	314	1963	100	1000
Large	50	100	1983	7854	1000	3000

In view of that, over the past few decades, small-scale wind turbines—which are frequently installed at low altitudes—have drawn a lot of attention due to their unique qualities, including their ease of installation (De Kooning et al., 2021), low environmental impact when compared to large wind turbines and farms (Chowdhury et al., 2022), and their notable financial advantages, (Aravindhan et al., 2023b). In addition, Small Wind Turbines (SWTs) are a significant part of the global energy landscape, since they provide an alternative for grid installations in both rural and urban areas as well as an off-grid energy collecting solution, (Tummala et al., 2016a).

The wind provides the energy that these devices transform. As such, the energy output will vary depending on the wind conditions. The energy conversion capacities of SWTs will also be impacted by mechanical and dynamic properties as well as variations in wind direction and speed, (Evans et al., 2018). Furthermore, wind turbines are gaining a lot of attention globally due to their higher efficiency compared to other renewable energy sources like solar energy (Zhang et al., 2023b).

Typically, these turbines have power ratings of up to 100 kW and rotor diameters of up to 20 m. They are distinguished by lightweight, sturdy constructions and straightforward designs. In addition, small-scale wind turbines provide more affordability and reliability due to their lower initial capital investment and lower operation and maintenance (O&M) costs. As a result, they are a viable energy alternative for off-grid rural and suburban regions (Sunderland et al., 2013).

Yet, the use of wind turbines is hampered by several significant issues, which is what motivated this review in the first place. Micro wind turbines combined with energy storage systems could offer a more reliable option to diesel generators used in remote homes and communication networks. This could lessen the likelihood of having or facing communication breakdowns during calamities like floods and wildfires, (Leary et al., 2019; Barzegar-Kalashani et al., 2023b).

However, there are certain disadvantages to these miniature wind turbines, including noise dispersion (Radun et al., 2022), and malfunctions or incapacity to function when high-speed wind conditions exist (Islam et al., 2013). Their low mass moment of inertia and ensuing quick dynamic responsiveness are the primary causes of the differences between observed and anticipated SWT performance. This observation suggests that SWTs behave differently from huge wind turbines and, as a result, require distinct analysis, (Lubitz, 2014; Ani et al., 2013). High turbulence tends to reduce the power output of large wind turbines because the system cannot adapt to variations in the wind (Wharton and Lundquist, 2012). This requirement may not always be met and will rely on the turbine's design.

In light of that, the intricate relationship between power production and dynamic reaction necessitates the creation of high-fidelity models, particularly in the highly turbulent wind. These models need to be able to replicate how the SWT behaves in various wind conditions and offer more trustworthy information about the SWT's actual power output, (Fields et al., 2016; Rodriguez-Hernandez et al., 2016)• Consequently, the following quotes highlight some of the most important topics that can be contested from a variety of angles. The social welfare of communities is impacted by a number of factors, including power outages, which are common in rural areas as a result of natural disasters like floods and bushfires.

Furthermore, in the event of phase-to-ground faults, the size of distribution power networks may contribute to wildfire phenomena. As such, these faults might also increase the frequency of power outages and require the development of new equipment, such as fast earth fault current limiters, to address these issues, (Barzegar-Kalashani and Mahmud, 2022; Barzegar-Kalashani et al., 2022). Thus, one potential answer to some of these problems is the creation of microgrids and nanogrids using renewable energy resources. Both big towns and rural areas frequently use micro-sources such as tiny wind turbines for a range of applications.

Hence, small-scale wind turbines used in conjunction with storage can almost eliminate these natural occurrences in such circumstances, eventually promoting social welfare. Owners of apartment complexes or other densely inhabited regions can generate energy more cheaply than with solar panels by installing small wind turbines. But residents are seriously threatened by turbine side effects, especially noise. Therefore, constructing the best turbines with the least amount of acoustic pollution is still a problem.

Furthermore, large-scale wind turbines operating in severe gusts may encounter a number of difficulties. Moreover, it is clear that the existence of large-scale wind turbines not only negatively impacts social welfare but also presents a health risk. For instance, the community's risk of heart disease may rise as a result of the usage of large-scale wind turbines, which usually produce noise (Radun et al., 2022). Although large- and medium-sized wind turbines are more effective, the installation and maintenance of these machines pose significant risks to ecosystems, including injury to birds and deforestation.

Micro wind turbines, on the other hand, are typically dispersed over a large area and installed at low altitudes, which reduces the likelihood of having an adverse environmental impact, (Nazir et al., 2020). Furthermore, because solar panel waste recycling is still a significant problem, micro wind turbines are more environmentally beneficial than solar panel production units. From an economic standpoint, and in addition to other factors, the unpredictability of the wind contributes to economic difficulties in the use of small-scale wind turbines in urban areas, (Greening and Azapagic, 2013), and with relation to system design expenses, (Loganathan et al., 2019). Therefore, the hybrid economic-environmental application of small wind turbines with other renewable energy sources and energy storage devices is recommended as a way to deal with these unpredictable conditions.

It is important to keep in mind, though, that high-speed wind conditions might make small-scale wind turbine integration with other generation units more troublesome in real-world applications, which calls for greater and more serious research (Rawa et al., 2021). The growth of small-scale wind turbines requires an upgrading of current policies from the viewpoints mentioned above.

To enable the use of these micro-sources, a number of criteria need to be taken into account, (winikoff, 2022). This is a significant problem for electrical and control engineers who want to reduce recurring over speeding failures by proposing more effective ways to manage wind turbines across a broad wind speed range. From a technical perspective, mechanical and electrical engineers are principally responsible for the creation of small-scale wind turbines, which is a significant technical project. Additionally, the output power will increase and the complexity will decrease as well if a significant number of micro wind turbines enhance the system's overall complexity, (Hansen et al.).

4.1. Technique

As a renewable energy source, wind energy has drawn a lot of interest, (Wu and Jiang, 2019; Li et al., 2019). Furthermore, the growing popularity of variable-speed wind turbines (VSWT) can be attributed to their high-quality and high-efficiency power output, (Ren et al., 2018; Song et al., 2017). By optimum rotor speed adjustment, the VSWT can capture maximum wind energy in the operational range from cut-ins to rated wind speeds.

Maximum power point tracking control (MPPTC) is the predominant control strategy used to capture the most wind energy from VSWT. It is primarily divided into two groups. Wind Turbines for Domestic Consumers operate constantly throughout the day and night, unlike solar energy, which is only supported when there is sunlight.This benefit has encouraged a lot of researchers to harness wind energy for home power generation.

To transform wind energy into electrical energy, there are essentially two types of wind turbines available: PMSG and MPPT, (Albuquerque and Matos.; Almohammadi et al., 2015). PMSG-related parameters are used in the simulations in this paper. Whereas the creation of an MPPT control strategy is made possible by a variable-speed operating situation. According to this plan, the turbine will be kept running at its optimal Cp speeds up to the nominal wind speed. Unvalued for all wind by raising the electro-mechanical torque of the generator and stopping the turbine from accelerating further when the maximum Cp is reached, is accomplished efficiently.

Numerous MPPT techniques have been developed, each based on a distinct type of sensor, (Fathabadi, 2016). SWTs have adopted their huge counterparts' habit of operating in calmer winds by designing them for maximum Cp, (Scappatici et al., 2016a). They adopted this tactic from their larger counterparts who often operate in calmer conditions. Large wind turbines' dynamic response is not a critical design characteristic due to their active pitch control and high blade inertia (Burton et al., 2011; Scappatici et al., 2016b). In that order, the majority of industrial small-scale wind energy conversion systems (SS-WECSs) are constructed with direct-drive shafts working in tandem with a suitable permanent magnet synchronous generator or squirrel-cage induction generator (SCIG).

Moreover, a variety of interface configurations are available to supply electricity to loads or grids; back-to-back inverters are the most controllable and versatile, (Song et al., 2022a; "84".). The cost and control complexity of this interface, however, is marginally higher than utilizing a passive rectifier in combination with a DC/DC converter, (Burton et al., 2011; Nanyang Technological University, 2014).

Since wind behavior is unpredictable, turbine dynamics are nonlinear, thus necessitating control of the wind turbine to maximize power extraction, (Sai et al., 2022). A multitude of mechanical and electrical (MPPT) control systems have been developed over the past few decades, utilizing both intelligent and non-intelligent techniques.

Examples of these include sensor less nonlinear controllers, (Fathabadi, 2017; Balbino et al., 2022), intelligent (MPP) trackers, (Kushwaha et al., 2020; Lin and Hong, 2010), torque components operated by MPPT (quadrature axis current component) (ICRERA 4. 2015 Palermo et al., 2015), observer-based MPP trackers, (Nayanar et al., 2016), and meta-heuristic MPPT approaches. As such, all MPPT control strategies exhibit distinct qualities about computational complexity, tracking velocity, accuracy, and the required quantity of sensors, (Seyedmahmoudian et al., 2016).

Wind turbines usually operate in the MPPT control mode in low and medium wind conditions. In high wind conditions, however, the control mechanism needs to be adjusted to prevent overspeeding and reduce mechanical and electrical damage, (winikoff, 2022; Hansen at al.). Both wind direction and speed have an impact on how well wind turbines operate. At different scales, active or passive yaw control systems can be employed to modify the turning direction in order to maximize wind energy (Song et al., 2022b).

Large-scale wind turbines use pitch control tactics through electro-mechanical structures (Bakdi et al., 2019), to deal with high wind speeds, while small-scale wind turbines rarely use these sophisticated systems due to their expensive cost (Tummala et al., 2016b). Generally speaking, there are three main methods for controlling wind turbines in high-speed wind conditions: mechanical, electrical, and electromechanical.

The mechanical methods of controlling wind turbines in over speeding circumstances make use of costly and inefficient technologies. Measuring wind speed and comparing it to the wind turbine's nominal speed is one of these techniques. The wind turbine can cease working when the wind speed is far higher than the cut-off speed by utilizing a braking device. This is insufficient, as strong gusts will prevent the wind turbine from producing any electricity. The yaw displacement or furling mechanism is one of these tactics (Chu, 2022), which is an electromechanical method wherein the wind's direction and speed maintain the wind system's placement.

However, the position of the turbine's nacelle is changed under varying wind-speed conditions, ("336".). Pitch control systems, akin to the yaw displacement strategy, are frequently employed in high-power wind turbines to modify the blade angle in reaction to wind speed, (Prasad and Padhy, 2020). These electromechanical techniques are not advised for small-scale wind turbines due to their size and expense, even if they can be successful, (Muljadi et al.).

4.2. Small wind turbines with low wind speeds

In low wind speed areas, especially in buildup areas, vertical axis wind turbines (VAWTs) are more frequently used than horizontal axis wind turbines (HAWTs), particularly when it comes to large wind turbines. The wind startup of VAWTS is lower than that of HAWTS. On the other hand, micro wind turbines in areas with low wind speeds were driven by either micro VAWTS or micro HAWTS. They are primarily used in isolated, rural areas or in areas with low wind speeds because the main problem in these areas is the lack of electricity, (B. and Sengupta.; NN Sorte, 2014), which has also produced similar outcomes.

The ideal aerodynamic wind turbine blade profile is determined by several factors, such as pitch angle, chord, twist, solidity, and angle of attack, (Suresh and Rajakumar, 2019). Hence, an efficient wind turbine profile must be created to provide an effective lift force, and a minimum drag force at low wind speeds, as wind turbine blade profiles are essential for producing higher power coefficients.

The aerodynamic performance of two different kinds of wind turbine blades has been reported by Lee and Shiah. They used blade element momentum theory (BEMT) for one blade's design and constant chord length and non-twist type for the second blade's design in their investigation. The BEMT blade's maximal power coefficient increased by 50 % when compared to the other, according to the results of numerical simulation and experimentation. The BEMT-based blade flows over the airfoil completely attached and without breaking. Yet, roughly around 76 % of the region is covered by the other type.

This is so because the BEMT blade's leading edge still has the flow over it that is connected to the blade root by twist angles. It is clear that the flow partitioning is well controlled by the twist angle of the BEMT blade. This indicates that the BEMT blade has a higher maximal power coefficient than the baseline at low tip speed ratios. Finally, it was found that flow separation happens on the deduction side near the leading edges of both blades at low tip speed ratios, (Lee et al., 2016).

Due to their low maintenance costs and ease of use, fixed pitch blades are found on the majority of SWTs, (Rutland, 1200 marine wind turbine, 2023). Because of their high blade attack angles, SWTs have starting torques that are comparable to the resistive torque of the drivetrain, (Vaz et al., 2018). These factors lead to longer startup times, shorter operating times, and higher starting wind speeds, (Rocha et al., 2018). SWTs have relatively higher energy costs than MW-scale LWTs. The system's increased economic attractiveness would be attributed to improved SWT aerodynamic efficiency, reduced energy costs and payback times, and increased energy harvesting.

Most large and small turbines these days run in the variable speed mode, which allows them to run around the ideal TSR over a wide range of wind speeds, increasing energy harvest. Whereas LWTs' high rotational inertia hinders them from keeping up with variations in wind speed, SWTs' low inertia allows them to react to changes in wind speed more quickly. However, because of measurement delays and control response times, the maximum power point tracking (MPPT) algorithm's-controlled rotor speed might not accurately track the wind speed, rotor inertia and the framework system, (Pourrajabian et al., 2019; Tang et al., 2013). Consequently, SWTs cover a wide range of TSR and blade attack angles,. To maximize energy capture, variable-speed turbines must maintain their high-power coefficient even when they are operating off-design, (Akour et al., 2018b).

The low Reynolds number of the airfoil was intended for use in small horizontal axis wind turbines in order to improve start-up performance at lower wind speeds, (Singh et al., 2012). It created a 1.26 m diameter, and two-bladed rotor with an AF300-coded blade for areas with low wind. In open-field tests, the wood rotor with its 18-blade pitch produced the maximum power output due to its low moment of inertia, (Akour et al., 2018b). It is built a 1 m diameter, and three-bladed BW3 rotor with a 3.5 design TSR. At TSR = 4.4, in which the peak power coefficient was 0.38.

It was proposed that a cluster of microturbines with the same total rated power would produce more energy at lower costs than a single SWT with diameters ranging from 5.5 to 9.2 m (Torres-Madroñero et al., 2020). It was hence found that a 1.7 m diameter, 2-blade Darrius VAWT with an ideal twisted winglet design produced a 6.7 % improvement in CP at the design TSR and a 10 % improvement in CP at off-design TSR values. The relevant graph showed how the winglet successfully reduced the strength of the tip vortices.

According to the findings of the computational fluid dynamic (CFD) study, (Zhang et al., 2020), the 2 m diameter VAWT with a straight blade and symmetrical airfoil achieved the highest power coefficient. In addition, among the tested NACA profiles, NACA0018 was found to be the best airfoil, maximizing the power coefficient, while thinner profiles experienced early stall. Recent years have also seen a rise in the amount of research on multi-bladed SWTs operating at low speeds, (Kanya and Visser, 2010; Scappatici et al., 2016c; Eltayesh et al., 2021a). They can produce a lot of starting torque because of their large solidity and pitch angles.

Low-speed multi-bladed SWTs are substantially quieter than high-speed 3-bladed SWTs of the same diameter because noise is proportional to the fifth power of rotor RPM (Sessarego and Wood, 2015). Dynamic rotor analyses (Porto et al., 2022), showed that five-bladed turbines responded to wind fluctuations with greater energy production than three-bladed turbines. In the commercial sector, three of the multi-bladed rotors shown are becoming more and more common. At a lower design level, rotors shaped from low-efficiency airfoils maximize their power coefficients, TSR (de F. Pinto and Gonçalves, 2017).

Consequently, further investigation has been carried out with the aim of developing TSR as a design parameter, (Pourrajabian et al., 2016). In the case of low induction rotors (LIRs), it is worth noting that recent research has concentrated on LWTs (offshore turbines with a power output of 10–15 MW in particular) (Jamieson, 2020; Ribnitzky et al., 2022). As the name implies, the LIR is set up for an axial induction factor that is lower than the ideal value of 1/3. Lower structural strength is required for LIRs. Lower tower, rotor construction, and material costs can result in lower energy costs, (Bortolotti et al., 2016). Under the designation of LIR, SWTs have not yet been studied in the published literature. Studies examining the effect of pitch angle on aerodynamic efficiency indirectly take into account rotors with varying degrees of induction (low or high), because the axial induction factor is highly sensitive to blade pitch angle, (Sant et al., 2020; Kaya et al., 2023).

4.2.1. Type of low-speed turbines

Wind turbines can be classified into two primary subclasses based on their axis of rotation: (a) vertical axis wind turbines (VAWTs), and (b) horizontal axis wind turbines (HAWTs), as illustrated in Fig. 3. HAWTs currently comprise the majority of installed turbines due to their wider effectiveness and longer lifespan as compared to VAWTs, (Howell et al., 2010; Wang and Zhuang, 2017b).

Still, horizontal axis wind turbines (HAWT), seem to have a number of advantages over vertical axis wind turbines (VAWT); they demonstrate lower noise emissions, a simpler construction, no need for a yaw system, and less expensive installation costs (Rezaeiha et al., 2017). Additionally, ground-mounted generators tend to run more steadily while operating them, (Wang and Zhuang, 2017b). Literature has shown

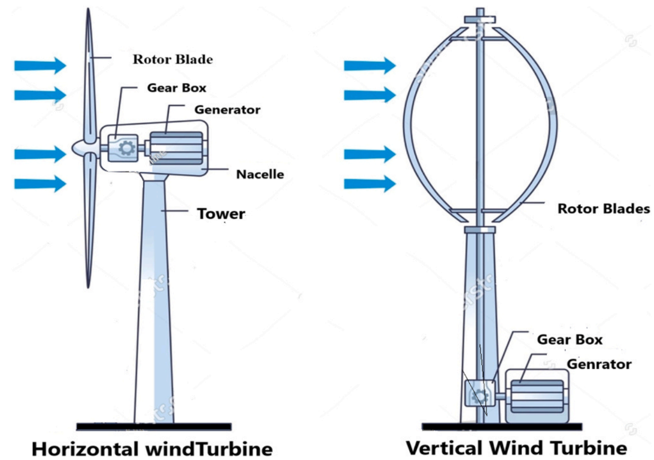

Fig. 3. Comparison between Offshore VAWT and Offshore HAWTs.

that horizontal wind turbines can run at lower wind speeds than vertical-axis wind turbines, (El Khchine et al., 2019).

The efficiency of each type of wind turbine varies based on the manufacturing and design process. In a similar spirit, the direction in which a wind turbine rotates determines its classification. Since the horizontal axis can adjust the blade's pitch angle to prevent strong windstorms and gather the maximum amount of wind energy for the time of day, it is believed to be more recognizable and commoner than the vertical axis. Therefore, the primary use of HAWTs is in wind farms, (Rathod and Kamdi.; Dhote and Bankar, 2015).

4.2.2. Vertical low speed turbines

Unprecedented interest has been shown in VAWTs for wind energy harvesting in both onshore and offshore applications. These turbines have omnidirectional operation capability, a robust architecture, and a low acoustic signature. They are also less expensive to manufacture, install, and maintain than HAWTs (Rezaeiha et al., 2018). Vertical-axis wind turbines (VAWTs) are a relevant topic to discuss when discussing lifetime energy harvest in SWTs as shown in Fig. 4. Despite their lower efficiency, VAWTs have a significant advantage over horizontal-axis wind turbines (HAWTs) in terms of omnidirectional wind capture (Zhang et al., 2020).

Consequently, in order to reduce performance loss, VAWTs must also maintain good off-design efficiency (tian Zhang et al., 2019; Worasinchai et al., 2012). Usually used to produce wind energy, variable-speed turbines must maintain their high-power coefficient even when they are operating off-design in order to maximize energy capture, (Akour et al., 2018b). Furthermore, VAWTs provide a more affordable, effective, and eco-friendly substitute for obtaining wind power in remote residential and commercial areas. Thus, the wind speed is much lower and more turbulent in built environments. Additionally, VAWTs offer a higher power density than HAWTs when arranged as optimized arrays (Dabiri.).

This is so because Vertical Axis Wind Turbines (VAWTs) are made to perform just well enough on mechanical works at low wind speeds. They are installed at a height of 20 m, where the average wind speed is comparatively low, at about 2–3 m/s. The inability to harvest energy with low availability at low wind speeds must be addressed by the invention of a wind booster that can improve VAWT performance.

However, standalone VAWTs are not enough to convert wind energy as efficiently as possible. To improve VAWT performance in low-speed scenarios, a few relevant studies have been carried out, (Takao et al., 2009). Such studies culminated in producing the device known as a "directed guide vane row", which controls airflow. This straight-bladed mechanism's inherent limitation stems from the fact that it can only collect wind in a single direction within a VAWT. To address this, (Li et al., 2023) developed omnidirectional guide vanes, which greatly increased VAWT's power output. Additionally, provided a numerical analysis to determine the operating angles of the stator veer for a VAWT. The ideal arrangement of the guide vanes was not taken into account in those studies, even though those devices have the ability to capture wind in any direction. Additionally, proved that these (VAWTs) turbines can power homes, farms, shelters, beacons, and other off-grid structures. Intermediate-sized wind power systems can be either off-grid or grid-connected, with capacities ranging from 100 kW to 250 kW, sufficient to power a village or multiple small businesses (Falama et al., 2023).

These turbines can be linked to diesel generators, batteries, or other distributed energy sources in remote locations where access to the grid design is restricted. A multitude of small enterprises worldwide, such as Wind Side, Global Wind Group, Urban Green Energy in New York, and Clearfield Energy have contributed to the development, manufacturing, and promotion of these wind turbines. Masdar City's annual records indicate that it is located in a low-wind or "poor" wind region. Darrieus VAWT is regarded as the best option because it can function at lower wind speeds and is less sensitive to wind direction than HAWT (Nessim et al., 2023)

This is especially true if the issue with the turbine's inability to start itself is fixed. Because it does not require wind direction adjustment systems to operate, it is ideal for low-speed zones and urban areas (Samora Sithole et al., 2023)

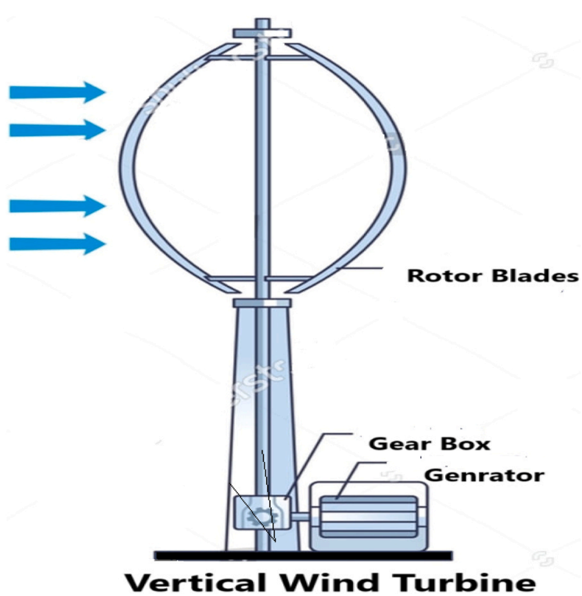

Fig. 4. Small Scale Vertical Wind Turbines.

4.2.3. Horizontal low wind speed

The HAWT can be extensively used in both small- and large-scale commercial electric power generation applications. Large-scale horizontal axis wind turbines (LSHAWTs) are installed in large numbers and used as a link to the electrical grid because wind farms have an abundance of unused space. These LSHAWTs typically operate at wind speeds exceeding 10 m/s, which is regarded as a relatively high wind speed (Yossri et al., 2021). Large horizontal axis wind turbines (HAWTs), small horizontal axis wind turbines, and vertical axis wind turbines are examples of wind energy conversion devices for locations with low wind speeds.

Large wind turbines (HAWTs) are important sources of wind energy for commercial applications. For large HAWTs, NREL researchers have been studying LWST systematically since the early 21st century (Rosato et al., 2024) However, it is challenging to achieve these velocities in residential areas due to the surrounding areas and the wind boundary layer. Because higher, more populated areas increase wind shear and require more energy, these topographies have a significant effect on wind characteristics. Thus, it is possible to conduct research on the LSHAWT in the tower at high elevations of 60–80 m with blade lengths between 30 and 40 m (Juan et al., 2021).

Such heights provided a high-resolution numerical analysis to assess the global wind using a measured database. They also showed the world onshore wind map eighty meters above the ground, the same height as the hub of the majority of modern, large-scale horizontal axis wind turbines (HAWTs). The map shows that most near-shore and continental regions have low to moderate wind speeds. The terms "low" and "moderate" wind speeds have ambiguous meanings and are relative. Nonetheless, a low wind speed is defined by the International Electrotechnical Commission (IEC) as less than 7.5 m/s on an annual average. Site data, which often includes wind velocity above the ground's boundary layer at elevations of approximately 50 m, dictates the designs of these devices. Thus, it is not appropriate to use LSHAWTs in residential areas (Nizamani et al., 2024)

As a result, small-scale horizontal axis wind turbines (SSHAWTs) are used in residential areas where the emphasis is on the household rather than LSHAWTs as shown in Fig. 5. These SSHAWTs have rotor diameters ranging from three to ten meters, and they are commonly seen on the market. These SSHAWTs can also be used to produce electricity in cities without access to the electrical grid. Accordingly, increasing the SSHAWT's power generation is of great interest. The SSHAWT is fixed near the ground, where the wind speed is influenced by the surroundings. Additionally, this work demonstrates that the rated velocity for the entire domestic SSHAWT scale remains highly relative to the velocities that can be recorded from urban and residential areas worldwide (Li et al., 2022)

Hence, a small wind turbine makes a big difference in these areas. The pinwheel-type horizontal axis wind turbine is a recent innovation in the wind turbine industry. In this instance, the blades have a pinwheel-like shape. Its ability to maximize efficiency at low wind speeds is its main advantage. As a matter of fact, characterization of wind speed fluctuations is necessary to improve system design and reduce the production costs of electricity. For a given position, the wind difference is usually calculated using the so-called Weibull distribution (Tasneem et al., 2020). Thus, to expand the SSHAWT's application in both residential and commercial settings, the researchers aim to improve its performance and redesign it with suitable airfoils (E. Hasan et al., 2023).

Furthermore, an investigation of the design of a small, programmable-pitch, programmable-speed horizontal wind turbine is to

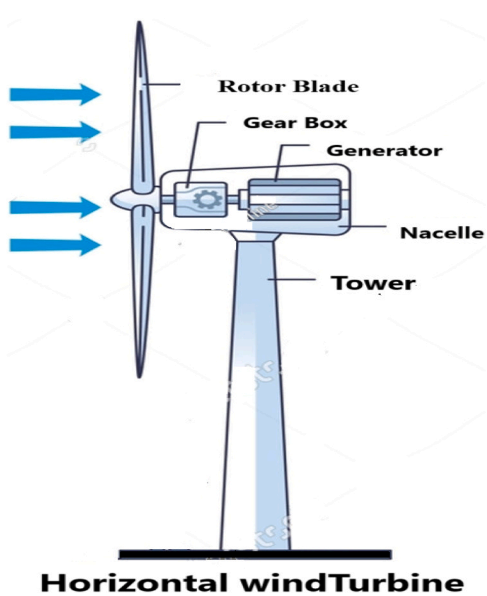

Fig. 5. Small-Scale Wind Turbines Horizontal.

be conducted. In (Institute of Electrical and Electronics Engineers, 2016), a mathematical model of a wind turbine is created. The mechanical power of the wind turbine is expressed in terms of the generator speed for different wind speeds. On a small scale, a high-torque, self--starting HAWT could be created to pump water. To solve the problem, the first practical step is to create the PVC-type HAWT concept. The development of an experimental setup for the apparatus, including its conception, fabrication, assembly, commissioning, and preliminary testing, is given in (Patil.). It suggests the advantages of employing four airfoils for the SSHAWT's aerodynamic performance in the 1–5 kW power range.

The blade had three distinct kinds of airfoils: SG6041, SG6042, and SG6043. At the base of the blade and extending up to 30 % of its length was the SG6040 airfoil. Several approaches have been attempted by researchers to use these airfoils in the design of SSHAWT (Kumar Gupta et al., 2017).

The findings of the research experiment showed a maximum inaccuracy of about 5 % and high agreement with empirical and numerical models of the power coefficient progression. Additionally, the composite airfoils demonstrated the SSHAWT's exceptionally excellent low wind speed capability. Therefore, by rebuilding the SSHAWT and improving its performance using appropriate airfoils, the researchers hope to increase the device's application in commercial and residential settings. The research study (Abdelsalam et al., 2021) suggested two small-scale HAWT designs and examined how well they performed in open-air jet test rigs through experimental means. The proposed linearized rotor design is the second one, and the first is a classical rotor with a non-linear chord and twist. A 1 m diameter rotor was used for the experiment, and wind speeds ranging from 5 to 10 m/s were used, along with blade pitch angles of 3, 0, and 3. According to the findings, the maximum Cp of linearized and classical rotors was 0.426, and 0.446, respectively. In contrast to the traditional rotor, which begins operating at 6 m/s, the linearized rotor operates at a lower wind speed of 5 m/s. In addition, the linearized rotor has a 26 % smaller volume than the conventional one. Numerous studies attempted to optimize small-scale wind turbine performance by various techniques, such as the use of shrouded wind turbine shape (Phillips et al.).

When a turbine is operating in a steady state, like in wind tunnel experiments, its power output is mostly determined by its power coefficient (Cp). The relationship between the turbine's power output and the available wind power is known as the Cp. This limit is referred to as the Betz–Joukowsky limit and has a maximum value of 0.593 (González-Hernández and Salas-Cabrera, 2021).

Nevertheless, the turbine's energy production will be influenced by factors other than the Cp in actual operating conditions. When only the Cp value is taken into account, the complex combination of dynamic and aerodynamic factors during wind speed changes and starting scenarios tend to incur differently from the expected power performance. Therefore, the results found that the EWM method had a reasonable agreement overall tip speed ratios (TSR), among other numerical methods. Their results demonstrated that at a given solidity, the CP increases with increasing blade number for all studied tests. Moreover, they showed that conducting results over a wide range of wind velocities is necessary (Kamal et al., 2022).

While the numerical results showed that the CP of the constant-chord wind turbine is improved by increasing the number of blades, this outcome was not verified in the experimental results. The only observed increase in CP was from increasing the solidity. They attributed the discrepancy between wind tunnel experiments and theoretical predictions to the Reynolds number range of operation. The study (Kulak et al., 2024) investigated numerically the effect of blade numbers 2, 4, 6, and 8 on the performance of ducted wind turbines using CFD. Numerical calculations were performed using the k-e turbulence model with a wall function. The inlet velocity was 12 m/s, and the turbine diameter was 1.4 m. It was found that increasing the number of blades leads to higher starting torque, and reduces the cut-in speed. On the other hand, a higher number of blades leads to more blockage and lower blade entrance velocity which leads to reduced CP (Rector et al., 2006).

5. Summary of horizontal wind turbines

Numerous studies have been conducted to analyze and enhance the performance of small-scale horizontal axis wind turbines (HAWTs) under diverse operating conditions. These research endeavors have delved into various factors influencing wind turbine performance, such as blade design, wind speed characteristics, power coefficient, and tip speed ratio (TSR). The following is a comprehensive summary of these studies as shown in Table 2, highlighting their objectives, methodologies, and key findings:

Mohammad Ali in 2023 conducted an experimental study focused on the impact of duct design on wind speed and turbine power enhancement. By examining factors such as rotor diameter ratio, the spacing between rotors, and independent rotor rotation, he used NVELOX ducts to increase wind velocity by 42 % (from 5 m/s to 7.1 m/s), resulting in a more than twofold boost in turbine power output.

Hyeongi Moon in 2023 addressed the issue of abrupt pitch control causing extreme loading and power loss due to turbulence. By precisely installing vortex generators (VGs) with laser tracking, the study achieved a 4.83 % improvement in power generation performance at high wind speeds, particularly at 10 m/s.

Jiahao Wen in 2023 used both numerical and experimental approaches to investigate how blade number and tip-speed ratio (TSR) affect vortex stability and wake patterns. The findings highlighted that increasing the blade number widened the wake and influenced the formation and breakdown of streamwise vortices.

Larissa Zajicek in 2023 conducted a comparative study on the environmental impacts of small wind turbine (SWT) technologies. The analysis revealed a wide range of efficiency and global warming potential (GWP), stressing that future advancements might alter the current understanding.

Yan Wang in 2022 focused on estimating the rotor power coefficient (Cp) and wake length for wind farm applications. Through simulations and Proper Orthogonal Decomposition (POD), the study achieved a maximum prediction error of only 1.7 % for Cp and found that the first-order mode captured over 99.5 % of inflow plane energy.

Mohammad Ali Rahmatian in 2022 optimized duct design to improve the aerodynamic performance of micro horizontal-axis wind turbines (HAWTs). The modified design increased inlet wind speed from 5 m/s to 10.7 m/s, resulting in a 164 % improvement in power coefficient and a 2.14-fold increase in wind speed.

Oktay Yilmaz in 2023 addressed off-design performance loss in turbines. Using a blade element momentum algorithm and adjusting TSR, the study identified enhancements in operational TSR as a key solution to mitigate performance declines.

Marco Pellegrini in 2021 examined the feasibility of micro-wind turbines in urban areas with low wind speeds, such as Forlì, Italy. Extensive monitoring revealed that low wind speeds significantly reduced electrical output, with a peak output of 1.17 kWh/day recorded during 10.8 hours of operation.

Saeed Rahgozar in 2020 studied blade performance improvements through linear distributions of chord and twist angles. The findings revealed that these designs enhanced starting performance with minimal loss of output power, offering an effective solution for turbine optimization.

Geetha Sravya in 2022 compared large-scale and small-scale wind turbines, emphasizing the practicality of small turbines for residential use. MATLAB simulations showed that optimal power generation occurs at a TSR of 7.7 with a blade radius of 18 m, highlighting TSR's critical role in performance.

Praveen Shakya in 2024 investigated blade cracks caused by stresses such as cyclic loading and material fatigue. Using CFD and FEA analyses, the study demonstrated that high-stress regions significantly reduced blade lifespan and affected turbine reliability.

Ahsan Ayaz in 2023 analyzed how low wind speeds constrain power generation. By optimizing the geometric parameters of INVELOX turbines, the study achieved a 3.2-fold increase in power generation capacity and enhanced the maximum velocity ratio from 2.125 to 3.13.

A.E. Abu El-Maaty in 2024 explored the effects of sand erosion on small-scale wind turbine blades. Simulations indicated that annual erosion could reach depths of up to 5.7 mm, with the prototype generating 106.4 W at a TSR of 5 under wind speeds of 8 m/s.

Kamran Shirzadeh Ajirlo in 2021 introduced a simulator as a cost-effective alternative to traditional wind tunnel testing for micro horizontal-axis wind turbines. The study showed that the simulator outperformed wind tunnels by eliminating blockage effects and improving turbine performance evaluation.

W. Yossri in 2023 evaluated bio-inspired blade designs modeled after the golden eagle and dragonfly. The golden eagle-inspired design achieved the highest power output of 4.5 W and a torque of 0.21 Nm, while the dragonfly-inspired design recorded the lowest power and torque performance.

Mohamed Khaled in 2019 optimized winglet geometry to improve small HAWT performance. The study found that increasing winglet length and adjusting cant angles significantly enhanced power and thrust coefficients, with the best results observed at a cant angle of 48.3° and a winglet length of 6.32 %.

These studies shed light on various aspects influencing the performance of small-scale HAWTs, including blade design considerations, wind speed variations, power coefficient dynamics, and tip speed ratio effects. They also address the challenges and potential solutions for improving the efficiency and feasibility of these turbines in different environments, ranging from urban settlements to wind farm applications.

6. Advantages of micro wind turbines

Although empirical investigations have been conducted regarding small-scale wind turbines intended for utilization in urban environments, the findings indicate that these turbines exhibit Important, small-scale wind turbines have low maintenance costs, high reliability, and a wider operational wind range than larger turbines. Despite the efforts to enhance these turbines' functional capabilities, the presence of low-speed wind conditions renders conventional wind turbines unable to operate efficiently, or if they achieve operation, they produce minimal energy output (Rahmatian et al., 2023).

Small wind turbines (SWTs) gain increased attractiveness due to various factors including their appropriateness for private investment, ecological considerations, and the potential to export surplus electricity to the electrical grid, contingent upon the legislative conditions within the respective country. Establishing grid connectivity is predominantly advantageous for larger-scale SWTs, attributable to the associated expenses linked with local zoning regulations, permitting processes, and utility interconnections. The financial burden associated with energy production from SWTs is progressively diminishing, which can be attributed to advancements in turbine efficiency and manufacturing methodologies. SWTs are characterized by a rated power capacity ranging from 1 to 5 kW function with blade Reynolds numbers that are below 5×10^5 (McKenna et al., 2022), in contrast to larger wind turbines (LWTs) that operate within the megawatt-scale, exhibiting Reynolds numbers from 4×10^6–10^7. Consequently, the aerodynamic performance of SWTs is inferior when juxtaposed with that of LWTs. It is customary for LWTs to incorporate three-bladed rotors designed with a (TSR) that spans from 8 to 10. In the process of engineering SWT rotors with diameters ranging from 1 to 2 m for operation at elevated tip speeds, their efficiency is adversely affected due to the diminished blade Reynolds number (Yilmaz, 2023).

The proliferating deployment of micro-wind turbines has the potential to facilitate not only the decentralized production of energy but

Table 2
Summary of horizontal wind turbines.

Ref.	Year	Type of Study	Problem	Factor	Method	Key Features
(Rahmatian et al., 2023)	2023	Experimental.	The study investigates the impact of the duct on increasing wind speed and subsequently enhancing wind turbine power.	The effect of rotor diameter ratio, the distance between rotors, and the independent rotation of rotors	Numerical. Used NVELOXes.	The constructed duct enhances the velocity of the wind by as much as 42 % (rising from 5 m/s to 7.1 m/s); thus, the wind turbine's power output experiences an increment exceeding twofold.
(Moon et al., 2023)	2023	Numerical.	Abrupt pitch control sometimes causes extreme loading to blades or even to wind turbine systems due to the high turbulence effect, which causes unwanted damage or reduction of blade resistance not to mention unavoidable power loss.	Wind speed, Lift coefficient	The VGs were precisely installed with the aid of laser tracking	Power generation performance at high wind speeds was enhanced by the attachment of vortex generators (VGs) to the wind turbine blades; at a wind speed of 10 m/s, power generation performance increased by 4.83 %.
(Wen et al., 2023)	2023	Num. and Exp.	The increase in blade number causes early instability of the tip and hub/root vortices, leading to the breakdown and formation of patterns of streamwise vortices in the far wake	Blades N and TSR	The numerical simulation and OMD	-The TSR directly affects the appearance of the double-peak distribution, whereas the blade number affects the positions where it vanishes. -an increase in the blade number increases the wake width, and the TSR has a similar effect on the wake width
(Ayaz et al., 2023)	2023	Comparison	Nevertheless, due to the heterogeneity of SWT technology, a high variety of environmental impacts of SWT exist	Efficiency, average speed	Performance measurements	The GWP for the Austrian grid is 0.256 g/kWh, 0.094 g/kWh for the Pig2F, and 0.062 g/kWh for the SW05. Nevertheless, from a future perspective, this will not hold.
(Wang et al., 2022)	2022	Numerical	Related to the estimation of the rotor power coefficient (Cp) and wake length (WL) in the context of wind turbine design and operational control for wind farm applications.	Energy recovery ratio, wind speed, power coefficient	Simulation and then use the Proper Orthogonal Decomposition (POD) method	- The new power coefficient prediction model demonstrates a maximum error of 1.7 % compared to traditional methods. - POD analysis indicates that the first-order mode captures over 99.5 % of inflow plane energy, primarily utilized by the wind turbine.
(Rahmatian et al., 2022)	2022	Experimental.	The problem is about optimizing the duct design to enhance the aerodynamic performance of the micro HAWT	Torque, wind speeds, power coefficient	Numerical and utilizing an encompassing duct on the aerodynamic	-The modified duct enhances inlet wind speed from 5 m/s to 10.7 m/s, achieving a 2.14-fold increase and a 47 % improvement. -The turbine's power coefficient increases from 0.33 to 1.2, exhibiting a 3.64-fold rise and a 164 % enhancement.
(Yilmaz, 2023)	2023	Numerical	Loss in off-design performance.	Cp, cl, wind speed.	Simulation and In-house built blade element momentum algorithm was employed	A modest enhancement in operational TSR was observed to significantly alleviate the decline in off-design performance. These attributes are essential for optimizing energy collection.
(Pellegrini et al., 2021b)	2021	Experimental.	One of the barriers to the diffusion of micro-wind turbines in urban settlements is the difficulty in estimating its feasibility based on the local wind resources,	Wind speed, LCOE	Extensive monitoring and analysis of a micro-wind turbine	The findings suggest that the technology is unsustainable in areas with low wind speeds, such as Forlì, Italy. Thus, low wind speeds negatively impact electrical output. The highest recorded output was 1.17 kWh/day on April 1, associated with 10.8 hours of operation and an average wind speed of 2.89 m/s, peaking at 15.8 m/s
(Rahgozar et al., 2020)	2020	Performance analysis	The problem statement deals with improving the starting performance of the most powerful blade by implementing linear distributions for both chord and twist angles.	Power coefficient, wind speed	The blade-element and use a genetic algorithm	Results indicate that linear distributions exhibit greater deviation from ideal distributions Findings reveal that linear distribution enhances starting

(continued on next page)

Table 2 (*continued*)

Ref.	Year	Type of Study	Problem	Factor	Method	Key Features
						performance with minimal sacrifice in output power.
(Varaganti et al., 2022)	2022	Compared and Analyses	Large-scale wind turbines" are commonly used to produce megawatts of power. They demand more space, involve high installation costs, and are unsuitable for residential purposes. An alternate approach is to use "small-scale wind turbines," which require less space, are cost-effective, and are quick to install.	Cp%, Air density, wind speed, power out	Simulation used MATLAB	Tip speed ratio (TSR) significantly impacts the performance of wind turbines. Optimal power generation is achieved at an ideal TSR of 7.7, given a blade radius of 18 m. This paper clearly emphasizes the importance of TSR in wind turbine performance and highlights the specific optimal value and conditions for maximum power extraction.
(Shakya et al., 2024)	2024	Numerical	Cracks in wind turbine blades significantly threaten structural integrity and performance, arising from cyclic loading, manufacturing flaws, material fatigue, or external forces. Such cracks may jeopardize blade stability, risking catastrophic failure if neglected.	Blades	CFD and FEA methodologies are employed to evaluate aerodynamic forces, deformation, and stress on blades across varying wind velocities.	The study indicated that anomalies in high-stress regions significantly shorten blade lifespan compared to lower-stress locations. turbine's effectiveness and reliability.
(Ayaz et al., 2023)	2023	Numerical. and Experimental.	However, low wind velocity is a limiting factor that significantly diminishes the power generation capacity of wind turbines	maximum velocity, wind speed	A numerical analysis was conducted to assess the influence of geometric parameters on INVELOX's power generation capacity.	-The findings revealed an enhancement in the maximum velocity ratio from 2.125 to 3.13. -power generation capacity increased by 3.2 times relative to the original INVELOX design by applying optimized geometric parameters and the semi-dome concept.
(Abu El-Maaty et al., 2024)	2024	Numerical	Sand erosion contributes to the deterioration of wind turbine blades, resulting in diminished performance and lifespan.	Wind speed, blades, and Cp	Simulation A numerical investigation of the performance and sand erosion of a Small-Scale Horizontal Axis Wind Turbine (SS-HAWT) is conducted.	-This prototype generates 106.4 W at a tip speed ratio of 5 and an air velocity of 8 m/s. -Annually, a maximum erosion depth of 5.7 mm is anticipated for this small-scale wind turbine under specified conditions.
(Shirzadeh Ajirlo et al., 2021)	2021	Numerical.	The issue centers on finding a cost-effective alternative to traditional wind tunnel testing for conducting wind simulations	wind speed, TsR, Power coffinite.	The simulator is employed to test and assess the design and the performance of micro horizontal axis wind turbines (HAWT).	-The simulator exhibits superiority over wind tunnels due to the absence of blockage effects, enhancing its utility for micro wind turbine performance evaluation. -The findings indicate that elevated TSR conditions lead to an increase in the velocity encountered by the turbine due to the blocking effect.
(Yossri et al., 2023)	2023	A comparison between the suggested bioinspired designs is provided	Addressed in the research paper is the evaluation of the efficiency of bioinspired blade designs for low-speed small-scale wind turbines with the presence of inflow turbulence effects	The torque, tip speed ratio, and power computation	The geometries of wind turbine blades are modeled after the wings of the golden eagle and dragonfly.	-The golden eagle's design achieved the highest power coefficient with a power output of 4.5 W and torque of 0.21 N m, -while the dragonfly's design recorded the lowest power coefficient and output at 2.2 W with a maximum torque of 0.11 N m.
(Khaled et al., 2019)	2019	Sim.	The research problem revolves around optimizing the geometric parameters of winglets to enhance the performance of a small HAWT.	CP% and thrust force coefficient, T S R	algorithm. ANN	The increase in winglet length at the same tip-speed ratio increased the power coefficient and thrust coefficient.When the cant angle was 48.3 and the winglet length was 6.32 %, the performance improved the most.
(Eltayesh et al., 2021b)	2021	Experimental and numerical	The addition of a shroud boosts rotor speed, yet it also creates extra drag, requiring structural reinforcement for both the rotor and shroud. Furthermore, shroud application may result in unsteady downstream wake patterns, causing variable flow conditions at the rotor's position.	TSR, CP% and number of blades	An experimental setup was created to investigate wind turbine rotors with three, five, and six blades at various tip speed ratios in a closed-circuit wind tunnel.	Reducing blade quantity in wind turbines indicates that a three-blade setup provides a better power coefficient than five or six blades, with improvements of around 2 % and 4 %, respectively. Research suggests that increasing blade numbers and

(*continued on next page*)

Table 2 (*continued*)

Ref.	Year	Type of Study	Problem	Factor	Method	Key Features
						blockage leads to higher torque and friction losses.

also contribute to the mitigation of greenhouse gas (GHG) emissions and bolster the transition towards the electrification of transportation systems (Pellegrini et al., 2021b).

7. Conclusion

The research indicates that micro wind turbine systems outperform large turbines in efficiency and cost. Small turbines excel in low-speed wind conditions. Furthermore, microturbines exhibit time and cost efficiency along with practicality and versatility. Nonetheless, their resourcefulness is contingent upon recognizing and understanding specific environmental conditions. Thus, comprehending wind flow characteristics is essential for wind energy applications. Previous studies lead to the conclusion that:

- This study presents a comprehensive review of wind turbine control strategies for high-speed winds, focusing on soft-stall techniques for adaptability and efficiency. It emphasizes the importance of selecting an appropriate maximum power point tracking (MPPT) control loop for effective strategies. The findings also suggest that a power control system adaptable to varying wind speeds is achievable due to wind variability. However, the general applicability of all MPPT techniques to real systems remains restricted. Given wind's unpredictability, turbines necessitate control for optimal power extraction due to their nonlinear dynamics. In recent decades, various mechanical and electrical MPPT control systems have been created.
- Previous studies have indicated that horizontal axis wind turbines (HAWT) exhibit advantages over vertical axis wind turbines (VAWT) in low wind conditions, including reduced noise emissions, simpler construction, and lower installation costs. Literature supports that horizontal turbines function efficiently at lower wind speeds compared to vertical-axis turbines.
- Researchers have persistently aimed to improve wind turbine performance under challenging operational conditions but face challenges such as flow separation, vortices at blade edges, and tip losses that diminish rotor effectiveness.
- The results indicate that augmentation devices can increase power output for small-scale turbines in low wind velocities. The study reveals that active and passive flow control devices can enhance power coefficients for vertical and horizontal axis wind turbines by modifying flow separation and vortices around the blades. Turbine blade design should prioritize maximizing power production while ensuring structural and aeroacoustics integrity.

This research advocates for future investigations to develop more efficient pitch/yaw control strategies for wind turbines in complex terrains to optimize downwind aerodynamic performance. Thus, integrating wind turbines with other renewable energy sources and energy storage systems is advisable to address these unpredictable conditions. Similarly, wind tunnel testing offers benefits over field measurements, including easier modeling, convenient adjustments, and reduced susceptibility to external factors. Additionally, wind tunnel experiments corroborate numerical model results.

Abbreviations

ANN: Artificial Neural Network
BEMT: Blade element momentum theory
Cp%Power coefficient
CFD: Computational fluid dynamic
HAWTs: Horizontal-axis wind turbines
IEA: The International Energy Agency
LCOE: Levelized Cost Of Energy
LSWT: Large-scale wind turbine
FEA: Finite Element Analysis
LSHAWTs: Large-scale horizontal-axis wind turbines
LWTs: Large wind turbines
LIRs: Low induction rotors
MPPTC: Maximum power point tracking control
OMD: Optimal mode decomposition
O&M: Operation and maintenance
PMSG: Permanent magnet Synchronous Generator
POD: Proper Orthogonal Decomposition
SDGs: Sustainable development goals
SS-WECSs: Small-scale wind energy conversion systems
SCIG: Squirrel-cage induction generator
SWTs: Small Wind Turbines
TSR: Tip speed ratio
WTBs: Wind turbine blades
WL: Wake length
WT: Wind turbine
VGs: Vortex generators
VSWT: Variable-speed wind turbines
VAWTs: Vertical axis wind turbines

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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