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Review Article

Advancements in Wind Energy: Exploring the Potential of Diffuser Augmented Wind Turbines (DAWTs)

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Abstract *- This paper explores recent advancements in wind turbine technology, focusing on Diffuser Augmented Wind Turbines (DAWTs). It provides a thorough review of the various research studies related to wind turbines equipped with diffusers, highlighting both numerical simulations and experimental data. The review categorizes the literature into two main areas: studies on the performance and operation of wind turbines with diffuser augmentation and comparative analyses of different types of DAWTs. The key parameters of diffuser design, such as length, open-angle, and the effect of flanged versus un-flanged configurations, are examined to determine their impact on power output and efficiency. The findings reveal that DAWTs significantly enhance wind turbine performance by increasing wind velocity through the rotor plane, surpassing the traditional Betz limit. This advancement results in higher power outputs, reduced noise, and improved tolerance to yaw angle variations. Despite these advantages, the commercialization of DAWTs faces challenges, including high initial costs, maintenance issues, and the complexity of integrating aerodynamic, material, and control system innovations. The paper concludes that while DAWTs offer promising improvements in wind energy efficiency, overcoming these challenges through innovative design and manufacturing approaches is crucial for their broader adoption in sustainable energy generation.*

Keywords *- Diffuser augmented wind turbines, Wind energy efficiency, Aerodynamic optimization, Power output enhancement, Small-scale wind.*

1. Introduction

Recently, there has been a noticeable increase in the focus on creating and using renewable energy sources. This shift is driven by the urgent need to address the quick depletion of fossil fuels, which are finite and increasingly scarce. As the availability of this traditional source of energy declines, there is a pressing necessity to find sustainable alternatives to meet the growing global energy demand. The reduction of sources of fossil fuels and the environmental impact of their irrational use have spurred increased interest in seeking alternatives. This includes developing, renovating, adapting, and even hybridizing various renewable. [1-3] and non-renewable energy generation sources [4]. The great capacity of wind turbine investments has acted as a catalyst for a significant influx of resources into the research and development of advanced wind turbine technologies. These investments are aimed at enhancing the reliability, efficiency, and cost-effectiveness of electricity generation through wind energy. As a result, there has been a concerted effort to innovate and improve various aspects of wind turbine design, manufacturing, and operation. COVID-19 has disrupted renewable energy construction and traditional sources of energy, making one increase investment in renewables and seeking chances to increase output and reduce manufacturing time. [5].

The estimated value of the global wind power potential, or WPP, is 94.5 TW. The regions with the largest potential are Europe (37.5 TW), Russia (36 TW), and the United States (11 TW) [6]. Nonetheless, less-speed winds are the most prevalent, according to the European Wind Energy Association, with winds being too sluggish to use massive wind turbines to produce power around 14% of the time. A significant portion of the coastal United States is predicted to have a gradual drop in wind energy resources, which might make it more difficult to install offshore large-scale wind turbines and fully exploit the region's WPP [7]. Furthermore, the unpredictability and variability of wind energy provide difficulties for power transfer in transmission networks, particularly in light of the inadequate grid infrastructure in isolated regions and the intrinsic unpredictability of wind. The Betz limit limits wind turbine power generation to not more than 59.3% of the kinetic energy of the wind. Furthermore, there has been a noticeable increase in the focus on creating and using renewable energy sources. Hence, even a minor rise in incident wind speed leads to a substantial rise in the production of energy. Researchers offered creative approaches to increase wind turbine power production.

Numerous techniques exist for enhancing wind turbine performance, including modifying the blade design, installing tip vanes on the rotor blades, building ducted wind turbines with diffusers, shrouds, and concentrators, and employing vortex-type augmentation devices. Diffuser Augmented Wind Turbines (DAWTs) are one of the most often utilized methods to increase power collected because they have benefits over other augmentation alternatives. In addition to pulling increased mass flow into the wind turbine and increasing wind velocity, the diffuser with a flange creates an area with low pressure at the outlet through vortex generation. An intake-perimeter converging ring-shaped shroud characterizes a simple diffuser with a shroud. Better airflow through the diffuser is directed by the shroud. The shroud generates reduced pressure, increasing wind velocity at the entry. The flange and shroud at the intake and exit peripheries, respectively, make up the flanged diffuser with the shroud.

However, despite the progress achieved in DAWT, much research remains to be done. Most of the available literature focuses on isolated design parameters or only on certain configurations, while a holistic understanding of how diffuser geometry, material innovations, and aerodynamic enhancements relate to each other is not well addressed. Moreover, the challenges of scaling DAWT designs to make them commercially viable and compatible with the existing grid structure still need to be addressed. The goal of this paper is to fill these gaps by analyzing major factors that influence DAWT performance and exploring new solutions to overcome barriers against their widespread adoption.

1.1. Key Terminology in DAWT

- DAWT: An Augmented Wind Turbine with a diffuser design for enhancing wind speed and, therefore power output.
- Diffuser: A casing surrounding the rotor in duct-like form to increase the velocity of wind passing through the turbine by creating a low-pressure zone.
- Flange: An edge or ring at the exit of the diffuser protruding outwards, enhancing the production of a low-pressure zone to enhance the speed of wind.
- Shroud: The cover or covering over the diffuser used to straighten airflow while avoiding turbulence.
- Rotor Plane: A vertical plane swept out by turbine blades, from which energy from wind changes into mechanical energy.
- Betz Limit: Theoretically, the maximum efficiency of any wind turbine in converting kinetic energy from the wind to mechanical energy is 59.3%.
- Yaw Angle: This is the angle between the wind direction and the rotor axis, impacting the turbine's performance.
- Power Coefficient (Cp): This is the ratio of usable mechanical energy obtained from the wind to the kinetic energy of the wind.
- Levelized Cost of Energy (LCOE): Total energy production costs spread over a turbine's life, including the costs of building, maintenance, and running, and then divided by total energy output.

2. Literature Review

2.1. Wind Turbine

An intricate electromechanical device made up of several parts and subsystems is a wind turbine. The generator, gearbox, mechanical shaft, rotor, bearings, sensors and power electronic interface are important parts. Induction generators with wound rotors, squirrel-cage induction generators, and synchronous generators are among the generator types that can be utilized with wind turbines. When wind speed fluctuates, the constant operating speed of the squirrel-cage induction generator may result in malfunctions. To solve this, an adaptive control strategy has been developed to assure the dependable functioning of permanent magnet synchronous generators under varying conditions; nevertheless, these generators necessitate full-scale power converters, which raises implementation costs.

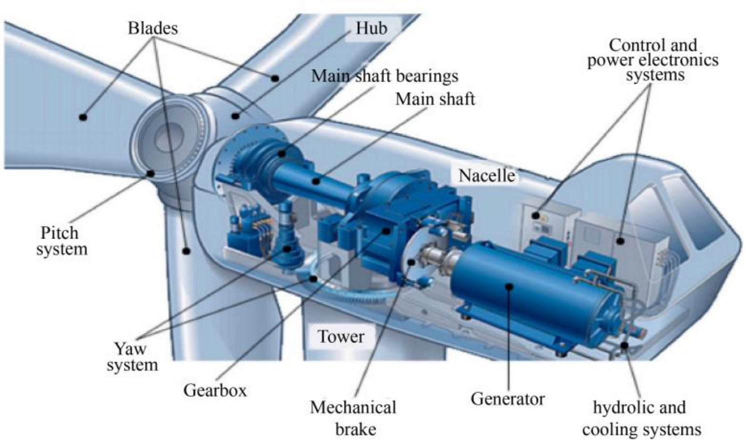


Fig. 1 Wind turbine main components [8]

Wound rotor induction generators, also known as Double-Fed Induction Generators (DFIG), are popular owing to their low converter rating, inexpensive cost, capacity to manage reactive power and active, minimal losses, and excellent efficiency. A large range of variable speeds may be operated by DFIGs, in contrast to fixed-speed synchronous generators.

The stator terminals of DFIG-based Wind Energy Conversion Systems (WECS) feed about 70% of the produced power immediately into the grid, with the remaining 30% coming from back-to-back converters comprised of a DC-link capacitor, rotor side converter, and a grid side converter.

Figure 1 illustrates the configuration and power flow within a typical wind energy conversion system based on DFIG. This arrangement highlights the integration and control of different components to efficiently convert wind energy into electrical power, ready for grid distribution.

2.2. Diffuser Augmented Wind Turbine (DAWT)

By enclosing a wind turbine in a duct or shroud, the DAWT technology is presented as a way to amplify its power output. To create additional power, the wind velocity is increased as it travels through the rotor plane. This design makes use of the fact that wind power is exactly related to the cube of the wind's free stream velocity. A DAWT can exceed the Betz limit by utilizing a diffuser to catch and guide more wind into the rotor for a specific turbine diameter and wind speed. [9].

In essence, a DAWT's ability to perform better is dependent on the mass flow of air through the duct; larger improvements may be obtained by lowering the diffuser exit back pressure. This innovative approach significantly boosts wind turbine efficiency and production by utilizing aerodynamic principles. [10].

One of the most extensively studied and used wind turbine types is the DAWT, often referred to as a ducted or shrouded wind turbine. Since the turbine has sectional circulation, it is housed inside an annular wing, which improves mass flow across the rotor. The turbine can now produce more power than the Betz limit in terms of both duct-exit area and rotor thanks to this arrangement. [11].

DAWTs provide various further benefits. They feature a slower cut-in speed and less tip loss. [12] and noise [13], and are less sensitive to changes in yaw angle [14, 15]. These characteristics make DAWTs suitable for airborne applications through which they can harness continuous and strong high altitude-wind flows. [16]. DAWTs might also efficiently generate wind power even in cities with a bit of direction change for their wind directions and rather moderate wind speeds, making it suitable for installation on this end. [17].

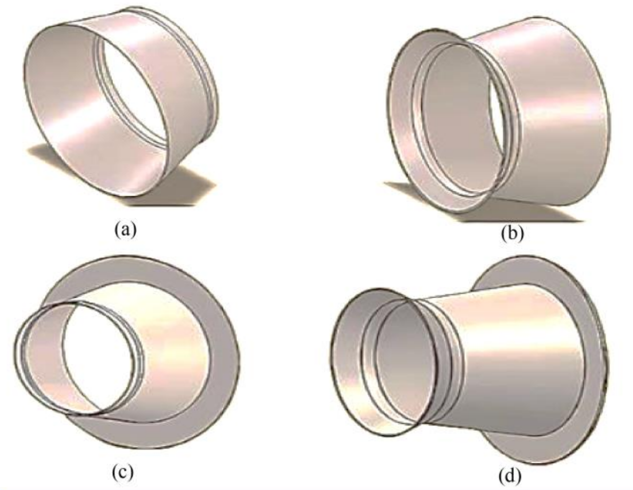


Fig. 2 Different Types of diffuser (a) Plane diffuser, (b) Plane diffuser with inlet shroud, (c) Flanged diffuser, (d) Flanged diffuser with Inlet Shroud [18]

Figure 2 shows some of the different diffuser models used in DAWTs and depicts differences in design and their implications in aerodynamics. (a) A Plane Diffuser is a simple diffuser design with no feature, mainly to ensure that airflow enters the rotor with minimum augmentation. (b) A Plane Diffuser with an Inlet Shroud has a shroud at the inlet; hence, it improves and stabilizes the flow condition in such a way that there is a better velocity distribution. (c) Flanged diffuser makes use of the flange at the exit, where it creates an area of low pressure across the rotor, increasing immensely the wind velocity passing through it and thus improving the power generated. Lastly, (d) a Flanged Diffuser with an Inlet Shroud combines a flange and an inlet shroud to optimize pressure differences and airflow control for further enhancement of performance. These designs indicate that the structural variations play a critical role in enhancing the DAWT efficiency and power-producing capability, as revealed in this paper.

2.3. Various Types of Diffuser Shapes

2.3.1. Rotating Diffusers

An innovative wind turbine system with revolving diffusers that revolve around the turbine's horizontal axis and create a rotor cowling has been patented by Anakata Wind Power Resources [19] In the UK. This design allows the diffuser to move with the rotor's rotation and includes features like slot gaps for airflow and guide vanes to reduce airflow twists. Rated at 370W at 12.5m/s wind speed, the 0.85m diameter A007 model is constructed from lightweight, long-lasting materials. While this design aims to reduce vibrations, the effects on aerodynamic drag and rotor RPM are still uncertain.

2.3.2. Multiple-Slotted Diffusers

By employing high-lift aerofoil diffuser rings, this method seeks to restore external airflow into the turbine's wake and reenergize the boundary layer along the diffuser's inner surface, leading to lower pressure distribution and increased air mass flow [20, 21]. Wood patented a DAWT in 2014 that uses diffuser rings to create a larger outlet area and slots for air bleeding, creating a suction effect. Slots are formed with diffuser rings. Airflow is facilitated by pre-rotation vanes, which are fixed to the rotor. By using more slots, you may minimize the amount of material and weight by decreasing the diffuser's length-to-diameter ratio.

2.3.3. The Simple Diffuser

Different diffuser types depend on several important parameters. These include the diffuser's cross-sectional profile, which can differ between aerofoil shapes or constant thickness designs. Other important factors are adjustments in the area ratio (the diffuser's cross-sectional area at the inlet divided by its output), the length-to-diameter ratio (The ratio of the diffuser's length to its diameter), and the overall diameter of the diffuser itself. For example, features a design where the inlet converges or narrows down before expanding outward into a diverging outlet. This implies that the diffuser's cross-sectional area grows as the airflow progresses through it. In this design, the rotor is positioned at the smallest diameter of the diffuser, which is typically at the inlet. This configuration helps manage the airflow efficiently and optimizes the diffuser's performance by directing the air through its varying cross-sectional profile.

2.3.4. Brim and Flange Technology

The "Wind-lens Technology" [22, 23] was created by Japanese researchers Ohya and Karasudani [24] At Kyushu University. Initially, they planned to incorporate a 5kW upwind "compact acceleration structure" (compact brimmed diffuser) to address issues including high weights of the structure and wind loads in a 500W DAWT. The Ciii type proved to be the most efficient 'compact' shape in the tests conducted to determine the best shape; it produced 2.6 times the power of a comparable naked turbine. Brim-based yaw control is included in the Wind-Lens technology, allowing for automatic correction to wind direction changes.

The compact design has proven successful in lowering structural loads and increasing rotor rotational efficiency. Power augmentations with this technique typically vary between 2 and 3 times the baseline. Utilizing single- and multiple-stage ejector systems designed to exceed the Betz limit is the basis of the mixer ejector technology. Walter et al. [25] Curved intake, rotating blades, stator vanes, and a mixer/ejector pump were all incorporated inside a shroud. This design seeks to improve the turbine's flow capacity by blending the low-energy outflow, whereas the high-energy wind stream enters via a secondary aperture. This method is expected to increase power output by three to four times that of an equal bare turbine. Such enhancements are predicted to greatly increase wind farm output, perhaps doubling it, while also making it ideal for urban areas due to its safety and reduced noise.

2.3.5. Vorticity-Based Turbines

DAWT technology uses vorticity, which measures the curving of velocity profiles and local fluid rotation, to decrease air pressure in the diffuser's wake, raising the pressure difference and pulling in additional air. Because of the fluctuating wind conditions, achieving a laminar flow profile is desirable yet challenging. Early studies by Okhio et al. [26] Investigated swirl rotation effects to reduce flow division in a diffuser with a large angle, finding that optimal swirl could reduce losses by 60%. However, excessive swirl led to additional losses due to re-circulating zones. Mariotti et al. [27] Examined many local recirculations to boost the diffuser's effectiveness, testing diffusers with different divergence angles. They found that smaller angles kept flow attached to the walls, while larger angles caused flow separation. Introducing optimal cavities enhanced pressure recovery and reduced momentum losses, resulting in a 25% increase in power coefficients.

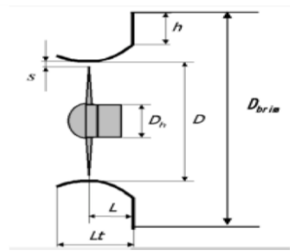
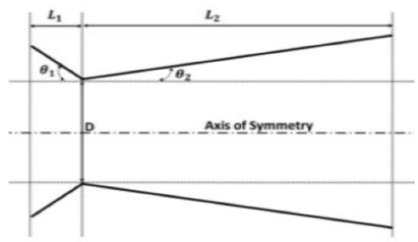
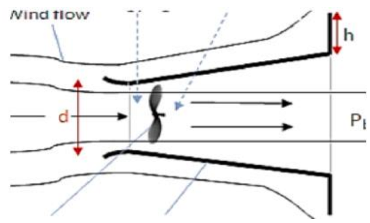
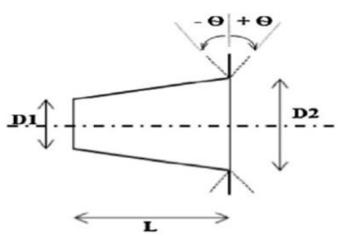
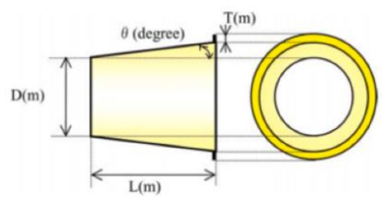
2.3.6. Mixer Ejector Wind Turbines

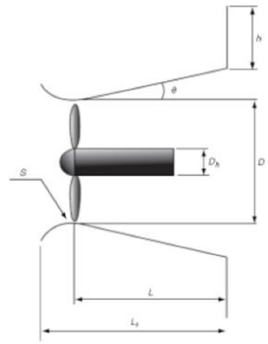
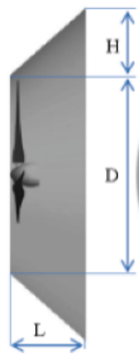
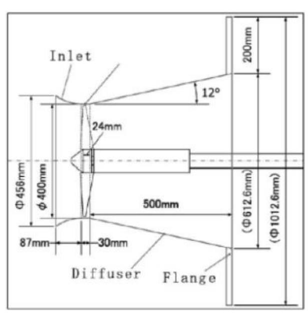
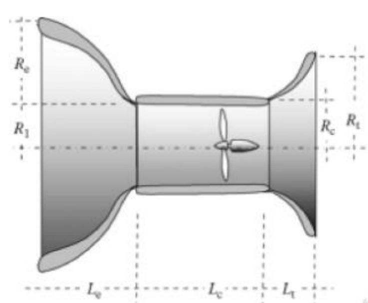
Mixer ejector technology, which employs both single- and multiple-stage ejector systems, is intended to exceed the Betz limitation. Walter et al. [25] Constructed a shroud with rotating blades, a mixer/ejector pump, stator vanes, and a curved intake. This layout tries to raise the turbine's flow volume by combining the poor energy flow with the high-energy wind flow arriving through a second-stage slot. This method is expected to increase power output by three to four times that of an equal bare turbine. Such enhancements are predicted to greatly increase wind farm output, perhaps doubling it, while also making it ideal for urban areas due to its safety and reduced noise.

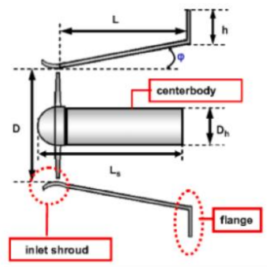
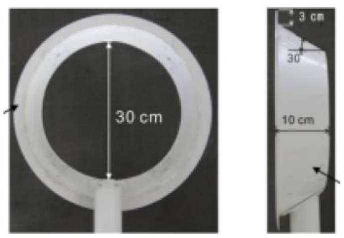
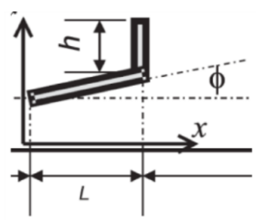
2.4. Comparative Studies on Diffusers Augmented Wind Turbines

Rahmatian et al. [28] Optimized a DAWT with convergent-divergent ducts in terms of the single objective through the two-dimensional CFD model, RSM and GA. They analyzed 79 geometrical models and simulation results to optimize the geometry of the duct with a maximum velocity at the duct throat as the objective function. An increase of optimized DAWT in the wind speed was by a factor of 2.18 times, and the power coefficient was by a factor of 3.94 times. The presence of a duct may help minimize noise resulting from the rotor. Shambira et al. [29] Applied RSM and a two-dimensional CFD model for developing and optimizing a DAWT that incorporates a concentrator at its inlet without a rotor. They observed that the throat velocity is extremely sensitive to the concentrator and diffuser length variations and increased the inlet wind speed at the throat position of the duct by 1.953 folds.

Table 1. Comparative studies on diffusers augmented wind turbine

Author	Diffuser Parameters	Diffuser Shapes	Increase in Output Power	Investigation Method
Ohya et al. [24]	D/h = 0.05 – 0.2 D = 1020 mm Lt = 0.225D, 1.47D and 0.221D		2–5 times	Experiment
Kishore et al [30]	L1 = 0.125D θ2 = D 10◦ θ1 = 15◦ L2 = 0.125D		1.4-1.6 times	Simulation (Fluent) and Experiment
Mansour et al. [31]	θ = 4◦ D/h = 0 – 0.5D D/L = 1.5		4 times	Numerical
El-Zahaby et al. [32]	D1 = 6 cm L = 9 cm h = 1.5 cm D2 = 7 cm θ = -25◦ – 25◦		1.953 times	Simulation
Gilbert et al. [33]	angle 60◦	Conical diffuser	4.25 times	Experiment
Matsushima et al. [34]	L = 2–4 m D = 1 m θ = 0◦ – 12◦ T = 0.1–0.5 m		2.4 times	Simulations and experiment
A. Tourlidakis et al. [35]	θ = 1.65◦ L = 4.8 m	Diffuser without, within the flange	Flanged diffusers can increase power coefficients by up to 3 times	Simulation

Ohya et al. [36]	L = 1.25D & 0.137D D = 600 mm & 1020 mm h = 0.5D and 0.1Dvz Lt = 1.5D & 0.225D θ = 12◦		An increase in the flow rate over the throat	Experiment and simulation
Jafari et al. [37]	D/L = 0.1 – 0.4 D/H = 0.025 – 0.35		A greater power coefficient was noted.	Simulations
B. Ahmed et al. [38]	θ = 2◦ L = 0.12 m	Flanged diffuser	Upstream wind speed may reach 154%, and power can increase by 3.65 times with flanged diffusers.	Simulation
Abe et al. [39]	D/L = 1.25 φ = 12◦ D/h = 0.5		4 times	Numerical & Experiment
Wang et al. [40]	Length = 0.915 m D central part is 0.613 meters. D entrance = 0.917 m.		2.2 times	Simulation and experiment

Ohya et al. [17]	D/L = 1.25 D/h = 0.5 φ = 4◦ − 12◦		4-5 times	Experiment
Chen et al. [41]	h = 3 cm L = 10 cm diffusion angle = 30◦		increased (varying) coefficient of power	Experiment
Abe et al. [42]	D/L = 1.5 φ = 4◦ D/h = 0-0.5		increased (varying) coefficient of power	Numerical
K Mansour et al. [31]	θ = 1.2◦ L = 0.2 m	Inlet-shrouded Flanged Diffuser	Intake shroud-equipped flanged diffusers can increase upstream wind speed by up to 1.6 times.	Simulations

2.5. Why is DAWT not used or Commercialized in the Market?

Numerous noteworthy obstacles confront small-scale wind power generation. Because of changes in wind patterns and small-scale turbine inefficiencies, its performance has historically been erratic and frequently falls short of anticipated outputs. Furthermore, small wind systems often have a high Levelized Cost of Energy (LCOE) [43]. This indicator, which calculates the average cost of power generation during a turbine's lifetime, is nonetheless significant because of the high initial outlay of funds, ongoing maintenance costs, and lower energy outputs in comparison to bigger wind plants. The introduction of small wind turbines is further complicated by concerns about noise and safety. [44]. Mechanical breakdowns and accidents provide a safety risk, particularly in residential or urban contexts. The noise produced by the turbines can also be a considerable disincentive, affecting surrounding inhabitants and wildlife. Some of these problems may be resolved with the use of DAWTs. They have the potential to produce much more power by adding a diffuser. [45], which is a device that improves the flow of wind through the turbine. This increased effectiveness may result in a decreased LCOE, increasing the technology's viability from an economic standpoint. However, significant difficulties remain in the way of commercialization. [46].

The design and operation of a small wind turbine is an intricate interdisciplinary system that involves several critical components. [47], each contributing to the overall functionality and efficiency of the turbine. Aerodynamics plays a pivotal role in the performance of wind turbines. [48]. The shape and design of the turbine blades must be optimized to capture the maximum amount of wind energy and convert it into rotational energy efficiently. [49]. This involves understanding the complex fluid dynamics of airflow over the blades, minimizing turbulence, and maximizing lift while reducing drag. Electrical control systems are also considered major management tools in managing the conversion from mechanical energy into electricity. Such systems will range from generators and inverters to controllers that ensure proper running efficiency and safety under any varying wind conditions. Also, important advanced algorithms in the control systems aim to optimize the turbine, as it will alter the blade pitch, yawing the turbine based on the direction of the wind at all times. Material science is an important factor in making the components of a small wind turbine. [50]. Materials to be used in blades, towers, and other structural components must be light, tough, and fatigue- and environment-resistant; they must withstand corrosion and UV degradation. [51]. Innovations in composite materials and coatings can enhance the longevity and performance of these components. Supply chains for manufacturing are another critical aspect of small wind turbines. [52]. The production process involves sourcing high-quality materials and components, maintaining cost efficiency, and ensuring the reliability of the supply chain.

Manufacturing techniques must be precise to meet the stringent quality standards required for turbine components, and the entire supply chain must be coordinated to handle the low production volumes typical of small wind turbines. Commercial operations encompass the business aspects of deploying and maintaining small wind turbines. This includes marketing, sales, installation, and after-sales service. Companies will need to deal with regulatory approvals, customer relationship management, and providing continued maintenance and support so that the turbines operate optimally throughout their operational life. Proper commercial operations are crucial to reaching financial viability and customer satisfaction. The supply chain for manufacturing small wind turbines is a challenging one since the materials are costlier, the production process is more complex, and the economies of scale are limited by low volumes. Expensive materials are the most significant challenge.

The components of small wind turbines - blades, towers, or any others - require sophisticated composite material that is as light yet strong enough to fight the turbulence of the environment. These are expensive materials, very costly which increases the costs of production. Complicated production also adds more complexity. Advanced techniques of great precision are required to manufacture the precise aerodynamic shapes of turbine blades, incorporate electrical control systems, and ensure the structural integrity of the turbine.

Such complex processes involve huge man-hours and technological investments that raise costs. Small wind turbines face a problem of volume at low cost. Their number of productions is far smaller compared to large utility-scale turbines. This is a lack of mass production, meaning that manufacturers cannot reap the cost reduction typically associated with higher volumes of production. Consequently, the per-unit cost is high, and price competitiveness in the market becomes challenging to achieve.

There are several obstacles in the way of small wind turbine marketing channels, especially when it comes to controlling the time costs associated with deal closure and striking a balance between transactional and enterprise sales. Small-scale or individual transactions are the norm for transactional sales, which may be completed more quickly but frequently result in lesser income per sale. To properly manage larger amounts of smaller sales, these transactions need a simplified procedure. On the other hand, enterprise sales entail bigger, trickier agreements with companies or groups; although they might provide more profits, they also need a lot of time and resources. Large-scale discussions, specialized solutions, and protracted sales cycles are frequently needed for enterprise sales. Small wind turbines have specialized uses in remote monitoring, telecommunications, mining, and agriculture. A 200 W device was developed, constructed, installed, and tested at the client's remote telecommunications location.

Table 2. Challenges and future scope

Challenges	Future Scope
Turbulence and Site Selection	Detailed site assessments, improved wind speed and direction prediction methods, and turbulence intensity studies.
Scale and Performance	Optimization of blade designs for small scales, use of efficient airfoils, and advancements in aerodynamic modelling.
Noise and Vibration	Advanced blade profiles, improved gearbox arrangements, and improved vibration-damping methods.
Grid Integration and Power Quality	Development of power conditioning systems, advanced control algorithms and energy storage solutions.
Maintenance	Implementation of remote monitoring systems, development of robust service networks, and consistent maintenance practices.
Cost and Affordability	Advances in manufacturing processes, government subsidies, and improved market competitiveness.
Durability	Use of durable materials, robust component designs, and adherence to proper maintenance practices.
Environmental Impact and Visual Aesthetics	Comprehensive environmental impact assessments, community interactions, and advancements in turbine design to reduce visual impact

3. Discussion

This paper provides a comprehensive review of prior research in wind energy, focusing specifically on diffuser augmentation. The literature on this topic was categorized into two main groups: the first group covered studies on wind turbines with diffuser augmentation, while the second group focused on comparative analyses of various Diffuser Augmented Wind Turbine (DAWT) challenges and future solutions. The review encompasses numerical simulations, experimental data, and theoretical analyses of diffuser-augmented wind turbines. Additionally, it offers a detailed examination of diffuser parameters, power output improvements, and investigation methods, as summarized in Table 1. Key parameters such as diffuser length and the diffuser's open angle were analyzed. The study concludes that recent research shows a consensus that DAWTs offer superior advantages over other augmentation solutions, particularly in generating power that exceeds the Betz limit. This enhancement is attributed to the increased small distance between the blade tips and the diffuser wall, which allows the turbine to be positioned near the diffuser's intake, resulting in upstream wind velocity. DAWTs are effective for micro and small wind turbines in both rural and urban settings because they do not require high elevation. Diffuser shapes with the proper exit-to-inlet area ratio, and open-angle are used to maximize their effectiveness. Furthermore, flange diffusers outperform un-flanged diffusers by generating vortices behind the flange, which Improves pressure differences downstream and boosts mass flow via the rotor. The flange also helps to detect flow direction, especially when the turbine has a yaw mechanism.

The study underlines the contribution of the geometry of diffusers toward achieving the said gains. Numerical simulation and experimental results have been used to show that the optimum configuration is vital, for instance, the length-to-diameter ratio of 1.5 and open-angle about 12°, to optimize performance. Further, inventions like multiple-slotted diffusers and brim-based designs have the promise to minimize material costs at high efficiency. Power coefficients increased up to 4.25 times in some instances. Despite these developments, several challenges remain. DAWTs have issues with scaling, high initial costs, and material durability. For example, while urban applications benefit from DAWTs' reduced noise and flexibility to lower wind speeds, the added complexity of the integration of advanced materials, such as composites and lightweight structures, increases the cost of production. This sensitivity to environmental conditions, such as turbulence and fluctuating wind conditions, highlights the need for enhanced predictive modelling and control algorithms. Critical discoveries here are the trade-off of performance with ease of implementation. Designs such as the mixer ejector turbine will give power increases up to 4 times the base. However, its complicated form of construction and maintenance are highly limiting factors in commercializing such designs. Integration with the existing energy grids would also be challenging due to their varying output, thus demanding changes in power conditioning systems and energy storage solutions. All the above-mentioned quantitative improvements observed in the performance of DAWT make it an interesting subject for further study. In that light, with proper solutions for technical and economic challenges observed here, DAWTs would certainly change small-scale, decentralized wind energy systems for renewable energy generation.

4. Conclusion

The advancement of wind turbine technology, particularly through innovations such as Diffuser Augmented Wind Turbines (DAWTs), presents significant opportunities for enhancing the efficacy and viability of small-scale wind power generation. This complexity and potential of the systems have been further underscored by the comprehensive analysis of various wind turbine components and subsystems, including the comparison between different types of generators and their operational characteristics. The design of DAWT, which has a unique approach of increasing the velocity of wind through the rotor plane using aerodynamic principles, is quite promising in surpassing the traditional Betz limit and achieving higher power outputs.

The studies reviewed have shown that, on the positive side, DAWTs are more powerful as compared to conventional technology, produce less noise than conventional wind turbines, and have a lower sensitivity concerning changes in yaw angle, hence applicable in urban and airborne setups. Despite these advantages, the commercialization of DAWTs and that of small wind turbines generally entails some challenges. The issues are the high initial costs, operating expenses, noise, safety, and maintenance. There are additional, intricate, interdisciplinary aspects to the turbine design process, including aerodynamics, material science, electrical control systems, and supply chain management, that further complicate widespread adoption. However, the prospects for DAWTs' improving efficiency and reducing LCOE are compelling enough for more research and development. Overcoming these existing challenges will require innovative solutions in design, manufacturing, and marketing strategies. In that sense, the concerns listed could be met, and DAWTs could be made to turn out cost-effective for the decentralized generation of wind energy with input in the area of sustainable energy.

Future work in DAWTs would focus on diffuser designs for optimal power output while keeping the material costs and production complexities at their lowest. Also, there is an area of integration of advanced materials like composites and lightweight structures, which would be used to further improve the efficiency and durability of DAWTs. Further research on hybrid systems where DAWTs are combined with other renewable energy technologies will open up more versatile and resilient energy generation solutions. Improved predictive models for the performance of turbines under changing environmental conditions will help refine the operational efficiency of DAWTs. In addition, overcoming the scalability challenges posed by large-scale deployment in offshore and remote locations is critical to the commercial success of DAWTs. Last but not least, research on socio-economic impacts and cost-benefit analyses of DAWTs in different regions is very important to guide the integration of DAWTs into the global energy market.

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