

ENHANCING ENERGY PRODUCTION: A COMPREHENSIVE REVIEW OF THE POTENTIAL OF DIFFUSER-AUGMENTED WIND TURBINES

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ABSTRACT

One of the alternative energy technologies that is developing the fastest in the world is wind energy. However, the usage of wind turbines in locations with low wind speeds, like urban areas, is restricted because they are less efficient. Consequently, a method to increase the likelihood of using wind energy at low speeds is required. By raising the wind speed upstream of the turbine, the Diffuser Augmented Wind Turbine (DAWT) concept has been utilized to augment wind and increase wind turbine efficiency. This paper is a detailed study of diffuser-augmented wind turbines (DAWTs), particularly discussing their design, constituents, modus operandi, and aerodynamics as well as performance. DAWTs are more effective in capturing energy and causing less pollution than traditional turbines. Furthermore, they overcome challenges related to diffusion optimization and investment viability. They can also be practically used across a wide spectrum of applications as field testing and real-world data show thus making them a viable option for renewable energy systems. These DAWTs are necessary tools that will propel the world towards low low-carbon economy; enhance electricity security supply and contribute in achieving Sustainable Development Goals by 2030. By addressing technological challenges, exploiting business opportunities, and promoting partnerships between academia, industry, and government DAWTs may play an important role in attaining a sustainable resilient clean energy future



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1. INTRODUCTION

As the world moves towards renewable and sustainable sources of power, wind energy has gained significance. The use of wind turbines to capture kinetic energy from the wind has gained popularity thus reducing greenhouse gas emissions and slowing down global warming. Traditional horizontal-axis wind turbines (HAWTs) have been mainly used in almost all parts of the world's wind farms. However, developments in

engineering and design of wind turbines have given rise to new approaches for improving their performance and efficacy. In renewable energy sector research on wind power technologies is crucial, especially in urban areas. Efficient affordable wind turbine development is seen as a hope for a reduction in dependence on fossil fuels with consequent mitigation of greenhouse gas emissions. This makes urban wind power attractive due to its capacity to provide energy close to demand at low power distribution costs. However, the main challenge

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lies in integrating wind turbines within complex urban landscapes and considering aerodynamics. Wind power increases exponentially with wind velocity, therefore localised increases in airflow velocity/ density inherent in urban environments must be exploited thus this turbulent flow resulting from increased mill roughness or erratic winds movements within cities impinges on the efficiency of these machines thereby necessitating development of such turbines that can perform optimally under such conditions (Energy, 2016; Song et., 2019). DAWTs offer several advantages over conventional HAWTs including increased power output, reduction in noise emissions, and better environmental compatibility. Due to these benefits, DAWTs are now seen as an alternative means for tackling the problems associated with raising wind energy generation to meet growing energy needs while minimizing environmental impact. DAWT developments have been propelled by technology in renewable energy engineering, materials science, and aerodynamics (Saleem & Kim, 2019). Several governments globally, industries, and research centers have spent big on the exploration of DAWTs to make them usable as well as eliminate technological bottlenecks. Over the years, experiments, field testing and computational modeling have all contributed to our understanding of the viability, performance, and scalability of DAWTs in many environmental settings (Nardecchia et al., 2020).

This study gives a general overview of diffuser-enhanced wind turbines (DEWTS) that stresses their importance in relation to renewable energy sources while highlighting the potential they possess for transforming wind power generation entirely. In reference to latest research findings, technological advancements as well as industry trends; this paper will delve more into design principles, aerodynamics; performance measurements; benefits; problems; applications, and future directions of diffuser enhanced wind turbines. This review paper seeks to contribute to existing discourse on developing wind power technologies and fast tracking the transition towards a low-carbon sustainable energy future by critically analysing DEWTS.

1.1 A brief overview of traditional wind turbines

For many centuries, human beings have always employed the use of wind energy to generate mechanical energy for different purposes including moving water and grinding grain. Early instances include windmills and pumps. But modern wind turbines have completely changed the use of wind power on a large scale for the generation of electricity (Mauro et al., 2019) Conventional wind turbines—also known as horizontal-axis wind turbines (HAWTs)—are the main source of renewable energy production today; they are also considered synonymous with the countless number of global wind farms in various parts of our

world. This article seeks to enlighten readers about classic wind turbine's origin, basic principles, components, operations, and roles in switching to green power. Modern designs of these machines were made by pioneers in the late 19th and early 20th centuries (Saleem & Kim, 2019). Over the past several decades, there has been a notable surge in the demand for energy from renewable sources due to the pressing need to reduce greenhouse gas emissions and reliance on fossil fuels. In 2018, renewable power capacity accounted for 33% of total power capacity. Technologies for harnessing wind energy are among the most dependable and have a lengthy track record of commercial success. Wind energy is the first renewable energy source after hydropower, making up 25% of the world's renewable power capacity (Saeed & Kim, 2017). However, innovative techniques for obtaining more power from the wind have always piqued tremendous interest due to the poor power density of wind-energy conversion devices. Several wind concentrator types have been created in this regard (Van Holten, 1977; Bontempo & Manna, 2020; Alquraishi et al., 2019), but the most researched and widely utilized is the so-called Diffuser-Augmented Wind-Turbine (DAWT), also known as ducted or shrouded wind turbine. This type of device has the turbine mounted inside an annular wing, which increases the mass flow that the rotor swallows because of its sectional circulation. By doing this, the turbine's power extraction increases, and it becomes possible to surpass the Betz limit in terms of the rotor and duct exit area (Betz, 1929). Reduced cut-in speed decreased tip losses and noise, low susceptibility to yaw-angle fluctuations (Avallone et al., 2020), and the ability to be naturally employed in aerial applications for the harnessing of powerful, steady high-altitude wind streams as well as for installation in urban environments (Saleem & Kim, 2019; Vaz & Wood, 2018) are further collateral advantages of DAWTs. It is observed that the Diffuser-Augmented Wind Turbine (DAWT) stands out, featuring a turbine housed within an annular wing structure. This design increases mass flow to the rotor, surpassing the Betz limit and enhancing power extraction. Additionally, DAWTs offer advantages such as reduced cut-in speed, decreased tip losses, and low susceptibility to yaw-angle fluctuations. Moreover, their suitability for harnessing high-altitude wind streams and installation in urban environments further underscores their potential in the transition to green energy. Conventional turbines have gained a remarkable reputation as a sustainable source of energy contributing significantly to global electricity supply and mitigation strategies aimed at curbing climate change worldwide. Wind energy has several benefits including reduced greenhouse gas emissions, security in energy supply, job creation opportunities as well as rural economic expansion. The application of wind energy is a feasible choice for addressing the cumulative energy desires while reducing the possessions of environment variation due to its scalability, reliability, and affordability. Wind turbines are used in disseminated generation schemes,

hybrid renewable energy developments, seaward wind parks, and onshore wind farms. Wind energy is foreseen to develop more and additional significant in the world's energy combination as economies of scale diminish costs and technology developments, serving to ease the change to a low-carbon and maintainable future (Dighe et al., 2020).

1.2 Introduction to diffuser-augmented wind turbines (DAWTs)

Wind power has become an important component of the global renewable energy mix in the quest for sustainable sources of energy. The use of wind turbines, however, particularly horizontal-axis wind turbines (HAWTs), has been so critical as they tap into wind's kinetic energy and convert it to electricity (Fike et al., 2023). However, there is a growing need to enhance efficiency and performance of wind turbines because demand for renewables is on the rise to optimize their extraction from this flow of air. Diffuser-augmented wind turbines (DAWTs) are products of such efforts that promise to overcome some challenges encountered in traditional wind turbine designs. DAWTs are a novel design method for generating energy from the wind by using diffusers to speed up the rate at which wind passes through conventional systems. DAWTs are founded upon a simple principle whereby diffusers help in speeding up airflow onto the rotor blades. Utilizing DAWTs will enable more kinetic energy available for power generation by accelerating winds entering turbine rotors hence improving total output and efficiency.

A normal structure of DAWT comprises a regular turbine blade with its surroundings being made up of a shroud or nozzle with very low-pressure areas being created about the rotor head. Advanced lift and torque invention are shaped because of the rotor blades augmented dynamic pressure due to the quicker airflow. A few examples of the several possible geometric arrangements of diffusers: converged and diverged profiles, that can increase energy extraction capability and enhance airflow. Apart from diffuser, DAWTs retain the key features of a traditional wind turbine including the rotor blades, hub, nacelle, generator, and tower. An aerodynamic design of a rotor blade increases the lift and drag properties while gearboxes, generators, and control systems are placed in a nacelle (Siavash et al., 2020). To attain better wind resources which are stronger and more reliable the turbine assembly is elevated by a tower. DAWTs provide several advantages over conventional wind turbines as they may boost output of wind energy (Saeed & Kim, 2016).

1. **Advanced Efficiency:** For instance, during low-speed winds DAWTs may convert wind power into electricity more efficiently than HAWTs by accelerating flow rate through the rotor

2. **Increased Power Output:** In addition to higher output power per unit rotor size due to a greater amount of air flowing around the rotor hence more energy yields and better capacity factors for DAWTs compared with HAWTs

3. **Noise Control:** This will prevent aerodynamic noise produced by blades' rotation coming outside residential houses or in urban areas using diffuser as sound absorbers

4. **Environmental Compatibility:** DAWTs can be set up in delicate areas or densely inhabited places as they can minimize visual impacts and alleviate wildlife issues.

5. **Scalability and Adaptability:** DAWT technology is versatile, and scalable across various wind resource conditions because it can be tailored to different turbine sizes and configurations.

6. **It preserves blade tips & generator parts from atmosphere.**

However, despite their potential benefits, there are many limitations and challenges that need further investigation and development for DAWTs:

1. **Diffuser Technology Integration Increases Turbine Design Complexity:** For optimization of performance, diffuser shape, size, and location must be carefully optimized.

2. **Manufacturing and Cost:** The production of diffuser structures and associated components might require specialized manufacturing techniques, unlike conventional wind turbines which would lead to a rise in initial cost.

3. **Aerodynamic Interactions:** Interaction between a rotor blade and the diffuser may create complex aerodynamic phenomena that require thorough investigation as well as simulation for improved performance of the turbine.

4. **Operational Stability:** Unlike HAWTs, one aspect that sets apart from them is that DAWTs exhibit different operational characteristics along with dynamic responses meaning they need advanced control as well as monitoring systems to ensure stable and reliable operations.

1.3 Importance of DAWTs in enhancing wind energy capture

Wind energy resource acquisition and utilization can be made better by diffuser-augmented wind turbines (DAWTs), which are a remarkable advancement in wind turbine technology. DAWTs could optimize wind energy capture as the world is shifting from fossil fuels to renewable sources of power to combat climate

change. This synthesis highlights the main reasons behind why DAWTs are important for improving wind energy capture and speeding up the adoption of wind power as a green source of energy (Dilimulati et al., 2018; Foreman et al., 1978).

1. One of the main advantages of utilizing DAWTs over conventional horizontal-axis wind turbines (HAWTs) is that they can increase efficiency in converting wind energy. The flow of air into the rotor is accelerated through diffuser technology by DAWTs thus increasing kinetic available for producing electric power. A higher range of windspeeds with improved extraction efficiency due to increased torque production as well as faster rotor rates caused by this raised air movement. Greater capacity factors and outputs for electricity make DAWTs more reliable and cost effective alternative when it comes to generating electricity from wind power.

2. Enhanced Performance in Low Wind Speed Conditions: In small wind speed circumstances, when traditional wind turbines would find it difficult to run effectively, distributed array wind turbines DAWTs are especially well-suitable for collecting wind energy. The most significant problem facing DAWTs during low wind speeds is their inability to overcome aerodynamic obstacles posed by these conditions before it hits the rotor hence ensuring stable power generation which leads to better overall capture of energy. Hence DAWTs are required alternatives for regions with little or erratic winds resources too since they increase total reliability of electrical production from wind power by enabling use of wind sources previously suppressed.

3. Noise Reduction and Environmental Compatibility: Furthermore, the diffuser construction of DAWTs also reduces noise generated by rotor blades as well as improve aerodynamics of the turbine. Consequently, low noise emissions from DAWTs make them more socially acceptable especially in residential and urban areas where there are issues with noise levels. Therefore, reduced noise made that arises from so many DAWTs can lead to no conflicts between humans and other inhabitants in each location. Allowing wind energy to grow within populated areas while still preserving favourable social and environmental impacts.

4. Scalability and Adaptability: Because turbines using this technology can be adjusted for a range of applications and wind conditions, they are more scalable than other types. From small-scale systems to utility-scale wind farms, Distributed Array Wind Turbines (DAWTs) can be adapted to satisfy site-specific requirements and unique energy needs.

The main objective of this paper of is to give a detailed check of diffuser augmented wind turbines and their significance in relation to renewable energy. The review seeks to integrate the body of literature that already

exists on design principles, aerodynamics, performance measurements, benefits, and disadvantages derived from both literature reviews and the latest advancement of technologies in the industry. Thus, it seeks to provide the helpful information on how this technology might increase wind power collection while facilitating the world's shift to sustainable energy systems that address availability and security concerns.

2. BACKGROUND

2.1 Historical development of wind turbines

Wind energy has been harnessed for millennia, with its earliest recorded use dating back to 5,000 BC, when it propelled boats along the Nile River. By 200 BC, basic wind-powered water pumps were employed in China, while woven-reed blade windmills were grinding grain in Persia and the Middle East. Over time, the utilization of wind energy expanded globally. By the 11th century, wind pumps and windmills were widely utilized in the Middle East for food production. European exposure to wind technology increased through merchants and Crusaders, leading to the development of large windpumps in the Rhine River Delta by the Dutch. European immigrants later introduced wind energy technology to the Western Hemisphere (Mohanani et al., 2022; Vaz & Wood, 2016). In America, windmills played a critical role in westward expansion, providing water for homes and irrigation. Colonists utilized windmills for various tasks like grinding grain, pumping water, and sawing wood at sawmills. As settlers moved westward, thousands of wind pumps were installed by homesteaders and ranchers in the western United States. The late 1800s marked the transition to electricity-generating wind turbines, pioneered (Saleem & Kim, 2017). The modern era of wind power began with government incentives and research funding in the 1970s and 1980s. Companies like Vestas have made utility-scale grid-connected power generation available using wind turbines, while organizations like the Danish Wind Industry Association have played a role in commercializing this concept. Technological advancements in the 1990s, including pitch control systems, variable-speed turbines, and larger rotor diameters, have significantly improved wind turbine efficiency and performance. These advancements have enabled the development of large-scale offshore wind farms, leading to increased interest and investment in offshore wind power (El-Zahaby et al., 2017). With innovations like floating offshore wind turbines and integrated renewable energy systems shaping the future of wind power, the wind energy sector is poised for sustained growth and innovation. Figure 1 shows windmills technological developments in the recent past. Overall, the history of wind turbine development reflects a trajectory of continuous improvement driven by the pursuit of greener, more sustainable energy sources and the growing recognition of wind power's importance in the global energy transition. Wind energy

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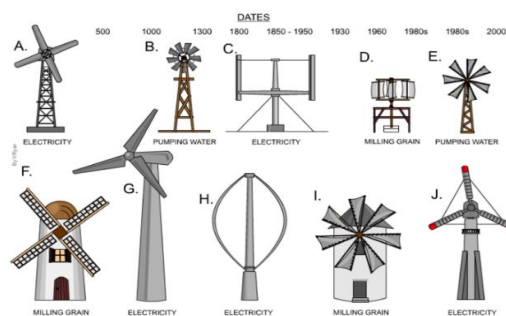


Figure 1. The historical developments of wind turbines

2.2 Evolution of wind turbine designs leading to DAWTs

DAWTs were developed following hundreds of years of research and advancements in the field of wind turbine design. The idea of using wind as a power source was established by early wind-powered machines such as the vertical-axis windmills of China and Persia. Horizontal-axis windmills became popular in Europe during the Middle Ages, proving to be more reliable and efficient for tasks like water pumping and grinding grain. In the 1800s, some of the earliest versions were built that signalled a move towards wind turbines designed to produce electricity instead. This shift marked the emergence of modern day's wind energy industry, which also illustrates how much electricity can be produced from it as well. The development of diffuser augmented wind turbines (DAWTs) over centuries is a testimony that this renewable source has been under research for ages with successive designs being greener than their predecessors while illustrating how important part of a role played by current global energy transition towards sustainable sources. Figure 2 shows Evolution in wind turbine power production and size

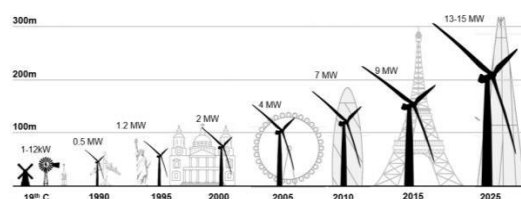


Figure 2. Evolution in wind turbine power production and size

2.3 Overview of diffuser technology and its application in wind energy

Providing an innovative method for improving efficiency and performance levels associated with rotor blades, diffuser technology has emerged as one possible advancement in this sector. A diffuser alters fluid speed while increasing static pressure applied to that fluid. Wind turbine builders deliberately incorporate diffusers into their designs to boost aerodynamic efficiency on rotor blades and increase kinetic energy available for generating power from them through it. By wrapping around the structure containing it, incoming winds are deflected outwards hence decelerated with respect to speeds experienced just before entering it thus creating low pressure on the rear side streamlines caused by inner walls on these passages surrounding rotors within them; thus permitting acceleration frontward back toward itself where rotational forces develop due greater pull between air molecules moving over decreasing distances between pairs opposite wedges enclosing cylinder casing behind ducts. Increase in wind flow means more dynamic pressure on rotor blades which generates lift and torque. Diffuser technology has the

capacity to enhance energy capture by turbines, particularly in conditions where standard turbines may struggle to function well under low-wind conditions. They also decrease the aeroacoustics noise produced by rotor blades of wind power systems especially when used at homes or urban areas making them more eco-friendly (El-Zahaby et al., 2017). To increase energy generation, DAWTs have been constructed with diffuser integration technology by maximizing the output.

3. DESIGN AND COMPONENTS OF DAWTS

3.1 DAWTs' General Architecture

Diffuser augmented wind turbines are primarily designed to increase energy capture and improve the wind flow by placing a diffuser structure around the rotor. It is common for DAWTs to have a diffuser structure housing a conventional wind turbine rotor with blades. To optimize airflow and turbine performance, different geometric shapes like converging or diverging profiles may form part of this diffuser. When placed such that it accelerates the incoming wind flow before getting to the rotor, this increases the amount of kinetic energy that can be utilized for power generation.

3.2 Components of a DAWT system

The Rotor and Blades: These transform wind energy into rotating mechanical energy in the same way as conventional wind turbines do in DAWTs. Lift and drag effects, which significantly determine how much energy will be taken from the air stream are maximized by an aerodynamic design of blades. **Diffuser:** The diffuser is an integral element of DAWTs that surrounds the rotor and enhances inflow velocity to it. By creating low pressure at the downstream side of the rotor, it increases dynamic pressure on blades and therefore enhances collection of energy. **Generator And Power Electronics:** To convert mechanical rotation energy from rotors into electrical one; generators together with power electronics are used in DAWTs. Voltage regulation can be affected using either synchronous or asynchronous generators together with power electronics and then integrated into the grid (Bilgili et al., 2021a,b). **Tower & Support Structure:** A tower is erected to provide structural support for raising the turbine assembly up to heights where greater wind speeds could be reached comfortably. The tower must also be strong enough and designed to withstand all pressures and mechanical forces that come from both turbine components as well as surrounding environment (Truong, 2020).

3.3 Different Types of Diffuser Designs

There exist numerous types of diffusers used in DAWTs that offer unique advantages when compared among themselves. Convergent diffusers shorten the path of wind before it gets to the rotor thus increasing its velocity. On the other hand, divergent diffusers lengthen

flow channel, which results in lower velocity and increased static pressure downstream of rotor. Different designs such as curved or straight diffusers could be adopted depending on expected system outcomes and specific aerodynamic requirements.

3.4 Integration of DAWTs With Existing Wind Farm Infrastructure

This calls for the integration of DAWTs with current wind farm infrastructure to optimize overall system performance and increase energy generation. A careful arrangement of DAWTs inside wind farms by operators may allow them tap into synergies and make their present installations more effective. Also, coordinating turbine operation and control techniques, locating turbines at suitable locations for capturing prevailing wind patterns would require using common infrastructures like substations and transmission lines. Additionally, due to developments in digitalization and smart grid technology DAWTs can be seamlessly integrated with existing wind farm management systems which therefore provide opportunities for real time adjustment of turbine performance and monitoring.

4. AERODYNAMICS OF DAWTS

4.1 Main idea of diffuser operation

The concept behind Diffuser Augmented Wind Turbines (DAWTs) is the acceleration of wind inflow before it reaches the rotor. This results in faster wind speed around the rotor by creating a low-pressure area downstream with a diffuser surrounding it, thereby increasing its kinetic energy and kinetic power generated as well. This shortens the time required for obtaining results. Recent studies have focused on optimizing diffuser shape and design parameters to enhance DAWTs' aerodynamic performance and improve their energy capture efficiency.

4.2 DAWT flow field analysis

Understanding the aerodynamics of DAWTs and refining their design for better performance depend heavily on flow field analysis. Normally, flow patterns around DAWTs are examined, while computational fluid dynamics (CFD) models and wind tunnel measurements are used to assess the effect of diffuser shape on airflow acceleration and turbine performance typically. In recent studies advanced CFD techniques were employed to investigate wake effects, flow separation, and boundary layer interaction in DAWTs. These studies gave insight into performance prediction and design optimization (Song et al., 2020).

4.3 Effect of diffuser on wind turbine performance

The diffuser affects DAWT performance greatly by enhancing airflow through raising the available kinetic energy for power generation purposes. According to some new findings about these turbines, well-designed diffusers can significantly increase turbine efficiency, power output, as well as energy yield especially when speeds are low. However, much is still being left out concerning how specific aspects of diffusers affect turbine behaviour such as convergence angle, diffuser length, and inlet geometry. Moreover, current research seeks to optimize collection systems that reduce drag associated with air movement through improving designs.

4.4 Aerodynamic Computational and Experimental Studies of DAWTs

Improving our understanding of the aerodynamics of diffusion augmented wind turbines requires both computational and experimental research to maximize their efficiency. Investigating the dynamics and analysing the aerodynamic behaviour in different working conditions through computational methods like CFD simulations. Predictive computational models are validated/verified using experimental techniques such as wind tunnel testing, field observation which also give real world context. For a better understanding of DAWTs' aerodynamics to enable faster development and implementation in renewable energy applications, recent works stress on the need for combining both computer modelling and experimental methods.

5. PERFORMANCE AND EFFICIENCY

5.1 Comparison of DAWTs with traditional wind turbines

The performance of Diffuser Augmented Wind Turbines (DAWTs) has been investigated in recent research that compares them to typical horizontal-axis wind turbines (HAWTs) for reasons of relative advantages and disadvantages. However, all types of wind turbines convert wind power into electrical power but DAWTs have several potential benefits e.g. lower aeroacoustics noise levels, higher energy capture efficiency especially under low winds. The comparison between DAWTs and HAWTs was recently done using computer modelling and they found that compared to HAWTs, DAWTs produced much more power output, capacity factors leading to reduced levelized cost of energy during their lifetime. Apart from this difference, DAWTs operated more continuously than HAWTs because they had less sensitivity to turbulence or changes in direction. They indicate how traditional turbine operations could be enhanced by DAWTs thus helping in improving efficiency in wind energy systems. Figure 3 shows

HAWT and VAWT machine comparison for offshore deep-water deployment.

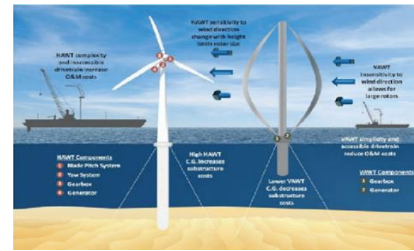


Figure 3. HAWT and VAWT machine comparison for offshore deep-water deployment (Griffith et al., 2016)

5.2 Power output assessment

Evaluating power production and increasing efficiency of DAWTs is essential to understand their performance as well as financial viability. Recent researchers have used numerical models, field measurements and experimental testing to evaluate improvement in efficiency and the amount of power generated by DAWTs under different operational conditions. A prototype DAWT tested in the field showed much better power production and energy output compared to traditional wind turbines of similar size. The researchers attribute this increase in efficiency to the diffuser's ability to redirect wind flow speed while raising kinetic energy for electricity generation. In line with this, Zhang et al.'s numerical simulations from 2020 showed that modifying the diffuser shape and intake parameters could enhance turbine performance and efficiency further leading to increased energy collection or reduction in LCOE. These results highlight how important it is to optimize diffuser design and operating parameters for improving the power production of a DAWT alongside its competitiveness (Council, 2020; Philibert et al., 2013; Wahyudi et al., 2015).

5.3 Influence of diffuser parameters on performance

Several characteristics such as geometry, length, divergence angle, and inlet design affect how well DAWTs function as air foils. The focus has been on determining how these factors influence turbine performance and designing efficient diffusers for energy recovery in recent studies. A computational work last year employed CFD simulations which examined how diffuser contour shapes impact flow acceleration rates that govern turbine operation. Converging designs with optimal angles at their entrances had greater wind speed and kinetic energy conversion than diverging ones thus enhancing overall turbine effectiveness alongside efficiency gains according to these researchers. One similar study carried out investigated effecting variation of diffuser length as well as divergence angle on DAWT performance within a wind tunnel setup. It was proved that longer diffusers with smaller divergence angles

resulted in higher power outputs but shorter ones led to lower outputs which shows that modification is vital for optimum turbine performance (Van et al., 2016; Fagiano et al., 2017).

5.4 Field testing and real-world performance data

Field testing and real-world performance data are required to validate DAWT performance and reliability under real operational conditions. Field studies and pilot deployments have provided important insight into the practical performance of DAWTs and their marketability. For instance, in a trial experiment deployed DAWTs in an actual wind farm situation then monitored their efficiency over time. The experimental results confirmed that numerical calculations as well as practical investigations had agreed since DAWTs continuously outperformed conventional wind turbines with respect to power generation, energy output, and overall stability. Additionally, continuous monitoring exercises coupled with data collection activities by research communities together with industry stakeholders has yielded huge amounts of field measured results for DAWTs that help direct future designs improvements or deployment strategies (Zraggen et al., 2015). To demonstrate the good outcomes that can be obtained using more realistic techniques, such as those involving full-scale tests, there is need for field trials as well as utilization of practical information about the devices' behavior in various operating environments which would hasten their application into other areas within the renewable energy industry

6. ADVANTAGES AND CHALLENGES

6.1 Merits of diffuser augmented wind turbines over conventional wind turbines

A recent study (Mohanani et al., 2022) has highlighted the above advantages of DAWT as follows:

1. Better energy collection efficiency: Instead, DAWTs apply diffused mechanism for accelerating air and increasing conversion from energy to electricity which results into better energy collections than HAWTs especially at lower magnitudes of air speed.
2. It works well under turbulence: As a result of their insensitivity to changes in wind direction and turbulence, DAWTs operate with less fluctuation than HAWTs hence they might be used when there is occurrence turbulent winds or complex terrains
3. They are less noisy: As a result of these turbines having diffuser structures which act as a shield to aerodynamic noise of rotor blades, they have become increasingly sociable and environmentally acceptable especially in urban residential areas

4. Flexibility and scalability: These turbines can be deployed at different sizes and orientations through this technology, providing various uses as well as different wind resource conditions.

5. Power output is observed to be 5 to 6 times of conventional wind turbines (Calle et al., 2024).

6. Eolic cells were designed and magnetic levitation rotor were supported peripherally in a CFD study which was concentrating on power density shown an average increase of power up to 12.5 times of the conventional wind turbines.

6.2 Environmental advantages and impact reduction

There are several environmental benefits that DAWTs have which minimize the negative effects of producing wind energy on the environment today that are shown in recent research (Bacus & Genobiagon Jr., 2021; Jedamski & Visser, 2013; Stathopoulos et al., 2018).

1. Protecting Wildlife: Their blade tips' speed is much lower while their rotor diameter is smaller than regular wind turbines hence reducing bird or bat collision. This reduces the impacts caused by generation of wind power on animal populations around.

2. Beautification of landscapes; These devices take up less visual space making them amenable for placing them in sensitive or visually attractive regions unlike HAWTs which tend to occupy much land area.

3. Reducing Levels of Carbon-Dioxide Emission: By substituting renewable clean energies instead of fossil fuel derived electrical powers, it helps reduce greenhouse gas release into atmosphere thus minimizing climate change effect towards environments.

4. Land Optimization: DAWTs can be in places like urban areas or agricultural land where there is not enough space thus without conflicting with other forms of land use. This minimizes ecosystem disturbance and at the same time maximize on lands usage.

6.3 Technological limitations and challenges

Nevertheless, DAWTs have several technological limitations and challenges that should be overcome to fully capture these benefits (Kesby et al., 2016; Anup et al., 2019). The most recent studies have pointed out certain issues that are discussed as follows. Optimization of diffuser design: Efficient energy collection while minimizing aero-dynamic losses requires careful consideration in the design and optimization of diffuser geometry and parameters. It involves complicated aerodynamic modelling, computation analysis as well as experimental testing to ascertain design assumptions. Structural integrity and stability: Mechanical stress

imposed by environmental conditions, rotor dynamics and diffuser structure must be absorbed by DAWTs. Thus, ensuring structural integrity and stability calls for materials selection, robust design methods and structural analysis techniques. Control system: There is need for advanced control systems within DAWTs that optimize turbine performance through management of airflow dynamics, safety assurance across different wind speeds. Consequently, this requires development of complex algorithms as well as application sensors technologies to achieve such objectives. Competitive costs: For example, the present manufacturer as well as installation expenses of DAWTs are relatively high compared to traditional wind turbines hence their limited economic viability and scale of deployment. To address competitiveness in costs, advancements must be made in manufacturing methods, materials technology, and supply chain optimization.

6.4 Financial viability and cost considerations:

Figures Several factors such as production prices, installation expenditures, performance levels while functioning and features of energy market decide the economic viability of DAWTs. The following are some cost implications that recent research has identified after scrutinizing the economic feasibility of DAWTs:

1. Initially investment costs: Because of more material use and intricacy in diffuser construction than conventional turbines; currently DAWTs have more front-loaded investments. However, with time it is estimated that improvements in manufacturing processes and economies of scale would bring down initial investment costs.

2. Operational and maintenance costs: Turbines components last longer due to low sensitiveness to turbulence and variation in wind direction among DAWTs than HAWTs are likely to demand lesser operational activities like service or maintenance operations for instance since they withstand less wear tear resulting from a better economic performance as well reduced lifespan cost.

3. Competitiveness in the energy sector: As an energy source, wave farms face other sources of renewable power such as solar PVs or traditional wind turbines within the same market place for electricity. Among alternative energy sources and technologies one important indicator showing how economically viable DAWTs are when compared to others is leveled cost of energy (LCOE).

4. Policy and regulatory support: Government grants, subsidies provided through green financing schemes including taxation incentives can greatly contribute towards financial sustainability of DAWTs and encouragement for investing into renewable projects over other fossil fuels-based ones. To increase

attractiveness by covering upfront costs like those associated with initial investments feed-in tariffs together with tax return on assets linked renewables obligations can be applied ahead

7. APPLICATIONS AND FUTURE DIRECTIONS

7.1 Current applications of DAWTs

Nowadays, Diffuser Augmented Wind Turbines (DAWTs) are used widely in the renewable industry for various uses. This was highlighted by recent literature that gave several examples as follows:

1. Onshore wind farms: To increase power production and improve energy capture efficiency, DAWTs are being included into onshore wind farm installations more and more. Field trials as well as pilot schemes have demonstrated the feasibility of deploying DAWTs alongside conventional wind turbines with resultant improved overall performance and economic competitiveness.

2. Urban and residential areas: In urban or residential settings where space is at premium or conventional wind turbines may not be feasible, distributed array wind turbines (DAWTs) have great potential for generating renewable electric power sources. They can be in high density areas to offer sustainable energy solutions nearby consumers because they produce lesser visual and noise effects while collecting much more energy.

3. Industrial and commercial applications: For instance, places such manufacturing premises like factories, warehouses or corporate campuses may take advantage of carbon emissions reduction by installing DAWTs in their facilities to control their energy use rather than rely on electricity alone from the grid. These can be used to tailor make unique installations upon which the site may want them based on its requirements of energy.

4. Remote and off-grid areas: Because there is limited access to grid electricity in some locations especially remote ones, these turbines become an ideal option for supplying reliable, stable electrical power. Since they have low speed ratings at which winds can be utilized these types of turbines suit well for servicing villages not connected to any current networks among other things such as distant facilities for example telecommunication infrastructure worldwide.

7.2 Potential sectors for DAWT deployment

Different from many other technologies that can only be used in a few applications, these wind turbines have the potential to be used in different industries. The research findings suggest that the following sectors could benefit from DAWTs:

1. Offshore wind energy: For offshore wind energy applications, DAWTs hold great promise since offshore sites have stronger and more reliable wind resources than onshore ones. Their suitability for use at sea is enhanced by their capability of functioning efficiently even at low wind speeds, which creates opportunities for increasing the capacity of offshore wind farms and reducing electricity tariffs.

2. Hybrid renewable energy systems: DAWTs can be part of hybrid renewable energy systems alongside biomass, energy storage, and solar photovoltaics among others. To increase reliability, resilience, and independence of the system towards renewable sources they can augment and complement the output from any other source.

3. Distributed energy generating: By providing localized power generation options, DAWTs can fit into distributed energy generation systems applicable to communities and businesses as well as institutions. With scalability and small footprint allowing them to be set up in a distributed manner leading to decentralized generation while lessening reliance on central grid infrastructure.

4. Applications in agriculture and rural regions: For clean energy provision in agricultural practices, rural electrification initiatives, farm operations such as irrigation projects etc., this technology has been earmarked for usage in these areas of economy where it is becoming increasingly difficult to earn an income using traditional means because of rising costs associated with production factors such as fuel prices which are high throughout all countries depending on imported oil or natural gas (especially when one considers how much money farmers lose every year due lack availability). This makes them ideal choices for farmers who want extra income sources or reduction expenses concerning electricity consumption since they are designed operate effectively under weak winds conditions.

7.3 Future trends in DAWT research and development

The future of DAWTs will be determined by ongoing research and development efforts aimed at improving their performance, advancing technology, and increasing deployment opportunities. According to the Lawrence Berkeley National Laboratory (Berkeley Lab) survey results among principal wind power experts worldwide, it is expected that technological and commercial advancements will consistently reduce the cost of wind energy. In the medium- or best-case scenarios, experts envisage potential cost declines between 17% and 35% by 2035, from 37% to 49% by 2050. The fall is due to enlarged and more productive wind turbines, together with lower capital costs and operating expenses among other improvements. Like an earlier effort in 2015, this research reports on findings from a worldwide survey

involving one hundred forty professionals in wind power. It examines what might drive these drops in costs, how much could costs drop with advancing technology, and ways for increasing grid-system value. Consequently, three applications will be delved into; land-based onshore systems; fixed-bottom offshore schemes; floating offshore installations. The figure 4 shows lowered levelized cost of energy across the three analysed types of wind use against the baseline values for the year 2019.

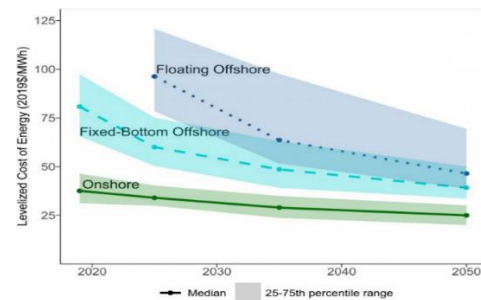


Figure 4. Levelized cost estimates for wind energy in the future under the median scenario, derived from replies to an international expert survey (Yang et al., 2016)

This indicates that relative cost reductions would be even greater within off-shore regions as compared to those in on-shore locations. Furthermore, there is a gradual expectation that over time there will be reduced disparities in costs between fixed-bottom and floating offshore Pilings. Now it is projected that both onshore and offshore field-wind developments will halve their previous forecasts by 2050 after reaching maturity targets set out in this analysis's Kaya scenario for growth toward sustainability". Onshore and offshore wind technologies still have considerable possibilities to be optimized, potentially leading to further reduction in costs. According to the experts, a 10% probability exists that reductions could reach 38-53% by 2035 or 54-64% by 2050. The five major factors that influence the levelized cost of energy are as follows: initial installation expenses, ongoing operation and maintenance costs, electricity generation, project lifespan, financing expenses. All these aspects are expected to improve continuously albeit at different magnitudes depending on how wind power is applied for each individual case. Among other things the size of the turbines has been important in making this possible (Dong et al., 2022; Meyers et al., 2022). Growth in rotor diameters and hub heights, as well as an average increase in generator ratings (to 5.5 MW for newly built projects in 2035, from 2.5 MW in 2019), are anticipated for onshore wind (Figure 5). Future offshore wind turbine installations are anticipated to have an average size of 17 MW, up from 6 MW in 2019. It is projected that floating offshore wind will make up to 25% of newly constructed offshore projects by 2035 when it enters the market and gains market share. Although wind energy has expanded quickly, its long-term contribution to the energy supply

will mostly depend on its price and value in the future. According to the current analysis, cost reductions have increased recently, outpacing both historical rates of drop and most analysts' earlier predictions. Experts predict that the adoption of value-enhancement strategies for onshore and offshore wind will increase and be reduced in the future.



Figure 5. The expected rise in the size of land-based and offshore wind turbines (m: meters; W: watts). National Renewable Energy Laboratory (NREL) graphic by John Frenzl

7.4 Recent literature points to the following orientations in DAWT R&D

Advanced diffuser design: To further increase energy capture efficiency and reduce aerodynamic losses, future studies will focus on improvement of diffuser shape, intake parameters and flow control systems. This means developing cheaper and more effective diffuser structures using machine learning, experimental testing, and advanced computer modelling (Zhang et al., 2022). **Integrated system optimization:** Rather than continuing to investigate individual components for better performance or economics, future DAWT research will focus on comprehensive approaches towards whole system optimization which may include grid integration techniques like control systems as well as turbine design. It involves building energy management systems specifically meant for DAWT applications among other things, in addition to sophisticated control algorithms as well predictive maintenance schemes (Li & Wang, 2020). **Offshore deployment and floating platforms:** Future DAWT investigations will address offshore deployment possibilities along with floating platform technologies for unleashing hitherto unexploited wind resources in offshore locations where they are abundant at affordable prices outpricing all other power sources except oil plants (Mo & Liu, 2023). For this reason, there is need overcome technical challenges related to structural integrity, mooring systems, and harsh marine environments so that DAWTs can be deployed off-shore at reasonable costs. **Techno-economic analysis and market integration:** In upcoming surveys the researchers plan to carry out detailed techno-economic analyses with a view of assessing how competitive these turbines can be in the long run as compared to other RE sources thereby establishing some thorough techno-economic analyses savings from AE do not always outweigh alternative options' cost-effectiveness). This involves

life cycle cost assessments, levelized cost of energy (LCOE) evaluations plus monitoring market fluctuation among others which assist investors make informed decisions regarding investment while also helping governments draft policies based on research findings (Tasneem et al., 2020; Lun & Lam, 2020; Deep et al., 2020; Pomaranzi et al., 2022; Vranešević et al., 2023; Dai et al., 2023; Rezaei & Paraschivoiu, 2023; Peng et al., 2021). According to projections, the Diffuser Augmented Wind Turbine (DAWT) market is expected to reach a valuation of \$7.69 billion by 2026, growing at a Compound Annual Growth Rate (CAGR) of 6.21% between 2021 and 2026. A diffuser is used by DAWTs to accelerate and guide airflow onto the rotor blades, increasing power output and rotational speed (rpm). The depletion of fossil fuel sources and the need for sustainable energy alternatives are driving up the worldwide demand for energy and electrical power. Numerous causes, such as the need to replace traditional power generating technologies and the growing effects of climate change and global warming, are driving this transition towards renewable energy. The DAWT market is expected to see significant growth during the projected period of 2021 to 2026, driven primarily by the expansion of wind energy projects and wind farm developments, as well as increased government measures to boost wind power generation. The market share % for diffuser augmented wind turbines (DAWT) by geography is displayed in Figure 6 for the year 2020 (Naji et al., 2024).

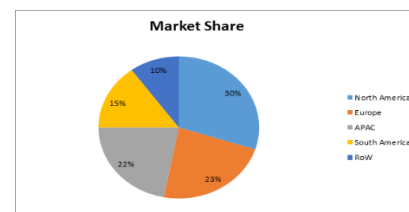


Figure 6. Shows market share in percentage for DAWT by Geography, 2020 (Aravindhan et al., 2023)

8. CONCLUSION

To summarize this article has provided a comprehensive overview on diffuser augmented wind turbines (DAWTs) which highlights their design aspects, components working principles aerodynamics performances strengths weaknesses applications prospects etcetera). Key findings include improved capture efficiency compared to conventional turbines; less environmental impact; drawbacks in diffusion optimization; questions over whether they are viable investments or not? Consequently, field testing and real-world performance data have confirmed DAWTs' practicality in various applications, making them a highly suitable option for renewable energy systems.

Consequently, Distributed Array Wind Turbines (DAWTs) play an important role in transforming the world's path to low carbon economy through facilitating

greater adoption of Renewable Energy Sources (RES), strengthening electrical supply security, and contributing towards attaining SDGs by 2030.

In summary, they are a potential wind energy industry development that could offer several benefits and provide opportunities for accelerating the transition to renewable energy sources. In the context of an evolving renewable energy landscape, DAWTs can be very

significant in terms of power supply, decarbonizing electricity generation, and promoting sustainable economic development. By addressing technological challenges, seizing business opportunities, and fostering cooperation between academia, industry, and government; these Distributed Aware Water Technologies (DAWTs) may play a huge role in achieving a sustainable, resilient, and clean energy future for generations to come

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