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Application of hybrid Darrieus–Savonius turbines with dimpled blades at the offshore platform for sustainable energy

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Abstract. In support with Abu Dhabi 2050 Vision to become carbon neutral and a world leader in renewable energy, this research examines the use of hybrid Vertical Axis Wind Turbine (VAWT) with surface dimples for offshore energy generation. The simulation phase utilized ANSYS Fluent with a *k-ω* SST turbulence model to assess aerodynamic behavior across traditional H-rotor, hybrid, and dimple-enhanced configurations. Conducted at wind velocities from 3 to 10 m/s and rotational speeds of 250 and 300 RPM, results showed that the dimpled hybrid turbine achieved superior performance metrics—reducing turbulent kinetic energy by up to 45%, delaying flow separation, and improving wake stability. These improvements directly contributed to higher lift-to-drag ratios and smoother airflow around the blades, particularly under rotational conditions typical of offshore environments. Parallel experimental tests involved a modular VAWT hybrid turbine equipped with adjustable turbine dimensions and NACA 0021 blades featuring circular dimples (10 mm diameter, 4 mm depth, Dimple Ratio = 0.4). Under a controlled wind speed of 7.5 m/s, the optimal setup (2.5 m height, 1 m width) achieved a daily energy output of 7.4 kWh and a peak performance coefficient (Cp) reaching 27.5% of Betz's theoretical limit. Smoke visualization confirmed the improved flow attachment and delayed boundary layer detachment over dimpled surfaces, consistent with the CFD findings.

Introduction

Wind energy deployment has seen substantial growth worldwide, with numerous countries investing in both onshore and offshore wind farms. Onshore wind farms are typically easier to establish and maintain, whereas offshore wind farms, though more challenging and costly to install, can harness the stronger winds available over the ocean, often resulting in higher energy yields. Investments in wind energy technology have led to more efficient turbine designs, better wind forecasting methods, and improved grid integration, thereby reducing costs and enhancing the feasibility of wind energy as a reliable power source. Moreover, wind energy plays a crucial role in many nations' strategies to achieve energy security and reduce greenhouse gas emissions in line with international climate targets [1-2]. Wind energy stands as a vital component in the global renewable energy portfolio, offering a viable solution to the escalating energy demands while concurrently addressing environmental concerns.

Wind energy has emerged as a pivotal component of the contemporary energy landscape, driven by its multifaceted benefits encompassing environmental and economic dimensions. Amidst the backdrop of heightened global awareness concerning climate change, the transition to renewable energy sources, particularly wind energy, assumes a paramount significance. This work underscores the paramount importance of wind energy in the prevailing energy paradigm through a comprehensive examination of various facets [3]. Firstly, wind energy distinguishes itself

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through its capacity for carbon emission reduction, as it constitutes a clean and environmentally friendly power source, devoid of greenhouse gas emissions during its operation. In this context, it assumes a central role in ameliorating the adverse effects of climate change, given its substantial capacity to curtail carbon emissions when substituted for conventional fossil fuel-based energy sources [1]. Secondly, the renewable and sustainable nature of wind energy merits emphasis. Wind, as a resource, stands as an inexhaustible asset, differing markedly from finite fossil fuels that are subject to price volatility. Wind energy thereby offers a sustainable solution to address the burgeoning global energy demand, ensuring a more stable and predictable energy supply [2]. Moreover, the harnessing of wind energy has the potential to enhance a nation's energy independence by reducing dependence on imported fuels. The distributed nature of wind energy further enhances energy security by mitigating the risks associated with centralized energy production. Thirdly, the economic dimension of wind energy cannot be understated. The wind energy sector has burgeoned into a significant employer, stimulating economic growth through the generation of employment opportunities in manufacturing, installation, maintenance, and associated services [4]. This sector also lends support to local economies, with particular significance in rural areas where wind farms are frequently situated. Furthermore, the perpetual technological advancements in wind turbine design, wind resource assessment, and grid integration have consistently bolstered the efficiency, reliability, and cost-effectiveness of wind energy [4]. Consequently, wind energy has grown increasingly appealing as an investment option for both private and public sectors. Lastly, wind energy is pivotal in supporting nations in their pursuit of renewable energy targets and their adherence to international climate commitments, making it a tangible manifestation of a country's dedication to a low-carbon future.

Chegini et al. [5] conducted a study on the efficiency enhancement of the Darrieus – Savonius hybrid wind turbine with the addition of deflectors in which various parameters – deflector position, deflector angle, and deflector distance – are scrutinized. They obtained greater power coefficients when the deflectors were positioned on the front and side upper portion of the rotors than those located on the front and side lower portions. In addition, by reducing the vertical distance between the upper deflectors and the hybrid rotor, the front deflector angles achieved 30° angle which promoted the airflow acceleration within the turbine upwind areas. By keeping the airflow constant at intermediate angles, the airfoil produces a smooth pressure gradient. However, as the AOA approaches a critical value, flow separation occurs along the trailing edge, creating turbulent eddies and increasing the turbulent kinetic energy and vorticity. This separation results in a large loss of lift and a sharp rise in drag, which is typically shown in pressure contours as erratic, chaotic low-pressure patches near the trailing edge [5].

Furthermore, it is worth noting that the passive flow control methods utilized on these turbines include the use of dimpled surfaces near the turbulent boundary layers. Dimples have been studied for a long time due to their improvement in heat transfer, and their effect of minimizing turbulent skin friction with increasing pressure drag. They alter the boundary layers of incoming airflow over the blade surface once laminar flow transitions to turbulent flow; also, they create small vortices that efficiently and effectively delay the onset of laminar flow separation [6]. Having said that, the hybrid turbine integrated these qualities and possible performance enhancements of Savonius and Darrieus turbines. Up to 14 percent increase in power and torque coefficients are extracted because of implementing both passive and active controllers, which makes the hybrid turbine highly adaptable at varying environment and load conditions [7].

The integration of wind energy into offshore oil and gas platforms represents not only a step towards cleaner and more sustainable energy sources but also constitutes a holistic approach to addressing an array of contemporary challenges encompassing climate change, energy security, and economic development. Considering these considerations, the significance of wind energy within the current energy landscape cannot be overstated [2]. Computational simulations and

experimental validation combination are used to focus on the flow separation mitigation, energy absorption efficiency maximization and maximum aerodynamic efficiency in the marine settings with low-moderate wind velocities. The small, high-omni construction of the hybrid turbine is perfectly able to handle offshore platforms where the limited space and maintenance difficulties do not permit the use of traditional horizontal axis schemes. The turbine's modularity, ease of manufacturing, and low-maintenance design offers strong potential for deployment on offshore oil platforms (Figure 1), desalination plants, and remote maritime stations. This work contributes to the practical advancement of offshore wind technologies and aligns with national objectives for clean energy integration, offering a scalable solution for sustainable electricity generation in the United Arab Emirates and beyond.

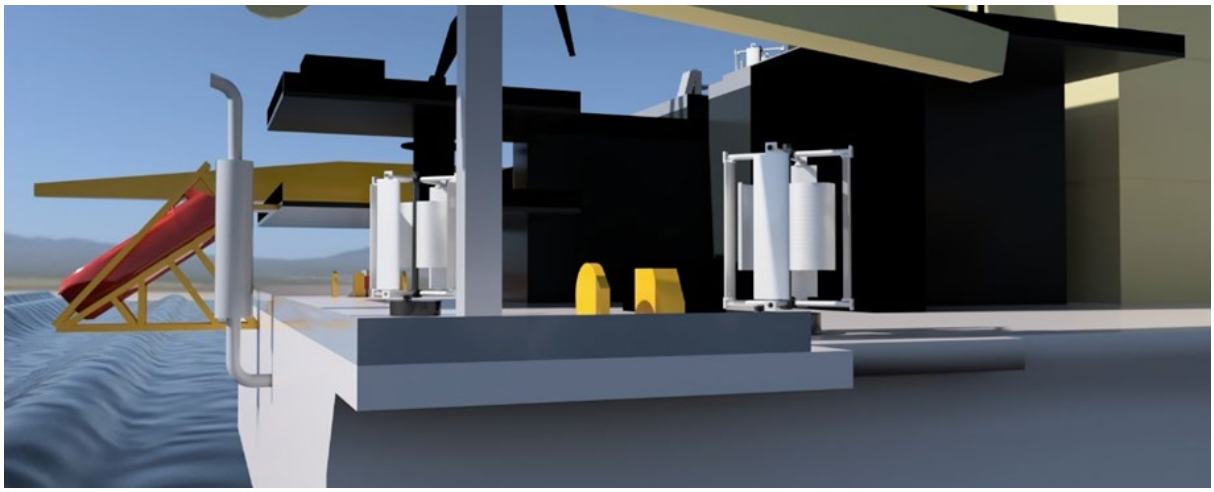


Figure 1. Side Profile Showing Modular Integratin of VAWTs on the Platform Edge

Methodology

Many existing CFD studies focus on isolated or tandem turbine wake dynamics, with limited exploration of large-scale interactions in multi-row wind farms. In real offshore settings, wake merging, secondary turbulence, and extended recovery zones significantly impact power output and structural loads. Simulating turbine arrays with realistic spacing and atmospheric inflow using coupled CFD–GFD models could better capture compound wake behaviors for improved wind farm layout design. The CFD findings underscore the critical role of vortex dynamics and flow separation in the aerodynamic efficiency and wake structure of VAWTs, providing insight for rotor design and performance optimization under real-world offshore and tilted operating conditions [8].

The unstructured mesh was applied to keep the total number of elements within a reasonable range, thus reducing CPU time to calculate the solution. The tetrahedral volume mesh tailored to concentrate resolution where the flow gradients are highest. The number of element is 2800420, with 517082 nodes. The part (a) in Figure 2 shows the coarse tetrahedral cells fill the far field enclosure, keeping the total cell count down, around the rotor a spherical refinement region (highlighted in red) dramatically reduces cell size, ensuring wakes and blade tip vortices are well resolved. Part (b) is the rotating zone, here the cell sizes shrink by an order of magnitude. The rotating zone moves with the blades with sliding mesh, so the mesh quality around the hub and blade roots remains uniform throughout the simulation. Finally, the part (c) is the blade surface detail. The skewness is 0.76 and orthogonal quality is 0.2. The blade airfoil is covered with a a dense triangular surface mesh that captures its curvature. Those surface triangles are extruded into tetrahedra in the volume, giving you high fidelity of pressure and velocity gradients right at the wall.

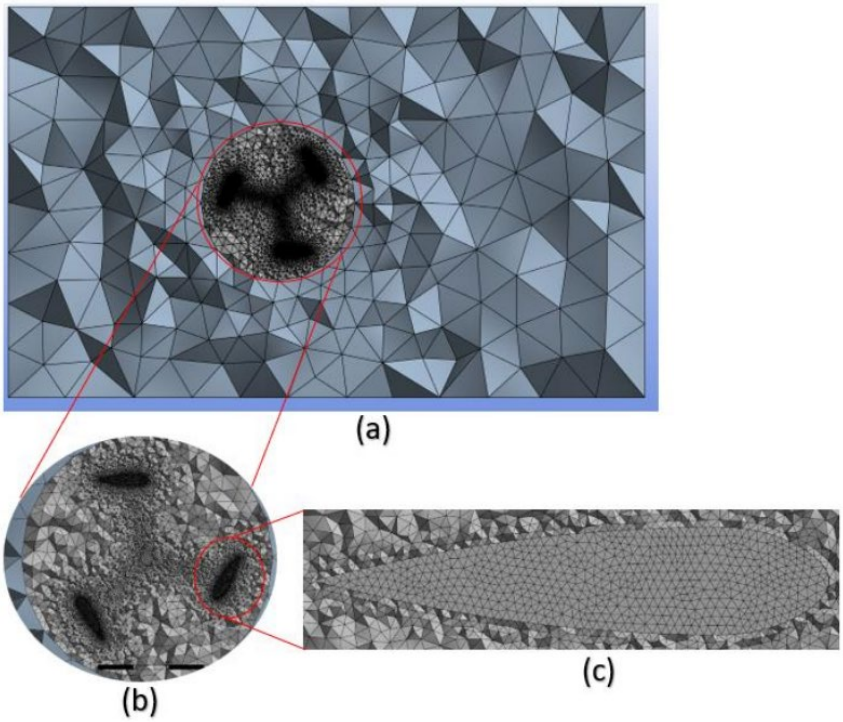


Figure 2. Meshing for the H rotor VAWT

The simulation solves the unsteady Reynolds-averaged Navier–Stokes (U-RANS) equations with the *k-ω* shear-stress-transport (SST) turbulence model. Velocity and pressure are coupled and solved using the Coupled algorithm, and a second-order upwind scheme is employed for momentum, turbulent kinetic energy, and dissipation-rate discretization. Boundary conditions consist of a velocity inlet at the upstream face, a pressure outlet downstream, and a no-slip wall on the airfoil surface. All other settings—viscous model setup, solution initialization, timestep selection, data auto-saving, and solver controls—are identical to those used in the 2D H-rotor base case.

The current work examined the aerodynamic performance of Vertical Axis Wind Turbine (VAWTs) through a detailed Computational Fluid Dynamics (CFD) approach, focusing on the comparative behavior of H-rotor, Hybrid Darrieus-Savonius, and dimple Savonius configurations. 2D simulation was performed to see the aerodynamic behavior of the H-rotor turbine under 5 different inlet velocities (3 m/s, 4 m/s, 5 m/s, 7 m/s, and 10 m/s) and 2 different angular velocities 250 RPM and 300 RPM. Later the study was the selection and validation of the *k-ω* SST turbulence model, which successfully captured the complex transient behavior inherent in VAWT simulations. This model's strength in accurately predicting flow separation, reattachment, and near-wall turbulence made it an ideal choice for this application, ensuring high-fidelity results. 3D analysis was initially performed on the base case which is the H-rotor 3 bladed wind turbine. hybrid turbine configurations in terms of flow stability and energy extraction. Additionally, comprehensive contour plots, vector fields, and streamlines provided an in-depth visualization of the velocity, pressure, and vorticity fields across different turbine designs. These visualizations confirmed that the dimpled savonius configuration minimized vortex shedding and promoted uniform flow behavior in the wake zone—a crucial factor for both energy efficiency and reducing fatigue-induced structural degradation.

Figure 3 shows the geometry of the Hybrid Darrieus and Savonius wind turbine, which is finalized model used in the study. The Savonius rotor is located at the center of the Darrieus rotor.

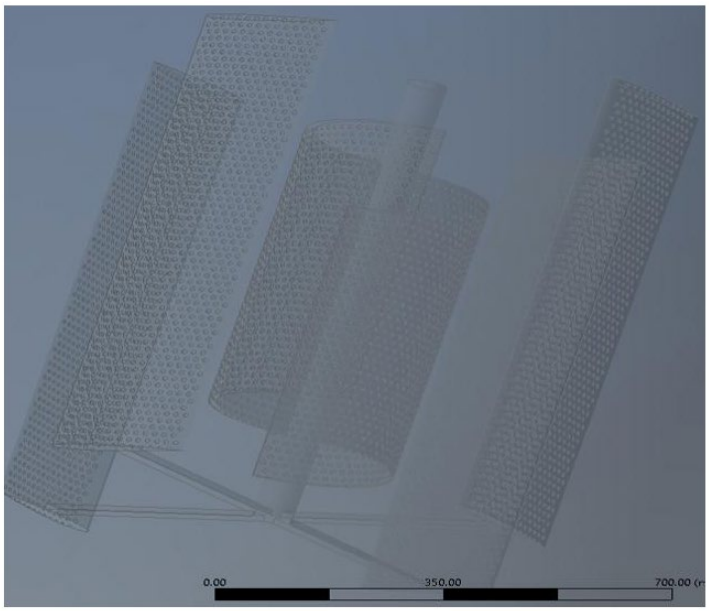


Figure 3. Geometry of Hybrid Darrius-Savonius (with dimples)

Results and Discussions

It was observed that as the inlet velocity increases from 4 m/s to 7 m/s, the flow behavior becomes more dynamic, characterized by enhanced flow acceleration, more significant wake formation, and a slight shift in the critical point of flow separation. With higher velocities, the system experienced increased turbulence and energy dissipation, as observed in the simulations. 2D results and simulation steps created a base for the 3D analysis and goal of the study which was to improve the wind turbine viability in low-speed regions. In the first, the study was about the hybrid model. By combining the lift-based advantages of Darrieus turbines with the drag-based benefits of Savonius rotors, the hybrid model demonstrated enhanced self-starting behavior and better wake management, even at low angular velocities. The hybrid model's ability to generate positive static torque across the entire azimuthal range allowed it to maintain consistent rotation without the need for external startup mechanisms—a critical requirement for standalone renewable energy systems in remote or distributed installations. Secondly, the study highlighted the effectiveness of passive flow control via dimpled blade surfaces. Dimples borrowed from biomimetic and sports engineering principles—proved capable of introducing micro-vortices that energize the boundary layer, thus delaying flow separation and reducing wake-induced turbulence. This effect was especially pronounced at 300 RPM, where the dimpled hybrid turbine exhibited reduced turbulent kinetic energy near the blade surface and in the downstream wake. These aerodynamic benefits directly translated into higher lift forces, smoother pressure distributions, and an increased lift-to-drag ratio.

Results discovered that the hybrid configuration outperformed the traditional H-rotor in both self-starting capability and aerodynamic stability. Moreover, the implementation of dimples on the blade surfaces led to significant improvements in airflow behavior—delaying flow separation, reducing recirculation zones, enhancing pressure gradients across the blade surfaces, and contributing to a more stable and efficient wake recovery. The velocity and turbulence plots show that the 3D Savonius turbine with dimples had the most chaotic airflow. The Turbulent Kinetic Energy (TKE) reached peaks of around 14.5 m^2/s^2, especially near the returning blade, where the flow reversed and swirled strongly. Compared to the other turbines, this setup created a much larger and messier wake. The H-rotor 3-bladed turbine, which is lift-based, had a much smoother flow. Its TKE values were much lower, around 4–6 m^2/s^2, with only small flow separation, and the

hybrid turbine, which combines Darrieus and Savonius features, showed moderate turbulence, with TKE values up to 9 m^2/s^2. Economic viability was assessed through a Levelized Cost of Energy (LCOE) analysis, which yielded a value of 0.203 AED/kWh—significantly below the national grid average of 0.30 AED/kWh. Figure 4 shows the conceptial image of dimpled VAWT's application on the offshore platform.

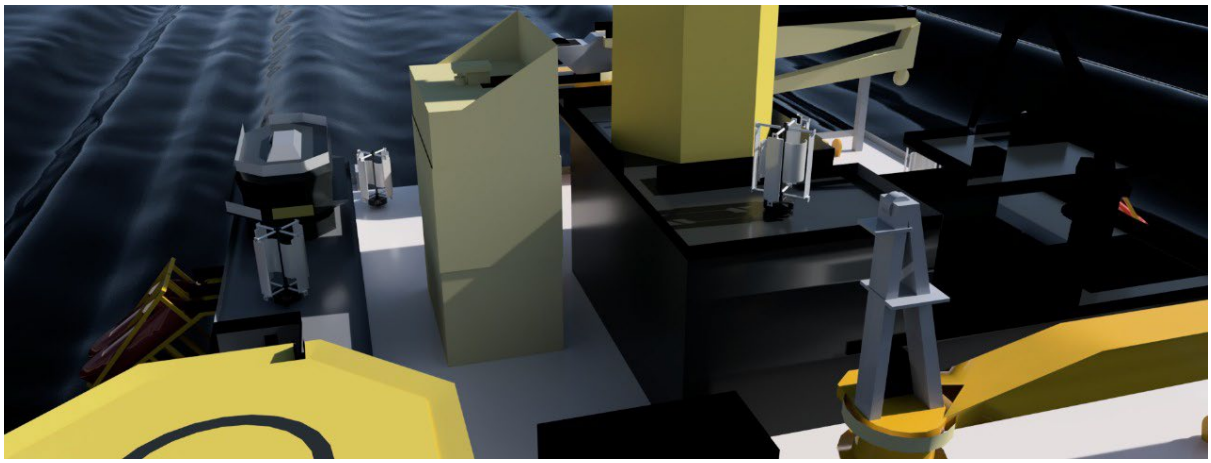


Figure 4. Top Deck View of Offshore Platform with Dimpled VAWTs

Conclusion and Future Work

Finally, increasing the RPM intensified flow interactions across all designs, with the most notable effects observed in the dimpled Savonius turbine. This underscores the sensitivity of drag-based turbines to changes in rotational speed and highlights the effectiveness of passive flow control methods, such as dimples, in altering aerodynamic behavior. These findings enhance the understanding of VAWT performance and support future design improvements, particularly for applications in urban or low-wind environments. Overall, the research validated the potential of dimple-based passive flow control and introduced a hybrid rotor design to achieve optimal performance. Together, the simulation and experimental results validate the aerodynamic and economic feasibility of the proposed system. This work contributes to the practical advancement of offshore wind technologies and aligns with national objectives for clean energy integration, offering a scalable solution for sustainable electricity generation in the United Arab Emirates and beyond. Future research could integrate structural analysis (via ANSYS Mechanical or Abaqus) with CFD to assess fatigue life, vibration modes, and resonance frequencies. This is particularly important for optimizing the mechanical reliability of the hybrid blades under cyclic aerodynamic loading. Future research and development in these areas could lead to more reliable, high-performing wind energy systems that can operate effectively in a wider range of environments and conditions.

References

[1] M. S. Khan, M. Alavi, N. Mohan, A. Azeez, A. Shanif and B. Javed, "Wind Turbine design and fabrication to power street lights," in 2017 International Conference on Mechanical, Aeronautical and Automotive Engineering, Malacca, 2017. https://doi.org/10.1051/matecconf/201710808010

[2] R. Kumar, K. Raahemifa and A. S. Fung, "A critical review of vertical axis wind turbines for urban applications," Renewable and Sustainable Energy Reviews, vol. 89, pp. 281-291, 2018. https://doi.org/10.1016/j.rser.2018.03.033

[3] Al Qubaisi, Abdulla Ahmed, Sharul Sham Dol, Mohammad S. Khan, and Abid Abdul Azeez. "Feasibility study and design of floating offshore wind turbine farm in United Arab Emirates." In

2018 Advances in Science and Engineering Technology International Conferences (ASET), pp. 1-5. IEEE, 2018. https://doi.org/10.1109/ICASET.2018.8376800

[4] L. A. M. E. Carlin PW, "The history and state of the art of variable speed wind turbine technology," National Renewable Energy Laboratory, pp. Technical report: NREL/TP-28607, 2001.

[5] S. Chegini, M. Asadbeigi, F. Ghafoorian and M. Mehrpooya, "An investigation into the self-starting of darrieus-savonius hybrid wind turbine and performance enhancement through innovative deflectors: A CFD approach," Ocean Engineering, vol. 287, no. 2, 2023. https://doi.org/10.1016/j.oceaneng.2023.115910

[6] Abdullah, Abdul Qader, and Sharul Sham Dol. "Aerodynamic investigation and design of dimpled-surface airfoil for UAV propellers." In 2020 Advances in Science and Engineering Technology International Conferences (ASET), pp. 1-5. IEEE, 2020. https://doi.org/10.1109/ASET48392.2020.9118346

[7] Pervaiz, Salman Shahid, Sharul Sham Dol, Abdulla Khamis Alhassani, Mohanad Tarek Abdallftah, and Mohammed Fares. "Numerical Modelling and Performance Optimization of a Vertical Axis Wind Turbine." In Energy and Environment in the Tropics, pp. 359-374. Singapore: Springer Nature Singapore, 2022. https://doi.org/10.1007/978-981-19-6688-0_22

[8] O. Kouaissah, N. Franchina and N. Franchina, "3D CFD study of a DeepWind demonstrator at design, off-design and tilted operating conditions.," Energy, vol. 291, p. 130313, 2024. https://doi.org/10.1016/j.energy.2024.130313