To VAWT, or not to VAWT: Feasibility of Vertical-Axis Wind Turbine Sublayers

Elena Hanabergh, Trevor Hunter, Steven Van Overmeiren

Arizona State University

MEE 441/579 Wind Energy

Dr. Ronald Calhoun

December 12, 2024

Abstract

This study evaluates the feasibility of integrating vertical-axis wind turbines (VAWTs) as sublayers within horizontal-axis wind turbine (HAWT) farms to enhance overall efficiency and energy density. Using theoretical analysis and numerical modeling, the research compared traditional HAWT-only farms with hybrid HAWT-VAWT systems, focusing on wake effects, energy capture, and economic implications. Despite some reduction in VAWT energy production within HAWT wakes, the hybrid system demonstrated higher overall annual energy production (AEP) and energy density. The study projected a 24% increase in farm-scale annual energy production for the hybrid model, translating to significant economic benefits. These findings suggest that hybrid HAWT-VAWT farms could improve wind farm efficiency, warranting further investigation into their optimization and implementation.

Keywords: Wind energy, wake interactions, vertical-axis wind turbines (VAWTs)

To VAWT, or not to VAWT: Feasibility of Vertical-Axis Wind Turbine Sublayers

Renewable energy is expected to play a significant role in meeting future world energy needs while mitigating climate change and environmental pollution. Wind energy, in particular, has seen rapid growth, with global installed capacity increasing from 24 GW in 2001 to over 743 GW by the end of 2020 (Dabiri 2020). This dramatic expansion is driven by wind energy's potential as a clean, abundant resource that can significantly contribute to electricity generation in many regions.

Achieving the ambitious growth targets set by many countries will require the design and implementation of highly effective wind farms to maximize power generation from available wind resources. Conventional wind farms utilizing horizontal-axis wind turbines have become the industry standard, benefiting from decades of technological advancement. However, as the most favorable onshore sites become saturated and offshore development accelerates, there is increasing interest in novel wind farm configurations that could potentially boost power density and overall farm efficiency.

One such concept gaining attention is the integration of vertical-axis wind turbines (VAWTs) as a sublayer within HAWT-based wind farms. This hybrid approach aims to leverage the complementary characteristics of the two turbine types - with VAWTs potentially able to extract additional energy from the complex wake flows generated by upstream HAWTs. While VAWTs have seen limited commercial deployment to date, their omnidirectionality and simpler generator systems make them an intriguing option for this application.

Exploring VAWT sublayers is motivated by the desire to increase the overall power output and energy density of wind farms within a given footprint. By utilizing the lower-speed, turbulent near-ground wake region that is often "wasted" in conventional farms, a VAWT sublayer could theoretically boost total energy capture. Additionally, the wake interactions between HAWTs and VAWTs may benefit wake recovery and farm-scale flows.

However, this hybrid concept remains largely theoretical at present. While some small-scale experiments and simulations have been conducted, there are currently no commercial implementations of VAWT sublayers in utility-scale wind farms. The concept represents an under-researched topic area that requires significant investigation to determine its true feasibility and potential benefits.

This report aims to evaluate the current state of research regarding VAWT sublayers and hybrid wind farm configurations, examining the theoretical basis, potential advantages, and key technical and economic challenges that must be addressed. By synthesizing existing literature and identifying critical knowledge gaps, we seek to comprehensively assess this novel wind farm concept for wind energy developers and researchers.

Review

Governing Equations/Math

The aerodynamic behavior of vertical-axis wind turbines differs significantly from that of horizontal-axis turbines, particularly in terms of wake characteristics. For HAWTs, the wake can be reasonably approximated using momentum theory and modeled as a continuous stream tube with a velocity deficit. The streamwise velocity in the far wake of a HAWT can be described by:

$$\frac{U(x)}{U_\infty} = 1 - \frac{2a}{(1+2kx/D)^2} \tag{1}$$

Where *U(x)* is the wake velocity at distance *x* downstream, U_∞ is the freestream velocity, *a* is the axial induction factor, *k* is the wake expansion coefficient, and *D* is the rotor diameter.

In contrast, VAWT wakes exhibit more complex, three-dimensional structures due to the cyclic variation in the angle of attack experienced by the blades. The near wake of a VAWT is characterized by pairs of counter-rotating vortices shed from each blade, which eventually break down and merge in the far wake. While no simple analytical model exists for VAWT wakes, computational fluid dynamics (CFD) simulations have shown that the time-averaged far wake can be approximated as a Gaussian velocity deficit profile:

$$\frac{U(x,r)}{U_\infty} = 1 - C_1 e^{-r^2/2\sigma^2} \tag{2}$$

where C_1 is the maximum velocity deficit and σ is the wake width.

The key distinction relevant to the sublayer concept is that VAWT wakes tend to be narrower and recover more quickly than HAWT wakes. This suggests that VAWTs may be able to operate effectively in the wake region of upstream HAWTs, where wind speeds are reduced but still contain significant kinetic energy (Xie 2016).

For analyzing the performance of a vertically staggered wind farm with both HAWTs and VAWTs, a modified "top-down" model can be used. This model divides the boundary layer into five layers:

1. A log layer between the ground and the bottom of the VAWTs
2. A wake layer covering the rotor area of the VAWTs
3. A log layer between the top of the VAWTs and the lower tip of the HAWTs
4. A wake layer covering the rotor area of the HAWTs
5. A log layer above the HAWTs

Each layer is characterized by specific equations that describe the wind velocity profile and momentum transfer. For example, in the VAWT wake layer, the effect of the turbines is parameterized as an added, uniform, and constant eddy viscosity:

$$(1 + \nu^*_V)\frac{du(z)}{d\ln(\frac{z}{H_V})} = \frac{u_*}{k} \tag{3}$$

where $v*_V$ is the effective eddy viscosity, u is the friction velocity, k is the von Kármán constant, and H_V is the hub height of the VAWTs.

These equations, along with those for the other layers, form a system that can be solved to determine the overall wind farm performance, including power output and wake interactions between the HAWT and VAWT layers.

Efficiency and Betz Limit Considerations

The theoretical maximum efficiency for a wind turbine, known as the Betz limit, is 59.3% $(16/27)$. This applies to both HAWTs and lift-driven VAWTs. However, in practice, VAWTs typically achieve lower efficiencies than modern HAWTs.

Common VAWT designs include:

1. Savonius rotor: A simple drag-driven design with a maximum efficiency of around 15-20%.
2. Darrieus rotor: A lift-driven design that can theoretically match HAWT efficiency, but typically achieves 30-40% in practice.
3. H-rotor: A simplified Darrieus design with straight blades, offering easier manufacturing but slightly lower efficiency.

The lower practical efficiency of VAWTs is due to factors such as:

- Cyclic variation in angle of attack, leading to dynamic stall
- Blade-wake interactions as blades pass through their own wake
- Structural limitations on tip speed ratio

However, recent research has suggested that closely spaced arrays of counter-rotating VAWTs may be able to exceed the Betz limit for the array as a whole, due to beneficial wake interactions (Barlas 2015). This finding, while still debated, highlights the potential for VAWT configurations to achieve higher power densities than conventional HAWT farms (Pierce 2013).

Maintenance Considerations for VAWT Sublayers

The integration of vertical-axis wind turbines as a sublayer within horizontal-axis wind turbine farms introduces complex maintenance considerations that must be carefully evaluated. This section examines the potential advantages and challenges associated with VAWT maintenance in a hybrid farm configuration, as well as the broader implications for overall farm operations and economics.

Potential Advantages

1. Ground-level components: The placement of critical mechanical and electrical systems at or near ground level in VAWTs potentially offers improved accessibility compared to nacelle-mounted systems in HAWTs.
2. Simplified blade design: VAWTs typically employ straight or moderately curved blades, which may be less complex to manufacture, transport, and replace compared to the large, aerodynamically optimized blades of HAWTs.
3. Yaw system elimination: The omnidirectional nature of VAWTs eliminates the need for a yaw control system, reducing the number of components requiring maintenance.

Challenges

1. Increased cyclic loading: VAWTs experience rapid changes in the angle of attack during each rotation, potentially leading to higher fatigue loads on blades, bearings, and support structures compared to HAWTs (Kavade 2024).

2. Technology maturity: The relative lack of long-term operational data for utility-scale VAWTs may result in less predictable maintenance schedules and the potential for unforeseen issues (Pierce 2013).
3. Interference with HAWT maintenance: The presence of VAWTs in close proximity to HAWTs may complicate access for large cranes and other equipment required for major HAWT component replacements.
4. Environmental factors: The lower positioning of VAWT rotors may increase their exposure to ground-level turbulence, dust, and debris, potentially affecting component longevity and maintenance frequency.

Economic and Operational Implications

A comprehensive cost analysis comparing VAWT and HAWT maintenance over the project lifetime is needed to fully assess the economic viability of hybrid farms. This analysis must account for factors such as:

1. Lifecycle cost modeling: Detailed projections of maintenance costs over the project lifetime, accounting for both routine maintenance and major component replacements.
2. Availability and production impact: Quantification of how VAWT maintenance activities may affect overall farm availability and energy production, including potential synergies or conflicts with a HAWT maintenance schedule.
3. Specialized equipment and training: Assessment of additional tools, equipment, and personnel training required for VAWT maintenance compared to traditional HAWT-only farms.
4. Spare parts logistics: Evaluation of inventory requirements and supply chain considerations for stocking VAWT-specific components in addition to HAWT parts.

In conclusion, while VAWT sublayers offer potential operational advantages in certain aspects, they also introduce new challenges that must be carefully managed. The success of hybrid VAWT-HAWT farms will depend on thorough planning, ongoing research into failure modes and maintenance strategies, and the development of specialized tools and procedures tailored to this novel wind farm configuration.

Methodology

Aim

The goal of this research is to conduct a first-level analysis to determine the potential value of implementing a hybrid HAWT-VAWT system. A HAWT has significant power in its wake region, and through this examination, the ability of a VAWT to capture this power efficiently will be investigated. This analysis will explore if the hybrid system is capable of capturing a substantial amount of energy as compared to a single HAWT. The simulation is done at both an individual turbine and wind farm scale to provide insight as to whether implementing VAWTs would be valuable both hypothetically and at a business scale. This work aims to determine whether future research is warranted given the potential value of a hybrid HAWT-VAWT system.

In-Depth Literature Review

To frame the boundaries of the simulation, it was important to understand the assumptions used in similar research scenarios. An in-depth literature review was conducted to observe the guiding principles used in other research and ensure research efforts were from a solid foundation. Furthermore, since this research is a first-level analysis, accurate assumptions need to be made given the simplicity of the model. The literature review provided insight into how to shape the model and the significant factors that need to be considered. The finding made it clear that the first-level analysis done in this work could not capture many of the complexities of turbulent airflow, as higher-level data analysis was required. The literature also outlined examples of advanced simulations and tests that could be conducted, if the results from this model demonstrated notable potential, justifying further research.

Assumptions

It was important to make a series of assumptions to help the model provide simple yet accurate and realistic wind turbine output by combining fundamental physics principles with practical engineering considerations. The two main assumptions accounted for were the Betz Limit Assumption and the Blade Element Momentum (BEM) Theory Assumption. The Betz limit assumption is reasonable given ideal conditions where the wind speed is uniform and the flow is constant. It is useful in providing an upper bound for the maximum theoretical efficiency of a wind turbine. The BEM is reasonable given that the flow is steady and the forces acting on the blades can be separated into lift and drag components. This assumption is useful because it allows for a detailed analysis of the aerodynamic forces on turbine blades, enabling the prediction of turbines under various conditions. It is important to note that complex wake interactions were not well represented due to our numerical modeling limitations, so to try and compensate for that, the Jensen wake model with a Gaussian wake deficit was used.

Analysis

Turbulent Kinetic Energy

Throughout the process of literature reviews, most related studies deduced that a critical aspect to analyze concerning VAWTs is turbulent kinetic energy (TKE). Since the wind behavior in the wake region is far more turbulent than typical wind behavior, quantifying this TKE is valuable. The design and placement of VAWTs are dependent on many factors and the intensity of turbulence in the wind flow will affect the ability of the VAWT to harness the wind energy.

To calculate the TKE, it was first necessary to find the wind speed profile. This wind speed profile equation is shown below. U_{ref} is the reference wind speed at hub height, α is the wind shear exponent, z_{ref} is the hub height, and Z is the non-zero heights above the ground and also excludes hub height. In the graph on the y-axis, the Z/H is the normalized height, where Z is the actual height above the ground, and H is the hub height of the turbine.

$$U(Z) = U_{ref} \cdot \left(\frac{Z}{z_{ref}}\right)^{\alpha} \quad (4)$$

After finding this wind speed profile value, the next step is to calculate the TKE. The equation below was used for the calculation.

$$TKE(Z) = 1.5 \cdot (I(Z) \cdot U(Z))^2 \quad (5)$$

Where I(Z) is turbulence intensity at height Z, and U(Z) is the wind speed at height Z. Then this information is plotted, as shown in figure N, with Z/H on the y-axis and TKE on the x-axis. For this investigation, the TKE of the air behind the HAWT was compared to the TKE from typical wind behavior. The goal of this plot was to analyze the TKE profile, identify at which normalized height is the TKE highest, and confirm the air within the wake region had more turbulent kinetic energy.

Annual Expected Power

One way to determine the feasibility of VAWT vertical sublayers is to illustrate the potential to extract more power out of the same wind. This is an important component as it directly correlates to the potential for value at the wind farm scale. In this study, this was evaluated by determining the annual expected power (AEP) yielded from turbines in various arrangements which were narrowed down into the two models evaluated throughout the study. The ‘traditional’ system is a HAWT only simulation based on the Vestas V52, whereas the ‘hybrid” system is a simulation of a HAWT with a VAWT in its wake path. To complete this analysis the data provided for Homework 1 was utilized, then the model was constructed in MATLAB for this research. The traditional system was intended to provide a baseline for the accuracy of the model. After testing this baseline, the AEP was calculated for an individual VAWT. For this calculation, the assumption is that the wind is going straight into the VAWT. Then the AEP was calculated for a ‘hybrid VAWT’ where the wind went into the VAWT after going through the HAWT. The next calculation was the AEP of a Vestas V52 turbine given the wind data. Finally, the AEP for a hybrid system, which combines the power generation of a HAWT with the power generation from a VAWT in its wake region was calculated. The comparison of these four calculations provides valuable insight into the potential of implementing VAWTs at a wind farm scale.

Mean Kinetic Energy Function

The turbulent kinetic energy plot was useful in proving a potential power density increase within a HAWT wake region. However, it was a very preliminary type of analysis that was solely confined to the scope of turbulent energy. After considering this, the mean kinetic energy of the wing was considered to provide a more transparent picture of the energy within the wake region as a whole, not just in the turbulent regions. To do this, a plot of the estimated mean kinetic energy profile was constructed using the air density in the region and spanning that with the wind velocity squared as reflected in the kinetic energy formula:

$$MKE = \frac{1}{2}\rho\mu^2$$

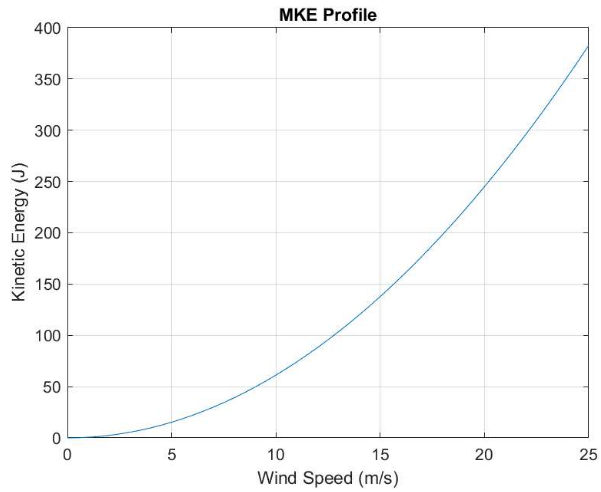


Figure 1. The Mean Kinetic Energy Profile Behind the HAWT

Findings and Discussion

Novel analysis conducted within this study into the feasibility of Vertical-Axis Wind Turbine (VAWT) sublayers in wind farms yielded several significant findings that warrant consideration. The study encompassed various aspects, including energy production, system comparisons, and economic implications, all of which contribute to a nuanced understanding of the potential benefits and challenges associated with hybrid Horizontal-Axis Wind Turbine (HAWT) and VAWT systems.

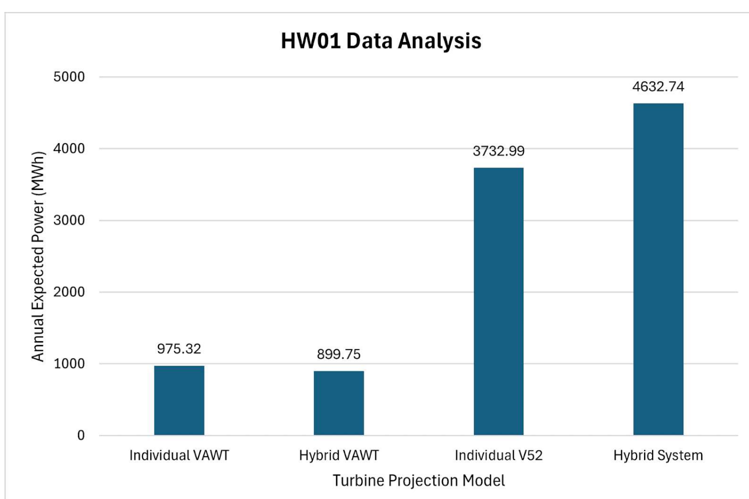
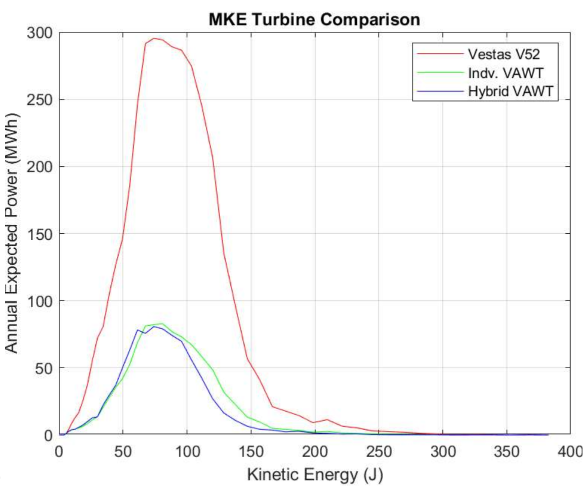
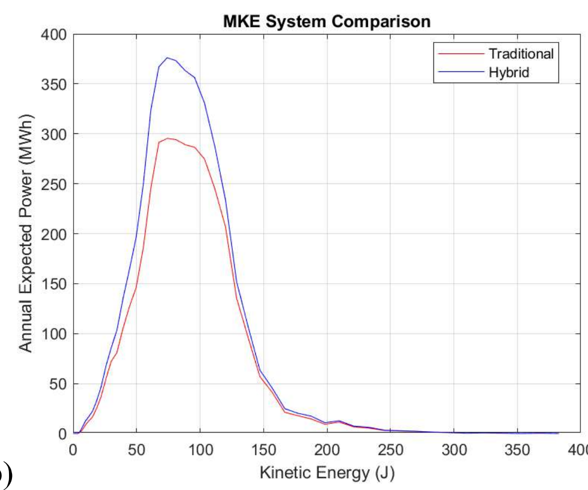


Figure 2. AEP bar chart for an individual VAWT, the VAWT in the hybrid system, an individual Vestas V52, and the total AEP of the hybrid system.

Initial analysis was conducted in a style consistent with previous work (HW01), giving the ability to validate results against previously established benchmarks. From this validation process, it was confirmed that findings aligned with expected values for Vestas V52 and VAWTs of similar sizing, providing a solid foundation for further exploration. Despite a minor reduction in VAWT energy production within the HAWT wake—attributable to slower mean wind speeds and limitations of the simplified model, which did not account for potentially beneficial wake interactions—the hybrid system *still* demonstrated a higher Annual Energy Production (AEP). This increased AEP translates directly into a higher energy density compared to traditional HAWT-only systems.



(a)



(b)

Figure 3. (a) AEP plotted as a function of Kinetic Energy for evaluated turbine models. (b) AEP plotted as a function of Kinetic Energy for evaluated systems.

Kinetic energy dynamics further illuminated the comparative performance of HAWTs and VAWTs in both individual and system-wide contexts. When comparing individual turbines, the Mean Kinetic Energy (MKE) analysis clearly illustrated the superior performance of a single

Vestas V52 HAWT over any single VAWT in terms of energy production. However, the system-wide MKE comparison revealed a more nuanced picture, the hybrid HAWT-VAWT system produced a higher overall AEP, despite the aforementioned minor loss of VAWT energy production in the HAWT wake. This finding suggests that the integration of VAWTs as a sublayer can effectively harness energy from turbulent wake flows, translating directly into the potential for economic impacts.

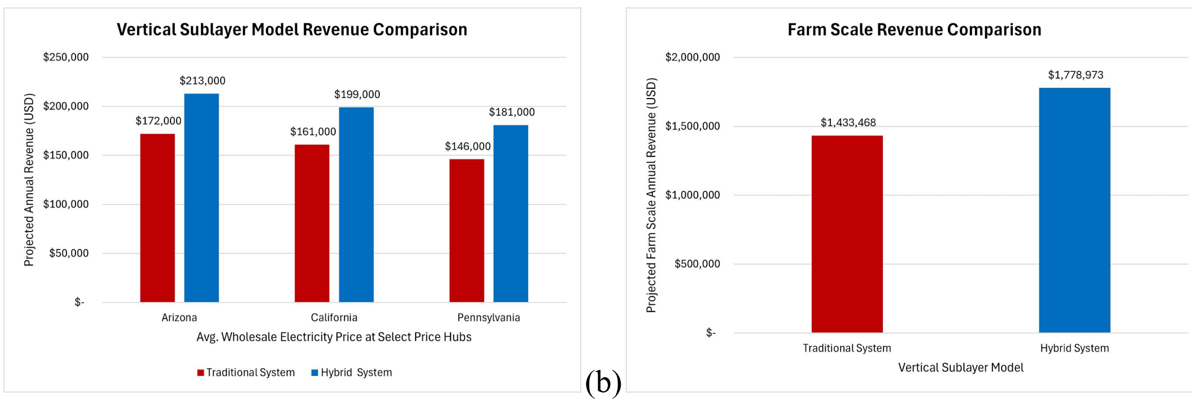
(a)


Figure 4. (a) Projected annual revenue for each system in various localities. (b) Projected farm-scale revenue for each system at a mean sale price.

The increased AEP observed in the hybrid system directly translates to tangible economic benefits. Economic analysis, comparing traditional HAWT-only (H) systems with hybrid HAWT-VAWT (H-V) configurations, projected a significant difference in annual revenue with a potential increase of $345,000 in annual revenue for the hybrid system. Representing a 24% increase in farm-scale AEP for the hybrid model, this is in line with the findings of the Xie et al. (2016) VS research paper which determined a 32% increase at farm scale. Given that the model developed in this report cannot account for non-linear beneficial wake interactions it should be no surprise that the number found is less than that of other papers, though still significant. Noting that these projections were derived from a conservative model suggests there may be potential for actual economic benefits to be more substantial with sophisticated modeling techniques and optimized system designs.

Conclusion

The findings of this study strongly indicate that there is significant scientific and economic potential in hybrid HAWT-VAWT systems, warranting further in-depth research and development. The observed increase in energy production and the corresponding economic benefits provide a compelling case for continued exploration of this innovative wind farm configuration.

The complexity of wake interactions and potential synergies between HAWTs and VAWTs present opportunities to increase overall farm efficiency and energy density. Future research should focus on refining wake interaction models using advanced computational methods, optimizing turbine placement and sizing, and conducting wind tunnel experiments and field analyses. Additionally, investigating long-term reliability, maintenance requirements, and lifecycle costs is crucial for determining commercial viability. As the wind energy sector evolves to meet growing renewable energy demands, VAWT sublayers may aid wind farm efficiency and economic viability on a larger scale. This approach could help contribute to a large movement toward sustainable energy production and climate change mitigation efforts, making it a promising area for continued academic and industry research.

References

Ahmad, A., Loya, A., Ali, M., Iqbal, A., Baig, F. M., & Afzal, A. M. (2020). Roadside vertical axis wind turbine (VAWT): An effective evolutionary design for Australian highway commuters with minimum dynamic stall. *Engineering*, *12*(09), 601-616. https://doi.org/10.4236/eng.2020.129042

Ashwill, T., Sutherland, H., & Berg, D. (2012, January 1). *A retrospective of VAWT technology.* Office of Scientific and Technical Information (OSTI). https://doi.org/10.2172/1035336

Barlas, E., Buckingham, S., & van Beeck, J. (2015). Roughness effects on wind-turbine wake dynamics in a boundary-layer wind tunnel. *Boundary-Layer Meteorology*, *158*(1), 27-42. https://doi.org/10.1007/s10546-015-0083-z

Dabiri, J. O. (2020). Theoretical framework to surpass the betz limit using unsteady fluid mechanics. *Physical Review Fluids*, *5*(2). https://doi.org/10.1103/physrevfluids.5.022501

Kavade, R. K., Sonekar, M. M., Choudhari, D. S., Malwe, P. D., Sherje, N. P., Ansari, M. A., Shah, M. A., Abdul Zahra, M. M., & Kumar, A. (2024). Investigation on fixed pitch darrieus vertical axis wind turbine. *AIP Advances*, *14*(7). https://doi.org/10.1063/5.0203609

Pierce, B., Moin, P., & Dabiri, J. (2013). Evaluation of point-forcing models with application to vertical axis wind turbine farms. *Center for Turbulence Research*.

Porté-Agel, F., Bastankhah, M., & Shamsoddin, S. (2019). Wind-Turbine and wind-farm flows: A review. *Boundary-Layer Meteorology*, *174*(1), 1-59. https://doi.org/10.1007/s10546-019-00473-0

Shao, Y., Su, J., Tu, Y., Kuang, L., Han, Z., Zhang, K., & Zhou, D. (2023). Assessment of the aerodynamic benefits of collocating horizontal- and vertical-axis wind turbines in tandem using actuator line model. *Physics of Fluids*, *35*(7). https://doi.org/10.1063/5.0156543

Syed, A. H., Javed, A., Asim Feroz, R. M., & Calhoun, R. (2020). Partial repowering analysis of a wind farm by turbine hub height variation to mitigate neighboring wind farm wake interference using mesoscale simulations. *Applied Energy*, *268*, 115050. https://doi.org/10.1016/j.apenergy.2020.115050

Xie, S., Archer, C. L., Ghaisas, N., & Meneveau, C. (2016). Benefits of collocating vertical-axis and horizontal-axis wind turbines in large wind farms. *Wind Energy*, *20*(1), 45-62. https://doi.org/10.1002/we.1990