**Proceedings of the Canadian Society for Mechanical Engineering International Congress 2022**
**CSME Congress 2022**
**June 5-8, 2022, Edmonton, AB, Canada**

# CFD Study of the aerodynamic performance of a Vertical Axis Wind Turbine in the wake of another turbine

Belkacem Belabes [1*], Marius Paraschivoiu [1]
[1] Department of Mechanical Engineering, Concordia University, Montreal QC, Canada
*e-mail: belkacem.belabes@concordia.ca

***Abstract*****—** An increased interest in Vertical Axis Wind Turbines (VAWTs) has been seen recently due to their ability to be placed closer together. Although individual vertical axis wind turbines (VAWTs) have lower efficiency than horizontal axis wind turbines (HAWTs), they may have a significant advantage when placed on a wind farm. The wake interaction between turbines is one of the main characteristics of flows around multiple wind turbines that affect the performance of VAWTs. This effect has not been thoroughly researched. The capability of CFD to accurately simulate the impact of the wake on the performance of different VAWT is explored in this paper. The effect of the wake on a downstream turbine is quite important as it affects the performance. A configuration of two H-Darieus wind turbines is modeled using RANS equations solved within the commercial tool STAR CCM+. The study of the wake generated by the first wind turbine and its effect on the wind turbine downstream with different distances is the focus of the current research. The space between the two rotors varies from 2.5 to 40 times the turbine's diameter.

***Keywords-Vertical axis wind turbine; Computational fluid dynamics; Power coefficient; wake, wind farm***

## I. INTRODUCTION

A vertical wind turbine is a wind turbine whose main rotor is perpendicular to the direction of the wind and has the generator placed close to the ground, which makes maintenance and repairs easy compared to the horizontal wind turbines. Most wind turbines currently installed are horizontal axis wind turbines. However, there are some important advantages of vertical axis wind turbines when used in urban areas or wind farms. In addition to ease of maintenance, VAWT offers several advantages, the most important of which is that they can be placed close to each other. Therefore, less space is occupied compared to HAWT.

Wind turbines are prone to wake losses if the wind farm is poorly designed. The layout of turbines in a wind farm requires understanding how individual wind turbines work together. It has been widely established that more space between turbines within a park lowers the chance of turbine wake losses. However, site constraints limit the space available for wind farms [5].

In the literature, most VAWT studies concentrate on isolated turbines, whereas in practice, multiple VAWTs are usually arranged together in a wind farm. Also, the vast majority of the literature studying the wake interactions between the turbines uses small vertical axis wind turbines, such as: Daribi [6], Sadra Sahebzadeh [7], Zanforlin et al. [8], Brownstein et al. (2019) [9], Brownstein et al. [10], Baloutaki et al. [11], Lam & peng [12], Chen et al. [13], Barnes & Hughes [14], Alexander et al. [15], Peng et al. [16].

Table I presents the main parameters related to the vertical wind turbine dimension such as diameter, blade chord...etc, and illustrates that most studies focus on small turbines.

TABLE I. OVERVIEW OF THE STUDIES ON DARRIEUS VAWT ARRAY

| **Author (date)** | **Diameter (m)** | **Distance between VAWT (xD)** | **Chord (m)** |
|---|---|---|---|
| Dabiri (2011) [6] | 1.2 | 14D | 0.127 |
| Sadra Sahebzadeh (2020) [7] | 1 | 1.5D | 0.060 |
| Zanforlin et al. (2016) [8] | 1.2 | 3D | 0.128 |
| Brownstein et al. (2019) [9] | 0.2 | 1.65D | 0.045 |
| Brownstein et al. 2016 [10] | 0.31 | 6D | 0.045 |
| Baloutaki et al. (2016) [11] | 0.3 | 3D | 0.045 |
| Lam & peng (2017) [12] | 0.3 | 2D | 0.045 |
| Chen et al (2017) [13] | 2.5 | 7.D | 0.400 |
| Barnes & hughes (2018) [14] | 3.4 | 10D | 0.136 |
| Alexander et al. (2019) [15] | 1.2 | 1.5D | 0.127 |
| Peng et al. (2020) [16] | 2.8 | 12D | 0.420 |
| **Present study** | **35** | **(2.5, 5, 10, 20, 30, 40)D** | **1.750** |

As seen in table I, all of the research listed explore the wake of a tiny wind turbines in terms of diameter and chord;

however, the original approach in this study is to compare the wake of two massive wind turbines of a relatively big size. A configuration of two wind turbines is explored in this study for different rotor spacing to compute the performance of both wind turbines.

## II. CFD SIMULATIONS

### A. *Wind turbine simulation models*

First, common parameters in the field of wind turbines are reviewed. The power available from the wind for a cross-section area (As) is given by:

$$P_{Wind} = 0.5\rho A_s U^3 \qquad (1)$$

where $\rho$ is the air density and U is the wind speed.

For an H-type vertical axis wind turbine, the swept area $(A_s)$ is a rectangle, calculated as the turbine diameter multiplied by the blade length. The power coefficient is a measure of the wind turbines ability to convert wind energy to mechanical energy, which is defined as:

$$C_p = \frac{P_{windturbine}}{P_{wind}} \qquad (2)$$

where $P_{windturbine}$ is the aerodynamic power output.

The power coefficient depends on the tip speed ratio TSR or λ, which is the ratio between the velocity of the blade and the wind speed, thus calculated as:

$$\lambda = \frac{\omega R}{U} \qquad (3)$$

where $\omega$ is the angular velocity of the turbine and R is the turbine radius.

### B. *Turbine geometrical and operational characteristics*

The straight-bladed Darrieus turbine or H-rotor was developed mainly in the UK by Peter Musgrove during the 1980s and 1990s as is shown in figure 1. This turbine of a two-blade 500 kW H-Type vertical axis wind turbine is considered for analyzing the effect of the wake on the wind turbine's performance.

Figure 1. A two-blade Darrius wind turbine installation of 0.5MW [17][18]

This configuration was chosen because it is a large wind turbine where the Reynolds number for a wind speed of 10 m/s is 23,340,000. Furthermore, the rotor only has two blades which reduce the number of elements in the mesh and therefore reduces the computational cost. The rotor geometrical specifications are reported in table II, while a picture of the installation is shown in figure 1.

The simulated wind turbines configurations are schematically depicted in figure 2 and figure 3. Experimental performance data was obtained from the VAWT demonstration project by Mays et al. [18]. This data is employed to validate the CFD methodology by Belabes et al. [19]. Results have shown a good concordance with other numerical and experimental studies.

TABLE II. GEOMETRICAL AND OPERATION CHARACTERISTICS OF THE TURBINES

| **Parameter** | **Value** |
|---|---|
| Number of blades, n [- ] | 2 |
| Diameter, d [m] | 35 |
| Height, H [m] | 24.30 |
| Swept area, A [m2] | 850.5 |
| Solidity, σ [- ] | 0.1 |
| Airfoil chord length, c [m] | 1.75 |
| Airfoil shape [- ] | NACA0018 |
| Rotational speed, Ω [rad/s] | 1.65 |
| Freestream velocity, U∞[m/s] | 7.13 |
| Tip speed ratio (based on U∞), λ [- ] | 2.9 |

To reduce the computational costs, the turbine is simplified by excluding the shaft and the connecting rods from the geometry. Also, note that earlier studies have shown that these structural components result in a small and systematic drop in the turbine power performance [20][21]. Therefore, neglecting these components is not expected to significantly influence the conclusions of this study.

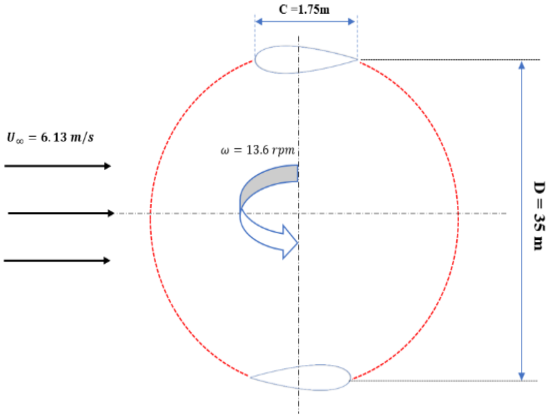

Figure 2. The geometrical and operational parameters of the turbines are provided in Table II

### C. *Computational domain and grid*

A 2D meshing is used with the number of cells ranging from 488978 to 2350669 cells corresponding to the isolated wind turbine and 40D configuration case, respectively. Figure 4 illustrates the computational grid for the rotor, which consists of 985026 polyhedral cells for the case configuration of 2.5D.

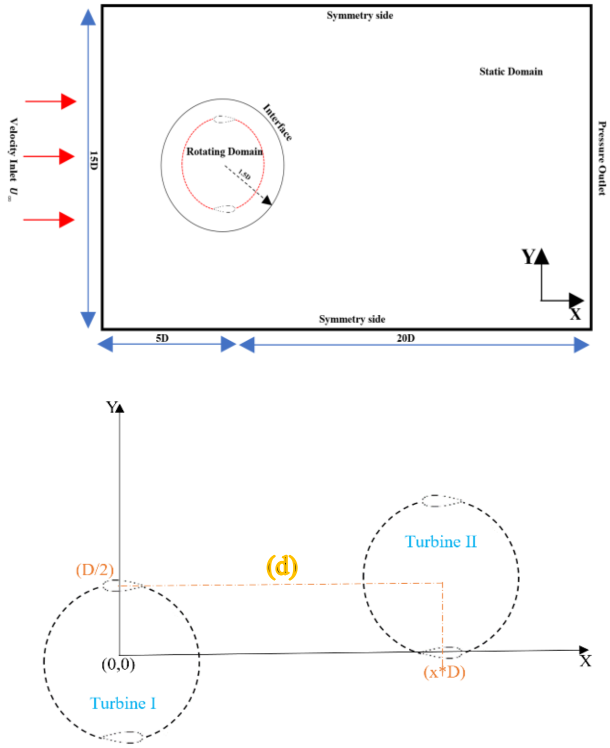

Figure 3. Schematic of computational domain with x and y distance indicated

The maximum and average y+ on the turbines blade is less than 1 for all cases, with 750 cells along the blade circumference. For the solo wind turbine, a domain with the same blockage ratio as the double rotor arrangements is made, as shown in figure 4. In this case, the computational grid consists of 195356 polyhedral cells.

The relative distance (d) of the two turbines is defined as the length of the turbines' center-to-center line, as shown in figure 3.

Domain size is 15D × 25D (width × length), selected based on the best-practice guidelines for VAWT CFD simulations. For all the simulations, there is a 5D distance between the upstream turbine's center and the domain inlet. In addition, there is a minimum distance of 20D between the downstream turbine and the domain outlet.

To guarantee the same distance between the symmetric side-boundaries and the upstream and downstream turbines, the longitudinal axis of the domain passes through the middle of the lateral distance of the two rotors. In other words, the wall sides were positioned at the same distance from the two rotors in all the simulations. Furthermore, a minimum distance of 7.5D from the boundary sides of the domain is considered in all cases.

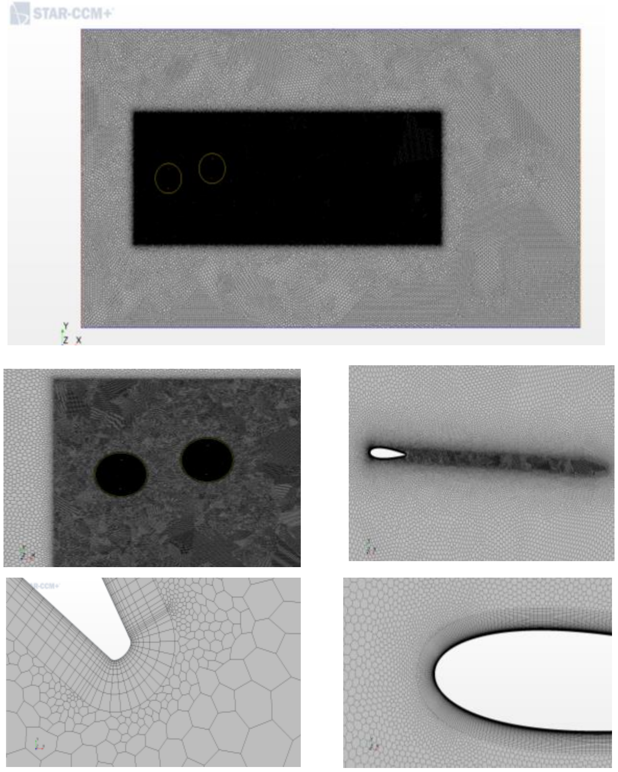

Figure 4. Computational grid for an arrangement with sample double rotor

### D. *Solver settings*

A flow simulation with moving boundaries is performed. In particular, the discretization of the computer field requires two zones; a rotating zone that contains the moving rotor and a fixed zone that models the far-field, as shown in figure 3. SIMPLE is used for the pressure-velocity coupling in the incompressible unsteady Reynolds-Averaged Navier-Stokes (URANS) equations. Second-order upwind discretization is employed both in time and space. Belabes et al. [19] recommend a time step associated with a half-degree rotation, and turbulence should be modeled by the SST k-omega turbulence model.

## III. RESEARCH OBJECTIVE

The research goals of this study are to understand the interactions of two rotors. The numerical study investigates the effect on the performance of the distance between these two rotors.

## IV. RESULTS AND DISCUSSION

A series of simulations are performed to investigate the effect of the downstream wake of a large wind turbine with a diameter of 35m. The first turbine is fixed however the second one was placed downstream at 2.5 times the diameter and as far as 40 times the diameter. According to the rotation

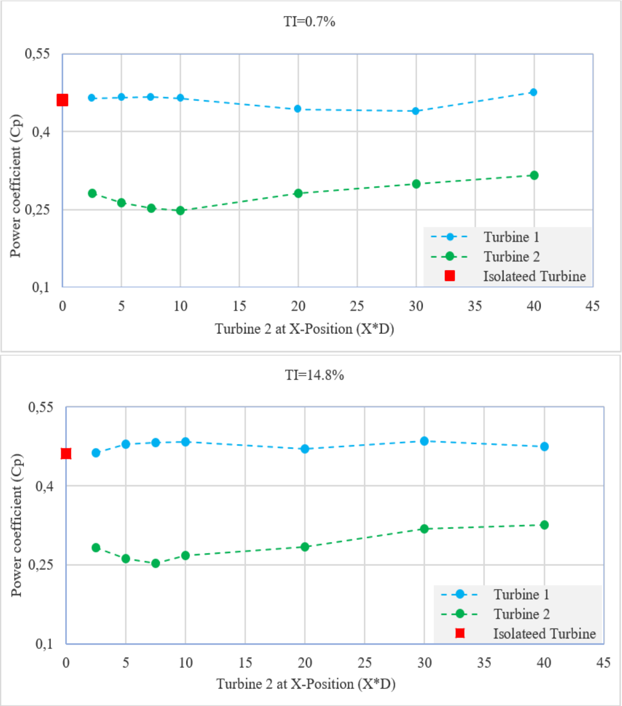

Figure 5. Cp against the different position of turbines 2 Turbine 2 at Y= -R (Right side)

direction, the wake generated by the first wind turbine is different on each side, which led to studying two different configurations. In the first configuration, the second wind turbine is installed on the left side of the first one, and in the second configuration, it is installed on the right side.

### A. *The second turbine installed on the right side of the first turbine: (Right side)*

To understand the effect of the spacing between the vertical wind turbines on the turbine performance, the power coefficient of each wind turbine is calculated and compared to the result of the isolated wind turbine.

Note that two values of turbulence intensity were used for all cases. It is shown in figure 5 the obtained power coefficient for different x-position of the second wind turbine.

One can observe a minimal effect of the turbulence intensity on the results. For this large turbine, it is concluded that the turbulence does not improve the dynamic stall characteristics of the turbine blades. It is also confirmed by Belabes et al. [19]; however, a significant improvement is found in the case of a small wind turbine.

A minor change of power coefficient is seen for the first wind turbine in each case compared to the Cp value of the isolated wind turbine. However, the obtained power coefficient for the second wind turbine is decreased by about 60% compared to the isolated wind turbine. This diminution is maintained from d=2.5D until d=10D. After that, the Cp increases proportionally with the augmentation of the distance between the wind turbines. The wake of the first wind turbine creates a low-velocity zone with significant vorticity, as shown in figure 6.

In figure 6, note that the second wind turbine rotates entirely in the heart of the wake of the first wind turbine until X=30D, where the second wind turbine starts receiving detached large eddies.

### B. *The second turbine installed on the left side of the first turbine: (Left side)*

The first thing to note is that the second turbine performs better on the left side. Secondly, the performance is better for the low turbulence intensity simulation, particularly after a distance greater than 20D. Lastly, the second turbine has an excellent performance when placed very close to a distance of 2.5D. Afterward, a significant decrease in the power coefficient of the second wind turbine is observed between the placements of d=2.5D to d=5D as shown in figure 7.

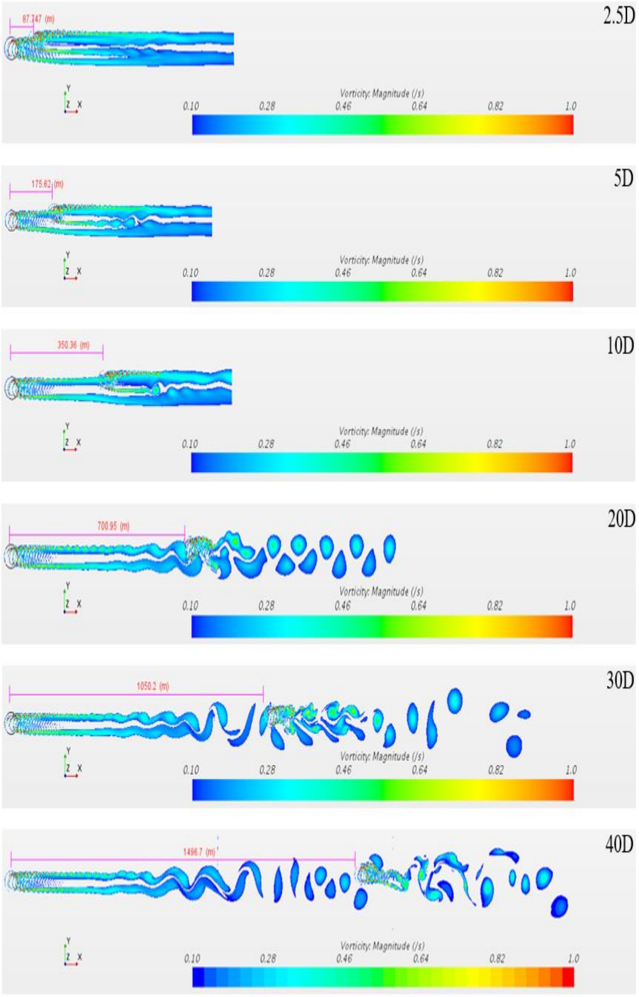

Figure 6. Vorticity distribution on downstream of the VAWTs for different distances (Left side)

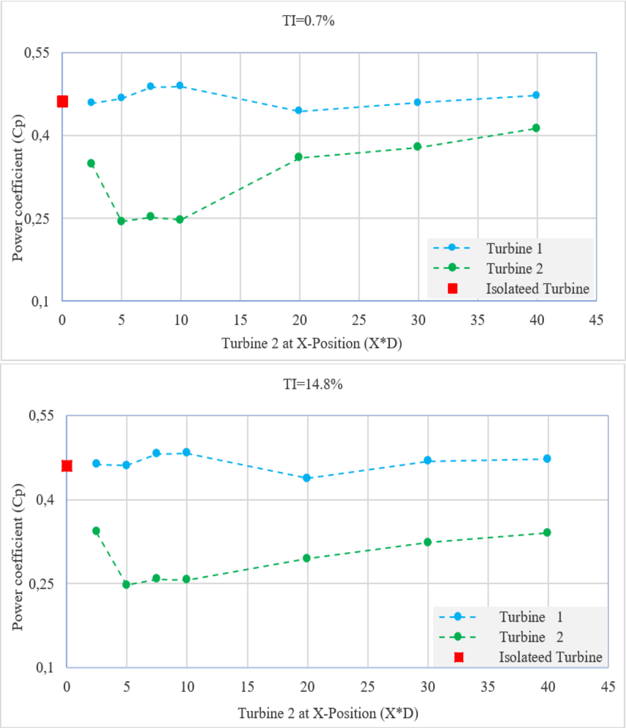

Figure 7. Power Coefficient (Cp) against the different position of turbines 2 Turbine 2 at Y=R (Left side)

A remarkable difference between results obtained by TI=07% and TI=14.8%, which in the case of TI=07% the Cp recover the value of the isolated turbine rapidly; compared with the case of TI=14.8%. This phenomenon may be explained by that the high turbulence intensity delays the disappearance of the wake generated by the first wind turbine, as one can see in figure 8.

## V. CONCLUSION AND PERSPECTIVES

This paper discusses the performance of two vertical-axis wind turbines placed in the same direction as the flow. The wake interaction between the turbine and the wake of the upstream turbine is studied. A parametric analysis has been conducted to identify the effects of rotor spacing on the flow field and the performance. The simulations are performed using a two-dimensional model and deal with two rotors layouts: (i) the second rotor on the left side, (ii) the second rotor on the right side.

By observing the velocity fields between the two turbines, it is evident that due to the presence of the neighboring turbine, the flow after the first rotor is decelerated in the wake, which remains well defined for a long distance. After a distance of 20D, this wake breaks down into large eddies. This study shows that it is better to place the turbine on the left side and avoid a placement between 5 to 15D.

Regarding the turbulence intensity effect, no remarkable difference between results obtained by TI=07% and TI=14.8% for both turbines up to 10D. After this distance, the turbine placement on the left side appears to have higher performance for the low TI.

The most interesting result of this study is that when the second turbine is placed, on the left side, at a distance of 2.5D, the performance of the second turbine is excellent. This placement needs to be studied further as it could lead to having very dense wind farms with high energy extraction.

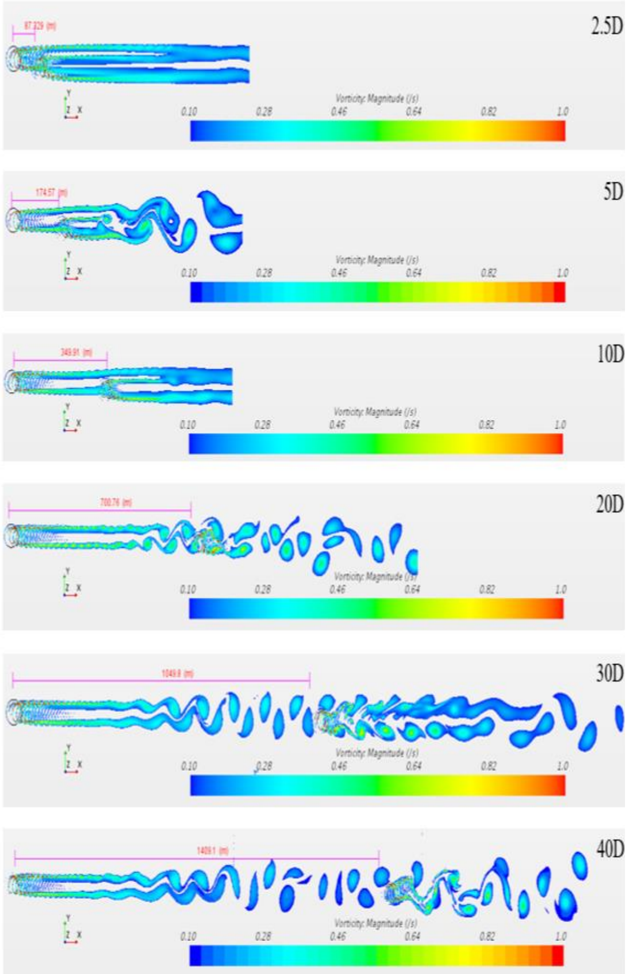

Figure 8. Vorticity distribution on downstream of the VAWTs for different distances (Left side)

## REFERENCE

[1] I. Janajreh, L. Su, and F. Alan, "Wind energy assessment: Masdar City case study," Renew. Energy, vol. 52, pp. 8–15, 2013.

[2] F. Balduzzi, A. Bianchini, and L. Ferrari, "Microeolic turbines in the built environment: Influence of the installation site on the potential energy yield," Renew. Energy, vol. 45, pp. 163–174, 2012.

[3] S. Bianchi, A. Bianchini, G. Ferrara, and L. Ferrari, "Small wind turbines in the built environment: influence of flow inclination on the potential energy yield," J. Turbomach., vol. 136, no. 4, p. 041013, 2014.

[4] A. Bianchini, G. Ferrara, and L. Ferrari, "Design guidelines for H-Darrieus wind turbines: Optimization of the annual energy yield," Energy Convers. Manag., vol. 89, pp. 690–707, 2015.

[5] S. Chowdhury, J. Zhang, A. Messac, and L. Castillo, "Unrestricted wind farm layout optimization (UWFLO): Investigating key factors influencing the maximum power generation," Renew. Energy, vol. 38, no. 1, pp. 16–30, 2012.

[6] J. O. Dabiri, "Potential order-of-magnitude enhancement of wind farm power density via counter-rotating vertical-axis wind turbine arrays," J. Renew. Sustain. Energy, vol. 3, no. 4, p. 043104, 2011.

[7] S. Sahebzadeh, A. Rezaeiha, and H. Montazeri, "Towards optimal layout design of vertical-axis wind-turbine farms: Double rotor arrangements," Energy Convers. Manag., vol. 226, p. 113527, 2020.

[8] S. Zanforlin and T. Nishino, "Fluid dynamic mechanisms of enhanced power generation by closely spaced vertical axis wind turbines," Renew. Energy, vol. 99, pp. 1213–1226, 2016.

[9] I. D. Brownstein, N. J. Wei, and J. O. Dabiri, "Aerodynamically interacting vertical-axis wind turbines: Performance enhancement and three-dimensional flow," Energies, vol. 12, no. 14, p. 2724, 2019.

[10] I. D. Brownstein, M. Kinzel, and J. O. Dabiri, "Performance enhancement of downstream vertical-axis wind turbines," J. Renew. Sustain—energy, vol. 8, no. 5, p. 053306, 2016.

[11] M. Ahmadi-Baloutaki, R. Carriveau, and D. S. Ting, "A wind tunnel study on the aerodynamic interaction of vertical axis wind turbines in array configurations," Renew. Energy, vol. 96, pp. 904–913, 2016.

[12] H. F. Lam and H. Y. Peng, "Measurements of the wake characteristics of co-and counter-rotating twin H-rotor vertical axis wind turbines," Energy, vol. 131, pp. 13–26, 2017.

[13] W.-H. Chen, C.-Y. Chen, C.-Y. Huang, and C.-J. Hwang, "Power output analysis and optimization of two straight-bladed vertical-axis wind turbines," Appl. Energy, vol. 185, pp. 223–232, 2017.

[14] A. Barnes and B. Hughes, "Determining the impact of VAWT farm configurations on power output," Renew. Energy, vol. 143, pp. 1111–1120, 2019.

[15] A. S. Alexander and A. Santhanakrishnan, "Mechanisms of power augmentation in two side-by-side vertical axis wind turbines," Renew. Energy, vol. 148, pp. 600–610, 2020.

[16] H. Y. Peng, Z. D. Han, H. J. Liu, K. Lin, and H. F. Lam, "Assessment and optimization of the power performance of twin vertical axis wind turbines via numerical simulations," Renew. Energy, vol. 147, pp. 43–54, 2020.

[17] P. Musgrove, "The evolution of the modern wind turbine, 1973 to 1990," in Wind power, 2010, pp. 87–124.

[18] I. D. Mays, C. A. Morgan, M. B. Anderson, and S. J. R. Powles, "Experience with the VAWT 850 demonstration project," in Proceedings 1990 European community wind energy conference, Madrid, Spain, 1990, pp. 482–87.

[19] B. Belabes and M. Paraschivoiu, "Numerical study of the effect of turbulence intensity on VAWT performance," Energy, vol. 233, p. 121139, 2021.

[20] A. Rezaeiha, I. Kalkman, H. Montazeri, and B. Blocken, "Effect of the shaft on the aerodynamic performance of urban vertical axis wind turbines," Energy Convers. Manag., vol. 149, pp. 616–630, 2017.

[21] A. Tummala, R. K. Velamati, D. K. Sinha, V. Indraja, and V. H. Krishna, "A review on small scale wind turbines," Renew. Sustain. Energy Rev., vol. 56, pp. 1351–1371, 2016.