PLATFORM - A Journal of Engineering

Received: 17 July 2021, Accepted: 17 December 2021, Published: 31 December 2021, Publisher: UTP Press, Creative Commons: CC BY-NC-ND 4.0

DESIGN IMPROVEMENT OF THE VERTICAL AXIS WIND TURBINE WITH APPLIED FLAPS THROUGH CFD ANALYSIS

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ABSTRACT

This research aims to optimise VAWT power generation capabilities through the design alteration of blades by the addition of flaps. The application is aimed to be applied in the United Arab Emirates, specifically at Abu Dhabi University campus in Al Ain to replace a margin of the consumed electrical energy (15%) powered by the typical non-renewable energy means. To study the effects of design alteration, relevant design parameters on the aerodynamic properties of the wind turbine, a typical standard design with standard dimensions were considered and used as a benchmark for comparison. Two aerodynamic simulation software were adopted, namely ANSYS FLUENT and QBlade, while the designs were drawn through AutoCAD. As per the simulation results, the addition of flaps resulted in an overall increase of 3.11% in power generation. The simulation results were then scaled up using dynamic similarity to obtain a total power consumption of 6 kW for each turbine suggesting that the newly built Al Ain campus would require 43 turbines to cover 15% of the total electricity consumption in a year. The building of a control system for active pitch control was not feasible due to increased complexity.

Keywords: *Vertical axis wind turbine, CFD, sustainability, wind turbines, wind energy, electrical energy, numerical simulation*

INTRODUCTION

The urge of shifting to renewable energy sources is mounting as they provide clean, reliable energy that can last for extensive periods compared to traditional energy sources; moreover, conventional energy sources will come to an end, and the hazard they lay on the environment is threatening. The acquirement of a clean renewable limitless flow of energy is a key factor in the development and urbanisation of mankind. Various initiatives aiming to minimise the consumption of burning fuel for energy were launched, to replace them with sustainable harmless power extracting mechanisms. In the Middle East, explicitly the United Arab Emirates, the progress towards sustainable clean energy sources is growing, in 2017 a national energy strategy for 2050 was launched with an initial budget of $160 billion to accommodate 50% of total energy consumption from renewable energy sources [1]. Out of the numerous methods offered to sustain renewable energy, wind turbines are considered to be the most effective [2]. More information can be found in Dol et al. [3].

Wind turbines are simplified to two basic types: Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs). Their selection depends upon market demand as well as application requirements; furthermore, current HAWT surpass VAWT when it comes to marketing, simply because of the horizontal designs that were manufactured before vertical ones, thus more experience and field assessment are present; moreover, investors find it difficult to take a risk and invest in latest innovative technology especially after several others did and resulted in a product that hardly competed with the ones that used horizontal turbines [2].

Straight blade VAWT (SB-VAWT) aerodynamic properties can be obtained experimentally utilising wind tunnel tests or theoretically by computational models and numerical simulations. In theoretical analysis, even though the structural analysis seems simple in comparison to the HAWT, the aerodynamics involved is rather complex; additionally, three standard aerodynamic computational models exist comprising momentum model, vortex model, and cascade model. Both momentum and vortex models are used frequently, and all models are key elements in determining the optimisation needed in individual parameters [4]. More information can be found in Azeez et al. [5].

For the straight blade VAWT (SB-VAWT), the structure schematic in Figure 1 is a straight-bladed VAWT that includes two to six blades, depending on the application [6]. The types of VAWT are known to have difficulties in self-starting and a noticeable noise when running. To overcome such challenges, active and passive flow control can be utilised to manage the blades' tip vortex and dynamic stall.

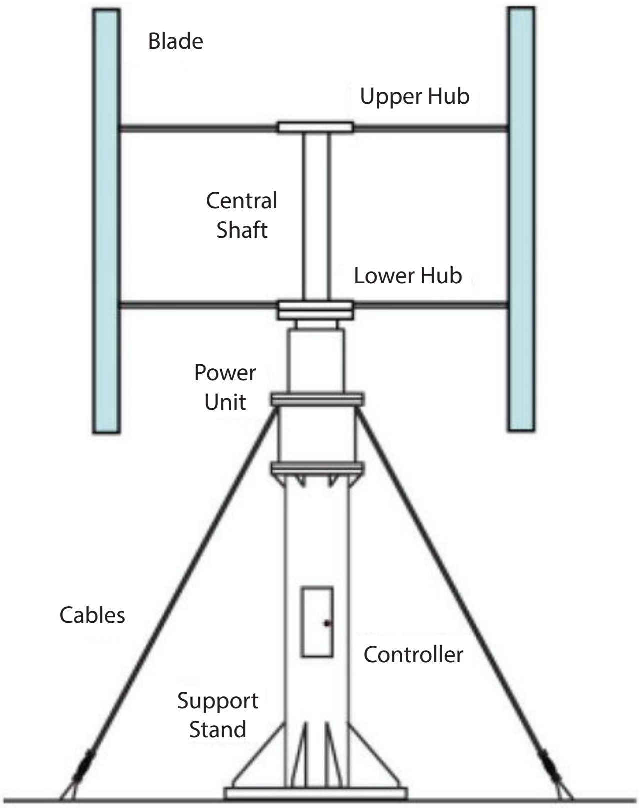


Figure 1 Straight-bladed VAWT
(Source: Li [7])

The momentum model studies the aerodynamic features of any wind turbine. It further expands to three main theories: momentum model, blade element model, and blade element momentum model (BEM). Established on the BEM model, Templin [8] suggested an aerodynamic computational model intended to discover the aerodynamic performance of the Darrieus VAWT, namely a single stream tube model. Wilson and Lissaman [9] established a more advanced model, the multiple stream tube model. Soon after, several models were proposed based on the stream tube model, out of them, the most compelling was hypothesised by Ion Paraschivoiu in 1981. This is the double-multiple stream tube model [10]. The double-multiple stream tube model proved most effective and is extensively used to analyse aerodynamic characteristics.

Syawitri et al. [11] implemented a Gurney Flap at the blade trailing edge to enhance its lift coefficient. Gurney Flaps would create counter-rotating vortices downstream with the majority of the flow shifting over the surface of the flap. The study utilised a RANS simulation combined with a stress-blended eddy simulation turbulence model for the investigation of flow characteristics. The study discovered the presence of Gurney Flaps enhanced the power coefficient substantially and delay the deep stall of the blades.

Wei and Li [12] stated that VAWT performance is a complex derivative due to the broad range of angles of attacks, poor start-up performance as well as a high dynamic stall. They designed and implemented a new Airfoil with attached flaps at trailing edges. The study utilised Xfoil and CFD with Spalart-Allarmas (S-A) turbulence model to simulate the VAWT blade profile accurately and compare the results with experimental data. The study illustrated the accuracy and physical significance of the selected turbulence model as well as computational methods.

This research aims at enhancing power output levels of a VAWT with optimised blade design through numerical simulation in ANSYS. The application is aimed to be used in the United Arab Emirates, specifically Abu Dhabi University campus in Al Ain city [13]. To replace a margin of the consumed electrical energy (15%) powered by the typical non-renewable energy means. During the research, several modifications were examined for possible adaptation in the final design. The structural layout of the final design was also investigated, including the blades, struts, rotating shaft, and tower design; in addition to that, the recommended materials, generator, and brake system to be utilised are noted.

METHODOLOGY

To ensure effective wind turbines, the study of wind speed that fuels the system to generate electricity is conducted. On average, wind speed in the UAE is about 5 m/s; during winter, the speed intensifies as the winds become sturdier and reach approximately 10 m/s. Figure 2 depicts the mean wind speed recorded in the year 2015 at a height of 50 m above sea level in the UAE. The mean wind speed data would be utilised to design a wind turbine that is suitable for applications considered in this study; in addition to that, the turbine must be compatible at either ground level or over buildings and houses, thus the implementation of a small-scale turbine must be investigated; furthermore, the aerodynamic performance should be optimised to increase efficiency and, hence, extract more wind power for electrical energy use [14].

Wind speed calculation is critical to the research as it determines the speed at which the turbine operates. Doing so will assist in predicting the performance of the designed wind turbine. As Travis suggested in his paper, the first step when designing a wind turbine is to determine the operating Tip-Speed Ratio (TSR).

$$TSR = \frac{\omega r}{V_\infty} \tag{1}$$

where ωr is the rotational velocity of the wind turbine, and V_∞ is the wind speed or velocity of the free stream. The type of the selected generator plays a role in selecting TSR value as some types do not operate with low rotational speed. After specifying the value

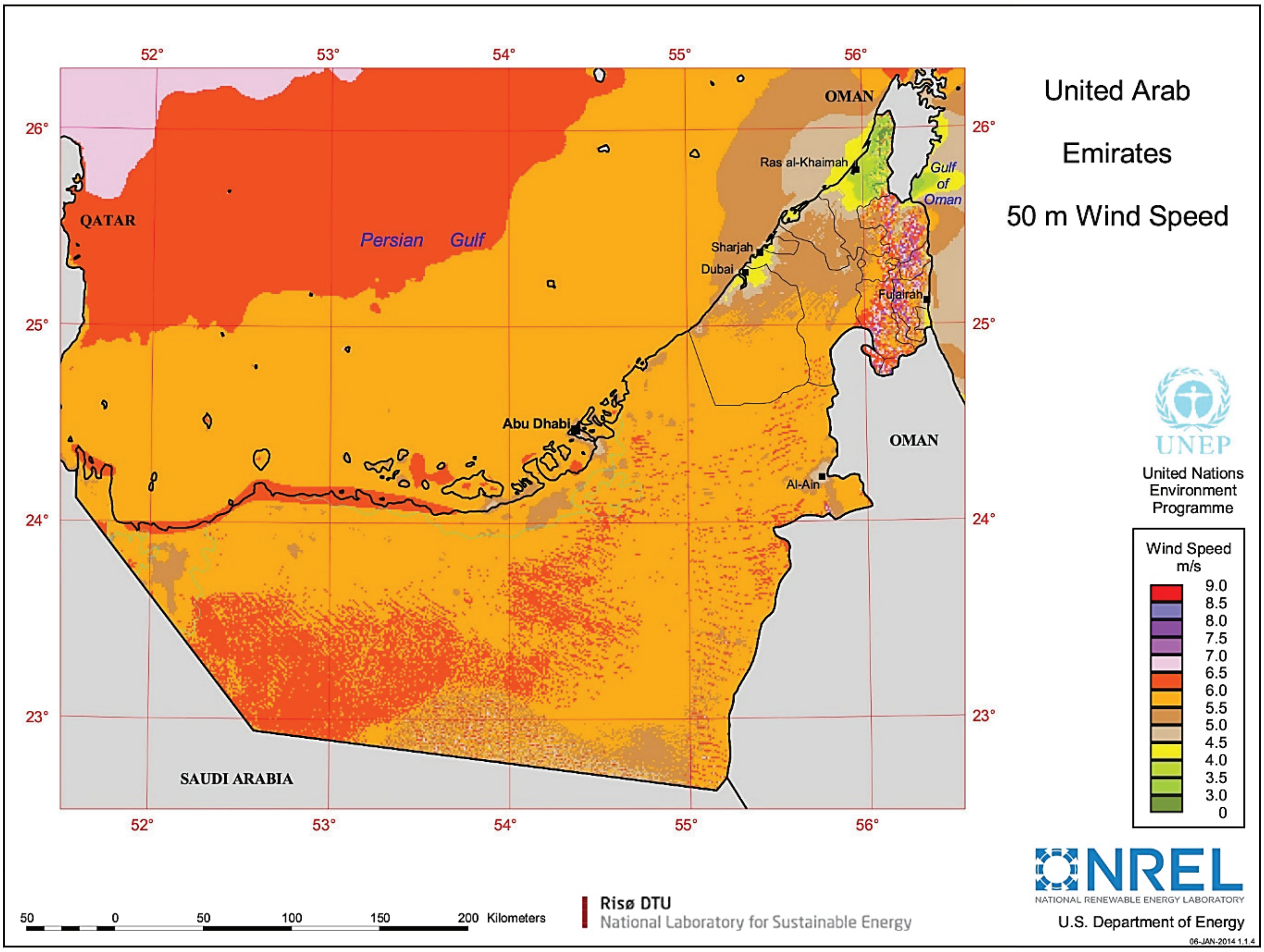


Figure 2 Average wind speed in UAE at 50 m height
(Source: NREL [14])

of TSR, the geometry of the vertical axis wind turbine can be defined using a dimensionless parameter known as 'solidity σ'. It represents the fraction of the area covered by the blades of the wind turbine that is called a swept area. The value of the solidity is not randomly selected [15].

$$\sigma = \frac{Nc}{d} \quad (2)$$

where 'N' refers to several blades, 'c' to the chord length of the blades, and 'd' to the diameter of the rotor.

The Darrieus VAWT will be considered in this study, in specific, the H-rotor turbine. According to Arpino et al. [16], simulations were conducted using CFD to examine the performance of Darrieus-type vertical axis micro wind turbine with a straight-blades configuration that is designed for small-scale conversion of energy at low wind speeds. In this study, the adopted configuration was an H-type wind turbine with three pairs of airfoils, placed at 120° to each other. Each pair consists of two blades with airfoils, whose characteristics are illustrated in Figure 3. For this study, a modified version of DU 06-W-200 airfoil was considered to be the blades type. In addition, the height of the model was to be 150 mm and its diameter equals 200 mm.

When the system rotates, the local angle of attack for each blade differs with the change of relative velocity W. Both the velocities V_i and ωr of the blades control the direction and magnitude of the relative velocity. In other words, it influences the lift L and drag D forces of the blade. Hence, the resultant force changes. In this case, $\alpha_1 = \alpha_2 = 13°$, $C_1 = 47.2$ mm, $C_2 = 27$ mm, $y = 13.8$ mm, and $x = 18.2$ mm.

Flap Addition to Benchmark Design

Flow separation has a direct impact on pressure distribution over the surface of the blade which would disrupt the pitch balance inflow process; moreover, due to flow separation, flow is highly unstable as per generated vortices leading to increased noise generation [17]. Flow separation is delayed through the addition of flaps at the trailing edges of the Airfoil as illustrated in Figure 4. Doing so would minimise the need for complex active flow control. The effect of the trailing-edge flap control mechanism on the airfoil's aerodynamic performance and noise characteristics in VAWT were investigated in this paper. The experimental findings show that the stall AOA (angle of attack) can be delayed about 14° to 16° in comparison with the original airfoil (without flaps). It was found that the maximum lift coefficient can be increased from 0.85 to 1.16 and by 37.12% at an angle of attack of 18°. Another finding of this study, using flaps would increase the power coefficient (*Cp*) by about 24.2% and 23.7% respectively at TSRs equal to 1.3 and 1.4 when compared with VAWT without flaps [18]. Air entering between the main part of the blde and the installed flap influences the parameters of the rotating vortices, resulting in variations in wind turbine output. For the studied cases, self-starting capabilities in the right direction of rotor rotation have improved. Numerical findings have revealed that as the flap angle is increased, turbine instability increases, prompting researchers to consider

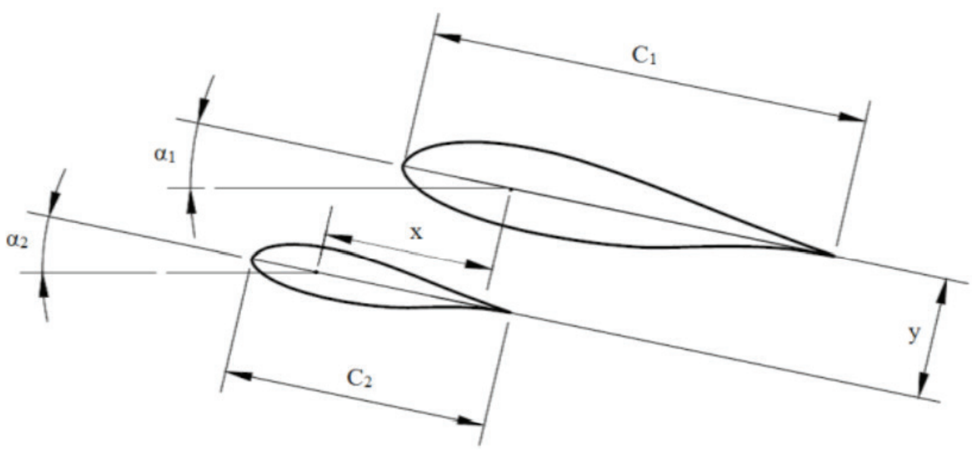
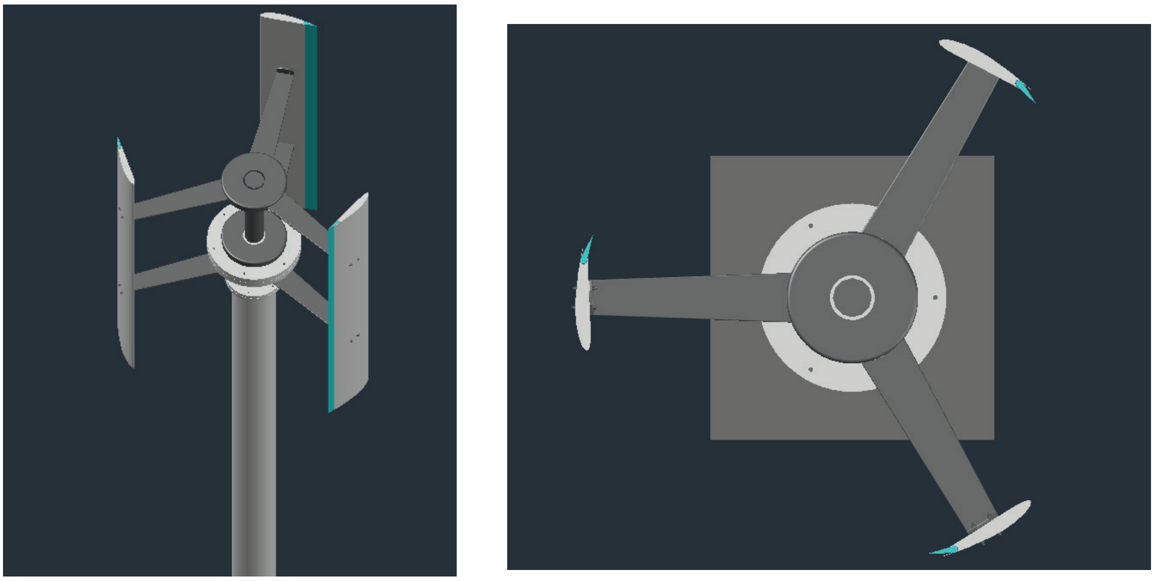


Figure 3 Two-bladed design schematic
(Source: Arpino et al. [16])



(a) (b)

Figure 4 (a) Isometric view of closed position design (b) Top view (flap addition to benchmark design) in open position

investigating the use of a flexible trailing-edge flap in modern VAWTs [19]. Further information can be found in Dol and ElGhazali [20].

Blade Profile

In early VAWT studies, symmetrical NACA00xx airfoils were implemented, mainly NACA0012, NACA0015, and NACA0018. These profiles were well known, and the data was available for various conditions; however, these profiles were developed for aviation applications; therefore, a need to develop more-suited profiles for VAWTs emerged. This need paved the way for the development of laminar flow airfoils, cambered airfoils, and increased thickness airfoils [21]. According to a 2D computational fluid dynamics simulation study testing 20 different symmetrical and asymmetrical airfoils, the cambered S-0146 had 26.83% higher power output and lower noise among all the test subjects, moreover, it was noticed that increasing solidity and TSR increases noise.

In light of this, comparing DU06W200 (an airfoil which has 20% thickness and 0.8% camber) and NACA0018, it was discovered that utilising DU06W200 airfoil results in a 5% increase peak power output; moreover, the TSR vs. *Cp* graph of the DU06W200 shifts towards the left signifying more generated torque at low-speed ratios making it more capable of self-starting. Although the DU06W200 airfoil has a better performance compared to the NACA0018 airfoil, the NACA0021 airfoil was found to have a similar performance to the DU06W200 airfoil without the camber [21].

Solidity

It is defined to be the ratio of the total blade area over the turbine swept area. Solidity is a measure of flow blockage that causes flow velocity reduction and local flow direction changes reduction. Higher flow blockage results in lower angles of attack in the upstream region; however, as TSR increases, the angle of attack decreases to a point that makes the generated torque lower than that of low solidarity. For low TSRs, the *Cp* increases with solidity, and with high TSR, the *Cp* decreases accordingly [21].

This study contemplated various CFD turbulence models and it was discovered that two-equations, namely SST k-ω and the one-equation Spalart-Allmaras models illustrated reliable results as the model is accurate for flow with stronger adverse pressure gradient [22]. The mesh structure consists of three components: background, flap, and wake refinement mesh. Dol et al. [23] performed a similar mesh independency study by observing the *y+* values for near-wall meshes based on the SST k-ω specific dissipation equation utilised in the turbulence model.

$$\frac{\partial\omega}{\partial t} + u_i\frac{\partial\omega}{\partial x_j} = aS^2 - B_{w^2} + \frac{\partial}{\partial x_j}\left((v + a_k v_r)\frac{\partial\omega}{\partial x_j}\right) + 2(1-F_1)\sigma_{w^2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial\omega}{\partial x_j} \qquad (3)$$

The findings of the study were shown in terms of dimensionless numbers, *Cp* and TSR. For the conducted experiment, a wind speed of 12 m/s was considered and used to measure and calculate *Cp* and TSR. The vertical wind turbine, in particular H-Darrieus, structure mainly consists of four distinct components that are the tower (including the base), the rotating shaft, the struts, and the blades. Each part has its mechanism and criteria to satisfy; therefore, a decision matrix on what material would best suit each part is used.

The effect of *Cp* concerning TSR of two-, three-, and four-bladed H-Darrieus VAWT is shown in Figure 5. The two VAWT blades have limited TSR, 0 to roughly 0.1, and exhibit shallow *Cp*, whereas the three and four-bladed turbines have a higher *Cp*. This data confirms that the 2-blade VAWT has low performance and low wind energy extraction characteristics. Where the four-blade VAWT scored the highest *Cp* result, nonetheless, it is limited to a wind speed of 6 to 11 m/s range, more than that the wind turbine illustrates low rotation and *Cp*. The three-blade VAWT showed more stable performance than the two and four-bladed turbines. It runs at a TSR higher than the four blades, thus increasing the *Cp* than the two blades [24].

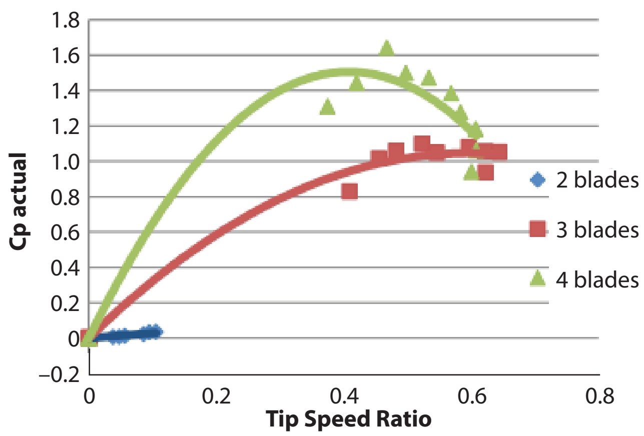


Figure 5 Power coefficient against tip speed ratio for three VAWT blades
(Source: Sunyoto et al. [24])

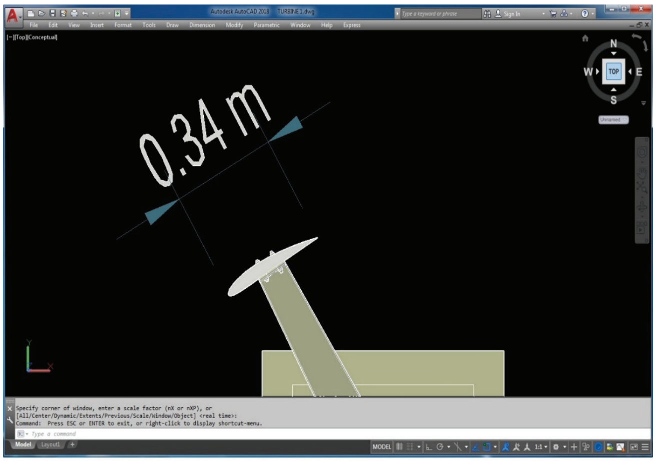


Figure 6 AutoCAD drawing of the Benchmark Chord length dimension

Design parameters

The turbine dimensions were scaled and modified from Nandurkar et al. [25] with a similar model determined by:

$$\left(\frac{Blade\ Length}{Chord\ Length}\right)_{Turbine_2} = \left(\frac{Blade\ Length}{Chord\ Length}\right)_{Turbine_1} \qquad (4)$$

The AutoCAD drawing of the benchmark design with dimensions is illustrated in Figure 6. The turbine radius was scaled to be 0.78 m with an optimum blade length at 2 m. The tower length was fixed at 7.6 m with an Inner diameter of 0.105 m.

QBlade

This study had to simulate various airfoils to select the ideal one for the turbine blades. QBlade utilised the code of XFoil to simulate several airfoils at different conditions and study the performance by visualising the Lift, Drag, and power coefficient levels. QBlade required fewer parameters, such as average temperature, Reynolds number, Mach number, and kinematic viscosity. The Reynolds number was calculated based on respective parameters achieving 63291 for the simulation and a Mach number of 0.01. The software tested seven distinct airfoils with the range of angle of attacks from –10° to 20° at increments of 0.5°. Figure 7 illustrates the comparison between the various airfoils in QBlade. The NACA4412 was manifestly the preferred airfoil as it illustrated the highest lift-to-drag ratio in comparison to the other six airfoils.

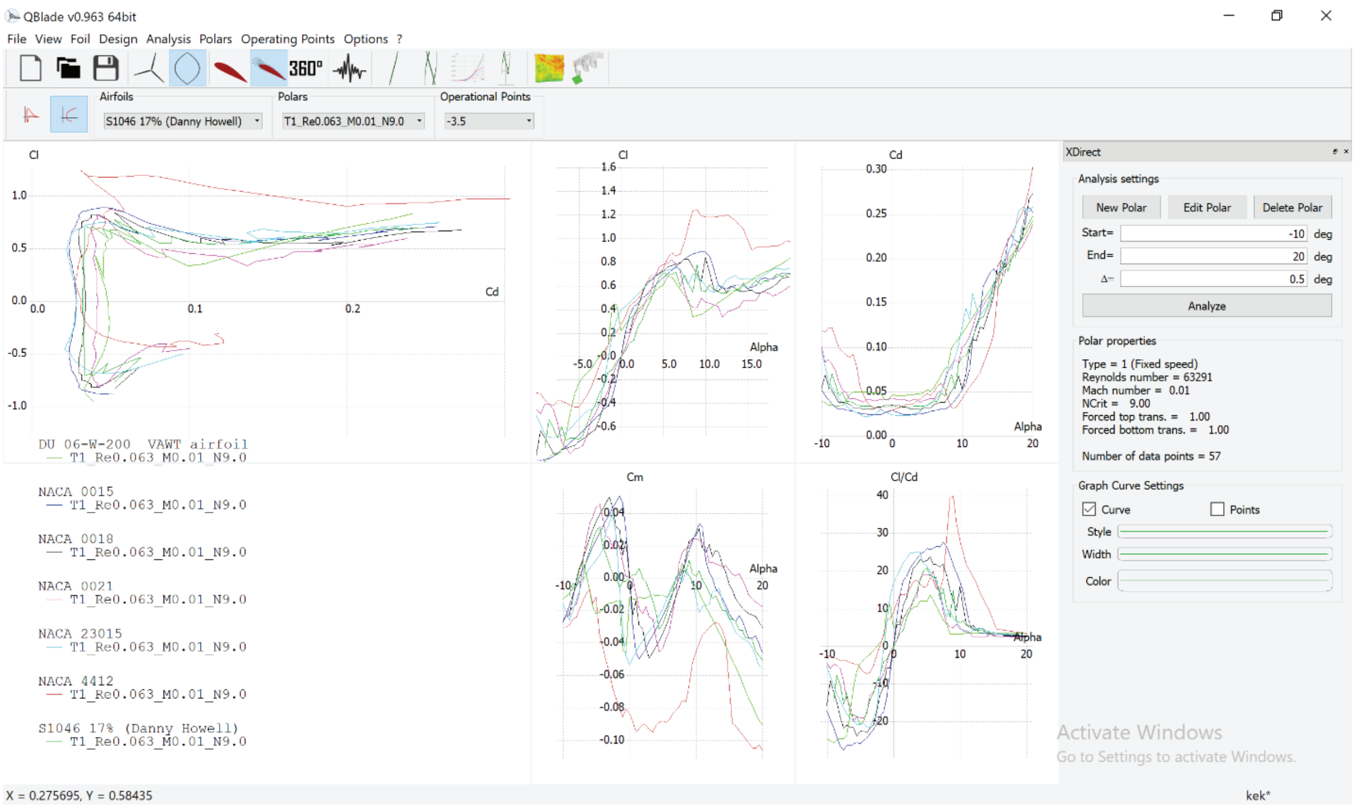


Figure 7 Airfoil results retrieved from QBlade

Simulation

The turbine geometry was imported into ANSYS after which a cylindrical enclosure of radius 1m and a height of 2.4 m was modelled enclosing the wind turbine. The rotating and static domain material was selected as Incompressible fluid. The meshing was performed through three meshing methods including body sizing, face sizing, and inflation. Face sizing was utilised on the turbine walls while inflation was applied at the turbine walls for further refinement; moreover, the skewness of the mesh was supported at 0.95 implying that the mesh is acceptable. Figure 8 shows the rotating and static domains mesh with a tetrahedral mesh and a 0.01 m element size.

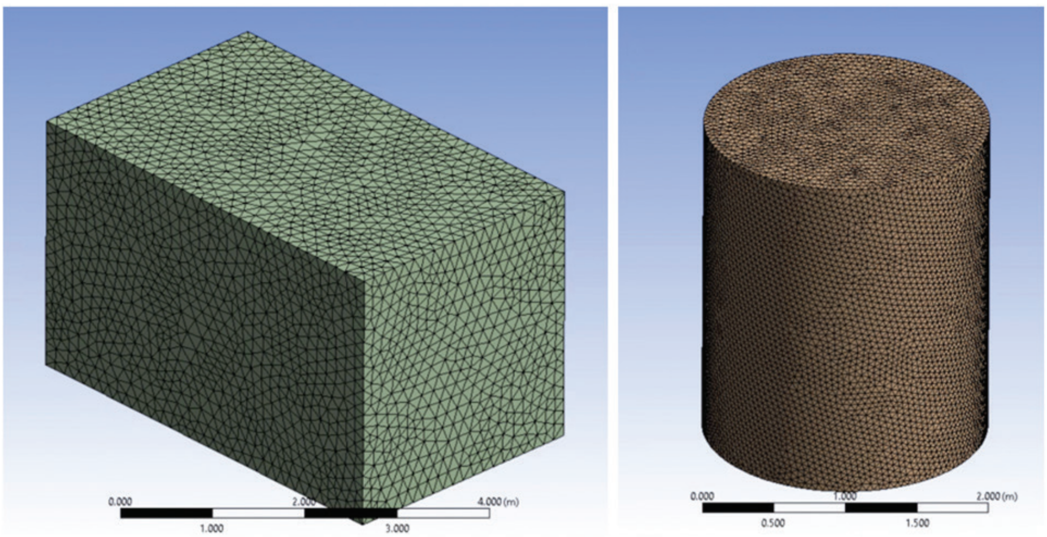


Figure 8 Dynamic and static domains mesh

After meshing, ANSYS fluent setup involved the pressure-based solver type with a transient solver. The turbulence model was specified as SST k- as it agrees with the experimental data based on the literature. The rotational speed or turbine linear velocity is calculated to be 153 RPM with a 2.5 power coefficient. Under Boundary conditions, the inlet velocity magnitude was changed to 5 m/s with the definition in turbine moment, lift and drag reports for a solution. The solver utilised hybrid initialisation with 100 Time Steps and 0.05 s Time Step Size.

RESULTS AND DISCUSSION

This section illustrates the numeric results retrieved from the simulation and provides a descriptive analysis through observation as well as the implementation of aerodynamic concepts.

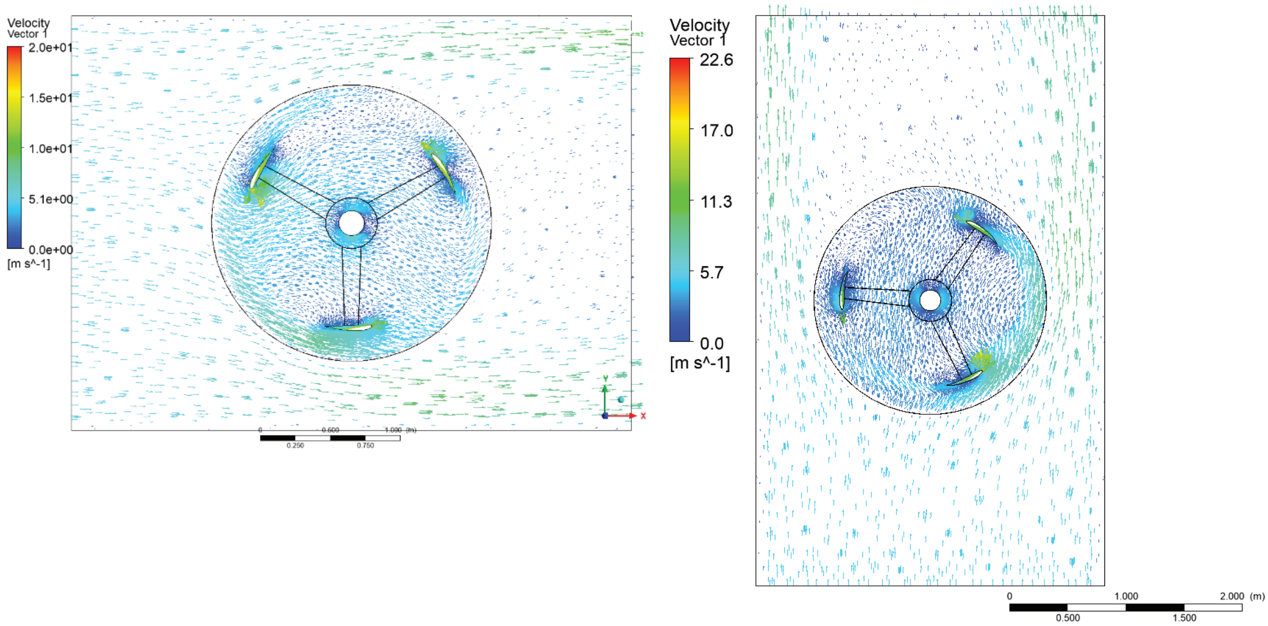
Flow field

Figure 9 illustrates the velocity vectors for the benchmark design, and through observation at the bottom Airfoil for the design, it has the highest velocity magnitudes in comparison to the benchmark. According to Figure 9a, the circulation around the blade design is higher, which leads to a higher lift. In a nominal wake structure, the vortices appear during the pitch-up period during a rotational cycle and the flow structure comprises circular spots or areas with large vorticity as depicted in Figure 9b. Another wake structure represents a wake that has evolved behind the flap with vortices that belong to Karman Vortex Street. The downstream vortices tend to come in contact with other blades passing through the wake as depicted in Figure 9b bottom blade [26]. The circulation around the blade of flap design is higher than the one in benchmark design; therefore, according to Kutta-Joukowski Theorem:

$$L = \rho V_\infty \Gamma \tag{5}$$

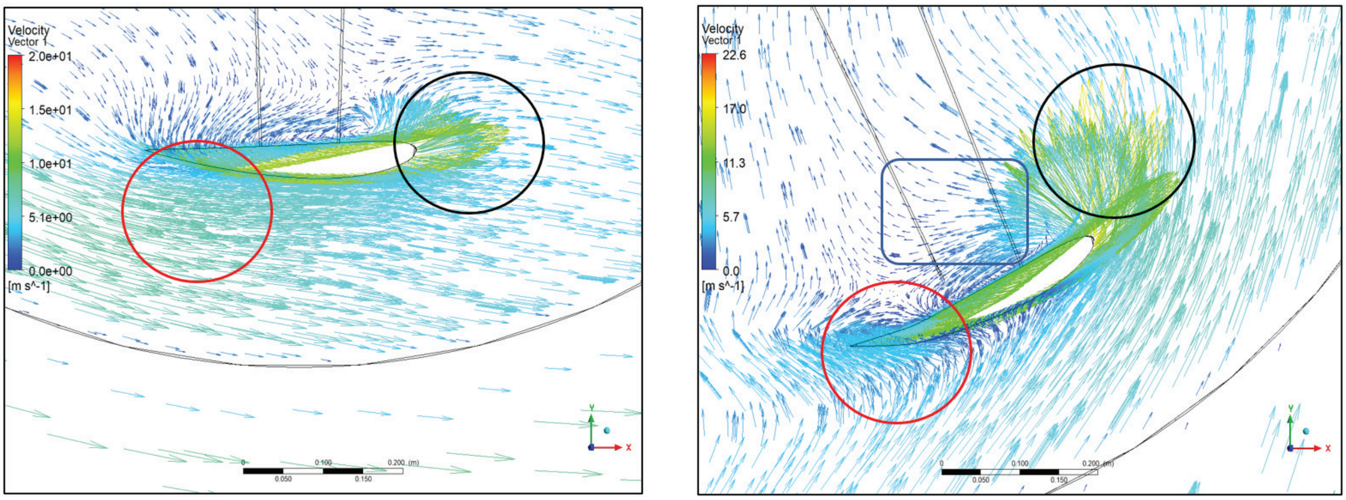
Implying that lift is directly proportional to circulation. Since the flap design has higher circulation, it should have higher lift, which is confirmed by the simulation results shown in Table 1.

In addition, as observed in Figure 10 the regions highlighted by blue rectangles (Airfoil experience approximately similar angle of attack with the respect to the upcoming flow), flow separation is delayed which explains the reduction of the drag when compared to the benchmark. It illustrates that the velocity vectors are aligned very much parallel to the Airfoil. At the leading edge of the Airfoil, the high magnitude vectors are present (as illustrated by the black circle), however, the external wind coming



(a) (b)

Figure 9 Velocity vectors for (a) Benchmark and (b) Design with flaps



(a) (b)

Figure 10 Velocity vectors for bottom airfoil for (a) Benchmark and (b) Design with flaps

towards the Airfoil is not fully supporting the motion, rather it is getting dispersed (as illustrated by a red circle).

From Figure 10a, similar observations are noticeable since high-velocity magnitude vectors are at the leading edge of the Airfoil (as illustrated by the black circle) in the rotation direction; however, on the trailing edge of the Airfoil, vectors with less magnitude are acting in opposite direction exerting drag.

The obtained inlet velocity for the scaled-down prototype of the adopted design (Addition of flaps) is 28.5 m/s as opposed to 5 m/s for the inlet velocity of the original model. Using the inlet velocity of the scaled-down prototype by the application of dynamic similarity, the following prototype simulations should result in accurate power output estimations, which would be used to calculate the total number of vertical axis wind turbines needed to achieve the desired percentage (15%) of total power consumption required in Abu Dhabi University – Al Ain campus.

Lift and Drag

For the design of the turbine, considerations included Lift force, Drag force, and Moment accordingly. Using ANSYS CFD, velocity vectors were shown to analyse the fluid particles' velocities at different points near the turbine walls. Figures 11 and 12 illustrate the graph obtained for Lift [N] and Drag [N] concerning Time [s] obtained from ANSYS numerical simulation of modified turbine design followed by mean calculations for precision.

$$average = mean + (peak - mean) \times \frac{2}{pi} \tag{6}$$

$$Lift\ Force = -375 + 477.75 = 102.75\ (N) \tag{7}$$

$$Drag\ Force = 1200 + 382.2 = 1582.2\ (N) \tag{8}$$

Power Coefficient (C_p)

The compiled electricity consumption of Abu Dhabi University Al Ain campus is about 5,646,953 kWh in the year 2020. The estimated number of working hours in ADU per week is 63 hours including 11 hours per day in working days, while 4 hours per day on the weekend. Then, the total power consumption in the year 2020 is given as:

$$P_{consumption} = \frac{5{,}646{,}953\ \text{kWh}}{63\ \ 52} = 1723.7\ \text{kW} \tag{9}$$

Since the designed turbine should provide 15% of the total power consumption and each turbine provides 6 kW, then the total number required is:

$$Number\ of\ VAMT\ Required = \frac{1723.7 \times 0.15}{6} = 43 \tag{10}$$

The total number of vertical axis wind turbines required to cover 15% of the total electricity consumption in ADU-AA Campus is estimated to be 43.

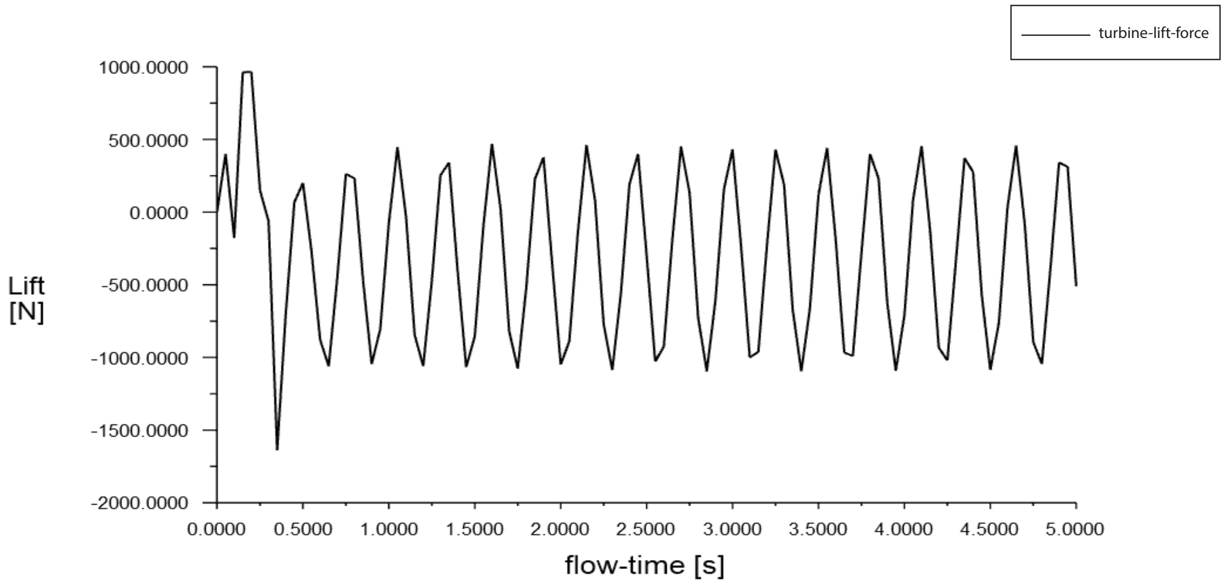


Figure 11 Lift Force [N] concerning Flow time per second [s]

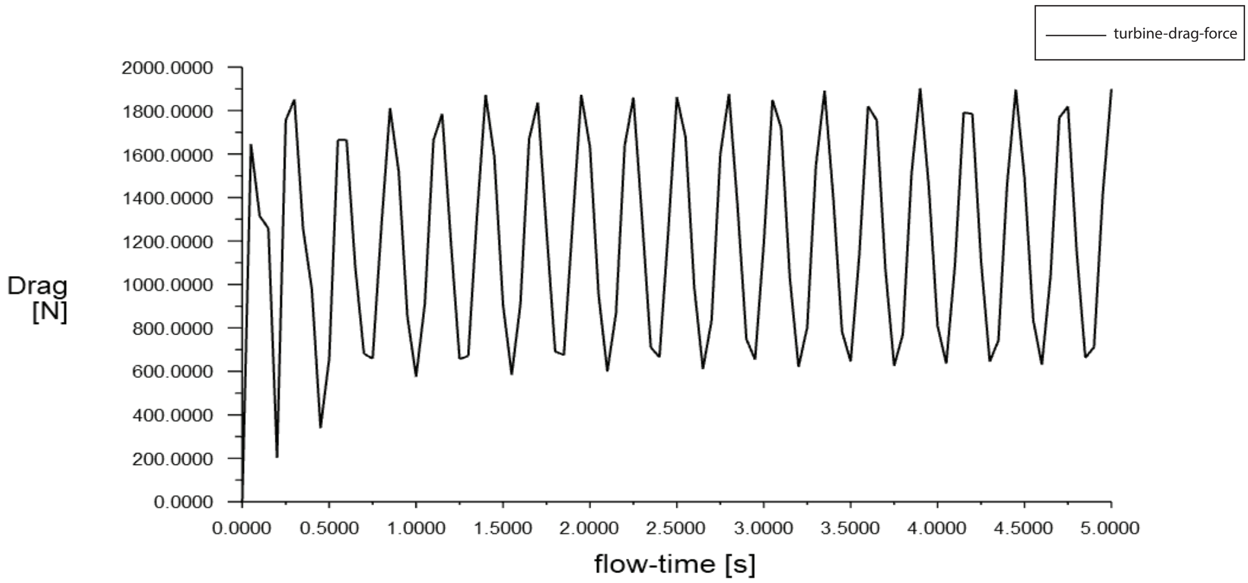


Figure 12 Drag Force [N] concerning Flow time per second [s]

Table 1 Compilation of ANSYS CFD Results

Design Parameters	Benchmark	Design 1 (Addition of Flap)
Torque Generated (N.m)	2.2055	2.274
Lift Force (N)	9.555	19.555
Drag Force (N)	99.555	86.37
Lift/Drag Ratio	0.096	0.226
Power Generated (W)	35.3	36.4
Self-Starting torque (N.m) (Max Torque reached within 0.5 sec)	3.25	4.8

CONCLUSION

The designs' aerodynamics properties were evaluated using ANSYS Fluent simulations and results showed that the design of addition of flaps provided a total increase of 3.11% in power generation. The addition of flaps design results was scaled up using dynamic similarity to obtain the power output for a swept area of a wind turbine of from . This resulted in a total power output of 6 kW per turbine, implying that Abu Dhabi university would require 43 wind turbines to cover 15 percent of the total electricity consumption in a year. Future scope includes utilising wind lens technology to increase the free-stream velocity entering the turbine and hence resulting in higher power generation and efficiency.

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