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Design and Numerical Analysis of Mid-Size Horizontal Axis Wind Turbine Blade for Kagbeni, Nepal

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Abstract

This study presents the aerodynamic design and steady-state CFD validation of a 100kW horizontal-axis wind turbine blade using NREL-S series airfoils, optimized for wind conditions in Kagbeni. The region's reliable and strong wind potential offers promising scope for clean energy generation, particularly in off-grid communities. This study addresses the critical need for site-specific turbine designs by optimizing a mid-size HAWT blade for high-altitude, low-density atmospheric conditions in Kagbeni, Nepal, enhancing local renewable energy potential. The blade geometry was generated in QBlade using site-specific wind data from the Global Wind Atlas and then exported in SolidWorks for CFD analysis. Steady-state RANS simulations were performed in ANSYS Fluent using the SST k–ω turbulence model with a sliding mesh approach of two zones. Mesh convergence was achieved at 4.47 million cells with a torque difference of less than 0.5%. At a tip speed ratio $\lambda = 7$ and a rotational speed of 42 RPM, the rotor produced a torque of 32,612.8Nm and a power output of 143.8kW, corresponding to a power coefficient of $C_p = 0.280$. The study contributes to developing region-specific wind energy solutions for high-altitude sites.

Keywords: Computational Fluid Dynamics; Horizontal Axis Wind Turbine; NREL; Renewable Energy; QBlade

1. Introduction

As the global demand for clean and renewable energy grows, wind energy has become an effective solution for sustainable electricity production. Among the various types of wind energy systems, the Horizontal Axis Wind Turbine (HAWT) remains the most widely used due to its high efficiency and ability to adapt to different sizes and power needs. In regions like Kagbeni, Nepal, known for strong and steady wind patterns, wind energy holds strong potential for reliable power generation.

Kagbeni, a region in Nepal, has strong and steady winds, making it a suitable location for wind energy projects. However, due to its specific wind conditions, specially designed airfoils are required to improve turbine performance. The NREL-S series airfoils, explicitly created for wind turbines, are considered well-suited. Despite Nepal's growing interest in renewable energy, there is limited literature on HAWT blade optimization tailored for its unique terrain and wind patterns. This research fills that gap by designing and numerically validating a 100-kW blade tailored to Kagbeni's steady but low-density winds.

This research focuses on designing and analysing a horizontal-axis wind turbine blade using QBlade software, which applies the Blade Element Momentum (BEM) theory. It also includes CFD simulation using ANSYS Fluent and experimental drag analysis of a 3D-printed model. The main goal is to evaluate the blade's aerodynamic performance and compare the simulation results with experimental data. This project aims to provide valuable insights for wind energy development in promising areas of Nepal. Nepal's first wind energy project was set up in Kagbeni, Mustang in 1985 with two 10 kW turbines. However, the project was dismantled after strong winds damaged the turbines (Forum, 2020). Wind speed in the Kagbeni region varies with height and season. In June, average wind speeds ranged from 7.05–7.6 m/s at 10 m and 9.04–9.75 m/s at 20 m. This corresponds to an annual energy potential of 3.98 MWh/m² at 10 m and 4.82 MWh/m² at 20 m. The highest recorded wind speed was 22.53 m/s

Horizontal-axis turbines offer high aerodynamic efficiency and operational reliability for utility-scale wind power. NREL's S-series airfoils provide robust lift-to-drag performance in rough, high-Re conditions (Somers, 2005; Sørensen, 2011). Kagbeni (2,800 m elevation, Mustang, Nepal) has a mean wind speed of 10 m/s—ideal for a 100 kW mid-size turbine (DTU, n.d.) (Authority, 2023).This work uses QBlade's BEM framework (D. Marten, 2013) and ANSYS Fluent to design blade geometry, verify mesh independence, and predict performance metrics (Malalasekera, 2007).

2. Materials and Methodology

Completing the research requires workflow tools and methodology for its systematic execution. Various software and tools were used to ensure this, and the methodology was followed.

2.1 Tools and software

a) QBlade v0.6: BEM-based blade designing.
b) ANSYS Fluent 2021 R1: Steady RANS CFD with SST k–ω and sliding mesh (Inc., 2021).
c) SolidWorks 2021: Airfoil lofting, blade exporting, and complete rotor assembly (Systèmes, 2021).
d) Global Wind Atlas (DTU, n.d.): High-resolution wind data.
e) Weather And Climate (Climate, n.d.): Local pressure and humidity.
f) Omni Calculator (Calculator, n.d.): Air density and viscosity.

2.2 Methodology

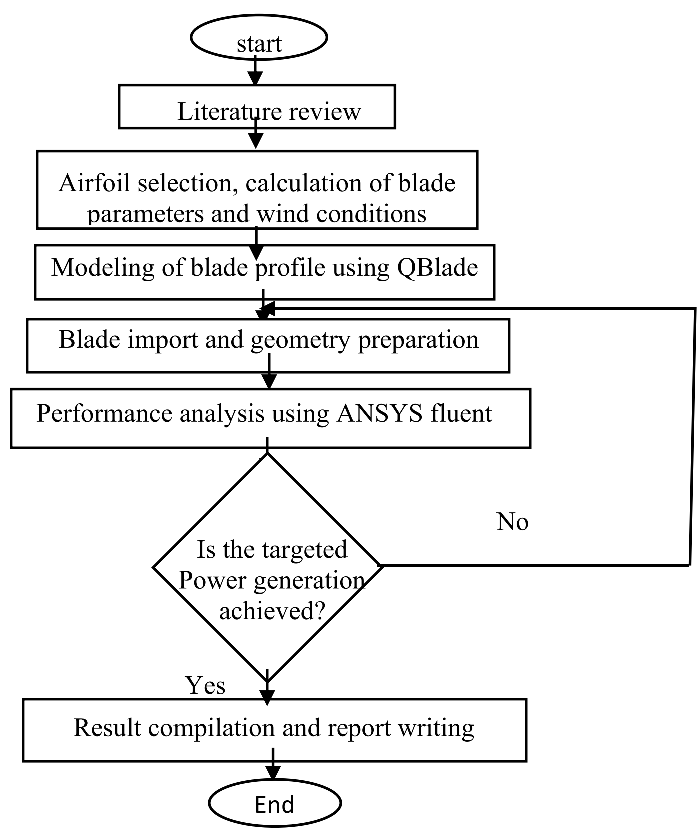

Figure 1: Methodological Chart

2.2.1 Density Approximation

Data for density consideration in the Kagbeni region was taken from "Weather and Climate." It is an online climate zone and data finder for 80,000+ locations worldwide based on climate classification. The weather data, i.e., temperature, pressure, and humidity from 2016 to 2020, are taken and analyzed. The obtained data shows that the density is approximately 1.24 kg/m^3.

Table 1: Kagbeni ambient data and density (Climate, n.d.)

Descriptions	Summer	Winter
Pressure (mb)	1022	1032
Temperature (°c)	34.46	-7.09
Humidity (%)	80	50
Density (kg/m³)	1.14	1.40

2.2.2 Blade Length Calculation

The blade length is calculated from the following procedure:
Considerations:
ρ= 1.240 kg/m3, v= 10m/s,
C_p=0.3
P_{output} = 100kW
k_w = 5%
k_m = 0.2%
k_e = 1.5%
$k_{e,t}$ = 5%
k_t = 3%
$\mu' = (1-k_m)\times(1-k_e)\times(1-k_{e,t})\times(1-k_t)\times(1-k_w)\times C_p$
μ'= 0.258
$P_{output} = \mu\times P_{wind}$ ($\therefore P_{wind} = 0.5\times\rho\times v^3\times\pi\times R^2$)
R = 14.540m
R ≈ 15m

2.2.3 Chord Length Calculation

Several theories exist for determining the optimal chord length, which can provide an initial approximation for each blade section. Among these, the theory presented in Wind Turbine Technology: Principles and Design by Muyiwa Adaramola (Adaramola, 2014), which offers the following calculation formula.

$$C(r) = \frac{2\pi r}{n}\frac{8}{9C_L}\frac{U_{wd}}{\lambda_r V_r} \tag{1}$$

where,

$$Vr = \sqrt{V_w^2 + U^2} \tag{2}$$

The average of C(r) is obtained as 1.23.

2.2.4 Airfoil selection

Since 1984, NREL has classified 35 airfoil families for various-sized rotors by performing different experiments. NREL has specified various combinations of airfoils for best performance. The selection of the combination of S830, S831, and S832 from root to tip was based on analyzing different experiments and various papers by NREL.

2.2.5 Rotational speed calculation

A 3-blade wind turbine typically operates best at a TSR between 6 and 8. This range offers a balance between efficiency and structural stability. A TSR that is too low (<6) results in slow rotor speeds, which reduce efficiencies due to high drag on the blades and loss of lift. A TSR that is too high (>8) may lead to excessive stress on the turbine blades, increasing noise and wear while also reducing efficiency due to increased drag and turbulence, so with this consideration, selecting the value of TSR (λ)=7.

$$N = \frac{V \times \lambda \times 60}{2 \times \pi \times R'} \tag{3}$$

Results N= 41.779

N≈ 42 RPM

The rotational speed of 42 RPM was obtained and used for the analysis.

2.2.6 Blade Modelling

The airfoil analysis data was taken from ‘airfoil tools. ' The airfoil profiles were organized in proper size, shape, and twist using built-in programs and codes. Thus, the obtained coordinates of the blade profile were extracted in SOLIDWORKS. Then, a single blade was prepared from the curves using a loft tool. The hub design, assembly, and all other adjustments are entirely done in SOLIDWORKS.

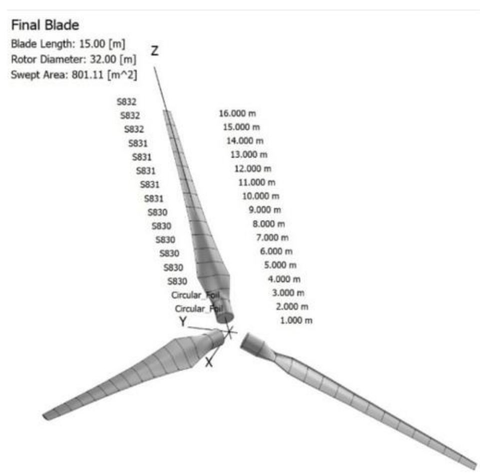

Figure 2: Blade modeling in qblade

2.2.7 The governing equations of the Multiple Reference Frame (MRF) approach

The Multiple Reference Frame (MRF) approach in Computational Fluid Dynamics (CFD) is a steady-state method used to simulate flows involving rotating components, such as fans, impellers, or turbines, without requiring a full transient (time-dependent) simulation. This method divides the computational domain into different zones: rotating zones, where the flow equations are solved in a rotating frame of reference, and stationary zones, where the standard Navier–Stokes equations are applied. The governing momentum equation is modified within the rotating zones to account for rotational effects by including additional source terms: Coriolis and centrifugal forces. The modified momentum equation becomes:

$$\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\vec{u} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\vec{u} - 2\vec{\Omega} \times \vec{u} - \vec{\Omega} \times (\vec{\Omega} \times \vec{r}) \tag{4}$$

2.2.8 Geometry preparation

The computational domain is a 3D rectangular enclosure with a rotating circular zone around the wind turbine rotor and a surrounding stationary zone. The rotating zone captures unsteady aerodynamic effects, while the stationary zone ensures proper air inflow and outflow. Their interaction is managed using the Multiple Reference Frame (MRF) approach to simulate rotor-induced flow dynamics accurately.

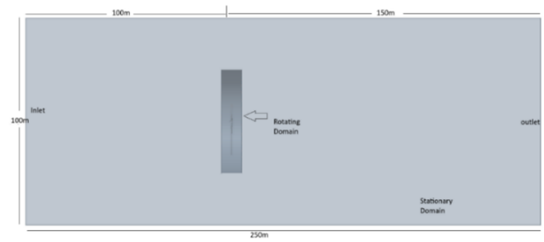

Figure 3: Side view of computational domain

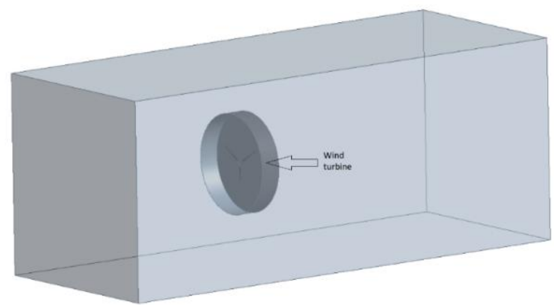

Figure 4: Isometric view of the domain

2.2.9 Meshing

This approach uses an unstructured tetrahedral grid, with a finer mesh near rotor blades for boundary layers and a coarser mesh elsewhere to ensure smooth transitions and accurate interactions with the stationary domain.

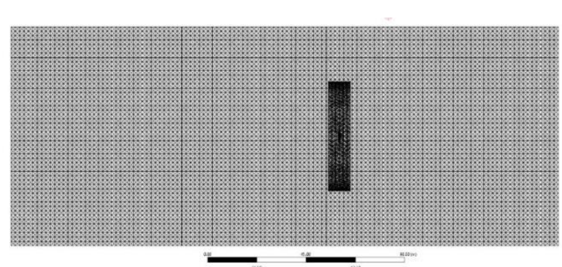

Figure 5: Wireframe mesh

2.2.10 Boundary Conditions

For the wind turbine simulation, a rotating reference frame (Sliding mesh type) designates the wind turbine as a wall boundary.

Table 1: boundary condition table

General	Solver	Pressure Based
	Time State	Steady
	Gravity	-9.81 m/s^2
Model	Viscous: SST K- Omega	
Material	fluid air	
Cell zone condition	Solid rotating zone at 42 RPM	fluid

Boundary Conditions	Inlet	Velocity= 10m/s
	Outlet	Pressure outlet
Solution Methods	Pressure-velocity compounding	Second-Order Upwind Scheme (SIMPLE)scheme
	Pressure	Second order
	Momentum	Second order
Initialization	Hybrid Initialization	

3. Mesh independence test

As the number of elements increases, the torque significantly increases, but the rate of change gradually decreases. Beyond approximately 4.4 million elements, the torque values stabilize, indicating that further mesh refinement has minimal impact on the results. There is no such significant change in the torque on the 4474215 elements, so the analysis was carried out in this number of elements.

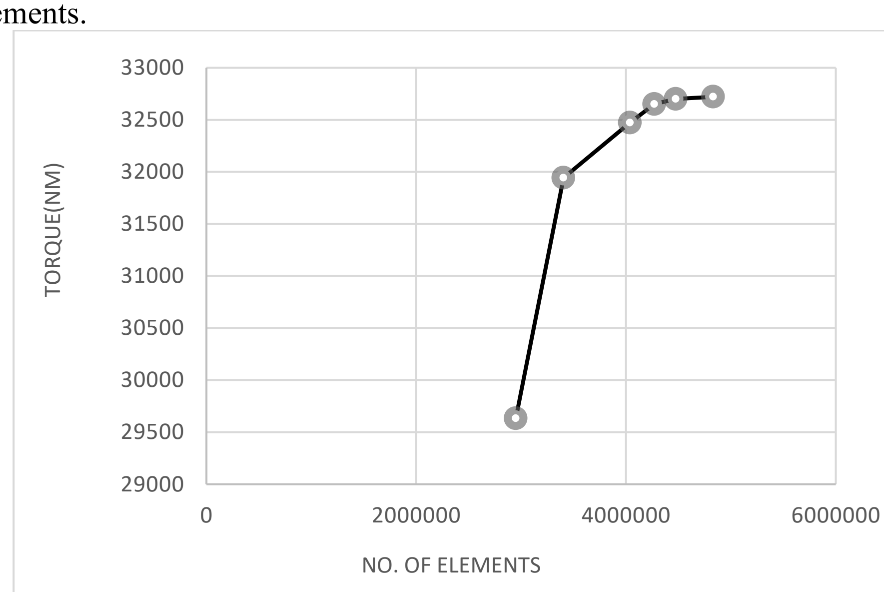

Figure 6: Mesh Independence Graph

4. Result

The CFD analysis of the wind turbine rotor at Tip speed ratio () =7 at 42 RPM revealed that the turbine produced a torque of 32612.824 Nm and a power of 143.83 kW.

When the pressure and velocity contours are analyzed, the higher pressure is concentrated near the blade root, while the lower pressure appears towards the tip. Velocity increases from the hub to the tip, reaching its peak at the blade ends. The pressure difference between the suction and pressure sides of the blades contributes to the lift force, which drives the rotor. The results confirm that the simulation accurately represents the wind turbine's performance under the given conditions.

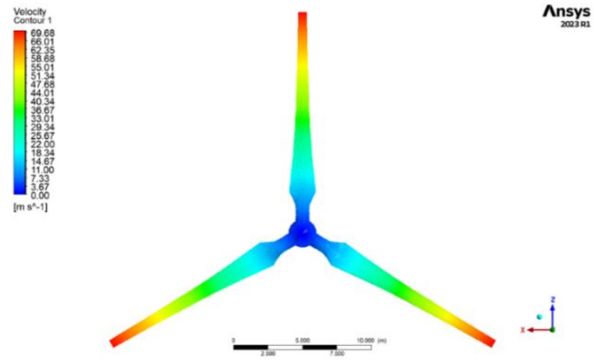

Figure 7: Velocity contour of full-scaled model

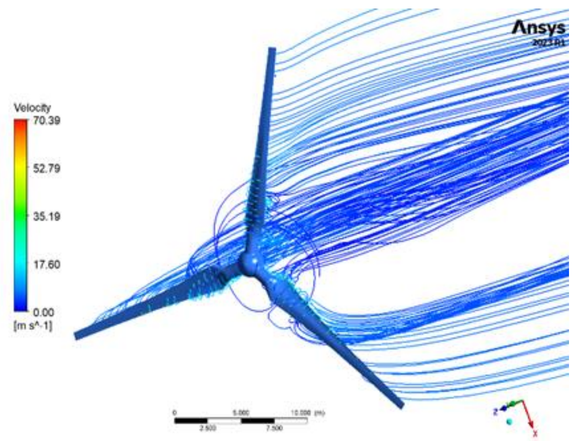

Figure 8: velocity streamline

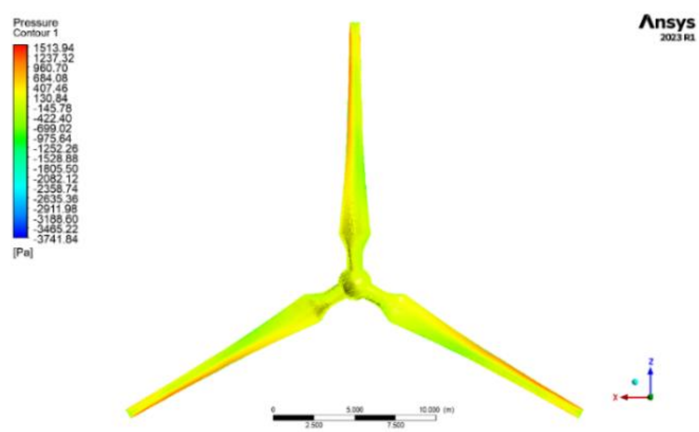

Figure 9: Pressure contour of full-scaled model

The velocity streamline shows that the flow separation is visible near the hub and along the blade root due to lower velocity and turbulence. The smooth, continuous streamlines around the blade tips indicate efficient aerodynamic performance.

5. Conclusion

A mid-scale HAWT blade using NREL S-series airfoils was designed for the Kagbeni region's wind conditions. By integrating site-specific wind data, aerodynamic modelling in QBlade, and scaled experimental validation, the blade demonstrated a power coefficient of 0.280 and a torque output of 32612.824Nm, generating 143.438 kW of power, consistent with the design objectives. An accurate wind tunnel experiment should be conducted to ensure the reliability of simulated values with experimental values. This will ensure future advancements in research on wind energy potential in the context of Nepal.

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