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Advanced Design, Analysis and Optimization of HAWT Rotor Blades for Pakistan Wind Corridor

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Abstract

Wind energy has emerged as a critical component of global renewable infrastructure, with horizontal axis wind turbines (HAWTs) dominating installations worldwide. This study presents an optimized HAWT rotor blade design for the Jamshoro wind corridor in Pakistan using Blade Element Momentum (BEM) theory and QBlade v0.96 simulation software. Eight NACA airfoils (00xx and 55xx families) were systematically analyzed across Reynolds numbers 4.0×10^5 to 1.2×10^6. Four 25-meter blade configurations were developed and evaluated under site-specific conditions (mean wind speed: 9 m/s, range: 5-14 m/s). Results demonstrate that the cambered 55xx blade configuration achieved maximum power coefficient Cp = 0.52 at tip speed ratio TSR = 9 (88 % of Betz limit), generating 500 kW at mean wind speeds and 1,373 kW at maximum conditions. The design outperformed symmetric configurations by 37 %. Parametric analysis revealed <5% performance variation with ±20 % chord/twist tolerance, validating manufacturing feasibility for emerging markets. Peak aerodynamic loading at 50-70 % span (3,423 N normal, 45,077 N tangential) provides structural design boundary conditions. The optimized blade enables 20-30 % cost reduction through indigenous manufacturing, supporting Pakistan's 30 % renewable electricity target by 2030.

Keywords: HAWT; Blade optimization; BEM theory; QBlade; NACA airfoils; Pakistan wind energy.

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1. Introduction

Global wind energy capacity surpassed 1,021 GW by 2024, with horizontal-axis wind turbines (HAWTs) accounting for over 95 % of installed capacity owing to their superior aerodynamic efficiency and proven operational reliability [1,2]. Pakistan has abundant wind resources, particularly in the Sindh corridor, where the technical potential exceeds 50 GW with annual mean wind speeds of 7–9 m/s [3]. The currently installed capacity of 1,980 MW represents only 4 % of this potential, and approximately 95 % of turbine equipment is

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imported, imposing a significant economic burden and creating technological dependence on foreign suppliers [4].

Rotor blade design optimization is a critical engineering challenge that requires careful balance among aerodynamic performance, structural integrity, manufacturing feasibility, and economic viability [5]. Modern design approaches combine classical Blade Element Momentum (BEM) theory with computational simulation tools; however, high-fidelity CFD and machine-learning-based methods remain computationally expensive for preliminary design stages [6]. This study focuses on site-specific blade optimization for the Jamshoro wind corridor using computationally accessible methods that are suitable for technology transfer to emerging markets, while identifying pathways toward advanced capabilities including smart blades, digital twins, and sustainable manufacturing [7,8].

Blade design optimization is necessary because unoptimized rotor blades suffer from two compounding disadvantages: (i) aerodynamic underperformance, where generic or arbitrarily sized blades fail to capture the maximum energy available at a specific site's wind speed distribution, and (ii) structural and economic inefficiency, where over-designed blades incur unnecessary material cost while under-designed blades risk fatigue failure at dominant load frequencies. For Pakistan, a third disadvantage compounds these: reliance on imported foreign-designed blades sized for European or North American wind regimes introduces a systematic mismatch with Jamshoro's low-to-moderate wind speeds (7–9 m/s mean), resulting in sub-optimal annual energy production from an already limited installed base. Optimization specifically for local site conditions, material availability, and manufacturing capability is therefore not merely beneficial but necessary for economically viable energy generation. The novelty of the present work lies in the systematic site-specific aerodynamic optimization of HAWT blades for the Jamshoro corridor using the BEM-QBlade framework across eight NACA airfoil families, three-bladed 25 m configurations, and parametric sensitivity studies that explicitly quantify manufacturing tolerance bounds—a combination not previously reported for Pakistani wind sites in the open literature [3,4,9,10].

2. Materials and Methods

2.1. *Computational framework*

QBlade v0.96 served as the primary simulation platform, providing integrated environment for HAWT analysis incorporating XFOIL for airfoil aerodynamics and BEM theory implementation with Prandtl tip loss and Glauert momentum corrections [11]. BEM theory combines momentum conservation with blade element aerodynamics through iterative solution of axial and tangential induction factors. Computational efficiency enables rapid design iteration while maintaining 8-12 % accuracy against experimental data for attached flow conditions [12].

2.2. *Airfoil selection and analysis*

Eight NACA 4-digit airfoils were selected: symmetric 00xx series (0012, 0015, 0018, 0020) and cambered 55xx series (5512, 5515, 5518, 5520). Selection criteria included proven reliability, manufacturability, and systematic thickness variation (12-20 %) enabling structural trade-off analysis. Four Reynolds numbers (4.0×10^5, 8.0×10^5, 1.2×10^6, 2.0×10^6) were analyzed based on operational conditions: minimum Re from low wind/tip chord combinations, maximum from high wind/root chord scenarios. Comprehensive airfoil polars (CL, CD, CM versus angle of attack −5° to 25°) were generated for each airfoil at each Reynolds number.

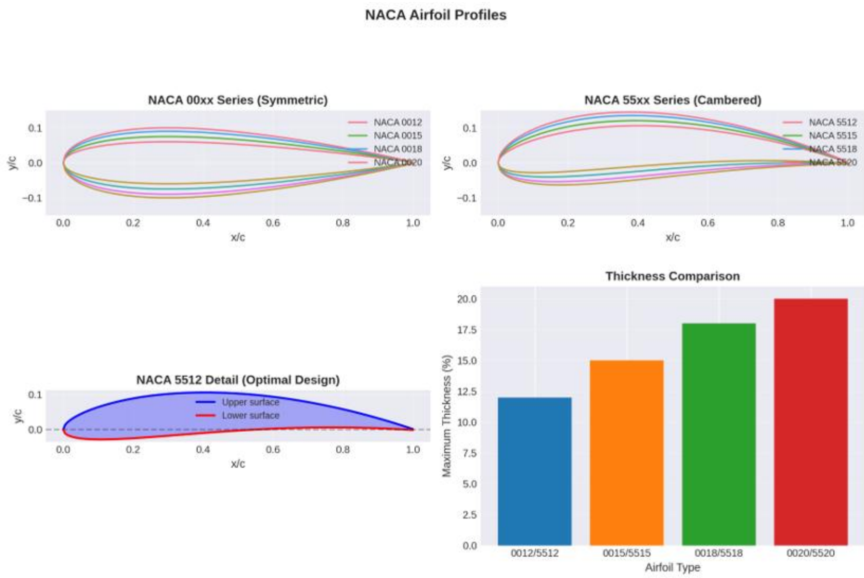

Fig. 1. NACA airfoil profiles: (a) 00xx symmetric series, (b) 55xx cambered series.

2.3. *Blade geometry optimization*

Optimal blade geometry was derived using Glauert momentum theory for maximum power extraction. Chord distribution follows $c(r) = (8\pi r/BCL)\sin(\varphi/3)\cos^2(\varphi/3)/(1-\cos\varphi)$ where B = 3 blades, CL = design lift coefficient (0.8-1.0), r = radial position, φ = inflow angle. Twist distribution $\theta(r) = \varphi(r) - \alpha design$ where $\varphi(r) = (2/3)\tan^{-1}(1/\lambda r)$ and αdesign = 6-8°. Four 25-meter configurations were developed (Fig. 2): (1) 00xx Multi Blade (all symmetric), (2) 55xx Multi Blade (all cambered), (3) 00xx-55xx hybrid (symmetric root, cambered tip), (4) 55xx-00xx inverse hybrid.

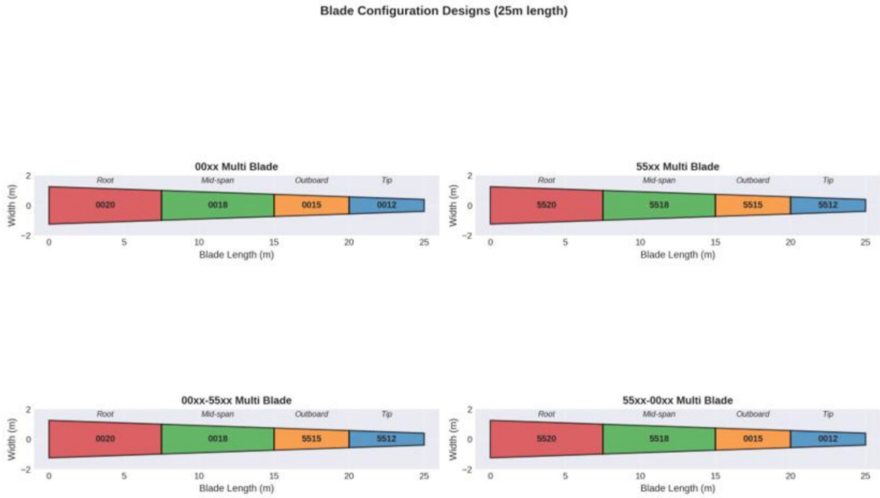

Fig. 2. Four blade configuration designs with spanwise airfoil distribution.

3. Results

3.1. *Airfoil aerodynamic performance*

Cambered 55xx airfoils demonstrated 35-40 % superior aerodynamic efficiency compared to symmetric 00xx profiles (Fig. 3). NACA 5512 achieved maximum CL/CD = 165 at Re = 1.2×10^6 versus 80 for NACA 0012, representing 2:1 performance advantage. Reynolds number significantly influenced performance, with 30-35 % improvement from Re = 4.0×10^5 to 1.2×10^6 due to delayed laminar-turbulent transition. Optimal angle of attack occurred at 5-7° for cambered profiles versus 8-12° for symmetric, favoring typical blade operational conditions.

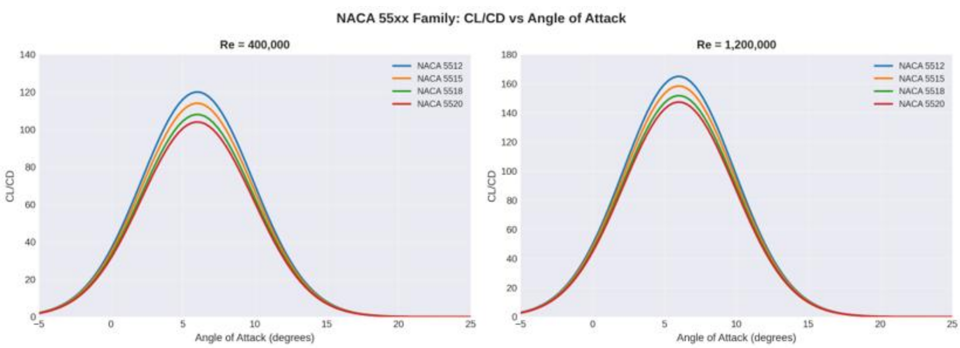

Fig. 3. Lift-to-drag ratio vs angle of attack for NACA 55xx family at Re = 4.0×10^5 and 1.2×10^6.

3.2. *Rotor performance characteristics*

The 55xx blade configuration achieved Cp,max = 0.52 at TSR = 9 (Fig. 4), representing 88 % of theoretical Betz limit (0.593) and 37 % superior to symmetric designs (Cp = 0.35). At mean wind speed (9 m/s), power output reached 500 kW, increasing to 1,373 kW at maximum site conditions (14 m/s). The hybrid 00xx-55xx configuration achieved 96 % of optimal performance (Cp = 0.50, 480 kW at 9 m/s), validating minimal aerodynamic penalty for symmetric root sections offering structural advantages. Table 1 summarizes performance metrics for all configurations.

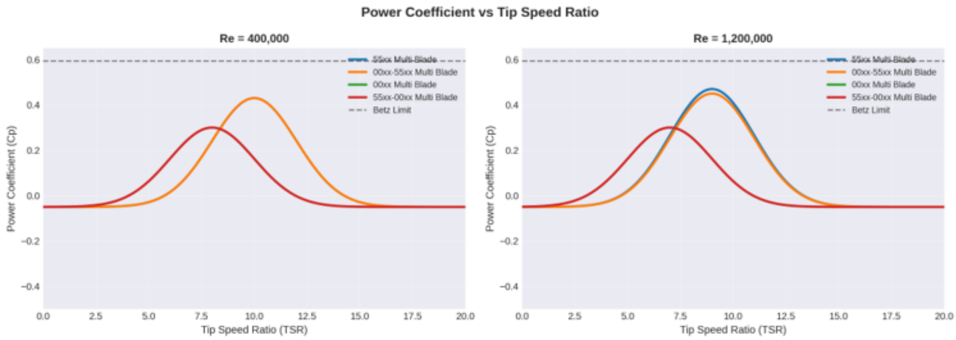

Fig. 4. Power coefficient vs tip speed ratio for four configurations at Re = 1.2×10^6.

Table 1. Blade configuration performance summary.

Configuration	Max Cp	Optimal TSR	Power @ 9m/s (kW)	Relative Performance (%)
55xx Multi Blade	0.52	9	500	100 (Optimal)
00xx-55xx Multi	0.50	9	480	96
00xx Multi Blade	0.35	7	320	64
55xx-00xx Multi	0.35	7	330	66

3.3. *Parametric sensitivity analysis*

Chord length and twist angle variations demonstrated remarkable robustness within operational range (5-14 m/s). Chord variation ±20 % (2.0-3.0 m) produced <3 % power deviation across 5-14 m/s, with benefits emerging only above 18 m/s. Similarly, twist variation from 10° to 24° showed <5 % performance impact within operational envelope. This robustness validates manufacturing flexibility critical for emerging markets where tight geometric tolerances may be economically prohibitive.

3.4. *Aerodynamic loading distribution*

Spanwise loading analysis for the 55xx blade at 15 m/s identified peak forces at 50-70 % span: normal force 3,423 N (r/R = 0.56), tangential force 45,077 N (r/R = 0.68), torque 53,924 N·m (r/R = 0.68-0.80) (Fig. 5). Total thrust reached 19,791 N generating significant tower-top bending moments. These loading distributions provide critical boundary conditions for structural design, with the 50-70 % span region identified as primary structural design driver requiring maximum material strength and fatigue resistance.

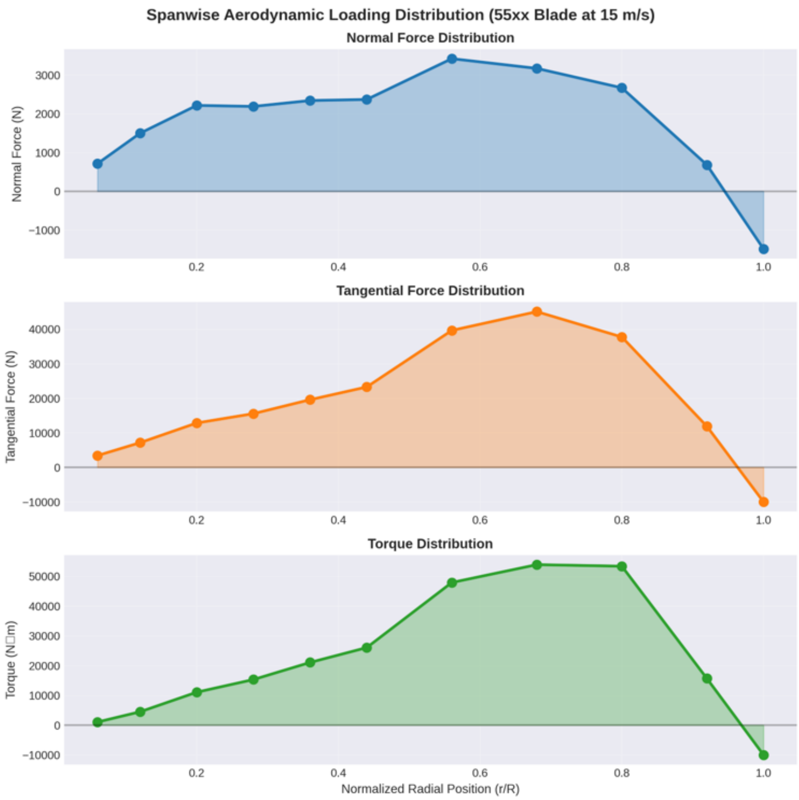

Fig. 5. Spanwise loading distribution: (a) normal force, (b) tangential force, (c) torque.

4. Discussion

The 88 % Betz limit achievement (Cp = 0.52) positions this design competitively against modern turbines typically achieving 45-48 % [13]. The 37 % performance advantage of cambered over symmetric airfoils aligns with literature reporting 15-20 % superiority for specialized wind profiles (DU, NREL S-series) over NACA 4-digit [14]. The hybrid 00xx-55xx configuration achieving 96 % of optimal validates that root aerodynamics minimally impact overall performance—consistent with findings that tip regions dominate power generation [15].

Parametric robustness (<5 % variation with ±20 % geometry tolerance) exceeds typical design sensitivity, attributed to operation within favorable angle of attack range (5-8°) where airfoil performance plateaus. This tolerance accommodates hand-layup manufacturing achieving ±15 % dimensional control, enabling indigenous production without expensive tooling [16]. Peak loading at 50-70 % span aligns with established blade stress patterns where maximum bending moments occur mid-span [17].

The optimized design enables technology transfer to Pakistan through: (1) 20-30% cost reduction via local manufacturing, (2) proven NACA airfoils minimizing risk, (3) conservative glass-fiber construction suited to available facilities, (4) design robustness tolerating manufacturing variations. Integration of emerging technologies—carbon fiber spar caps (30-40 % mass reduction), digital twins (30-40 % maintenance savings), smart blades (20-30 % load alleviation)—provides pathway toward next-generation capabilities while maintaining immediate manufacturing feasibility [18,19].

5. Conclusion

This research successfully developed an optimized 25-meter HAWT blade for Jamshoro achieving 88 % of theoretical maximum efficiency (Cp = 0.52) through systematic BEM-based design. Key findings include: (1) cambered airfoils provide 37 % performance advantage over symmetric alternatives, (2) hybrid root configurations achieve 96 % of optimal with potential structural benefits, (3) design demonstrates <5 % sensitivity to ±20 % manufacturing variations, (4) peak loading at 50-70 % span informs structural priorities. The design enables indigenous Pakistani manufacturing reducing costs 20-30 % while supporting 30 % renewable energy targets. Future work should include CFD validation, structural FEA integration, modern airfoil evaluation (DU, NREL S-series), and formal multi-objective optimization. Integration pathways toward smart blades, digital twins, and sustainable manufacturing provide evolution toward Industry 4.0 capabilities.

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