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Performance Evaluation of a NACA 4415-Based Horizontal Axis Wind Turbine for Coastal Wind Conditions in Lombok, Indonesia

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Abstract

The growing demand for renewable energy has encouraged the development of wind energy technologies as sustainable alternatives to conventional power generation systems. This study evaluates the performance of a horizontal axis wind turbine (HAWT) based on the NACA 4415 airfoil under coastal wind conditions in Lombok, Indonesia. The aerodynamic characteristics of the airfoil were analyzed using QBlade software, including lift coefficient, drag coefficient, pressure distribution, boundary layer behavior, and 360° polar extrapolation. Subsequently, a wind turbine blade was designed using the NACA 4415 airfoil and assessed through Blade Element Momentum (BEM) analysis. Turbulent wind field conditions representative of the coastal environment were incorporated into the simulation to provide realistic operating conditions. The results indicate that the NACA 4415 airfoil exhibits favorable aerodynamic characteristics, characterized by high lift generation and relatively low drag within the operational range of angles of attack. The 360° polar extrapolation provided comprehensive aerodynamic data suitable for turbine performance prediction under both normal and stalled conditions. Furthermore, the turbulent wind field simulation demonstrated the capability of the turbine model to operate under fluctuating wind conditions typical of coastal regions. Overall, the findings suggest that the NACA 4415 airfoil is a promising candidate for horizontal axis wind turbine applications in coastal areas of Lombok and may contribute to the development of small-scale renewable energy systems in Indonesia.

Keywords: Wind energy; Horizontal axis wind turbine; NACA 4415; QBlade; Coastal wind conditions

1. Introduction

The increasing global demand for energy, coupled with concerns regarding environmental sustainability and greenhouse gas emissions, has accelerated the development and utilization of renewable energy resources. Among various renewable energy technologies, wind energy has emerged as one of the most promising alternatives due to its abundant availability, technological maturity, and capability to generate electricity without producing direct carbon emissions [1,2]. According to recent global energy reports, wind power continues to contribute significantly to the expansion of renewable electricity generation worldwide, making it an essential component of the transition toward sustainable energy systems [3].

Indonesia possesses considerable renewable energy potential, including solar, hydro, geothermal, biomass, and wind energy resources. As an archipelagic nation with extensive coastal areas, Indonesia experiences favorable wind conditions in several regions, particularly in eastern Indonesia [4]. The utilization of wind energy is expected to support national energy diversification programs and reduce dependence on fossil-fuel-based electricity generation. However, the implementation of wind energy systems in Indonesia remains limited compared to its available resource potential, indicating the need for further technical assessments and site-specific studies [5].

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Lombok Island, located in the Province of West Nusa Tenggara, is characterized by extensive coastal regions that are exposed to seasonal wind patterns throughout the year. Several coastal areas in Lombok have been identified as having potential for wind energy development due to relatively consistent wind speeds and open terrain conditions. The coastal environment offers favorable opportunities for the installation of small- to medium-scale wind turbines capable of supplying electricity for local communities, tourism facilities, and distributed energy systems [6]. Nevertheless, the successful deployment of wind turbines requires appropriate aerodynamic design and performance evaluation under local wind conditions.

The aerodynamic performance of a horizontal axis wind turbine (HAWT) is strongly influenced by the characteristics of the airfoil employed in the blade design [7]. Among the various airfoil profiles available for wind turbine applications, the NACA 4415 airfoil has attracted significant attention because of its favorable lift-to-drag ratio, good aerodynamic efficiency, and stable performance over a wide range of angles of attack [8,9]. These characteristics make the NACA 4415 airfoil suitable for small-scale and medium-scale wind turbine blade designs operating under moderate wind speed conditions. Furthermore, advances in computational tools such as QBlade have enabled detailed aerodynamic and structural analyses of wind turbine blades through the integration of airfoil modeling, blade design, Blade Element Momentum (BEM) analysis, and turbine performance simulation [10].

Previous studies have investigated the aerodynamic characteristics of NACA-series airfoils and their applications in wind turbine blade development [11,12]. However, limited studies have focused on evaluating the performance of NACA 4415-based horizontal axis wind turbines under the specific coastal wind conditions of Lombok, Indonesia. Therefore, a comprehensive assessment combining airfoil analysis, blade design, rotor performance evaluation, and turbine simulation is required to determine the suitability of the selected airfoil for wind energy harvesting in the region.

This study aims to evaluate the performance of a horizontal axis wind turbine employing the NACA 4415 airfoil using the QBlade simulation platform. The investigation includes aerodynamic characterization of the airfoil, blade design development, structural blade assessment, and rotor performance analysis using the Blade Element Momentum (BEM) method. Furthermore, the turbine performance is evaluated under representative coastal wind conditions in Lombok, Indonesia, to assess its potential for renewable electricity generation in coastal environments.

2. Material and Methods

2.1. Study Area and Wind Data

This study was conducted to evaluate the performance of a horizontal axis wind turbine (HAWT) utilizing the NACA 4415 airfoil under coastal wind conditions in Lombok, Indonesia. The selected study area was Kuta Beach, Lombok, a coastal region characterized by relatively consistent wind patterns throughout the year. Wind statistics used in this study were obtained from long-term wind observations available from the Kuta Bay-Lombok wind database (Figure 1). The wind rose analysis indicates that the prevailing wind direction is dominated by easterly and southeasterly winds, while the majority of wind speeds are distributed within the moderate wind-speed range suitable for small-scale wind energy applications.

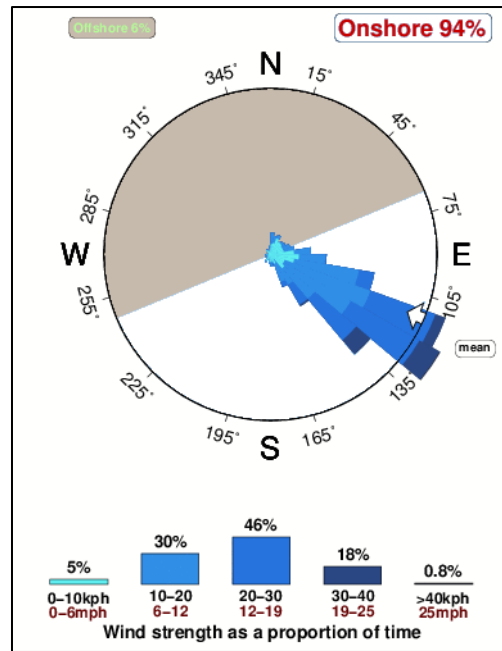


Figure 1 Kuta Bay-Lombok, Indonesia wind statistics, June average since 2006 (<https://www.surf-forecast.com/breaks/Kuta-Bay-Lombok/wind-stats>) [13]

The wind data were used as the reference environmental condition for evaluating the aerodynamic and operational performance of the designed wind turbine. The dominant wind speed range obtained from the site assessment was subsequently applied as the input condition for turbine performance simulations

2.2. Airfoil Design and Aerodynamic Analysis

The blade design was based on the NACA 4415 airfoil, which is a four-digit NACA airfoil characterized by a maximum camber of 4% located at 40% of the chord length and a maximum thickness of 15% of the chord length (Figure 2). The airfoil geometry was generated and analyzed using the QBlade software package.

Aerodynamic characteristics including lift coefficient (C_l), drag coefficient (C_d), lift-to-drag ratio (C_l/C_d), pressure distribution, boundary layer development, and moment coefficient (C_m) were evaluated over a range of angles of attack. Furthermore, 360° polar extrapolation was performed to obtain aerodynamic data required for the Blade Element Momentum (BEM) calculations under both normal and stalled operating conditions.

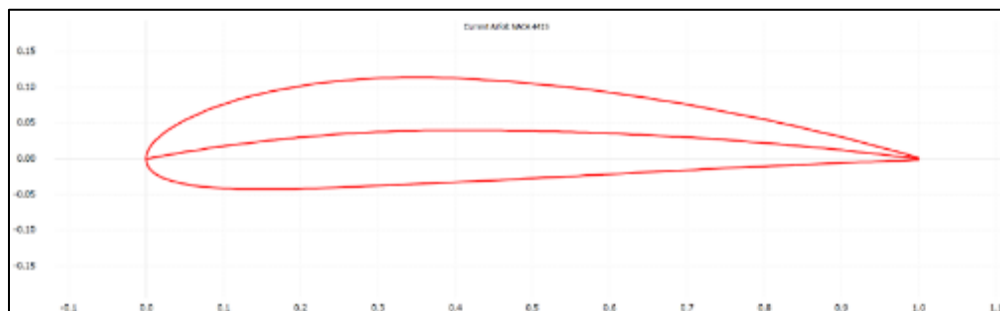


Figure 2 Geometry of the NACA 4415 airfoil used for wind turbine blade design

Table 1 Geometric characteristics of the NACA 4415 airfoil

Foil name	Thickness (%)	At (%)	Camber (%)	At (%)	Points	LE Flap (deg)
NACA 4415	15.00	30.50	4.00	39.70	201	0.00

2.3. Wind Turbine Blade Design

The wind turbine blade was designed using the Horizontal Axis Wind Turbine (HAWT) configuration. Blade geometry was developed in QBlade based on the aerodynamic characteristics of the NACA 4415 airfoil. The blade design process included the determination of chord distribution, twist distribution, and radial blade sections to achieve optimal aerodynamic performance.

Structural properties of the blade were also evaluated, including flapwise stiffness (EI_x), edgewise stiffness (EI_y), torsional stiffness (GJ), and longitudinal stiffness (EA). These parameters were used to assess the structural integrity of the blade under aerodynamic loading conditions.

2.4. Turbine Modeling and Simulation Setup

A complete wind turbine model was created in QBlade for performance evaluation. The turbine was configured as a three-bladed upwind horizontal axis wind turbine. The Unsteady Blade Element Momentum (UBEM) method was employed to simulate aerodynamic interactions between the rotor and incoming wind flow.

The primary turbine parameters included rotor geometry, tower configuration, wake model settings, blade discretization, and dynamic stall modeling. The simulation environment was defined using standard atmospheric conditions with an air density of 1.225 kg/m^3 and gravitational acceleration of 9.81 m/s^2 .

The operating conditions were specified through rotational speed, tip speed ratio (TSR), and wind speed inputs. Wind inflow was assumed to be uniform and aligned with the rotor axis. Additional simulation parameters such as timestep size, simulation duration, convergence criteria, and aerodynamic correction models were set according to the default recommendations provided by QBlade.

2.5. Blade Element Momentum Analysis

The aerodynamic performance of the rotor was evaluated using the Blade Element Momentum (BEM) method integrated within QBlade. The BEM approach combines blade element theory and momentum theory to estimate the aerodynamic forces acting on each blade section.

Performance indicators analyzed in this study included the power coefficient (C_p), thrust coefficient (C_t), torque distribution, and angle of attack variation along the blade span. These parameters were used to determine the efficiency of the turbine in converting wind kinetic energy into mechanical power under the prevailing coastal wind conditions of Lombok.

2.6. Turbine Performance Evaluation

The final stage of the study involved evaluating the overall turbine performance based on the simulation results. Performance indicators such as rotor efficiency, aerodynamic power extraction capability, and operational characteristics were analyzed. The obtained results were then discussed in relation to the suitability of the NACA 4415 airfoil for small-scale wind turbine applications in coastal areas.

The performance assessment was conducted by examining the relationships among wind speed, power coefficient, thrust coefficient, and blade aerodynamic behavior. The findings provide insights into the feasibility of implementing NACA 4415-based horizontal axis wind turbines as a renewable energy solution for coastal regions in Lombok, Indonesia.

3. Result and Discussion

This section presents the aerodynamic characteristics of the NACA 4415 airfoil and the performance-related parameters obtained from the QBlade simulations. The analysis begins with the evaluation of the airfoil aerodynamic behavior, including lift, drag, pressure distribution, and boundary layer development. Subsequently, the extended aerodynamic characteristics obtained through the 360° polar extrapolation are discussed to assess the airfoil performance over a wider range of operating conditions. Finally, the turbulent wind field characteristics employed in the simulation are examined to evaluate the influence of realistic wind fluctuations on turbine operation. These analyses provide the basis for assessing the suitability of the NACA 4415 airfoil for horizontal axis wind turbine applications under coastal wind conditions in Lombok, Indonesia.

3.1. Aerodynamic Analysis of the NACA 4415 Airfoil

Figure 3 presents the aerodynamic characteristics of the NACA 4415 airfoil obtained from QBlade analysis. The lift coefficient (C_l) (Figure 3a) increases progressively with increasing angle of attack, indicating the capability of the airfoil to generate aerodynamic lift efficiently. The maximum lift coefficient is achieved before the onset of stall, demonstrating favorable aerodynamic performance for wind turbine applications. The drag coefficient (C_d) (Figure 3b) remains relatively low at moderate angles of attack and increases significantly at higher angles, which is consistent with the expected aerodynamic behavior of cambered airfoils.

The pressure distribution (Figure 3c) shown in the figure indicates a significant pressure difference between the upper and lower surfaces of the airfoil. Lower pressure on the upper surface and higher pressure on the lower surface contribute to lift generation. Furthermore, the boundary layer (Figure 3d) development remains attached over most of the airfoil surface under normal operating conditions, suggesting stable aerodynamic performance and delayed flow separation.

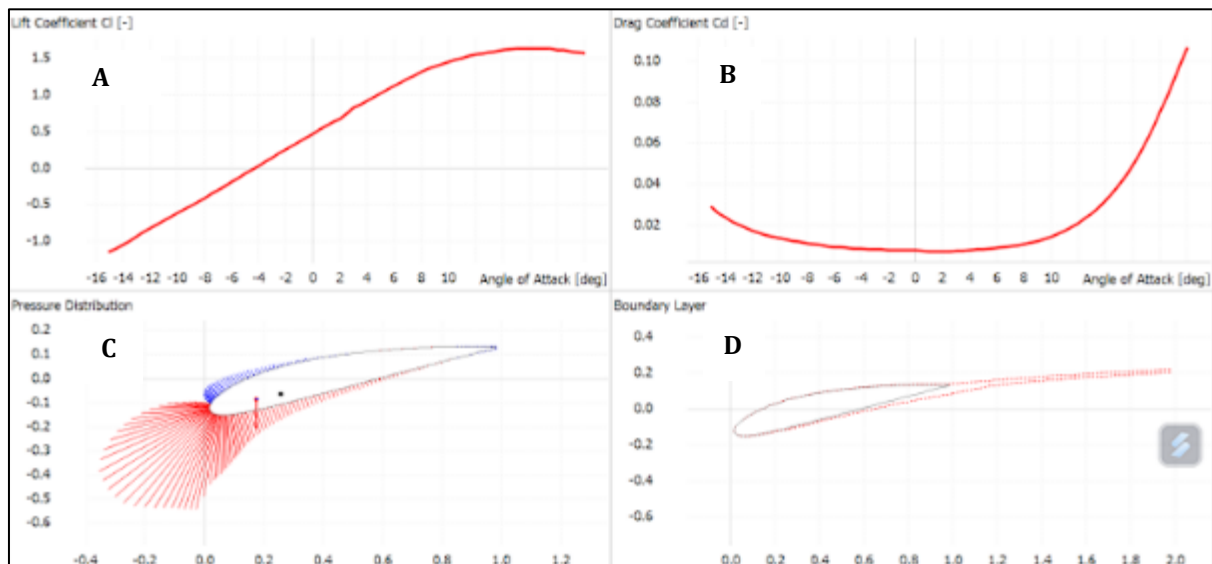


Figure 3 Aerodynamic characteristics of the NACA 4415 airfoil obtained from QBlade analysis

Overall, the aerodynamic characteristics demonstrate that the NACA 4415 airfoil possesses a favorable balance between lift generation and drag reduction, making it suitable for horizontal axis wind turbine blade design.

3.2. Polar Extrapolation Analysis of NACA 4415

Figure 4 illustrates the 360° polar extrapolation results of the NACA 4415 airfoil, including the lift coefficient (C_l), drag coefficient (C_d), and moment coefficient (C_m) over a complete range of angles of attack. The extrapolation process is essential for Blade Element Momentum (BEM) simulations because wind turbine blades may experience both attached-flow and stalled-flow conditions during operation.

The lift coefficient curve (Figure 4a) exhibits the expected variation with angle of attack, reaching positive maximum values in the operational range before decreasing as stall conditions occur. Similarly, the drag coefficient (Figure 4b) remains relatively low near the normal operating region but increases substantially under large positive and negative angles of attack due to flow separation effects. The moment coefficient curve (Figure 4c) indicates the aerodynamic pitching behavior of the airfoil, which is important for evaluating blade stability and load distribution.

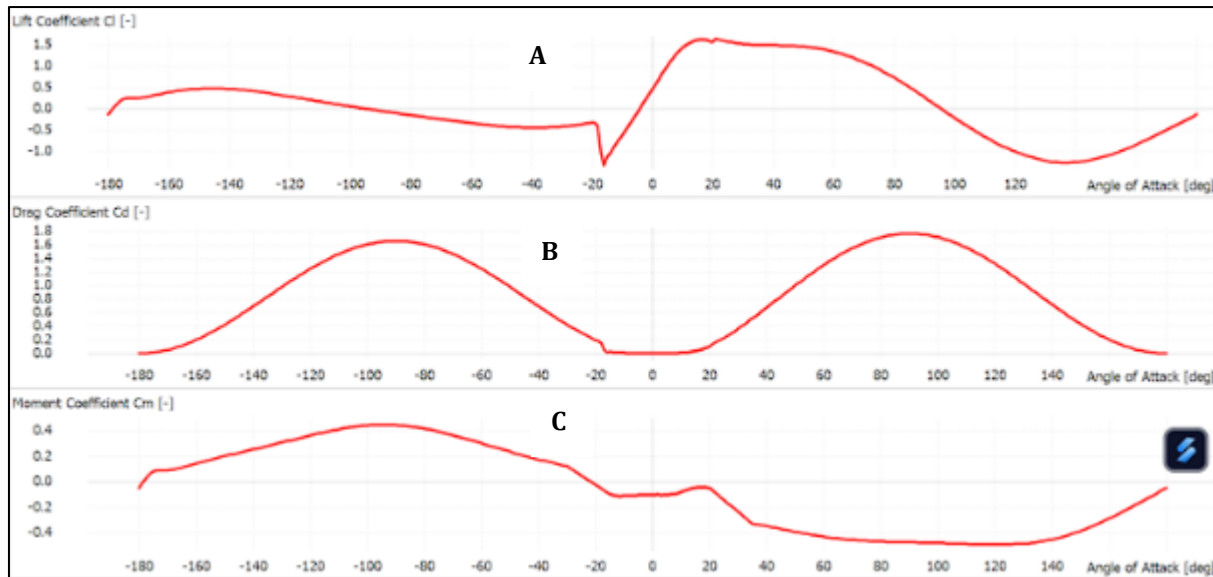


Figure 4 360° aerodynamic polar characteristics of the NACA 4415 airfoil

The availability of aerodynamic data over the entire 360° range allows more accurate prediction of rotor performance under transient and off-design operating conditions. Therefore, the extrapolated polar data improve the reliability of the subsequent BEM-based turbine performance simulations.

3.3. Turbulent Wind Field Characteristics

Figure 5 presents the turbulent wind field generated for the simulation environment. The generated wind field contains temporal variations in the velocity components, representing realistic atmospheric turbulence conditions encountered by wind turbines operating in coastal environments.

The longitudinal velocity component shows fluctuations around the mean wind speed, indicating the presence of varying wind energy input to the rotor. The lateral and vertical velocity components also exhibit random oscillations, reflecting the stochastic nature of atmospheric turbulence. These variations are important because they directly influence aerodynamic loading, rotor dynamics, and power production [14].

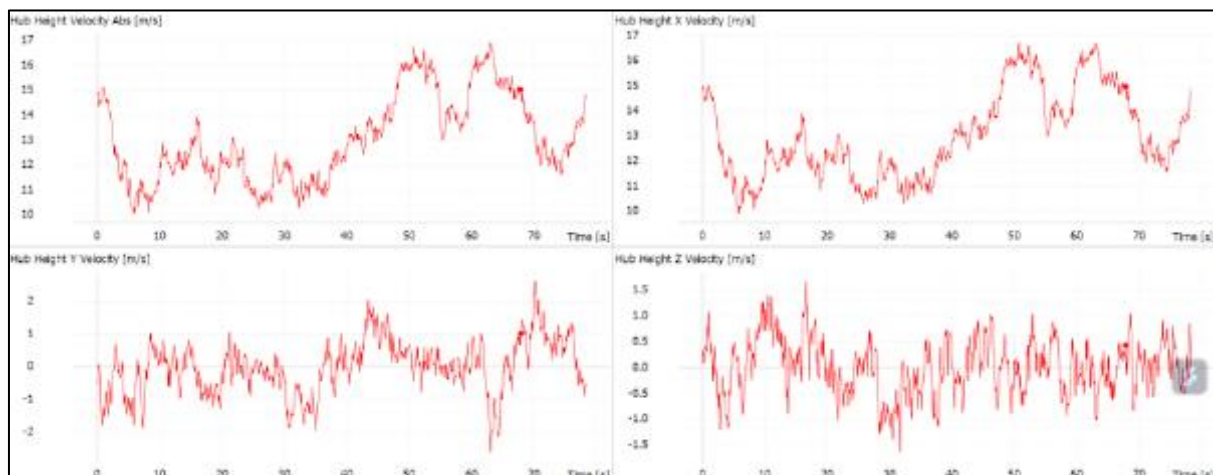


Figure 5 Turbulent wind field characteristics at hub height used in the turbine simulation

The implementation of a turbulent wind field enables a more realistic assessment of turbine performance compared with uniform wind assumptions [15]. Consequently, the simulation results better represent the actual operating conditions expected in coastal regions such as Kuta Beach, Lombok. The generated turbulence characteristics provide a suitable basis for evaluating the robustness and aerodynamic response of the NACA 4415-based horizontal axis wind turbine under fluctuating wind conditions.

4. Conclusion

This study investigated the aerodynamic performance of a NACA 4415-based horizontal axis wind turbine using QBlade simulation under representative coastal wind conditions in Lombok, Indonesia. Based on the obtained results, the following conclusions can be drawn:

- The NACA 4415 airfoil demonstrated favorable aerodynamic characteristics, including a progressive increase in lift coefficient with increasing angle of attack and relatively low drag within the normal operating range. These characteristics indicate its suitability for wind turbine blade applications.
- The pressure distribution and boundary layer analyses showed stable aerodynamic behavior over the airfoil surface, contributing to efficient lift generation and delayed flow separation under typical operating conditions.
- The 360° polar extrapolation successfully extended the aerodynamic database of the airfoil, providing lift, drag, and moment coefficient information over the full angle-of-attack range. This extended dataset is essential for reliable Blade Element Momentum (BEM) simulations and off-design operating condition analysis.
- The turbulent wind field simulation reproduced realistic wind fluctuations commonly observed in coastal environments. The generated wind conditions enabled a more representative assessment of turbine performance compared with uniform wind assumptions.
- The overall simulation results indicate that the NACA 4415 airfoil has significant potential for use in horizontal axis wind turbines operating in coastal regions of Lombok. Its aerodynamic performance and adaptability to varying wind conditions suggest its suitability for small-scale renewable energy generation applications.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper. No financial, personal, or professional relationships with individuals or organizations have influenced the outcome or content of this manuscript.

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