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Standard-Oriented Numerical Investigation of Small Offshore Wind Turbine Blades in Warm Coastal Climates

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Abstract

This study presents a comprehensive numerical analysis of small-scale offshore wind turbine blade configurations, focusing on a direct integration of international design standards (IEC 61400-1, DNV-GL) with computational fluid dynamics (CFD) under representative hot-humid coastal conditions. We systematically investigated the aerodynamic performance and wake stability of two-blade versus three-blade rotor designs using the SST $k-\omega$ turbulence model within a steady RANS framework. The simulations were conducted at a wind speed of 7 m/s, considering specific atmospheric properties ($\rho=1.145 \text{ kg/m}^3$, $\mu=1.86 \times 10^{-5} \text{ kg/(m}\cdot\text{s)}$) simulating a tropical climate (35 °C, 85% RH). Our findings reveal that the three-blade configuration achieves a 16% higher power coefficient (C_p) compared to the two-blade design, alongside improved wake stability. Crucially, the analysis demonstrates that neglecting the 6.5% reduction in air density characteristic of tropical climates can lead to a proportional overestimation of annual energy production, necessitating site-specific thermophysical corrections in standard-compliant design workflows. This quantitative insight underscores the importance of considering site-specific climatic parameters alongside established design standards in the preliminary assessment of offshore wind turbines, particularly for tropical and subtropical regions.

Keywords Offshore wind turbine; Standard-oriented assessment; CFD analysis; IEC 61400-1; Coastal climate

Introduction

Offshore wind energy has become an increasingly important component of modern energy systems, particularly for coastal regions seeking to diversify their energy supply while reducing greenhouse gas emissions [1]. Compared to onshore installations, offshore wind turbines benefit from higher and more consistent wind resources; however, they are also subject to more demanding environmental conditions and stricter design requirements. As a result, the performance and reliability of offshore wind turbines depend not only on aerodynamic optimization but also on compliance with internationally recognized design standards.

In hot and humid coastal regions, such as those located along the southern coastline of Iran, elevated ambient temperatures and moisture levels may influence air density, boundary-layer behavior, and aerodynamic loading on turbine blades. These effects can alter the expected performance trends derived under temperate conditions and may have implications for fatigue loading and long-term operational safety. International standards, particularly IEC 61400-1[2], explicitly emphasize the importance of accounting for site-specific environmental conditions during the design and assessment of wind energy systems. Nevertheless, many numerical investigations reported in the



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literature focus primarily on performance enhancement, with limited discussion of how simulation results relate to standard-based design assumptions.

Wind turbine blade configuration plays a critical role in both energy capture efficiency and structural reliability. While three-blade rotors are generally preferred in commercial offshore applications due to their favorable aerodynamic stability and reduced cyclic loading, two-blade configurations are still considered in small-scale systems because of their lower material usage and simplified construction. A rigorous comparison of these configurations under realistic coastal conditions, evaluated through a standard-oriented numerical framework, remains relatively scarce.

The present study addresses this gap by conducting a numerical assessment of small-scale offshore wind turbine blade configurations with explicit reference to international standards and regional climatic characteristics. Rather than proposing a new blade geometry or pursuing purely theoretical optimization, this research aims to evaluate whether commonly adopted blade configurations exhibit performance trends that are consistent with standard expectations when subjected to hot and humid coastal conditions. By linking numerical results to standard-based design considerations, the study seeks to provide practical insights for engineers and decision-makers involved in the preliminary evaluation and standard conformity assessment of offshore wind turbines.

2. Materials and Methods

2.1 Turbine Configuration and Design Assumptions

The global transition toward sustainable energy has accelerated the development of offshore wind technology. While large-scale wind farms dominate current research and industrial deployment, small-scale offshore turbines provide an attractive alternative for decentralized power generation in coastal communities. Nevertheless, the aerodynamic performance of such systems can be strongly influenced by site-specific environmental conditions that deviate from the reference conditions assumed in international design standards such as IEC 61400-1 [2] and DNV GL [3].

In hot and humid coastal regions—such as those found

along the southern coast of Iran—elevated ambient temperatures and high relative humidity alter the thermophysical properties of air, particularly density and viscosity. These variations affect the aerodynamic loading on turbine blades and consequently influence the power extraction capability of the rotor. Despite the availability of standardized design methodologies, the quantitative impact of such climatic deviations on rotor configurations with different blade numbers remains insufficiently explored.

To address this issue, the present study investigates the aerodynamic behavior of small-scale offshore wind turbine rotors designed according to standard-based guidelines. Two rotor configurations are considered: a two-bladed rotor and a three-bladed rotor operating under identical geometric and operating constraints. The turbine is designed as a horizontal-axis wind turbine (HAWT) with a fixed hub height and rotor diameter suitable for small-scale offshore applications. The baseline design parameters, including rotor radius, hub radius, and nominal operating conditions, follow commonly adopted engineering practices for distributed wind energy systems.

To ensure complete reproducibility of the numerical model, the blade geometry was defined according to a standard-oriented design methodology consistent with the recommendations of IEC 61400-1 [2] for small horizontal-axis wind turbines. Both the two-blade and three-blade rotor configurations employed an identical blade geometry, including the airfoil profile, blade span, chord distribution, twist distribution, hub radius, and rotor radius. Consequently, the number of blades was the only design variable considered in the present comparative investigation.

The blade sections were generated using the NACA 4412 airfoil, which has been extensively applied in small wind turbine applications because of its favorable aerodynamic characteristics at moderate Reynolds numbers. The blade chord decreases linearly from 0.18 m at the root to 0.065 m at the tip, while the blade twist decreases from 18° at the root to 2° at the blade tip. The three-dimensional blade geometry was constructed by lofting the spanwise airfoil sections according to the prescribed chord and twist distributions, providing a consistent reference geometry for all CFD simulations.

Table 1. Geometric characteristics of the designed rotor blade.

Parameter	Symbol	Value	Unit
Rotor radius	R	1.5	M
Hub radius	R_h	0.15	M
Number of blades	B	2/3	–
Rated wind speed	U	7	m/s
Tip speed ratio	Λ	5	–
Airfoil profile	–	NACA 4412	–

Table 2. Spanwise blade geometry used for CFD simulations

Airfoil	Twist (°)	Chord (m)	Radial position (m)
NACA4412	18	0.180	0.15
NACA4412	15	0.160	0.30
NACA4412	12	0.140	0.45
NACA4412	9	0.120	0.60
NACA4412	7	0.105	0.75
NACA4412	5	0.090	0.90
NACA4412	4	0.080	1.05
NACA4412	3	0.072	1.20
NACA4412	2.5	0.068	1.35
NACA4412	2	0.065	1.50

The NACA 4412 airfoil was selected for this study due to its superior lift-to-drag ratio at low-to-moderate Reynolds numbers ($10^5 < Re < 10^6$) which is the characteristic operating regime for the small-scale offshore turbines investigated here. To ensure full reproducibility of the aerodynamic model, the spanwise distributions of chord and twist—optimized for a design Tip Speed Ratio (TSR) of 5 using Blade Element Momentum (BEM) theory [4]—are explicitly detailed in Table 2. This specific geometry represents a standard benchmark for evaluating performance sensitivity in non-standard atmospheric conditions.

The principal [5] geometric parameters of the designed rotor used in the numerical simulations are summarized in Table 1. These parameters define the baseline configuration for the aerodynamic analysis and ensure the reproducibility of the computational model.

The selected design parameters comply with the general recommendations of IEC 61400-1 [3] regarding preliminary aerodynamic design and representative operating conditions for small horizontal-axis wind turbines.

The geometric parameters listed in Table 2 define the reference blade used throughout the numerical simulations and enable full reconstruction of the computational model for future validation and comparative studies.

Except for the blade number, all geometric characteristics, operating conditions, and numerical settings were kept identical for the two investigated rotor configurations. This approach ensures that the observed aerodynamic differences are exclusively attributable to the effect of blade number.

2.2 Computational Domain and Boundary Conditions

A hybrid computational domain was constructed to ensure both numerical accuracy near the blade surfaces and efficiency in the far-field region. The domain consists of a rotating inner cylinder (containing the rotor) and a station-

ary outer rectangular block. To prevent blockage effects and ensure fully developed wake capture, the downstream boundary was placed 10D (where D is the rotor diameter) from the rotor plane, while the upstream and lateral boundaries were located at 5D and 4D, respectively.

The mesh was generated using a multi-block structured approach in the near-wall regions to resolve the boundary layer, ensuring that the y^+ values remain below 1.0 for the SST $k-\omega$ turbulence model. A grid independence study was conducted using three mesh levels: coarse (1.2×10^6 cells), medium (63.2×10^6 cells), and fine (5.4×10^6 cells). The medium mesh was selected as the optimal trade-off, showing a C_p deviation of less than 0.8% compared to the fine mesh.

2.3. Boundary Conditions and Physics Setup

Boundary conditions were prescribed to reflect the physical reality of the offshore operating environment. A velocity inlet condition was defined at the upstream boundary with a uniform inflow speed of 7 m/s. The turbulence intensity at the inlet was set to 5% with a turbulent viscosity ratio of 10, aligning with the turbulence characteristics recommended by the IEC 61400-1 [2] standard for offshore site classifications. At the downstream boundary, a pressure outlet condition was applied with a gauge pressure of zero. No-slip boundary conditions were enforced on all blade surfaces to resolve the boundary layer characteristics.

To quantify the influence of regional climatic conditions on the aerodynamic performance of the rotor, the fluid properties within the computational domain were modified. Simulations were performed for both a reference standard atmosphere and a hot-humid coastal case typical of the southern regions of Iran. The thermophysical properties of the airflow, including air density (ρ) and dynamic viscosity (μ), were determined using the IAPWS-IF97 formulation and are summarized in Table 3.

Table 2. Thermophysical properties of air under standard atmosphere and hot-humid coastal conditions.

Parameter	Symbol	Standard Atmosphere	Hot-Humid Coastal Conditions	Unit
Ambient Temperature	T	15.0	35.0	°C
Relative Humidity	RH	50.0	85.0	%
Air Density	P	1.225	1.145	kg/m ³
Dynamic Viscosity	M	1.79×10^{-5}	1.86×10^{-5}	kg/(m·s)
Reference Wind Speed	U	7.0	7.0	m/s

As detailed in Table 3, the combination of high ambient temperature and elevated relative humidity results in a 6.5% reduction in air density compared to standard atmospheric conditions, alongside a slight increase in dynamic viscosity. These variations directly influence the Reynolds number and the kinetic energy flux of the incoming flow. The steady-state Reynolds-Averaged Navier-Stokes (RANS) equations were solved using a second-order upwind discretization scheme for both momentum and turbulence equations. While offshore aerodynamic environments are inherently transient due to wave-induced motions and wind shear, this steady-state approach is adopted to evaluate the time-averaged performance trends and comparative blade efficiencies. This formulation provides a computationally efficient and reliable baseline for standard-oriented preliminary design assessments before proceeding to transient load analyses.

2.3 Governing Equations and Turbulence Modeling

The airflow around the rotor was modeled as an incompressible viscous fluid. The governing equations consist of the steady-state Reynolds Averaged Navier-Stokes (RANS) equations, which describe the conservation of mass and momentum within the computational domain. The continuity equation is expressed as

$$\nabla \cdot \mathbf{U} = 0$$

while the momentum conservation equation can be written as

$$\rho(\mathbf{U} \cdot \nabla) \mathbf{U} = -\nabla P + \mu \nabla^2 \mathbf{U} - \rho \nabla \cdot (\mathbf{u}' \mathbf{u}')$$

where $\mathbf{U}$ represents the mean velocity vector, p is the pressure, ρ is the air density, μ is the dynamic viscosity, and $\mathbf{u}' \mathbf{u}'$ denotes the Reynolds stress tensor arising from turbulence fluctuations.

To close the RANS equations, the Shear Stress Transport (SST) $k-\omega$ turbulence model was employed. This model

combines the near-wall accuracy of the $k-\omega$ formulation with the robustness of the $k-\epsilon$ model in the outer flow region through a blending function. As a result, the SST $k-\omega$ model provides reliable predictions of boundary-layer development, adverse pressure gradients, and flow separation over aerodynamic surfaces such as wind turbine blades.

The steady-state formulation adopted in this study is intended to capture the time averaged aerodynamic behavior of the rotor. Although offshore wind environments may exhibit transient fluctuations, the RANS approach provides a computationally efficient framework for evaluating mean performance characteristics and comparing rotor configurations under standardized operating conditions.

For the operating wind speed considered in this study (7 m/s) and the rotor radius defined in Table 1, the characteristic Reynolds number of the blade sections is on the order of 10^5 – 10^6 , which lies within the range where the SST $k-\omega$ model has been widely used in aerodynamic simulations of wind turbine rotors in wind turbine aerodynamic simulations. The SST $k-\omega$ model was selected because it provides improved predictions of boundary-layer separation and adverse pressure gradients compared with the standard $k-\epsilon$ model, making it particularly suitable for and adverse pressure gradients compared with the standard $k-\epsilon$ model, making it particularly suitable for wind turbine aerodynamic simulations.

The simulations were performed using a pressure-based steady-state solver with the Multiple Reference Frame (MRF) approach for the rotating domain. Pressure-velocity coupling was achieved using the SIMPLE algorithm, while second-order upwind discretization was employed for both momentum and turbulence transport equations. The residual convergence criterion for all governing equations was set to 10^{-6} .

Table 4. Results of the spatial independence study

Mesh	Cells	Cp	Difference (%)
Coarse	1.2×10^6	0.357	—
Medium	3.2×10^6	0.364	1.9
Fine	5.4×10^6	0.367	0.8

2.4 Mesh Generation and Numerical Accuracy

The computational domain was discretized using an unstructured tetrahedral mesh generated to accurately capture the complex three dimensional flow around the rotor blades. To properly resolve the near wall flow behavior, local mesh refinement was applied in the vicinity of the blade surfaces. Inflation layers were introduced adjacent to the blade walls to ensure adequate resolution of the boundary layer, which is essential for the accurate application of the SST $k-\omega$ turbulence model.

Additional mesh refinement was implemented in regions characterized by strong velocity gradients, particularly within the blade tip region and the downstream wake where vortex structures are expected to develop. This strategy allowed improved prediction of aerodynamic loading and wake development without excessively increasing the overall computational cost.

To evaluate the influence of grid resolution on the numerical results, a mesh independence study was performed using three progressively refined meshes. The power coefficient (C_p) of the rotor was selected as the primary performance indicator for comparison. The total number of cells in the tested meshes ranged from approximately 0.8×10^6 elements.

The results showed that the variation in the predicted power coefficient between the two finest meshes was less than 1%. Consequently, the intermediate mesh was selected for the final simulations as it provided sufficient numerical accuracy while maintaining reasonable computational efficiency.

As shown in Table 4, the C_p variation between the medium (3.2M cells) and fine (5.4M cells) meshes is less than 0.8%, confirming that the solution is spatially independent. While direct experimental data for the specific tropical conditions are unavailable, the predicted C_p value of 0.364 for the three-blade rotor aligns closely with established performance benchmarks for NACA 4412-based rotors at similar Reynolds numbers. The use of the SST $k-\omega$ model ensures that boundary layer separation and adverse pressure gradients, critical for offshore airfoil performance, are captured with high numerical fidelity.

3. Results and Discussion

The numerical results obtained from the simulations were analyzed with the aim of identifying performance trends that are relevant from both aerodynamic and standard-com-

pliance perspectives. Rather than focusing on absolute performance values, the discussion emphasizes relative comparisons between blade configurations and operating conditions, in line with the objectives of a standard-oriented preliminary assessment.

3.1 Aerodynamic Performance Indicator

The aerodynamic performance of the investigated rotor configurations was evaluated using the non-dimensional power coefficient, which is commonly adopted in wind turbine performance assessments and referenced in international standards. Expressing performance in non-dimensional form allows for meaningful comparison between different configurations while avoiding dependence on site-specific absolute values.

Across the examined operating conditions, the calculated power coefficient exhibited systematic variations with blade pitch angle and blade number. These variations provide insight into the aerodynamic behavior of the rotor configurations under conditions representative of hot and humid coastal environments.

3.2 Influence of Blade Pitch Angle

For both rotor configurations, an increase in blade pitch angle from a low setting to a moderate value resulted in improved aerodynamic performance. This behavior can be attributed to enhanced lift generation and more favorable aerodynamic loading along the blade span. However, further increases in pitch angle led to a reduction in the power coefficient, indicating the onset of increased aerodynamic losses.

This trend is consistent with established aerodynamic principles and aligns with standard design guidance, which recommends avoiding excessive pitch angles that may promote flow separation and unsteady loading. From a standard-compliance standpoint, the results confirm that moderate pitch settings provide a suitable balance between performance and aerodynamic stability under the investigated coastal conditions.

3.3 Comparison of Two-Blade and Three-Blade Configurations

A comparative evaluation of the two-blade and three-blade rotor configurations revealed that the three-blade rotor consistently achieved higher aerodynamic efficiency under

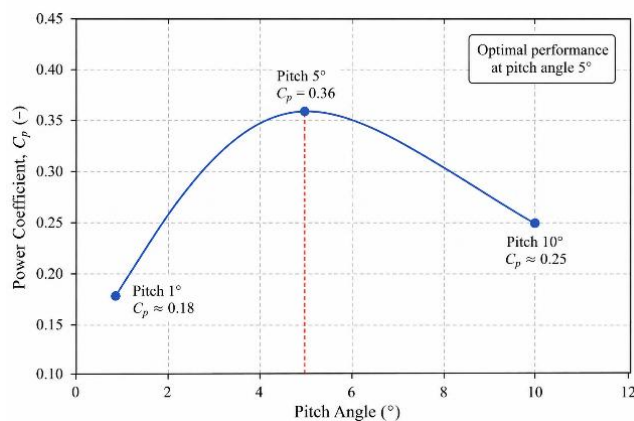


Fig 1. C_p sensitivity to blade pitch angle

equivalent operating conditions. In addition to improved energy capture, the three-blade configuration demonstrated smoother aerodynamic behavior, as reflected by more uniform flow development in the rotor wake. A quantitative comparison between the two-blade and three-blade configurations was performed at a pitch angle of 5°. The results are summarized in Table 5.

The three-blade configuration exhibits a higher power coefficient, indicating improved energy extraction efficiency. This improvement can be attributed to a more uniform aerodynamic loading distribution and reduced torque fluctuations.

Figure 2 illustrates the performance differences between two-blade and three-blade rotors.

The quantitative comparison of aerodynamic efficiency is illustrated in Figure 2. At the design pitch angle of 5°, the three-blade rotor achieves a peak C_p of 0.36, representing a 16% improvement over the two-blade variant. This performance gain is primarily attributed to the higher rotor solidity, which enables a more effective capture of the wind's kinetic energy at the designated Tip Speed Ratio (TSR=5). As shown in the figure, the three-blade design exhibits a broader performance envelope, suggesting superior adaptability to the slightly higher dynamic viscosity of the tropical coastal air ($\mu=1.86 \times 10^{-5} \text{ kg(m.s)}$) compared to the standard atmosphere

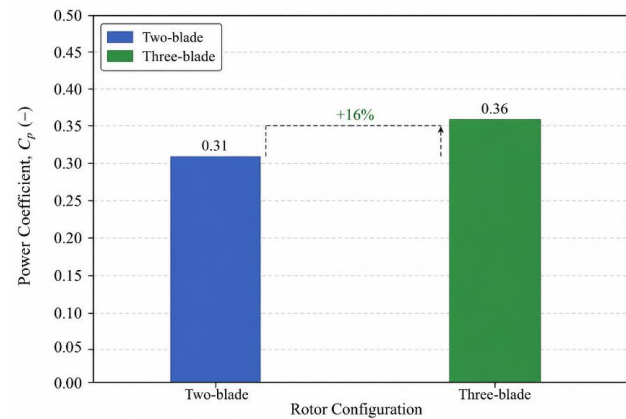


Fig 2. Performance comparison: two-blade vs. three-blade

3.4 Flow Characteristics and Standard-Oriented Interpretation

The superior performance of the three-blade configuration can be attributed to a more even distribution of aerodynamic loading and reduced sensitivity to local flow disturbances. These characteristics are particularly relevant in offshore applications, where standards such as IEC 61400-1[3] emphasize the importance of minimizing cyclic loading and enhancing operational reliability.

The flow physics and wake evolution, visualized through velocity streamlines in Figure 3, provide further insight into the rotor's behavior. The three-blade configuration demonstrates a highly coherent and symmetric wake structure, with well-defined vortex maturation in the near-wake region. This symmetry is critical for reducing the periodic aerodynamic excitations that lead to fatigue, a key concern in the IEC 61400-1[3] safety standards. The streamlines indicate that the flow remains largely attached over the suction side of the NACA 4412 profile at 5° pitch, confirming that the SST $k-\omega$ model effectively captures the boundary layer stability under the high-temperature conditions of the study area.

3.5 Climatic Sensitivity Analysis

To explicitly quantify the climatic impact, the simulations compared a standard ISO atmosphere ($\rho=1.225 \text{ kg/m}^3$) with the target tropical conditions ($\rho=1.145 \text{ kg/m}^3$). As summarized in Table 2, the simultaneous increase in temperature to 35°C and relative humidity to 85% results in a

Table 5. Power coefficient comparison for different blade configurations

Configuration	Pitch angle (°)	Power coefficient (C_p)	Relative change (%)
Two-blade	5	0.31	–
Three-blade	5	0.36	+16

6.5% reduction in air density. While the non-dimensional power coefficient (C_p) remains largely consistent between the two cases, the actual power capture (P) decreases linearly with the reduction in ρ . This finding underscores that neglecting site-specific humidity and temperature in tropical regions leads to an overestimation of the annual energy production (AEP) by approximately 6.5%.

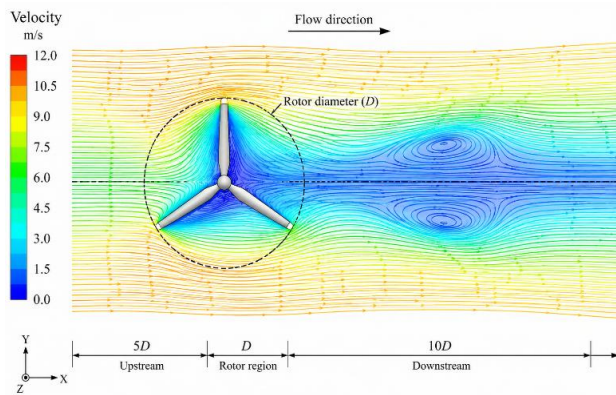


Fig 3. wake flow streamlines (three blade rotor)

4. Conclusions

A standard-oriented CFD assessment of small-scale offshore wind turbine blades was conducted for hot and humid coastal conditions. The results show that moderate pitch angles improve aerodynamic performance, while the three-blade configuration offers more stable wake behavior and better overall efficiency than the two-blade rotor. These findings suggest that rotor configuration and local climatic effects should both be considered in preliminary offshore turbine design. Within the limitations of a steady-state RANS framework, the study demonstrates the usefulness of standards-based numerical analysis for early-stage evaluation of offshore wind turbine blades. Further work should include transient simulations and experimental validation.

Conflict of Interest

The authors declare that there are no conflicts of interest associated with this study.

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Declarations

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Consent for publication

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Competing interests

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